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Robert W. Schlegel[1,2,3,*], Sofia Darmaraki[1], Jessica A. Benthuysen[4], Karen Filbee-Dexter[5,6], Eric C. J. Oliver[1]

[1]Department of Oceanography, Dalhousie University, Halifax, NS, Canada
[2]Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA, United States
[3]Laboratoire d'Océanographie de Villefranche, Sorbonne Université, Villefranche-sur-mer, France
[4]Australian Institute of Marine Science, Indian Ocean Marine Research Centre, Crawley, WA, Australia
[5]School of Biological Sciences and Oceans Institute, Indian Ocean Marine Research Centre, University of Western Australia, Crawley, WA, Australia
[6]Institute of Marine Research, Nye Flødevigveien 20, 4817 His, Norway
[*]Corresponding author: robert.schlegel@imev-mer.fr; Laboratoire d'Océanographie de Villefranche, 181 chemin du Lazaret, F-06230 Villefranche-sur-mer, France

Abstract

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

1. Introduction

Extreme climatic events such as heat waves, droughts, cyclones or cold snaps are expected to become more frequent with climate change (Drijthout et al., 2015; Collins et al. 2019). Understanding why extreme events occur, how they are changing, their role in disrupting ecosystems and impacting ecological function and services are important for assessing ecosystem resilience and trends. Temperature extremes are of particular importance to ecosystems as they may occur at the limits of species' thermal niches, posing a risk for their survival. With global warming, there has been increasing attention on extremely warm ocean temperature events, known as marine heatwaves (MHWs), which occupy the warm end of this temperature range (Hobday et al., 2016; Frölicher et al., 2018; Oliver et al., 2018; Holbrook et al., 2019; Smale et al., 2019). In contrast, extremely cold water events - marine cold-spells (MCSs) - have received less comprehensive and global attention despite a rich history of ecological and physically-based studies demonstrating acute and enduring impacts on marine ecosystems (e.g. Crisp, 1964; Hurst, 2007). Yet extreme cold temperature events are ecologically important phenomena which can shift the distribution of species, alter composition of communities and even bring about evolutionary change (Parmesan, 2006; Campbell-Staton et al., 2017). In some parts of the ocean, recent cold events have been found to have comparable magnitude with major warm events (e.g. Southwest/Southeast Atlantic; Lentini et al., 2001; Florenchie et al., 2004).

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

Other approaches to identify extremely cold water events use statistical methods with remotely sensed SST data and, for example, long time series to construct climatological measures of cold extremes based on local temperature variability, i.e. the 10th percentile (Schlegel et al., 2017). Another common method is the analysis of SST anomalies over a specific period or the application of principal component analysis or empirical orthogonal functions (e.g. Walker, 1987; Miles et al., 2009; Kataoka et al., 2014). For climate mode analyses, prolonged cold water events have been classified using indices based on SST anomalies and the exceedance from standard deviation over several months (e.g. Larkin and Harrison, 2001; Lutz et al., 2013; 2015; Pirhalla et al., 2015) or based on spatially averaged temperature anomalies below fixed thresholds (Lentini et al., 2001; Florenchie et al., 2004). In addition to remote sensing, field-based studies targeting ecological impacts use on-site observations, *in situ* data, and field survey results to characterise periods of extremely cold waters (Schwing and Pickett, 2004; Aretxabaleta et al., 2006; Lirman et al., 2011).

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

2. Marine cold-spells in the literature

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

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

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

2.1. Impacts on marine ecosystems and services

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

2.1.1. Marine ecological impacts

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

Although most reported impacts of MCSs are during the winter, there are scenarios where an event which occurs during the summer could have ecological consequences. For example, a summer MCS that coincides with a larval growth period could lead to lower larval survival and reduced recruitment for the species the following year (e.g., Lotterhos and Markel, 2012; Velázquez, 2003). A dramatic drop in summer temperature, which overcomes an organism's ability to acclimate, could also impact performance, even if it does not cross lower thermal limits for the species. Therefore, as species can have different thermal optima for reproduction, growth, and survival, a summer MCS may impact these sensitive stages (Bennett et al., 2019).

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

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

Even if MCSs do not cause direct mortality, these events can often have sub-lethal impacts such as suppressed growth, metabolic stress or reduced fitness (e.g., Burgess et al., 2009). For example, manatees are at risk to cold stress syndrome during winter events (Barlas et al., 2011) because they are unable to tolerate cold water temperature extremes below 20°C for extended periods (Irvine, 1983; Bossart et al., 2003). MCSs can potentially affect the foraging behaviour of seabirds by altering the distribution of their prey (Schumann et al., 1988). Cold periods weaken immune functions of fish leading to loss of energy and nutrition because of reduced feeding activities (Lee et al., 2014). This weakening can also cause reductions in a prey species' ability to evade predation (Thomson and Lehner, 1976). However, if the MCS develops slowly or if it is preceded by gradually decreasing temperatures, it has been hypothesized that species may have a higher probability of survival as they may acclimatise better than they would during a rapid temperature decrease (Gunter, 1951; Moore, 1976; McEachron et al., 1994).

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

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

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

MCSs are not always damaging for marine ecosystems and they may even benefit native taxa by reducing the abundance of non-native species. Rapid cooling during MCSs can incapacitate and kill non-endemic species rarely exposed to such low temperatures (e.g. Storey, 1937; Wells et al., 1961). Based on the climate variability hypothesis, tropical species have lower tolerance for winter minimums compared to temperate species, so MCSs could have more severe impacts on these species, and halt or slow tropicalisation (Holt and Holt, 1983; Vergés et al., 2014). Off Florida, MCSs have caused more severe reductions to the abundance of non-native fish than native and more resilient species (Rehage et al., 2016). Off Japan, persistent and extremely cold temperatures in winter 2017/18 led to mortality of non-native coral and tropical reef fish which had colonised Tosa Bay because of temperature increases (Leriorato and Nakamura, 2019). In the Gulf of Mexico, the winter 1970/71 MCS caused greater mortalities in tropical fish species compared to endemic species (Thomson and Lehner, 1976). The aftermath of a MCS has been proposed to provide a management opportunity for targeted interventions to maintain (or exploit) the reduction in the abundance of non-native species (Rehage et al., 2016). In addition to reducing abundance of non-native species, MCSs that are related to upwelling may have beneficial impacts on productivity. For example, enhanced populations of primary and secondary phytoplankton bloom species were recorded during an anomalous upwelling event in East Australia towards the end of the 1997/98 El Niño, which increased nutrient levels to their 99th percentile value over the last 57 years (Lee et al., 2001). MCSs have also been associated with increased coastal primary production around New Zealand (Chiswell and O'Callaghan, 2021).

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

2.1.2. Marine ecosystem service impacts

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

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

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

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

2.2. Atmospheric and oceanic mechanisms

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

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

where T_{mix} is the vertically-averaged mixed layer temperature, t is time, c_p the specific heat capacity of water, ρ is the seawater density, h the mixed layer depth, $\boldsymbol{u}_{mix} = (u, v)$ the two-dimensional mixed-layer horizontal velocity vector, and w the vertical velocity; the vertical average is represented by $x_{mix} = \frac{1}{h}\int_{-h}^{0} x dz$. Q_{net} represents the sum of the air-sea heat fluxes (shortwave, longwave, latent, sensible) with $Q_{sw(-h)}$ being the small fraction of shortwave radiation that escapes the base of the mixed layer. This equation relates the rate of mixed layer temperature change to the transfer of heat through air-sea heat flux, horizontal and vertical advection and the entrainment of deeper waters into the mixed-layer. The residual comprises additional mechanisms such as lateral induction and lateral and vertical diffusion, which usually have a much smaller contribution to heat changes than the terms explicitly described above.

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

2.2.1. Ocean, atmosphere, and climate drivers of MCSs

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

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

An alternative mechanism for MCS development is horizontal flows of cool waters associated with changes in the winds, along with vertical temperature advection related to upwelling processes. The expansion and/or intensification of upwelling areas has emerged as one of the most common drivers of MCS, e.g. in South Africa (Schumann et al., 1988; Schlegel et al., 2017), in Venezuela’s Morrocoy National Park in 1996 (Laboy-Nieves et al., 2011), and in the Gulf of Mexico in 1998 (Muller-Karger, 2000), while La Niña has been associated with extreme cold temperatures in the eastern Tropical Pacific (Mora and Ospina, 2002). In the southeast Atlantic, local air-sea heat fluxes were found to play a rather passive role, acting as a buffer to regulate surface cold events (between 1982-1999), referred to as Benguela Niñas, via latent heat flux anomalies. In the Benguela region, MCSs tended to occur due to wind anomalies generated in the western and central equatorial Atlantic (Florenchie et al., 2004) or a strengthening of equatorward winds (Walker, 1987), such as the prolonged 1981-1983 MCS owing to an acceleration of upwelling-favourable winds (Walker, 1987). In the Southern tropical Indian Ocean intraseasonal cooling events have been associated with reduced solar radiation, enhanced evaporation and strong entrainment during the austral summer (Saji et al., 2006). Vertical processes at the base of the mixed layer were found responsible for these cooling events mostly when the thermocline was shallow, whereas atmosphere heat fluxes dominated the events when the thermocline was deep (Vinayachandran and Saji, 2008). Similarly, cold blob events in the Northeast Pacific have been attributed to vertical entrainment processes when their peak occurs during the summer, where the mixed layer depth is shallower, whereas atmosphere heat fluxes and winds appear to dominate cold events whose peak occurs during the winter (Tang et al., 2021).

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

2.2.2. Climate Feedbacks

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

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

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

3. Defining marine cold-spells

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

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

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

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 (°C)	i_{mean}: mean temperature anomaly during the MCS
Maximum intensity (°C)	i_{max}: lowest temperature anomaly during the MCS
Cumulative intensity (°C days)	i_{cum}: sum of daily intensity anomalies over the duration of the event

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

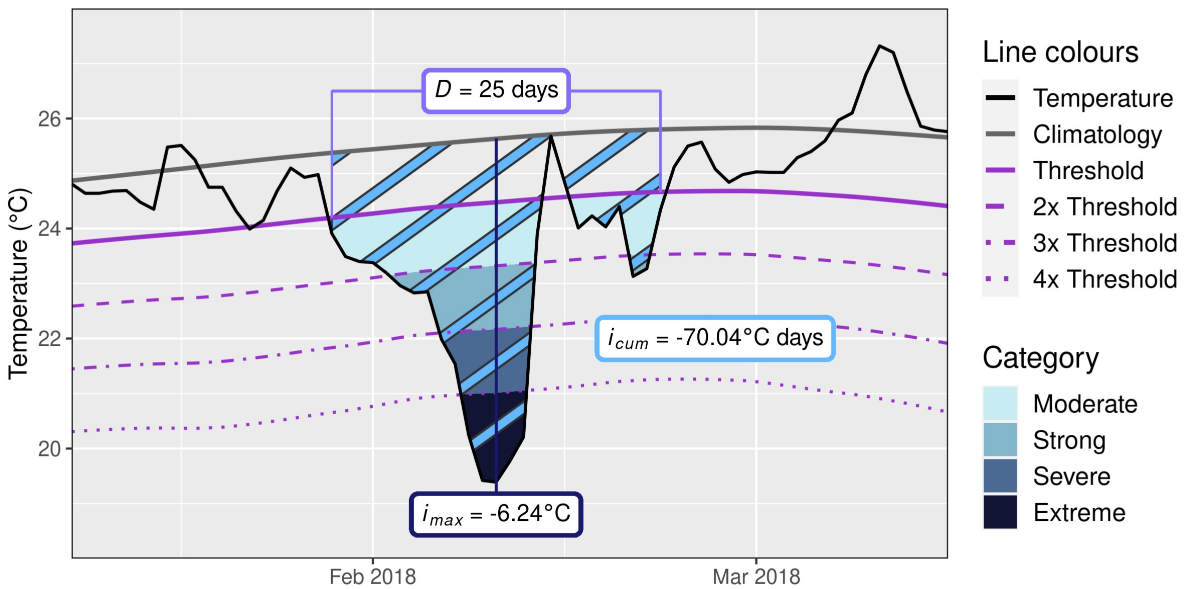

Figure 1: An example of a marine cold-spell (MCS). The portion of the time series experiencing one of the four possible categories are filled accordingly. The metrics shown are

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

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

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

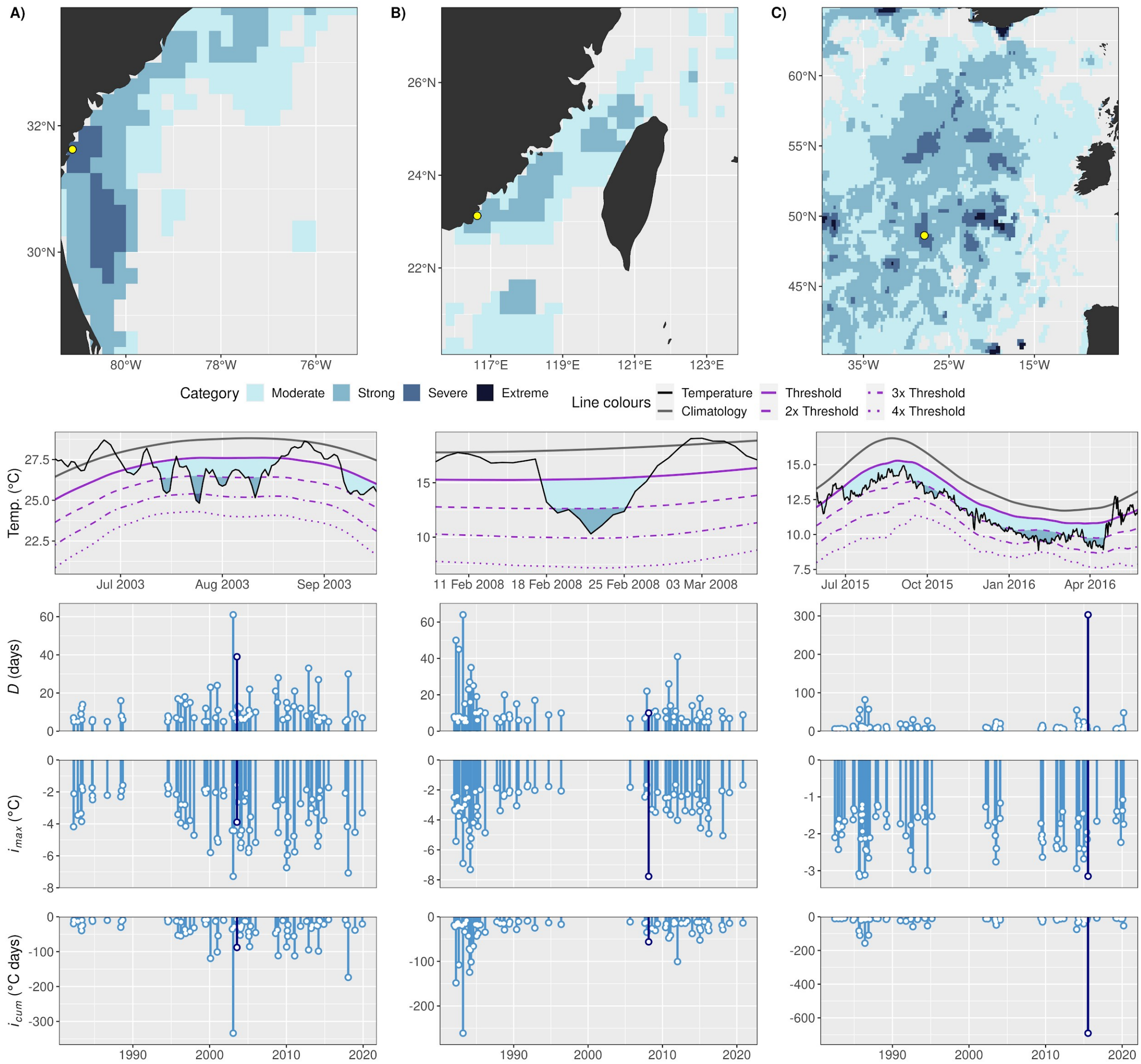

Figure 2: Three notable marine cold-spells (MCS) from the literature. Column A) shows the 2003 Summer Florida MCS; B) the 2008 Taiwan Strait MCS; and C) the North Atlantic Ocean cold blob of roughly 2013-2016. The top row of panels show the highest MCS category that occurred in each pixel during the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

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).

Case Study: Taiwan Strait 2008 marine cold-spell

In late January/early February 2008, a rapid decrease in winter ocean temperatures (~11°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).

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.

4. Global patterns in marine cold-spells

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

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

4.1. Mean state

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

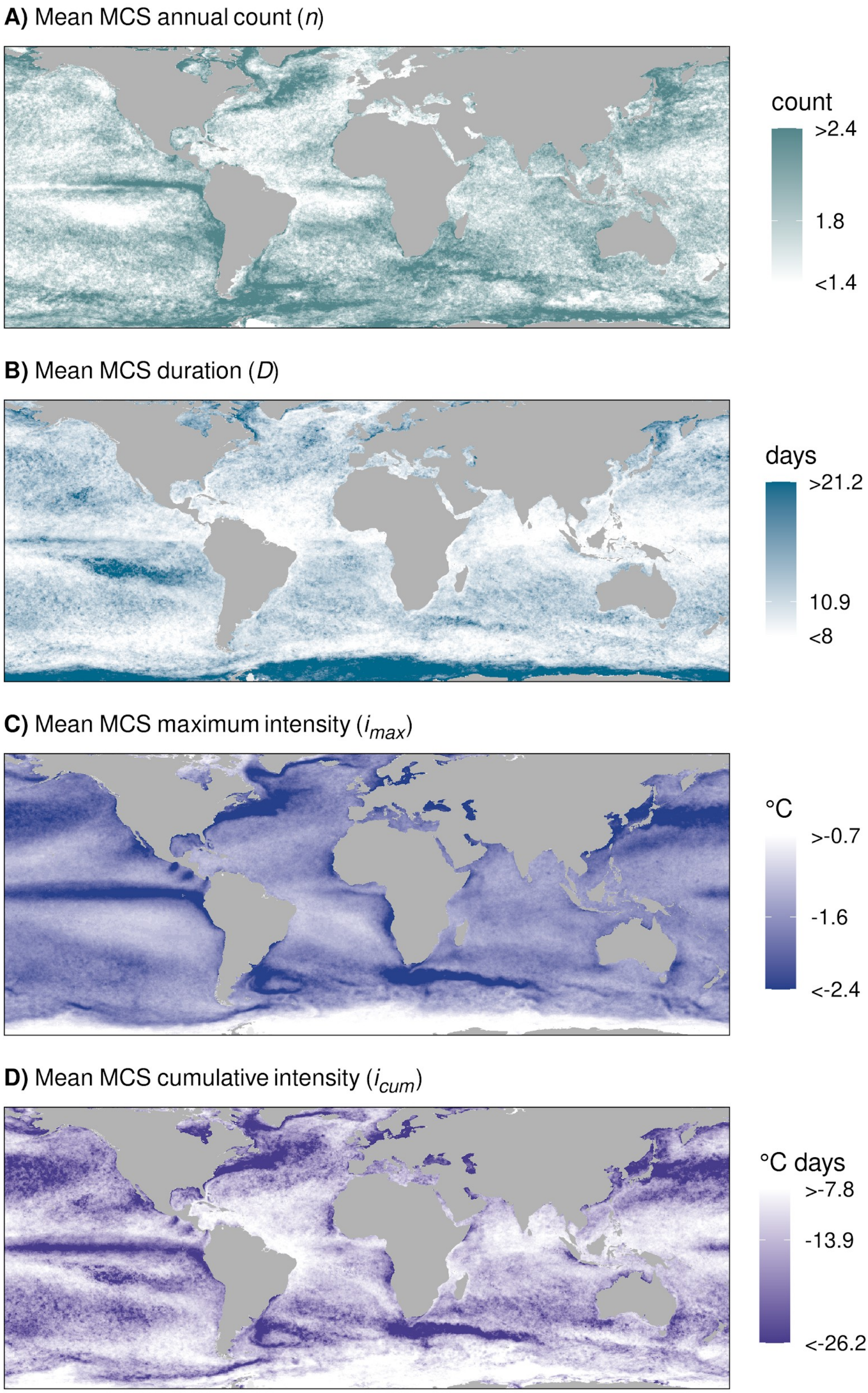

Figure 3: Global patterns of mean annual marine cold-spell (MCS) metrics calculated from 1982-2020. Maps shown for annual mean A) count (*n*); B) duration (*D*; days); C) maximum

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

4.2. Trends

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

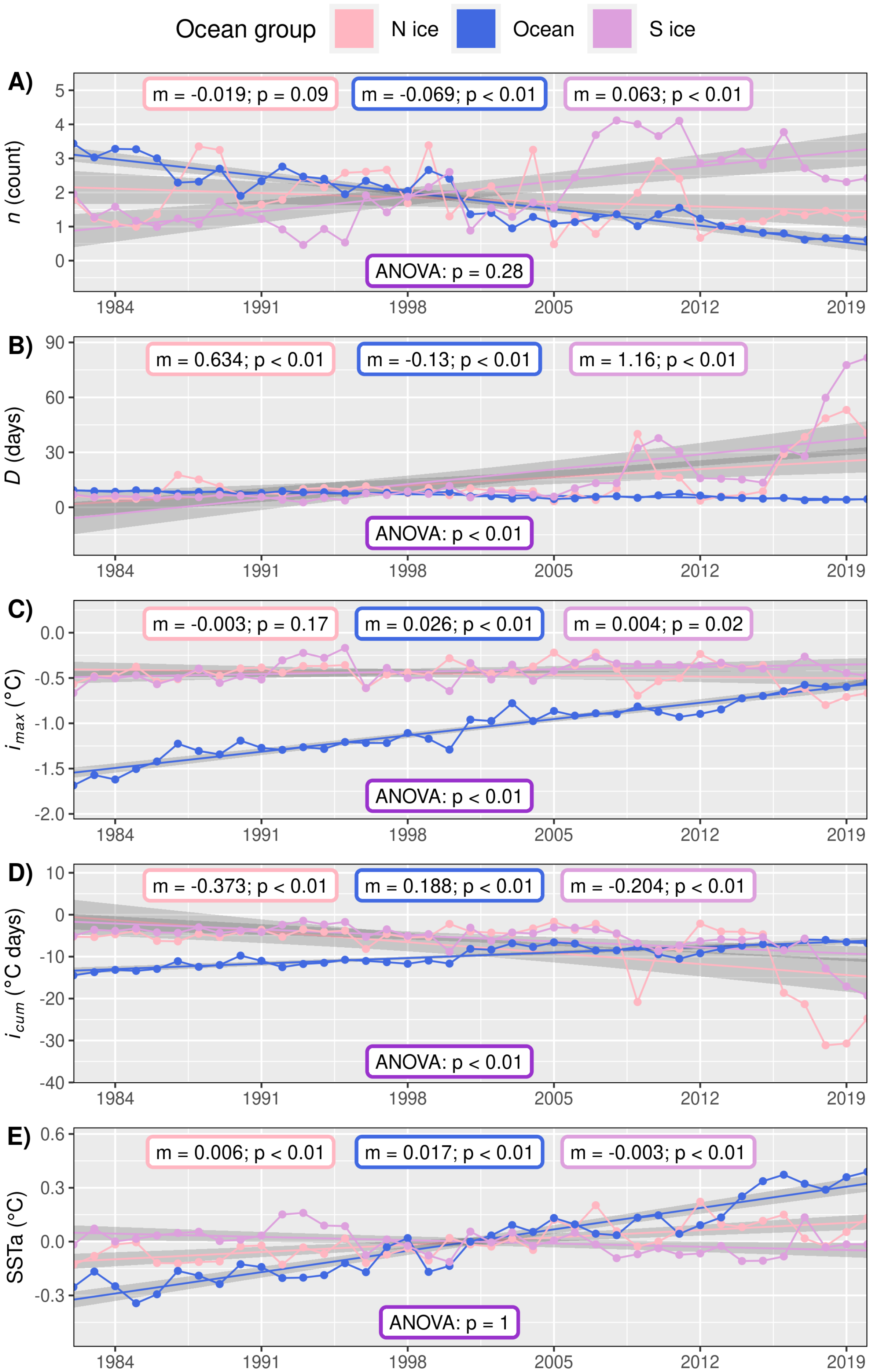

Figure 4: Trends in the marine cold-spell (MCS) metrics for the open ocean (blue) and northern (pink) and southern near-ice regions (purple). The near-ice regions are defined as

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

The most rapid decreases in MCS count were in the high-latitude and tropical North Atlantic, the tropical Indo-Pacific, and the mid-latitude regions of the North Pacific and South Pacific, where the significant declines exceed one fewer event per decade ($p < 0.05$; Figure 5A). Much of the eastern Pacific has had no noticeable change in MCS count, with most of the Southern Ocean experiencing significantly increased counts ($p < 0.05$). Given the record length (39 years), this spatial pattern confounds the influence of long-term climate change with multi-decadal variability, which is most notably due to the Atlantic Multidecadal Oscillation and the Interdecadal Pacific Oscillation (e.g. as for MHWs in Oliver et al., 2018).

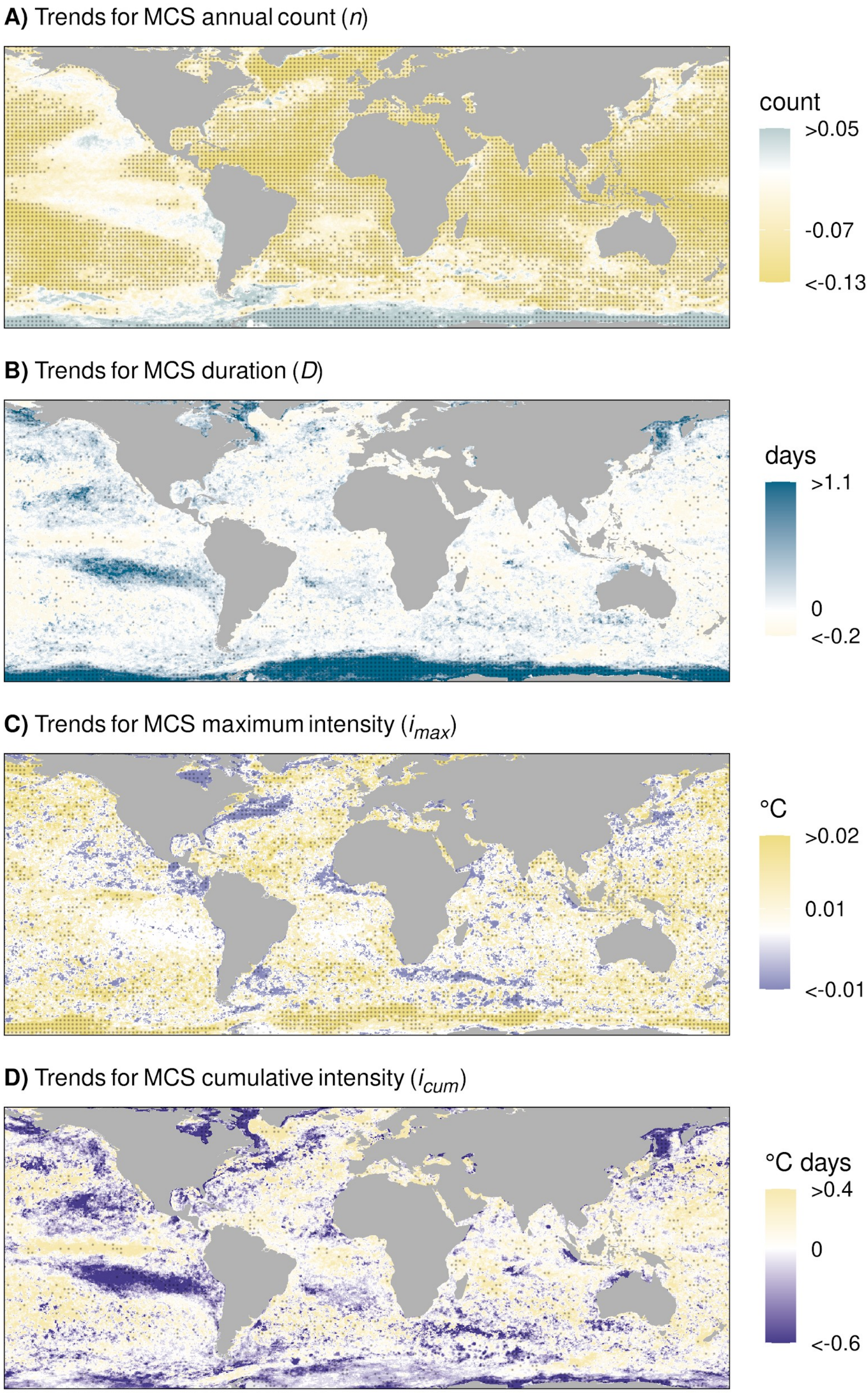

Figure 5: Global patterns of annual trends in marine cold-spell (MCS) metrics calculated from 1982-2020. The values in the colourbar labels for each panel are unit/year: A) count

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

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

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

The cumulative intensity of MCSs changed significantly in all three regions ($p < 0.01$; Figure 4D). The open ocean showed a weakening (+0.188°C days/year; $p < 0.01$), while the northern near-ice region (-0.373°C days/year) and southern near-ice region (-0.204°C days/year) showed strengthening. The trends in cumulative intensity use the same sign convention as for maximum intensity, which means that negative values indicate a strengthening trend. The changes in the cumulative intensity of MCSs most closely matches the changes to the duration of these events, with increasing event duration strengthening the corresponding cumulative intensities (Figure 5D; $r = -0.67$). Changes in cumulative intensity will be reflected in changes to both intensity and duration. Since the changes to MCS intensity are either negligible or slightly weakening, the changes in MCS duration are controlling the reported changes in cumulative intensity. Note however that this pattern does not hold in the Southern Ocean, which is seeing the most dramatic increases to MCS duration accompanied by decreases to maximum intensity.

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

4.3. Asymmetry between MHWs and MCSs

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

This asymmetry can be explained by the underlying temperature distribution. If the SSTa distribution was normally distributed, the warm and cold tails would be symmetric with warm and cold extremes to be of equivalent intensities and opposite in sign. However, if the temperature distribution is skewed, then the intensity of extremes on the skewed side of the distribution can be expected to be more intense than on the non-skewed side. For example, the portions of western boundary current extensions dominated by cold-core eddies (the equatorward side) will have a negative SST skewness, while areas dominated by warm-core eddies (the poleward side) will have a positive SST skewness (see Thompson and Demirov (2006) for an analogous signal in sea surface heights). A comparison of the SSTa skewness (Figure 6B) with the asymmetry between MHW and MCS intensity (Figure 6A) shows that areas of positive SST skewness correspond to areas of greater MHW intensity while areas of negative SST skewness correspond to areas of greater magnitude MCS intensity (r = 0.48).

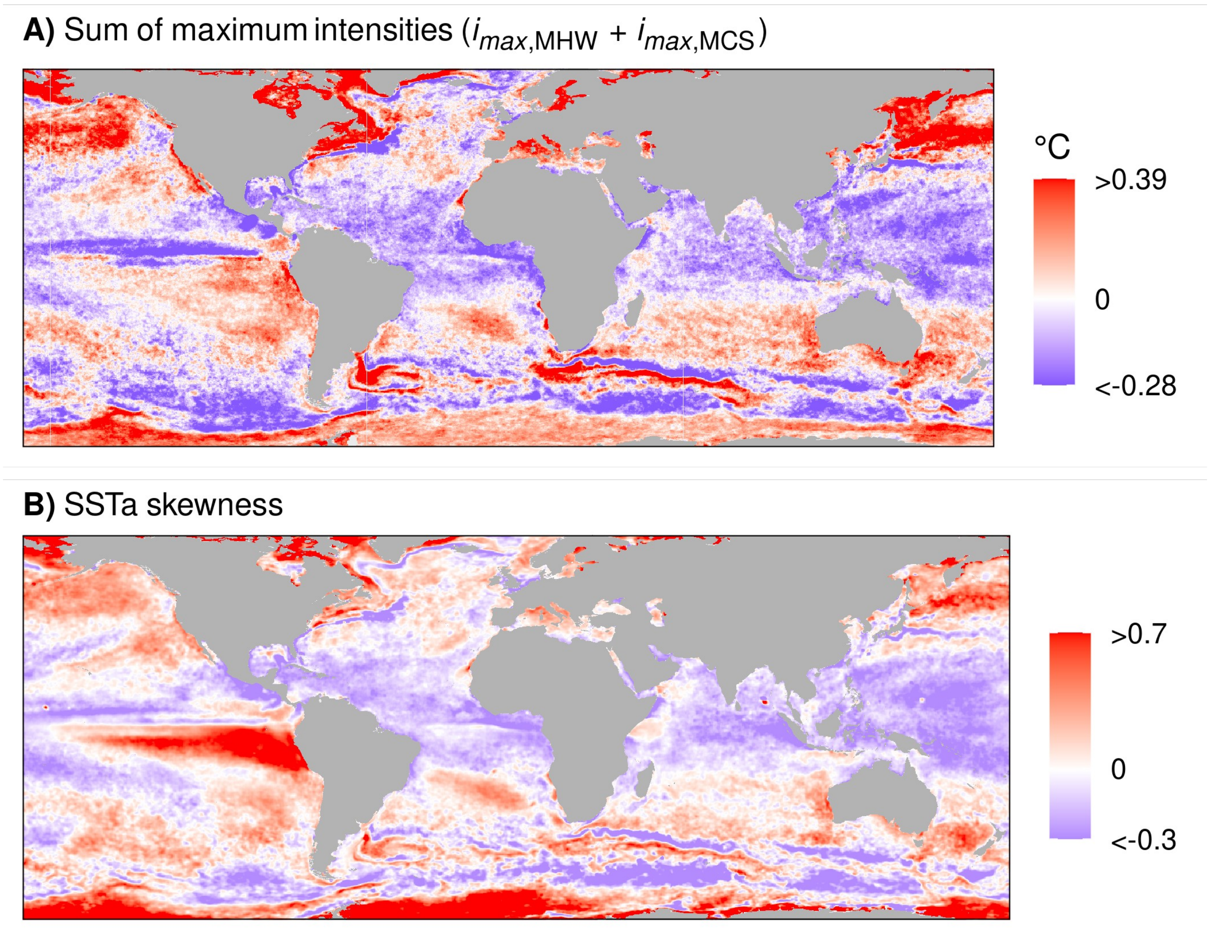

Figure 6: The global relationship of the sum of marine heatwave (MHW) and marine cold-spell (MCS) intensities with SST anomaly (SSTa) skewness calculated from 1982-2020. A) The sum of the maximum intensities of MHWs and MCSs as determined by adding the average maximum intensity of the events at each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

4.4. Categories

At a global scale, the category ranks of MCSs are decreasing (Figure 7). The average MCS days per year was highest in 1982 at 26 days and lowest in 2005 at 7 days (Figure 7A; left y-axis). There was a temporary increase in the average MCS days per year from 2007, peaking in 2011, before decreasing again to around 12 days/year. Almost all MCS days in any given year have been “I Moderate”, but the proportion of “II Strong” days has remained steady since 2005. Based on the contribution of MCS days from the southern near-ice area (Figure 7A; purple shading), the increase in MCS days has been largely due to the increasing duration of MCSs in the Southern Ocean (Figure 5B). The average number of MCS days per year in the open ocean (non-shaded region) has decreased significantly from 26 days in 1982 to 7 days in 2020 (linear trend of -0.5 days/year; R^2 = 0.71; p < 0.01; Figure 7A). At the start of the satellite period, roughly 6 - 7% of the surface of the ocean was experiencing a MCS of any given category on any day of the year (Figure 7A; right y-axis). This coverage has reduced roughly in half since 2012 with now only 2 - 4% of the ocean experiencing MCSs on any day. The proportion of the daily coverage of MCSs of any category other than “I Moderate” has almost disappeared.

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

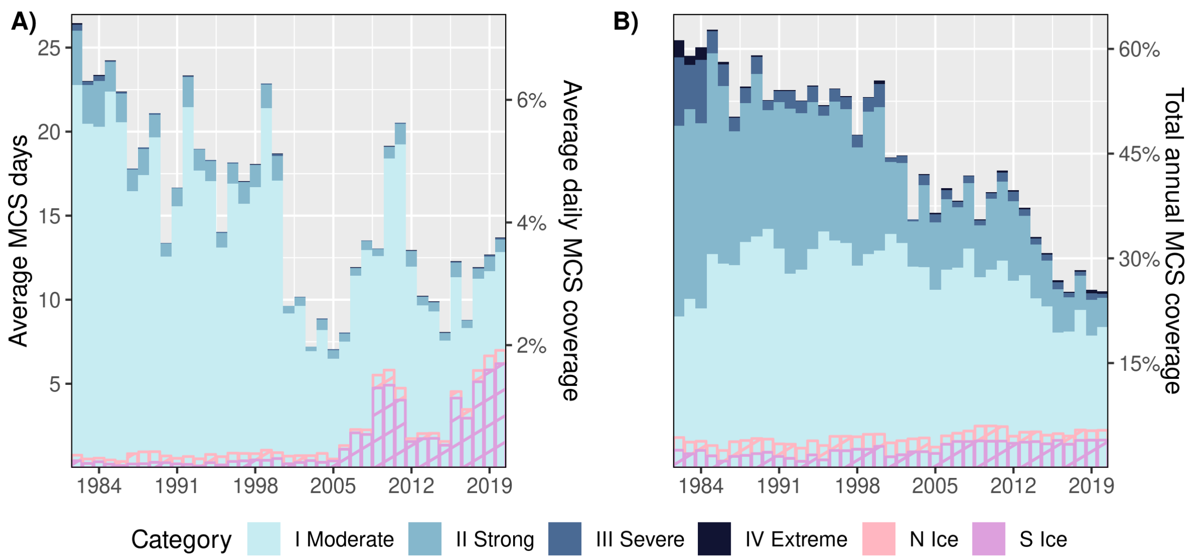

Figure 7: Global annual summary of marine cold-spell (MCS) categories. A) Average annual MCS days for the ocean (left y-axis), which may be divided by 365 to determine the average daily coverage (% area) of the ocean for a given year (right y-axis); B) The total area (%) of the ocean that experienced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

5. Discussion and conclusions

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

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

This work is an important synthesis and extension of the diverse body of existing knowledge on MCSs. This study is the first investigation to quantify and report on MCS occurrence and trends in a global context. These results can be used as a road map for policy makers and managers to know where, and to what degree, certain parts of the ocean are exposed to MCSs, and the degree to which this exposure may be changing with time. Importantly, we show that MCSs lead to significant impacts on marine ecosystems, with the potential to disrupt fisheries and aquaculture operations.

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

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Author contributions

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

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Supplementary figures

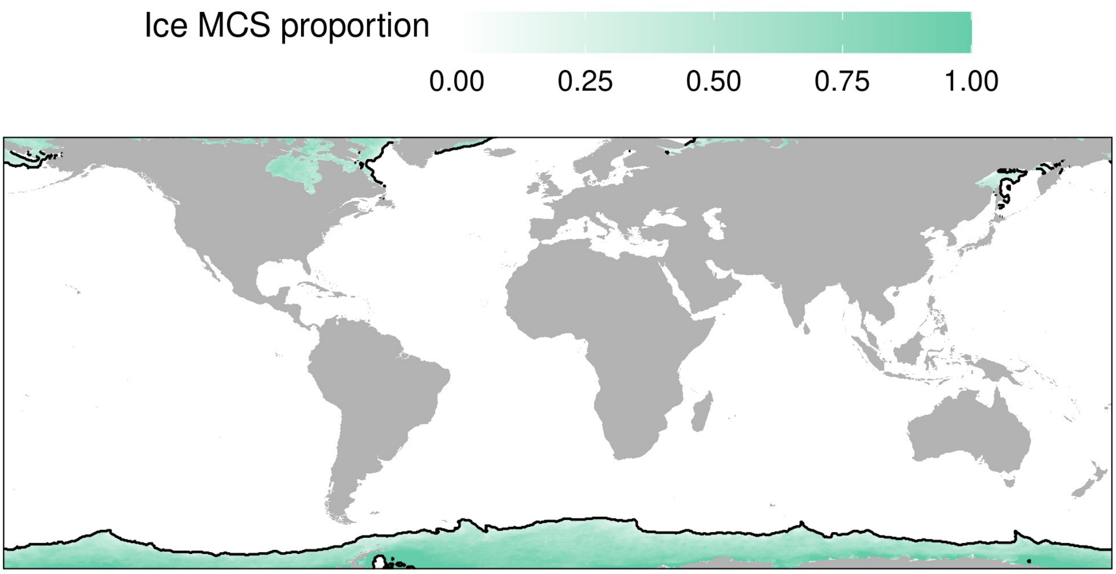

Figure S1: The areas of the ocean that have been denoted as “near-ice” are denoted by black contours and are determined when at least one marine cold-spells (MCSs) has been flagged as an “Ice” event at any point over the 39-year time series. Within these near-ice regions, values (green shading) show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

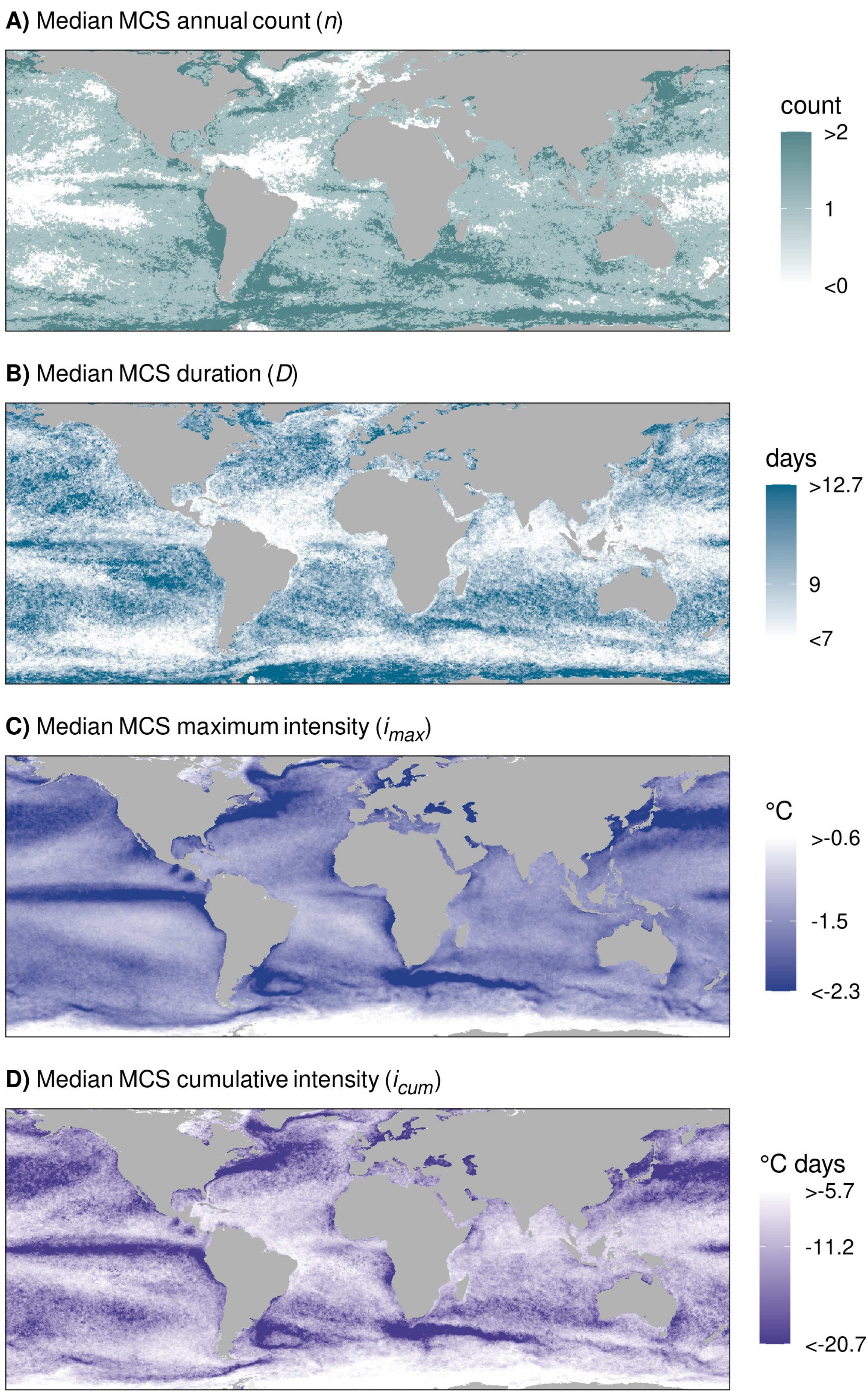

Figure S2: As in Figure 3, except with the median values per pixel, rather than the means. Note that the same broad patterns are seen in both, with only minor changes to the 5th, 50th, and 95th percentile values shown in the legends of each panel. The difference between the mean (Figure 3) and median (Figure S2) values is most pronounced in the count of events (panel A).

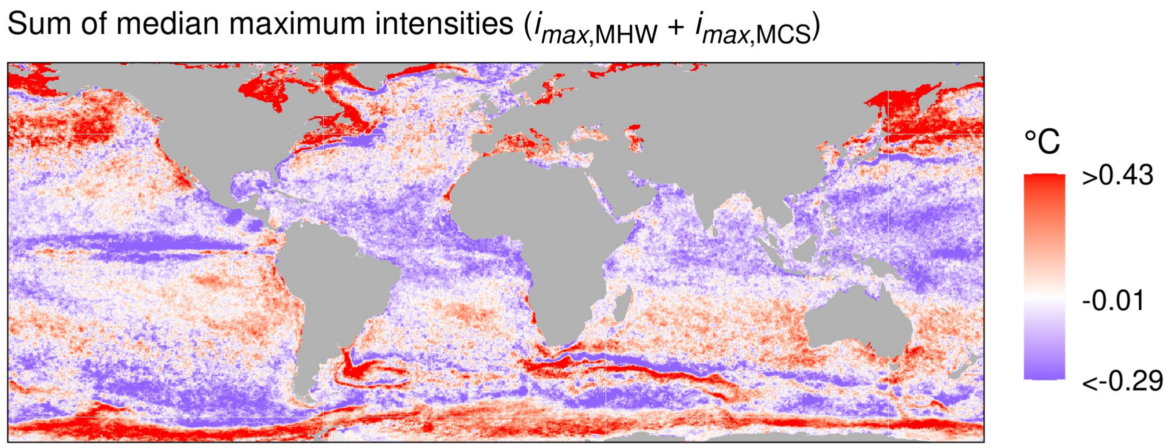

Figure S3: As in in Figure 6A, but with median values rather than means. Note that the same patterns are clearly visible with only minor changes to the 5th, 50th, and 95th percentile values in the legend.

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