


Sensitivity of a cold-water coral reef to interannual variability in regional oceanography

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Abstract

Aim: We assessed the effects of regional oceanographic shifts on the macrofaunal biodiversity and biogeography of cold-water coral reefs (CWCRs). CWCRs are often hotspots of biodiversity and ecosystem services and are in the frontline of exposure to multiple human pressures and climate change. Almost nothing is known about how large-scale atmospheric variability affects the structure of CWCRs' communities over ecological timescales, and this hinders their efficient conservation. This knowledge gap is especially evident for species-rich macrofauna, a key component for ecosystem functioning.

Location: The Mingulay Reef Complex, a protected biogenic ecosystem in the north-east Atlantic (120–190 m).

Methods: A unique time series (2003–2011) at 79 stations was used to make the first assessment of interannual changes in CWCRs' macrofaunal biodiversity, biogeography and functional traits. We quantified the impacts of interannual changes in North Atlantic Oscillation Index (NAOI)—the major mode of atmospheric variability in the North Atlantic, bottom temperature and salinity alongside static variables of seafloor terrain and hydrography.

Results: Environmental gradients explained a significant amount of community composition ($R_{adj}^2 = 26.7\%$, $p < .01$) with interannual changes in bottom temperature, salinity and NAOI explaining nearly twice as much variability than changes in terrain or hydrography. We observed significant differences in community composition, diversity and functional traits but not in species richness across interannual variability in bottom temperature. In warmer years, the biogeographic composition shifted more towards a temperate and subtropical affinity.

Main Conclusions: Our findings highlight the necessity for thorough investigations of faunal communities in CWCRs as they may be sensitive to interannual changes in regional oceanography. Considering the scientific consensus on the substantial warming of North Atlantic by 2100, we recommend the establishment of programmes for the monitoring of CWCRs. This will support an advanced understanding of CWCRs' environmental status over time and will serve their conservation for the future.

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KEYWORDS

cold-water corals, deep sea, distribution, diversity, global climate change, long-term ecosystem changes, macrofauna, marine protected areas, North Atlantic Oscillation

1 | INTRODUCTION

Large-scale fluctuations in the atmosphere can affect the water mass characteristics and shape hydrography, biodiversity and food webs that are critical components of the marine environmental status (Mittermeier et al., 2011; Myrberg et al., 2019). In the North Atlantic, the dominant mode of atmospheric variability is the North Atlantic Oscillation (NAO), which can be described through the North Atlantic Oscillation Index (NAOI, hereafter) using an empirical orthogonal function of sea-level pressure anomalies over the Atlantic sector (Hurrell et al., 2003).

The NAO is a major driving force for basin-scale interannual variability in circulation and water mass characteristics. The NAO influences the strength and extent of the subpolar gyre (Lohmann et al., 2009) and upper ocean temperature/salinity values in the subpolar North Atlantic (Hátún et al., 2005; Johnson et al., 2013). A negative NAOI is associated with westward subpolar gyre retraction enabling the intrusion of relatively warm and salty subtropical waters into the eastern North Atlantic (Hátún et al., 2005; Johnson et al., 2013) and subsequently onto the western European shelf (Johnson et al., 2020 and references therein). The NAO can mediate the timing and biomass of primary production (Basterretxea et al., 2018), shifts in zooplankton biogeography and biodiversity (Beaugrand et al., 2002) and cause regime shifts in food webs (Molinero et al., 2008). However, studies on effects of the NAO on benthic marine biodiversity hotspots remain scarce.

Cold-water coral reefs (CWCRs hereafter) are structurally complex ecosystems characterized as hotspots of biodiversity, biomass, elemental cycling and socioeconomic values (Armstrong et al., 2019; De Clippele et al., 2021; Henry & Roberts, 2017). CWCRs' spatial distribution is mainly controlled by the availability of hard substrates, seawater temperature, chemistry and hydrodynamics which facilitate the supply of food (Roberts et al., 2006; Hebbeln et al., 2019). As a response to their environmental requirements, CWCRs are often found in the (upper) bathyal zone and continental shelves.

CWCRs in the continental shelves and the bathyal zone are exposed, in overall, to multiple pressures such as physical damage (e.g. bottom trawling, oil & gas activities), ocean warming, deoxygenation and contaminants (Clark et al., 2019; Hennige et al., 2020; Roberts et al., 2016; Sweetman et al., 2017; Weinnig et al., 2020). While CWCRs located at relatively shallow depths on the continental shelf might act as refugia for the effects of ocean acidification (Turley et al., 2007), they are still threatened by warming, physical damage and microplastics (Bindoff et al., 2019; La Beur et al., 2019). As human activities expand, adaptive spatial management measures are required. This, in turn, needs a better understanding of variability in biodiversity and ecosystem functioning over space/time as well

as the development of integrated monitoring programmes (Cormier et al., 2019).

Macrofauna are a key constituent in ecosystem functioning globally: they are extremely species-rich (Grassle & Maciolek, 1992) and shape benthic elemental cycling (Janas et al., 2019). Macrofaunal biodiversity and functional traits are usually correlated with a system's capacity to buffer environmental stressors and offer a useful proxy of marine ecosystem health (Gunderson, 2000; HELCOM, 2018; Hooper et al., 2005). Studies have examined the effects of size and type of biogenic habitat (Bourque & Demopoulos, 2018; Jensen & Frederiksen, 1992; O'Hara et al., 2008) as well as bathymetric and hydrographic gradients in shaping macrofaunal biodiversity (Henry et al., 2013; Kazanidis et al., 2016). Notably, these studies focussed on a single time point, and work examining macrofaunal communities in CWCRs over time is lacking. This is a major knowledge gap that hinders our understanding about the response of macrofauna to temporal environmental changes. Addressing this knowledge gap is crucial as studies over geological timescales have found compelling links between the decline of CWCRs' biodiversity and climatic/oceanic perturbations (Douarin et al., 2014).

Our work aims to advance our understanding on the effects of spatial gradients in seafloor characteristics and current speed as well as the effects of interannual variability in regional oceanography on CWCRs' macrofauna. We focus on the Mingulay Reef Complex, a hotspot of marine biodiversity on the western European shelf. Mingulay Reef Complex is included in the East Mingulay Marine Protected Area (Figure 1). Increasing our understanding on the functioning of CWCRs enables efficient implementation of marine policies and the protection of these extremely fragile ecosystems for the future.

2 | METHODS

2.1 | Study area

The Mingulay Reef Complex (MRC, hereafter) is one of the best-studied CWCRs in the world and is located on the northeast Atlantic continental shelf, in western Scotland (e.g. Henry et al., 2013; Roberts et al., 2005). The MRC contains reef mounds that are 13–60 m wide, 16–108 m long and between 2 to 34 m tall, which are formed by the cosmopolitan scleractinian coral *Lophelia pertusa* (De Clippele et al., 2017). X-ray computed tomography of seabed cores revealed cycles of different ecosystem phases (reef initiation, framework expansion, framework collapse, coral rubble) over the mid-Holocene to late Holocene (Douarin et al., 2014).

Today, the MRC is primarily bathed by North Atlantic Water which is a warm (10.0–10.5°C), salty (35.4 psu) water mass that flows

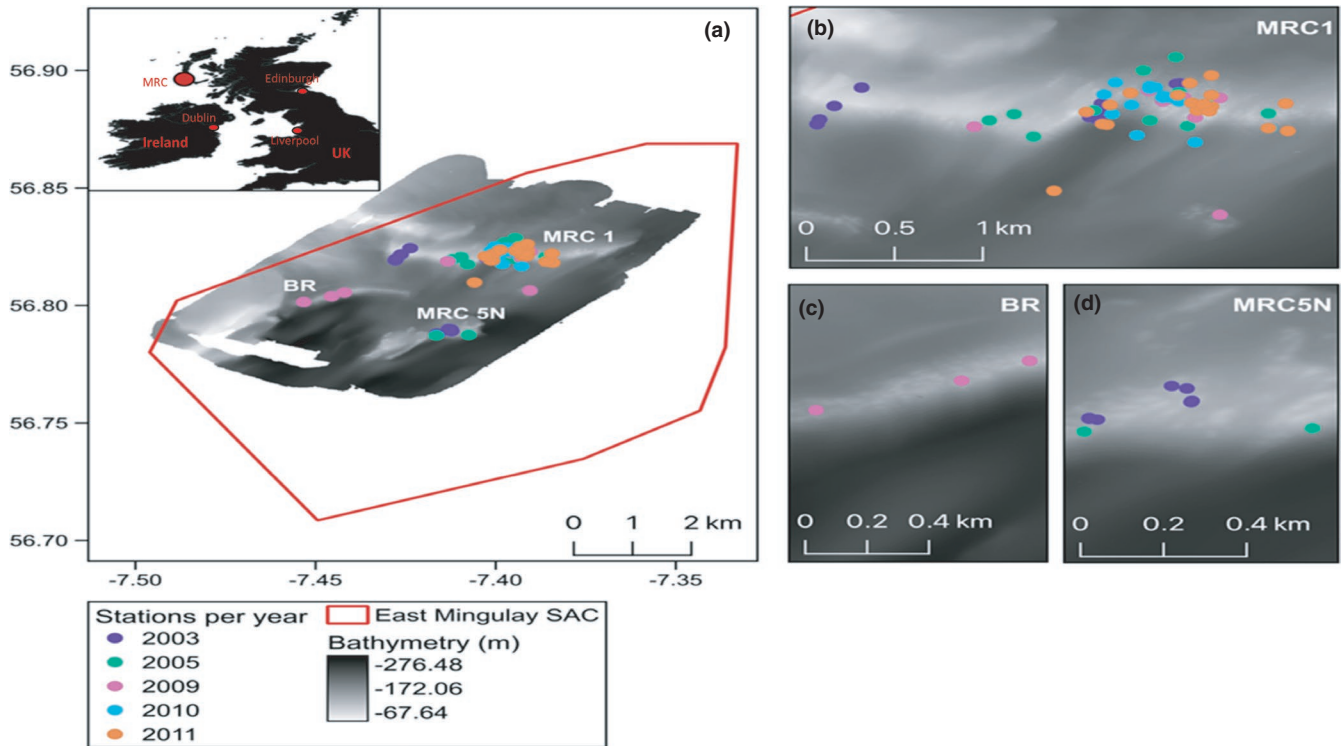


FIGURE 1 (a) Location of the Minguly Reef Complex (total area $\sim 100 \text{ km}^2$) in the Sea of the Outer Hebrides (northeast Atlantic), with the red polygon delineating the east Minguly Marine Protected Area. Colourful circles represent the years of sampling. (b) Locations of sampling stations at Minguly Reef Complex 1 (MRC1), (c) at Banana Reef (BR) and (d) at Minguly Reef Complex 5 North (MRC5N). Colour shading represents bathymetry, see legend. For more details on stations, see Table S1

onto the European Shelf from the eastern subpolar North Atlantic (Johnson et al., 2013; Porter et al., 2018). Over multi-annual time scales, the bottom temperatures and salinities at MRC show a statistically significant inverse relationship with the NAOI (Johnson et al., 2020). Specifically, in years with weak atmospheric forcing and a negative NAOI, warmer and more saline bottom conditions are found at MRC, while cooler and fresher bottom values are seen during a positive NAOI (Johnson et al., 2020). In contrast, the fresher Scottish Coastal Current has a minor influence at the MRC, particularly at the seabed (Inall et al., 2009).

Acoustic surveys of the MRC using multibeam echosounders combined with seabed video revealed mounds of *L. pertusa* in five Minguly sites, in water depths ranging from 120 to 190 m. These five reefs include the following: Minguly Reef Complex 1 (MRC1, hereafter), Minguly Reef Complex 5 North (MRC5N, hereafter), Minguly Reef Complex 5 South, Banana Reef and Four Mounds (Duineveld et al., 2012; Roberts et al., 2009). As MRC1, MRC5N and Banana Reef are the most data-rich reefs in terms of environmental and macrofaunal data, we used these sites to investigate links between spatial and temporal environmental variability and marine ecosystem structure and function (Figure 1).

We analysed macrofaunal communities and environmental data from 79 stations sampled between 2003 and 2011 (Figure 1; Table S1). The number of stations sampled per year is as follows: 18 in 2003, 14 in 2005, 14 in 2009, 15 in 2010 and 18 in 2011 (Figure 1;

Tables S1–S2). Sampling in remote, CWCRs is logistically challenging, and thus, the MRC stations that have been sampled to date may not be fully representative of the whole Marine Protected Area (Figure 1). It should be clarified though that (a) the Marine Protected Area itself contains also soft sediments and (b) our stations have been carefully selected for sampling CWCRs habitats of which the MRC1, Banana Reef and MRC5N are the most-well developed that we know of.

Considering data resolution and previous findings at MRC (NAOI—Hurrell et al., 2003; temperature, salinity—Findlay et al., 2013; bathymetry, topography, current speed, macrohabitat—Roberts et al., 2009; Henry et al., 2013), we classified a priori the bathymetry, topography and current speed as “spatial variables” (i.e. mainly changing across space), and the bottom potential temperature (hereafter mentioned as “bottom temperature”), bottom salinity and the NAOI as “temporal variables” (i.e. variables mainly changing across time).

2.2 | Benthos

Benthic samples (total $n = 79$) were collected using a modified Van Veen Grab (sampling 0.1 m^2 per deployment) in 2003, 2005, 2009, 2010, 2011 (Figure 1; Table S1). Samples were sieved at 1 mm, macrobenthos collected and stored in 4% seawater formalin and

transferred to 70% industrial methylated spirit. Specimens were identified to the lowest possible taxonomic level using best available taxonomic keys for North Atlantic marine invertebrates and guidance from expert taxonomists.

Accounting for the existence of both colonial and solitary taxa, we have recorded species' presence/absence (Henry et al., 2013). We acknowledge that the use of presence-absence (and not abundance/biomass) data may have some effect on the outcomes of our analyses but these effects are not expected to be major (Buchner et al., 2019). Furthermore, we feel that presence-absence data was the optimal approach as for many species (e.g. encrusting bryozoans) measurements on abundance and/or biomass would not be accurate. Following previous biodiversity studies at MRC (Henry et al., 2013), we have also excluded sponges due to a lack of taxonomic resolution across this group. Presence/absence data were assembled in a species assembly matrix using PRIMER (Clarke & Gorley, 2015).

Ecological functional traits reflecting species' functions in the ecosystem were considered (after Bates et al., 2017). Specifically, specimens were assigned to a feeding type (i.e. suspension/filter feeder, deposit feeder/grazer, predator, omnivore), mobility/orientation type (i.e. sessile encrusting, sessile horizontal, sessile erect, mobile) and body size (i.e. 0–10, 10–50, 50–100, >100 mm) using the information in Henry et al. (2013), Kazanidis et al. (2016), Hayward and Ryland (2017).

Specimens identified at the species level were also assigned to one of the 30 biogeographic realms identified by Costello et al. (2017) using the information on each species' geographic distribution from the Ocean Biodiversity Information System (<https://obis.org/>). Information for each species' bathymetric distribution, temperature and salinity ranges was then extracted from the Ocean Biodiversity Information System and recorded.

2.3 | Spatial variables: bathymetry, topography and current speed

Topographic terrain variables were calculated from bathymetric data (depth). Specifically, the following metrics were derived from the bathymetry data: slope, ruggedness (equivalent to rugosity), northness and eastness (via aspect), standardized broad- and fine-scale bathymetric position index (inner radius of 1 and outer radius of 5 and 3 cells, respectively). We used these bathymetry-related variables to have a good coverage of the seabed terrain parameters that change across space and to quantify their role in macrofaunal biodiversity patterns. Previous studies at the MRC (Henry et al., 2010, 2013) and elsewhere (e.g. Savini et al., 2014; Sundahl et al., 2020) have shown that bathymetry-related variables such as bathymetric position index and slope have a significant contribution in explaining spatial patterns in cold-water coral communities.

The Spatial Analyst and Benthic Terrain Modeler toolboxes in ArcGIS were used in this study as they are toolboxes widely used in the literature for similar studies (Henry et al., 2010, 2013; Woodall et al., 2015; Lacharite and Metaxas, 2018; Murillo et al., 2020 amongst others). The average values of each spatial variable were extracted

using the ArcGIS v.10.6.1 spatial Analyst Toolbox. In addition, average and maximum current speed (m/s) were also obtained at each station from a high-resolution 3D ocean model created for MRC. Average and maximum current speed values (m/s) were extracted using the ArcGIS v. 10.6.1 Spatial Analyst toolbox using data generated by a high-resolution 3D ocean model created for the MRC by Moreno Navas et al. (2014). The nested system consisted of a coarse-resolution outer model which covers part of the Sea of the Hebrides and, a fine-scale inner model covering the MRC (horizontal resolution ~100 m).

Macrohabitat was also treated as a spatial variable. Based on previous studies at MRC (Henry et al., 2010, 2013), macrohabitat was classified in six types, representing six levels of structural complexity. These types were as follows: "muddy sand" (i.e. the least structurally complex macrohabitat), "rubble," "rock," "live coral," "dead framework" and "mixed live and dead framework" (i.e. the most structurally complex habitat).

2.4 | Temporal variables: Bottom temperature, bottom salinity and NAOI

Following previous studies (e.g. Birchenough et al., 2018; Zettler et al., 2017), we have used data for the winter NAOI (December-January-February-March) (Hurrell et al., 2003). These data were downloaded from the National Center for Atmospheric Research/University Corporation for Atmospheric Research website (climate-dataguide.ucar.edu). This was done both for the year of biological sampling (noted as "same year") and for the year prior to it (noted as "previous year"), following Zettler et al. (2017) (Table S2). Annual averages of bottom temperature (± 0.01) and bottom salinity (± 0.001) for the same and previous year were extracted from the grid point nearest to MRC in the UK Meteorological Office's EN4 objectively analysed observational data set (Good et al., 2013).

2.5 | Data analysis

To avoid statistical bias and Type I error inflation, all explanatory variables were checked for correlation (R package "corrplot" version 0.84; Wei & Simko, 2017) and variables with significant correlation scores (Pearson's $r > .7$ or $< -.7$) were discarded (Figure S1). The species data were Hellinger-transformed, giving lower weights to rare species and maintaining linear correlations between species and gradients of environmental variables (Legendre & Gallagher, 2001).

The variance of macrofaunal communities explained by spatial and temporal environmental variables was examined using redundancy analysis (RDA). This multivariate statistical method combines regression and principal component analysis and can model response variables as a function of multiple explanatory variables (Borcard et al., 2018). The RDA model was built with the species assembly matrix as the response variable and all the non-correlated environmental variables as the explanatory variables. A forward stepwise selection was applied to retain the statistically significant explanatory variables (R package "vegan"

version 2.5-6; Oksanen et al., 2019). In order to quantify the variance of macrofaunal communities explained by (a) spatial, (b) temporal and (c) interactions between spatial and temporal variables, a series of RDA and partial RDA (pRDA) models were constructed (Borcard et al., 1992). The significance of fitted environmental vectors was determined by calculating the goodness of fit defined as the squared correlation coefficient r^2 using permutation tests with the command `envfit()` of package "vegan" (Oksanen et al., 2019). Species under the influence of each specific environmental variable were identified through visual inspection of the total RDA and pRDAs biplots, with species selection based on RDA scores (R package "vegan" and "RcolorBrewer" version 1.1-2; Neuwirth, 2014). All RDA and pRDA analyses were conducted in R. R code is provided in the Supporting Information.

Species richness (SR), Margalef diversity index (d) and average taxonomic distinctness (Δ^+) were measured in PRIMER with values of SR and Δ^+ being normalized to the number of samples collected each year (Clarke & Gorley, 2015; Table S1). Statistical differences in SR, d , Δ^+ and functional traits across (a) interannual changes in bottom temperature, bottom salinity, NAOI (same year), NAOI (previous year) and (b) areas (i.e. MRC1, MRC5N and BR) were examined in R. First, the normality of the distributions was checked with the Shapiro-Wilk test and the equality of variances with the Bartlett test. In the case of normal distribution and equal variances, the hypothesis that the groups have the same mean was tested through one-way analysis of variance. In the case of normal distributions and unequal variances, the hypothesis that the groups have the same mean was tested through one-way analysis of means. In the case that the normal distribution criterion did not hold, the hypothesis that the groups have the same median was tested through the Kruskal-Wallis test. These tests were followed by pairwise comparisons to identify the presence of statistically significant differences in pairs of groups. In the case of one-way analysis of variance, multiple comparisons were carried out through the Tukey's test. In the case of one-way analysis of means, the comparisons were carried out through the Games Howell test (Burk, 2018). When the Kruskal-Wallis test was used, the pairwise comparisons were carried out through the Dunn test (Dinno, 2017). Accounting for the multiple comparisons, the p values were adjusted using the Bonferroni correction (Armstrong, 2014).

3 | RESULTS

3.1 | Macrobenthos taxonomic, mobility and functional traits' composition

In total, 342 taxa were identified across 13 phyla, with 62% of the taxa being identified to species level (Table S3). Phyla with the highest number of taxa were Annelida (37.6% of total taxa), Bryozoa (24.3%), Arthropoda (16.0%) and Mollusca (10.1%). Almost half of the 342 taxa were suspension- and filter-feeding species (48.5%) followed by deposit feeders/grazers (25.1%), predators (20.5%) and omnivores (0.1%). In terms of mobility/orientation, most of the taxa were mobile (54.1%), followed by sessile erect (19.9%), sessile encrusting (16.1%) and sessile horizontal (9.6%). Finally, in terms of

TABLE 1 Results of the permutation test on the partial redundancy analyses (RDA) showing the amount of variance explained by each of the statistically significant temporal and spatial variables. r^2 : squared correlation coefficient (goodness of fit statistic)

	RDA1	RDA2	r^2	p Value
Temporal variables (13.7%)				
Bottom temperature (same year)	-0.91210	0.40997	.5685	.001
Bottom salinity (same year)	-0.16893	0.98563	.5738	.001
NAOI (same year)	-0.64973	-0.76016	.5734	.001
NAOI (previous year)	-0.92202	-0.37003	.1333	.007
Spatial variables (7.2%)				
Bathymetric position index	0.95996	-0.28013	.3073	.001
Ruggedness	-0.56025	-0.82833	.2293	.003
Macrohabitat	0.28145	-0.95958	.1415	.005
Average current speed	0.05328	-0.99858	.0892	.045

Abbreviation: NAOI, North Atlantic Oscillation Index.

body size, most of the taxa were 0–10 mm (42.7%), followed by those at 10–50 mm (31%), 50–100 mm (14%) and >100 mm (12%).

3.2 | Drivers of macrobenthic community structure

The forward stepwise selection of environmental variables retained four spatial and four temporal variables that had a statistically significant contribution ($p < .05$) in explaining macrofauna variance. In total, 26.7% of the variance was explained: 13.7% by the temporal variables, 7.2% by the spatial variables and 5.7% by the interactions between spatial and temporal variables. The spatial and temporal variables with a statistically significant contribution in explaining macrofaunal variance can be seen in Table 1.

3.3 | Species richness (SR), Margalef diversity index (d), average taxonomic distinctness (Δ^+) and community composition across time and space

Statistically significant differences were seen for Margalef diversity index (d) values across bottom salinities and NAOI values (same and previous year) and marginally across the different bottom temperatures (Figure 2; Table S4). Average taxonomic distinctness (Δ^+) showed statistically significant changes over the interannual shifts in bottom temperature, bottom salinity and NAOI and across the areas (Figure 2; Table S4). These maximum Δ^+ values (seen in 2005) were significantly different from the Δ^+ values seen in years with

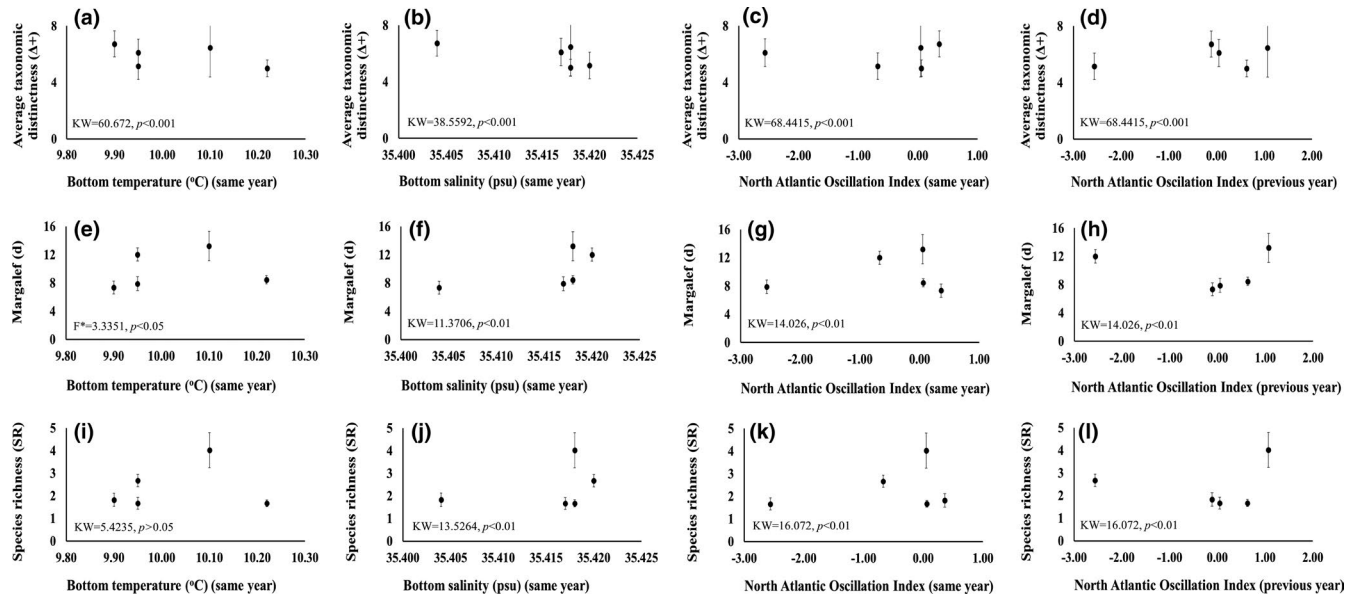


FIGURE 2 (a–d) Average taxonomic distinctness [Δ^+], (e–h) Margalef diversity index [d] and (i–l) species richness [SR] across interannual changes in bottom temperature (same year), bottom salinity (same year), North Atlantic Oscillation Index (NAOI; same year) and NAOI (previous year) at the Mingulay Reef Complex. Annual average values (circles), standard error (error bars), outcomes of statistical tests (F = one-way ANOVA; F^* = one-way analysis of means not assuming equal variances; KW = Kruskal–Wallis rank sum test) and p values are given. The outcomes of the pairwise comparisons are shown in Table S4

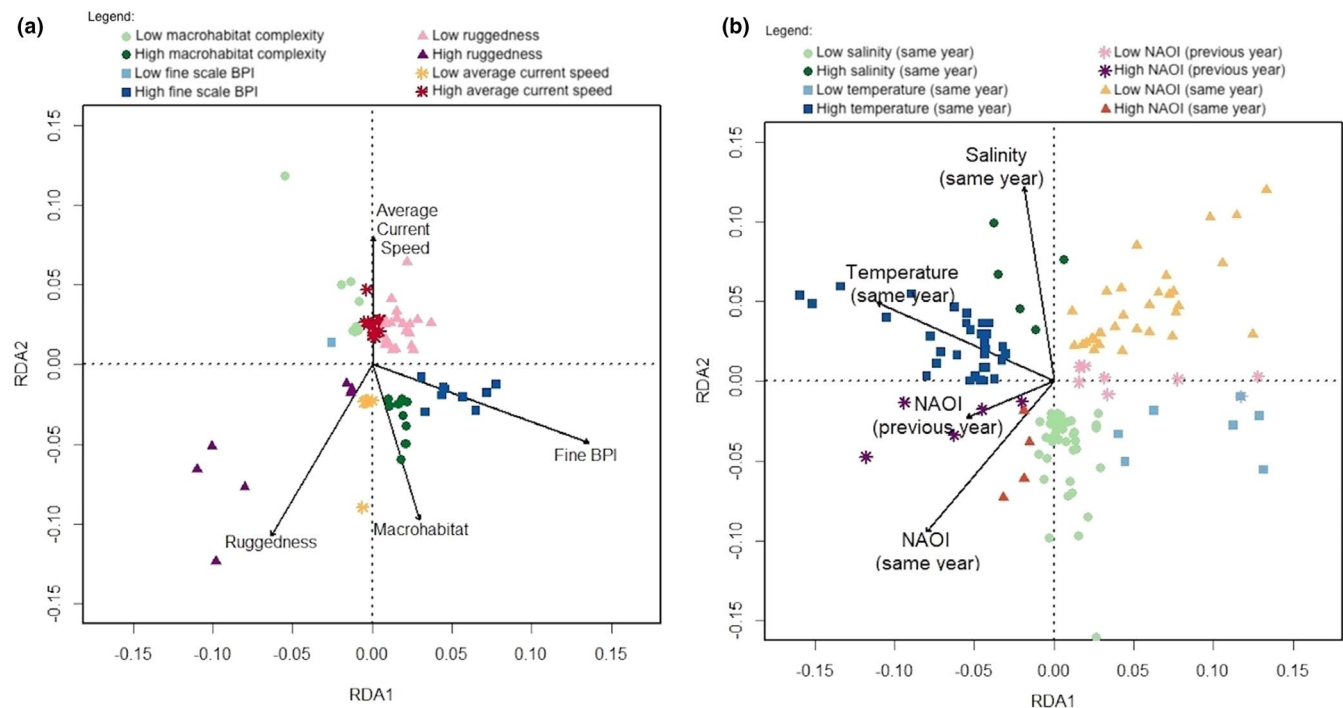
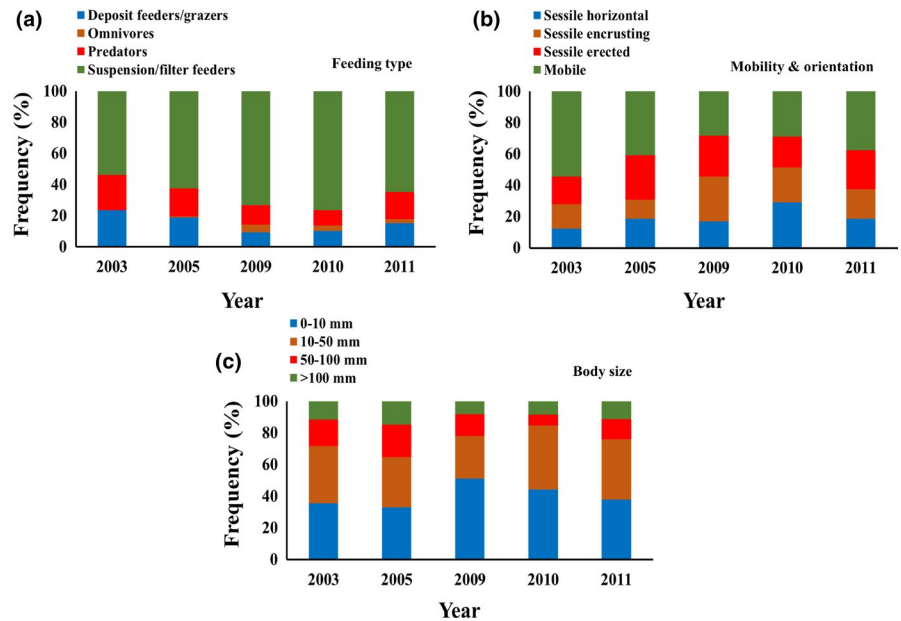


FIGURE 3 Biplots of pRDA model showing species associated with (a) the spatial variables [fine-scale bathymetric position index (BPI), macrohabitat, ruggedness, average current speed] and (b) the temporal variables [bottom temperature, bottom salinity, North Atlantic Oscillation Index (NAOI; same year) and NAOI (previous year)] at the Mingulay Reef Complex. Each symbol colour combination represents a group of species associated with a state of an environmental variable (see legend). For species names, see Figure S2 and Tables S5, S6

higher bottom temperatures, higher bottom salinities, lower values of NAOI (same year) and lower and higher values of NAOI (previous year) (Figure 2; Table S4).

Species richness (SR) did not show statistically significant changes over the interannual changes in bottom temperature (Figure 2; Table S4). SR , however, showed statistically significant shifts over the interannual

FIGURE 4 Changes in (a) feeding types, (b) mobility/orientation types and (c) body size across years at the Mingulay Reef Complex. The outcomes of the pairwise comparisons are shown in Table S7



changes in bottom salinity, NAOI (same year) and NAOI (previous year) (Figure 2; Table S4).

3.4 | Macrofaunal groups under the influence of environmental gradients across space

Species linked to higher fine-scale bathymetric position index values were mainly sessile suspension feeders, while those associated with structurally complex macrohabitats included a rich mixture of functional traits with predators (e.g. *Porania (Porania) pulvillus*, *Eunice norvegica*), mobile deposit feeders/grazers (e.g. *Galathea strigosa*) and sessile suspension- and filter-feeding species (e.g. the bivalve *Hiatella arctica*) (Figure 3a; see also Figure S2a and Table S5). Species found in highly rugged areas were mainly erect suspension feeders with larger more robust morphologies (e.g. the anthozoan *Parazoanthus anguicomus*), while about one-third of species found in less rugged areas were encrusting bryozoans (e.g. *Schizomavella (Schizomavella) linearis*). Species linked to high average current speed areas were mainly suspension- and filter-feeding species (the erect bryozoan *Buskea dichotoma*) and omnivores, while those in low average current speed areas were mainly deposit feeders (e.g. the isopod *Uromunna petiti*). In areas with higher structural complexity, there were more predators than suspension- and deposit-feeding species; on the contrary, in areas with lower structural complexity there were more suspension-feeding species than predators and deposit-feeding species (Figure 3a; see also Figure S2a and Table S5).

3.5 | Macrofaunal groups under the influence of environmental gradients across time

A single assemblage seemed to be associated with higher bottom temperatures (13 species) and another one associated with lower

bottom temperatures (seven species) (Figure 3b; see also Figure S2b and Table S6). Species associated with higher bottom temperatures at the MRC (e.g. the polychaete *Lysidice unicornis*) are commonly found in warmer areas like the Caribbean, Indo-Pacific Seas, Gulf of Suez and Red Sea biogeographic realms. In contrast, species associated with lower bottom temperatures (e.g. the bryozoan *Disporella hispida*) are also found in cooler areas like the Norwegian Sea and the Arctic Seas biogeographic realms (Figure 3b; See also Figure S2b and Table S6).

Three species were associated with higher bottom salinity values (e.g. the isopod *Janira maculosa*) while 29 species (molluscs, polychaetes, bryozoans and echinoderms) (Figure 3b; see also Figure S2b and Table S6) were associated with slightly fresher bottom waters. Seven species were associated with the higher NAOI (same year) (e.g. the suspension-feeding polychaete *Serpula vermicularis*) and the higher NAOI (previous year) values (e.g. the erect anthozoan *Parazoanthus anguicomus*). In contrast, a much larger number of species ($n = 22$) were associated with the lower values of the NAOI (same year). These were mainly encrusting suspension feeders (e.g. the bryozoan *Amphiblestrum flemingii*), small suspension feeders (e.g. the bivalve *Modiolula phaseolina*) and deposit feeders (e.g. the ophiuroid *Amphipholis squamata*) (Figure 3b; see also Figure S2b and Table S6).

3.6 | Macrofaunal functional traits

Almost all the groups of functional traits showed statistically significant changes over the interannual changes in bottom temperature, bottom salinity and NAOI (Figure 4; Table S7). The frequency (%) of the suspension/filter feeders and the sessile erect organisms had their lowest values during highest bottom temperatures (Figure 4). This lowest frequency of suspension/filter feeders and sessile erect organisms was statistically different ($p < .05$) from the frequencies

recorded under lower temperatures (Figure 4; Table S7). On the contrary, the frequency of predators had its maximum values under the highest bottom temperatures (Figure 4); this peak in the distribution of predators was statistically different from the frequency of predators recorded under lower bottom temperatures (Figure 4; Table S7).

4 | DISCUSSION

This study has unravelled the effects of both spatial and temporal environmental gradients on macrofaunal communities in a cold-water coral reef. Interannual changes in regional oceanography explained almost double the variance explained by spatial gradients, the latter which were solely considered in previous studies. (Bourque & Demopoulos, 2018; Buhl-Mortensen et al., 1995; Cordes et al., 2008; Henry et al., 2013). Interestingly, there were no significant changes in SR over bottom temperature changes but there were changes in community composition, Δ^+ and functional traits and marginal changes for d . This highlights the necessity for thorough examinations of macrofaunal communities to identify changes in ecosystem structure and functioning.

Due to the relatively short time series examined here, it is challenging to draw a definite conclusion on the effects of temperature, salinity, and NAOI interannual variability on CWCR macrofauna. Models predict an increase of up to 2.0°C for bottom temperatures at Mingulay by 2100 (Findlay et al., 2013) while temperatures between 200–1,000 m in the North Atlantic are predicted to rise, on average, by 1.8°C over the same period (Puerta et al., 2020; Sweetman et al., 2017). Considering that changes in biodiversity and functional traits were observed over a range of 0.32°C, we highlight the need for the establishment of monitoring programmes at MRC and at CWCRs in general.

4.1 | On the role of spatial gradients

Many species associated with topographic highs or high average current speed were sessile suspension feeders suggesting that these conditions are highly favourable, possibly due to enhanced food supply (Davies et al., 2009; Kazanidis & Witte, 2016).

Macrohabitat was also an important driver of species distribution. Areas dominated by live and dead coral framework hosted a richer mixture of functional traits than areas with muddy sand. This is likely related to the fact that higher structural complexity increases the number of ecological niches (Tews et al., 2004). The presence of predators (e.g. *Eunice* polychaetes) is also possibly related to the fact that they feed on anthozoans and tunicates which are abundant in coral framework (Kazanidis & Witte, 2016). Regarding ruggedness, larger sized and erect suspension feeders were found in highly rugose areas while encrusting delicate forms proliferated in smoother areas. Large/erect/robust body forms likely proliferate in rugose areas under turbid waters due to enhanced food capture rates. In contrast, low-lying and delicate forms are preferably found in less energetic environments (Henry et al., 2013).

4.2 | On the role of temporal gradients in water mass characteristics and regional oceanography

A recent study showed a statistically significant inverse relationship between bottom conditions in the eastern North Atlantic and the strength of the NAO (Johnson et al., 2020). The westward retraction of the subpolar gyre during a weak NAO (Lozier & Stewart, 2008), enables the northward extension of warm and salty subtropical waters (Hátún et al., 2005, 2017; Johnson et al., 2013). A similar signal was observed at the MRC, with warmer and more saline bottom conditions again observed during a weak NAO (Johnson et al., 2020). The similarity in time series from the two areas suggests that bottom conditions at the MRC reflect changes observed in the wider eastern North Atlantic. It appears that subpolar gyre dynamics affect the MRC and contribute to biodiversity changes over ecological timescales.

Shifts in faunal biogeographic affinity are probably related to changes in water mass characteristics. Most of the species associated with the higher values of bottom temperature are also found in temperate areas on both sides of North Atlantic as well as in subtropical areas. Two possible scenarios are suggested. First, warmer conditions enhance species' reproductive success (Byrne, 2011; Holopainen et al., 2016; Lewis et al., 2002; Rupp, 1973). Second, during a weak NAO/westward retraction of the subpolar gyre, the northward expansion of the warm and salty North Atlantic Water facilitates the extension of species from lower to higher latitudes. Most species associated with warmer waters at MRC are mobile polychaetes and arthropods. Their higher mobility and pelagic larvae (Iannotta et al., 2007) could support their dispersal.

NAOI (same year) had a stronger contribution than the NAOI (previous year) in explaining biological variability, suggesting a relatively rapid response of macrofauna to NAOI. This mirrors findings from the intertidal/upper subtidal zone in the North Sea (Birchenough et al., 2018 and references therein), the Mediterranean bathyal (Cartes et al., 2009) and the abyssal northeast Atlantic (Smith et al., 2009) where the winter NAO caused shifts in the structure and functioning of benthic communities in subsequent seasons and years.

A high-resolution ocean model shows that the NAO has a positive correlation with bottom kinetic energy at the MRC (Johnson et al., 2020). A high NAOI/increased kinetic energy likely enhances food supply supporting the proliferation of some suspension/filter feeders such as *P. patelliformis* and *S. vermicularis* (Table S6). In contrast, deposit feeders and encrusting organisms (Table S6) were associated with a low NAOI/decreased kinetic energy which likely enhances the food capture by these low-lying species.

It is important to note that a large part of biological variability remains unaccounted for. About 80% of the polychaetes species are distributed over a relatively wide range of bottom temperatures and salinities (OBIS, 2019). Thus, environmental gradients experienced at the MRC are likely within their niche envelope and will not explain any variability. Unexplained variability could also be linked to limited dispersal. Indeed, 40% of the species not associated with

environmental gradients were found at only one station. Limited dispersal obscures any relationship between biological and environmental sampling scales (Bullock et al., 2006; Selmoni et al., 2020). Third, the temporal resolution of environmental sampling may be somewhat coarse and biased towards species with perennial life spans.

4.3 | Implications for biogenic ecosystem functioning

The changes seen at the MRC macrofauna over time, including common species (Henry et al., 2013; Kazanidis et al., 2016), indicate that the macrofauna may be susceptible to interannual changes in water mass characteristics. When the MRC was subjected to higher bottom temperatures, there was a significant decrease in suspension/filter feeders and a significant increase in predators (Figure 4; Table S7). The mechanisms driving these shifts are not known, and longer time series are needed to draw a firm conclusion. It is noteworthy, though, that ~70% of the suspension/filter-feeding species that were not recorded during higher temperatures have to date also not been recorded in (sub)tropical areas. This indicates their preference for higher latitudes and colder waters (Hayward & Ryland, 2017; Jensen & Frederiksen, 1992; Klitgaard, 1995). In addition, predators recorded during higher bottom temperatures at MRC have been found in (sub)tropical areas indicating their affiliation with a wide range of bottom temperatures (Frogliia & Speranza, 1993; Simon et al., 2014).

Suspension and filter feeders are usually primary consumers which channel organic matter from the lower to the higher trophic levels. Studies in tropical reefs and CWCRs have shown their key role in food web functioning through the high assimilation of dissolved organic carbon and its conversion to biomass (de Goeij et al., 2017; Rix et al., 2016). Their role is also pronounced in areas where strong bottom currents prevail, for example CWCRs, as they trap food sources which otherwise would have been transported away (Gili & Coma, 1998; Roberts et al., 2009).

Experimental work has shown that ocean warming has negative impacts on the health status of some suspension/filter feeders (bivalves, Mackenzie et al., 2014; tunicates, Nagar & Shenkar, 2016; sponges, de Goeij et al., 2017) affecting thus their important role in ecosystem functioning (Bell et al. 2018). Recent studies have shown the negative impacts of increased temperatures on the abundance of low-trophic level consumers (Garzke et al., 2015) and biomass transfer from secondary production to fish stocks, globally. This reduced efficiency is expected to be more severe in cold-water ecosystems. Studies at ecosystems for which we have a relatively advanced understanding compared to CWCRs (e.g. plankton, macroalgae, fish, marine mammal and seabird systems; Beaugrand et al., 2008; Poloczanska et al., 2016; Ramirez et al., 2017) have given insights into how the rapid northwards expansion of tropical species can lead to substantial shifts in temperate marine ecosystem functioning (Vergés et al., 2014).

4.4 | Implications for CWCR conservation

Our findings contribute to the conservation of the MRC in several ways. Firstly, the European Union's Marine Strategy Framework Directive has set 11 descriptors for the achievement of Good Environmental Status (European Commission, 2017). Biodiversity (Descriptor 1), non-indigenous species (D2), food webs (D4) and seafloor integrity (D6) are four key descriptors in this Directive. The present study advances our knowledge about biodiversity, habitat integrity and food web structure at MRC Marine Protected Area over time and space serving conservation and achievement of Good Environmental Status. Furthermore, sampling benthos over the years has served the establishment of baselines for marine litter (D10 in the Directive) at MRC (La Beur et al., 2019). Furthermore, improving the understanding about the effects of interannual variability on MRC fauna could help improve predictions of the ecosystem functioning under future scenarios. This progress serves the establishment of monitoring programmes at MRC, which are currently missing. Indeed, the current study has shown that MRC may be sensitive to interannual changes in water mass characteristics, and thus, the establishment of regular monitoring programmes is necessary for reef conservation. Our findings contribute also to the conservation of CWCRs on a regional scale. Specifically, biological and environmental (meta)data from MRC are archived in online repositories (e.g. PANGAEA) serving the upscaling of findings from the local to the regional level, which is necessary for the achievement of Good Environmental Status (Kazanidis et al., 2020). In addition, our findings contribute to the identification and management of climate change refugia, a mitigation strategy for the conservation of species susceptible to climate change (Morelli et al., 2016). The shoaling of the aragonite saturation horizon by 2100 (Orr et al., 2005) is expected to cause major reductions in habitat suitability for North Atlantic CWCRs as they will be bathed in more acidic waters (Morato et al., 2020). However, CWCRs on the continental shelf, such as the MRC, are expected to be less affected by the shoaling of the aragonite saturation horizon, and thus, they may serve as climate change refugia (Morato et al., 2020; Turley et al., 2007). Data continuity, accessibility and affordability are important obstacles in the identification of fine-scale climate change refugia (Morelli et al., 2016). Advancing knowledge on the temporal dynamics of continental shelves' CWCRs and sharing of gathered (meta)data serve the establishment of monitoring programmes and CWCR conservation for the future.

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CONFLICT OF INTEREST

The author declare there is no conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

All the data used in the present study have already been deposited (11/05/2020) to the online archive PANGAEA (DOI: <https://doi.pangaea.de/10.1594/PANGAEA.915974>).

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REFERENCES

- Armstrong, C., Vondolia, G. K., Foley, N. S., Henry, L.-A., Needham, K., & Ressurreição, A. (2019). Expert assessment of risks posed by climate change and anthropogenic activities to ecosystem services in the deep North Atlantic. *Frontiers in Marine Science*, 6, 158. <https://doi.org/10.3389/fmars.2019.00158>
- Armstrong, R. (2014). When to use the Bonferroni correction. *Ophthalmic and Physiological Optics*, 34, 502–508. <https://doi.org/10.1111/opo.12131>
- Basterretxea, G., Font-Muñoz, J. S., Salgado-Hernanz, P. M., Arrieta, J., & Hernández-Carrasco, I. (2018). Patterns of chlorophyll interannual variability in Mediterranean biogeographical regions. *Remote Sensing of Environment*, 215, 7–17. <https://doi.org/10.1016/j.rse.2018.05.027>
- Bates, A. E., Stuart-Smith, D., Barrett, N. S., & Edgar, G. J. (2017). Biological interactions both facilitate and resist climate-related functional change in temperate reef communities. *Proceedings of the Royal Society B: Biological Sciences*, 284, 20170484. <https://doi.org/10.1098/rspb.2017.0484>
- Beaugrand, G., Edwards, M., Brander, K., Luczak, C., & Ibanez, F. (2008). Causes and projections of abrupt climate-driven ecosystem shifts in the North Atlantic. *Ecology Letters*, 11, 1157–1168. <https://doi.org/10.1111/j.1461-0248.2008.01218.x>
- Beaugrand, G., Reid, P. C., Ibañez, F., Lindley, J. A., & Edwards, M. (2002). Reorganisation of North Atlantic marine copepod biodiversity and climate. *Science*, 296, 1692–1699. <https://doi.org/10.1126/science.1071329>
- Bell, J. J., Rovellini, A., Davy, S. K., Taylor, M. W., Fulton, E. A., Dunn, M. R., Bennett, H. M., Kandler, N. M., Luter, H. M., & Webster, N. S. (2018). Climate change alterations to ecosystem dominance: how might sponge-dominated reefs function? *Ecology*, 99, 1920–1931.
- Bindoff, N. L., Cheung, W. W. L., Kairo, J. G., Aristegui, J., Guinder, V. A., Hallberg, R., Hilmi, N., Jiao, N., Karim, M. S., Levin, L., O'Donoghue, S., Purca Cuicapusa, S. R., Rinkevich, B., Suga, T., Tagliabue, A., & Williamson, P. (2019). Chapter 5: Changing ocean, marine ecosystems, and dependent communities. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegria, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. M. Weyer (Eds.), *IPCC special report oceans and cryospheres in changing climate* (pp. 447–588). Cambridge University Press.
- Birchenough, S. N. R., Reiss, H., Degraer, S., Mieszowska, N., Borja, Á., Buhl-Mortensen, L., Braeckman, U., Craeymeersch, J., De Mesel, I., Kerckhof, F., Kröncke, I., Parra, S., Rabaut, M., Schröder, A., Van Colen, C., Van Hoey, G., Vincx, M., & Wätjen, K. (2018). Climate change and marine benthos: A review of existing research and future directions in the North Atlantic. *Wires Climate Change*, 6, 203–223. <https://doi.org/10.1002/wcc.330>
- Borcard, D., Gillet, F., & Legendre, P. (2018). *Numerical Ecology with R*. Springer International Publishing.
- Borcard, D., Legendre, P., & Drapeau, P. (1992). Partialling out the spatial component of ecological variation. *Ecology*, 73, 1045–1055. <https://doi.org/10.2307/1940179>
- Bourque, J. R., & Demopoulos, A. W. J. (2018). The influence of different deep-sea coral habitats on sediment macrofaunal community structure and function. *PeerJ*, 6, e5276. <https://doi.org/10.7717/peerj.5276>
- Buchner, D., Beermann, A. J., Laini, A., Rolaufts, P., Vitecek, S., Hering, D., & Leese, F. (2019). Analysis of 13,312 benthic invertebrate samples from German streams reveals minor deviations in ecological status class between abundance and presence/absence data. *PLoS ONE*, 14, e0226547.
- Buhl-Mortensen, P., Hovland, M., Brattegard, T., & Farestveit, R. (1995). Deep water bioherms of the scleractinian coral *Lophelia pertusa* (L.) at 64°N on the Norwegian Shelf: Structure and associated megafauna. *Sarsia*, 80, 146–158. <https://doi.org/10.1080/00364827.1995.10413586>
- Bullock, J. M., Shea, K., & Skarpaas, O. (2006). Measuring plant dispersal: An introduction to field methods and experimental design. *Plant Ecology*, 186(2), 217–234. <https://doi.org/10.1007/s11258-006-9124-5>
- Burk, L. (2018). *Tadaatoolbox Package. R package version 0.16.1*. Retrieved from <https://github.com/tadaadata/tadaatoolbox>
- Byrne, M. (2011). Impact of ocean warming and ocean acidification on marine invertebrate life history stages: Vulnerabilities and potential for persistence in a changing ocean. *Oceanography and Marine Biology: an Annual Review*, 49, 1–42.
- Cartes, J. E., Maynou, F., Fanelli, E., Papiol, V., & Lloris, D. (2009). Long-term changes in the composition and diversity of deep-slope megabenthos and trophic webs off Catalonia (western Mediterranean): Are trends related to climatic oscillations? *Progress in Oceanography*, 82, 32–46. <https://doi.org/10.1016/j.pocean.2009.03.003>
- Clark, M. R., Bowden, D. A., Rowden, A. A., & Stewart, R. (2019). Little evidence of benthic community resilience to bottom trawling on seamounts after 15 years. *Frontiers in Marine Science*, 6, 63. <https://doi.org/10.3389/fmars.2019.00063>
- Clarke, K. R., & Gorley, R. N. (2015). *PRIMER v7: User Manual/Tutorial PRIMER-E: Plymouth*. PRIMER-E Ltd.
- Cordes, E. E., McGinley, M. P., Podowski, E. L., Becker, E. L., Lessard-Pilon, S., Viada, S. T., & Fisher, C. R. (2008). Coral communities of the deep Gulf of Mexico. *Deep-Sea Research I*, 55, 777–787. <https://doi.org/10.1016/j.dsr.2008.03.005>
- Cormier, R., Elliott, M., & Rice, J. (2019). Putting on a bow-tie to sort out who does what and why in the complex arena of marine policy and

- management. *Science of the Total Environment*, 648, 293–305. <https://doi.org/10.1016/j.scitotenv.2018.08.168>
- Costello, M. J., Tsai, P., Wong, P. S., Cheung, A. K. L., Basher, Z., & Chaudhary, C. (2017). Marine biogeographic realms and species endemicity. *Nature Communications*, 8, 1057. <https://doi.org/10.1038/s41467-017-01121-2>
- Davies, A. J., Duineveld, G. C. A., Lavaleye, M. S. S., Bergman, M. J. N., van Haren, H., & Roberts, J. M. (2009). Downwelling and deep-water bottom currents as food supply mechanisms to the cold-water coral *Lophelia pertusa* (Scleractinia) at the Mingulay Reef complex. *Limnology and Oceanography*, 54, 620–629. <https://doi.org/10.4319/lo.2009.54.2.0620>
- De Clippele, L. H., Gafeira, J., Robert, K., Hennige, S., Lavaleye, M. S., Duineveld, G. C. A., Huvenne, V. A. I., & Roberts, J. M. (2017). Using novel acoustic and visual mapping tools to predict the small-scale spatial distribution of live biogenic reef framework in cold-water coral habitats. *Coral Reefs*, 36, 255–268. <https://doi.org/10.1007/s00338-016-1519-8>
- De Clippele, L. H., Rovelli, L., Ramiro-Sánchez, B., Kazanidis, G., Vad, J., Turner, S., Glud, R. N., & Roberts, J. M. (2021). Mapping cold-water coral biomass: An approach to derive ecosystem functions. *Coral Reefs*, 40, 215–231. <https://doi.org/10.1007/s00338-020-02030-5>
- de Goeij, J. M., Lesser, M. P., & Pawlik, J. R. (2017). Nutrient fluxes and ecological functions of coral reef sponges in a changing ocean. In J. L. Carballo, & J. J. Bell (Eds.), *Climate change, ocean acidification and sponges* (pp. 373–410). Springer International Publishing.
- Dinno, A. (2017). *Dunn.test Package. R package version 1.3.5*. Retrieved from <https://cran.r-project.org/web/packages/dunn.test/dunn.test.pdf>
- Douarin, M., Sinclair, D. J., Elliot, M., Henry, L.-A., Long, D., Mitchison, F., & Roberts, J. M. (2014). Changes in fossil assemblage in sediment cores from Mingulay Reef Complex (NE Atlantic): Implications for coral reef build-up. *Deep Sea Research Part II*, 99, 286–296. <https://doi.org/10.1016/j.dsr2.2013.07.022>
- Duineveld, G. C. A., Jeffreys, R. M., Lavaleye, M. S. S., Davies, A. J., Bergman, M. J. N., Watmough, T., & Witbaard, R. (2012). Spatial and tidal variation in food supply to shallow cold-water coral reefs of the Mingulay Reef complex (Outer Hebrides, Scotland). *Marine Ecology Progress Series*, 444, 97–115. <https://doi.org/10.3354/meps09430>
- European Commission (2017). Commission Decision (EU) 2017/848 of 17 May 2017 laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardized methods for monitoring and assessment, and repealing Decision 2010/477/EU. *Official Journal of the European Union* L 125/43. ELI. <http://data.europa.eu/eli/dec/2017/848/oj>
- Findlay, H. S., Artioli, Y., Moreno Navas, J., Hennige, S. J., Wicks, L. C., Huvenne, V. A. I., ... Roberts, J. M. (2013). Tidal downwelling and implications for the carbon biogeochemistry of cold-water corals in relation to future ocean acidification and warming. *Global Change Biology*, 19, 2708–2719. <https://doi.org/10.1111/gcb.12256>
- Froglia, C., & Speranza, S. (1993). First record of *Dyspanopeus sayi* (Smith, 1869) in the Mediterranean Sea (Crustacea: Decapoda: Xanthidae). *Quaderni Istituto Ricerche Pesca Marittima*, 5, 163–166.
- Garzke, J., Ismar, S. M. H., & Sommer, U. (2015). Climate change affects low trophic level marine consumers: Warming decreases copepod size and abundance. *Oecologia*, 177, 849–860. <https://doi.org/10.1007/s00442-014-3130-4>
- Gili, J.-M., & Coma, R. (1998). Benthic suspension feeders: Their paramount role in littoral marine food webs. *Trends in Ecology and Evolution*, 13, 316–321. [https://doi.org/10.1016/S0169-5347\(98\)01365-2](https://doi.org/10.1016/S0169-5347(98)01365-2)
- Good, S. A., Martin, M. J., & Rayner, N. A. (2013). EN4: Quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates. *Journal of Geophysical Research: Oceans*, 118, 6704–6716. <https://doi.org/10.1002/2013JC009067>
- Grassle, J. F., & Maciolek, N. J. (1992). Deep-sea species richness: Regional and local diversity estimates from quantitative bottom samples. *The American Naturalist*, 139, 313–341.
- Gunderson, L. H. (2000). Ecological resilience – in theory and application. *Annual Review of Ecology and Systematics*, 31, 425–439. <https://doi.org/10.1146/annurev.ecolsys.31.1.425>
- Hátún, H., Sando, A. B., Drange, H., Hansen, B., & Valdimarsson, H. (2005). Influence of the Atlantic subpolar gyre on the thermohaline circulation. *Science*, 309, 1841–1844. <https://doi.org/10.1126/science.1114777>
- Hátún, H., Scott-Azetsu, K., Somavilla, R., Johnson, C., Mathis, M., Mikolajewicz, U., ... Ólafsson, J. (2017). The subpolar gyre regulates silicate concentrations in the North Atlantic. *Scientific Reports*, 7, 14576. <https://doi.org/10.1038/s41598-017-14837-4>
- Hayward, P. J., & Ryland, J. S. (2017). *Handbook of the marine fauna of North-West Europe*. Oxford University Press.
- Hebbeln, D., da Costa Portilho-Ramos, R., Wienberg, C., & Titschack, J. (2019). The fate of cold-water corals in a changing world: a geological perspective. *Frontiers in Marine Science*, 6, 119. <https://doi.org/10.3389/fmars.2019.00119>
- HELCOM (2018). State of the Baltic Sea – Second HELCOM holistic assessment 2011–2016. Baltic Sea Environment Proceedings 155. <https://helcom.fi/baltic-sea-trends/holistic-assessments/state-of-the-baltic-sea-2018/reports-and-materials/>
- Hennige, S. J., Wolfram, U., Wickes, L., Murray, F., Roberts, J. M., Kamenos, N. A., ... Etnoyer, P. J. (2020). Crumbling reefs and cold-water coral habitat loss in a future ocean: Evidence of “coralporosis” as an indicator of habitat integrity. *Frontiers in Marine Science*, 7, 668. <https://doi.org/10.3389/fmars.2020.00668>
- Henry, L.-A., Davies, A. J., & Roberts, J. M. (2010). Beta diversity of cold-water coral reef communities off western Scotland. *Coral Reefs*, 29, 427–436. <https://doi.org/10.1007/s00338-009-0577-6>
- Henry, L.-A., Moreno Navas, J., & Roberts, J. M. (2013). Multi-scale interactions between local hydrography, seabed topography, and community assembly on cold-water coral reefs. *Biogeosciences*, 10, 2737–2746. <https://doi.org/10.5194/bg-10-2737-2013>
- Henry, L.-A., & Roberts, L. M. (2017). Global biodiversity in cold-water coral reef ecosystems. In S. Rossi, L. Bramanti, A. Gori, & C. Orejas (Eds.), *Marine Animal Forests: The Ecology Of Benthic Biodiversity Hotspots* (pp. 1–21). Springer International Publishing.
- Holopainen, R., Lentiniemi, M., Meier, M., Albertsson, J., Gorokhova, E., Kotta, J., & Viitasalo, M. (2016). Impacts of changing climate on the non-indigenous invertebrates in the northern Baltic Sea by end of the twenty-first century. *Biological Invasions*, 18, 3015–3032. <https://doi.org/10.1007/s10530-016-1197-z>
- Hooper, D. U., Chapin, F. S. III, Ewel, J. J., Hector, A., Inchausti, P., Lavorel, S., ... Wardle, D. A. (2005). Effects of biodiversity on ecosystem functioning: A consensus of current knowledge. *Ecological Monographs*, 75, 3–35. <https://doi.org/10.1890/04-0922>
- Hurrell, J. W., Kushnir, Y., Ottersen, G., & Visbeck, M. (2003). An overview of the North Atlantic Oscillation. In J. W. Hurrell, Y. Kushnir, G. Ottersen, & M. Visbeck (Eds.), *The north Atlantic oscillation: Climatic significant and environmental impact* (pp. 1–35). American Geophysical Union.
- Iannotta, M. A., Patti, F. P., Ambrosino, M., Procaccini, G., & Gambi, M. C. (2007). Phylogeography of two species of *Lysidice* (Polychaeta, Eunicidae) associated to the seagrass *Posidonia oceanica* in the Mediterranean Sea. *Marine Biology*, 150, 1115–1126. <https://doi.org/10.1007/s00227-006-0405-2>
- Inall, M., Gillibrand, P., Griffiths, C., MacDougal, N., & Blackwell, K. (2009). On the oceanographic variability of the North-West European Shelf to the West of Scotland. *Journal of Marine Systems*, 77, 210–226. <https://doi.org/10.1016/j.jmarsys.2007.12.012>
- Janas, U., Burska, D., Kendzierska, H., Pryputniewicz-Flis, D., & Łukawska-Matuszewska, K. (2019). Importance of benthic macrofauna and

- coastal biotopes for ecosystem functioning – Oxygen and nutrient fluxes in the coastal zone. *Estuarine, Coastal and Shelf Science*, 225, 106238. <https://doi.org/10.1016/j.ecss.2019.05.020>
- Jensen, A., & Frederiksen, R. (1992). The fauna associated with the bank forming deepwater coral *Lophelia pertusa* (Scleractinaria) on the Faroe shelf. *Sarsia*, 77, 53–69. <https://doi.org/10.1080/00364827.1992.10413492>
- Johnson, C., Inall, M., Gary, S., & Cunningham, S. (2020). Significance of climate indices to benthic conditions across the northern North Atlantic and adjacent shelf seas. *Frontiers in Marine Science*, 7, 2. <https://doi.org/10.3389/fmars.2020.00002>
- Johnson, C., Inall, M., & Häkkinen, S. (2013). Declining nutrient concentrations in the northeast Atlantic as a result of a weakening Subpolar Gyre. *Deep-Sea Research I*, 82, 95–107. <https://doi.org/10.1016/j.dsr.2013.08.007>
- Kazanidis, G., Henry, L.-A., Roberts, J. M., & Witte, U. F. M. (2016). Biodiversity of *Spongosorites coralliophaga* (Stephens, 1915) on coral rubble at two contrasting cold-water coral reef settings. *Coral Reefs*, 35, 193–208. <https://doi.org/10.1007/s00338-015-1355-2>
- Kazanidis, G., Orejas, C., Borja, A., Kenchington, E., Henry, L.-A., Callery, O., Carreiro-Silva, M., Egilsdottir, H., Giacomello, E., Grehan, A., Menot, L., Morato, T., Ragnarsson, S. A., Rueda, J. L., Stirling, D. E., Stratmann, T., van Oevelen, D., Palialexis, A., Johnson, D., & Roberts, J. M. (2020). Assessing the environmental status of selected North Atlantic deep-sea ecosystems. *Ecological Indicators*, 119, 106624.
- Kazanidis, G., & Witte, U. F. M. (2016). The trophic structure of *Spongosorites coralliophaga*-coral rubble communities at two north-east Atlantic cold water coral reefs. *Marine Biology Research*, 12, 932–947. <https://doi.org/10.1080/17451000.2016.1216569>
- Klitgaard, A. (1995). The fauna associated with outer shelf and upper slope sponges (Porifera, Demospongiae) at the Faroe Islands, north-eastern Atlantic. *Sarsia*, 80, 1–22. <https://doi.org/10.1080/00364827.1995.10413574>
- La Beur, L., Henry, L.-A., Kazanidis, G., Hennige, S., McDonald, A., Shaver, M. P., & Roberts, J. M. (2019). Baseline assessment of marine litter and microplastic ingestion by cold-water coral reef benthos at the East Mingulay Marine Protected Area (Sea of the Hebrides, Western Scotland). *Frontiers in Marine Science*, 6, 80. <https://doi.org/10.3389/fmars.2019.00080>
- Lacharite, M., & Metaxas, A. (2018). Environmental drivers of epibenthic megafauna on a deep temperate continental shelf: A multiscale approach. *Progress in Oceanography*, 162, 171–186.
- Legendre, P. D., & Gallagher, E. D. (2001). Ecologically meaningful transformations for ordination of species data. *Oecologia*, 129, 271–280. <https://doi.org/10.1007/s004420100716>
- Lewis, C., Olive, P. J. W., Bentley, M. G., & Watson, G. (2002). Does seasonal reproduction occur at the optimal time for fertilization in the polychaete *Arenicola marina* L. and *Nereis virens* Sars? *Invertebrate Reproduction and Development*, 41, 61–71. <https://doi.org/10.1080/07924259.2002.9652736>
- Lohmann, K., Drange, H., & Bentsen, M. (2009). A possible mechanism for the strong weakening of the North Atlantic subpolar gyre in the mid-1990s. *Geophysical Research Letters*, 36, L15602. <https://doi.org/10.1029/2009GL039166>
- Lozier, M. S., & Stewart, N. M. (2008). On the temporally varying northward penetration of Mediterranean Overflow Water and eastward penetration of Labrador Sea Water. *Journal of Physical Oceanography*, 38, 2097–2103. <https://doi.org/10.1175/2008JPO3908.1>
- Mackenzie, C. L., Ormondroyd, G. A., Curling, S. F., Ball, R. J., Whiteley, N. M., & Malham, S. K. (2014). Ocean warming, more than acidification, reduces shell strength in a commercial shellfish species during food limitation. *PLoS One*, 9(1), e86764. <https://doi.org/10.1371/journal.pone.0086764>
- Mittermeier, R. A., Turner, W. R., Larsen, F. W., Brooks, T. M., & Gascon, C. (2011). Global biodiversity conservation: the critical role of hotspots. In: F. E. Zachos, & J. C. Habel (eds.), *Biodiversity Hotspots*. Springer-Verlag Berlin Heidelberg. https://doi.org/10.1007/978-3-642-20992-5_1
- Molinero, J. C., Ibanez, F., Souissi, S., Buechers, E., Dallot, S., & Nival, P. (2008). Climate control on the long-term anomalous changes of zooplankton communities in the Northwestern Mediterranean. *Global Change Biology*, 14, 11–26. <https://doi.org/10.1111/j.1365-2486.2007.01469.x>
- Morato, T., González-Irusta, J.-M., Dominguez-Carrió, C., Wei, C.-L., Davies, A., Sweetman, A. K., ... Carreiro-Silva, M. (2020). Climate-induced changes in the suitable habitat of cold-water corals and commercially important deep-sea fishes in the North Atlantic. *Global Change Biology*, 26, 2181–2202. <https://doi.org/10.1111/gcb.14996>
- Morelli, T. L., Daly, C., Dobrowski, S. Z., Dulen, D. M., Ebersole, J. L., Jackson, S. T., ... Beissinger, S. R. (2016). Managing climate change refugia for climate adaptation. *PLoS One*, 11(8), e0159909. <https://doi.org/10.1371/journal.pone.0159909>
- Moreno Navas, J., Miller, P. L., Henry, L.-A., Hennige, S. J., & Roberts, J. M. (2014). Ecohydrodynamics of cold-water coral reefs: A case study of the Mingulay Reef Complex (Western Scotland). *PLoS One*, 9, e98218. <https://doi.org/10.1371/journal.pone.0098218>
- Murillo, F. J., Kenchington, E., Koen-Alonso, M., Guijarro, J., Kenchington, T. J., Sacau, M., ... Rapp, H. T. (2020). Mapping benthic ecological diversity and interactions with bottom-contact fishing on the Flemish Cap (northwest Atlantic). *Ecological Indicators*, 112, 106135. <https://doi.org/10.1016/j.ecolind.2020.106135>
- Myrberg, K., Korpinen, S., & Uusitalo, L. (2019). Physical oceanography sets the scene for the Marine Strategy Framework Directive implementation in the Baltic Sea. *Marine Policy*, 107, 103591.
- Nagar, L. R., & Shenkar, N. (2016). Temperature and salinity sensitivity of the invasive ascidian *Microcosmus exasperatus* Heller, 1878. *Aquatic Invasions*, 11, 33–43. <https://doi.org/10.3391/ai.2016.11.1.04>
- Neuwirth, E. (2014). RColorBrewer: ColorBrewer Palettes. R package version 1.1-2. <https://CRAN.Rproject.org/package=RColorBrewer>
- Ocean Biodiversity Information System (OBIS) (2019). <https://obis.org/>
- O'Hara, T. D., Rowden, A. A., & Williams, A. (2008). Cold-water coral habitats on seamounts: Do they have a specialist fauna? *Diversity and Distributions*, 14, 925–934. <https://doi.org/10.1111/j.1472-4642.2008.00495.x>
- Oksanen, J., Blanchet, G., Friendly, M., Kindt, R., Legendre, P., McGlenn, D., ... Wagner, H. (2019). *vegan: Community Ecology Package. R package version 2.5-6*. Retrieved from <https://cran.r-project.org>, <https://github.com/vegandevs/vegan>
- Orr, J. C., Fabry, V. J., Aumont, O., Bopp, L., Doney, S. C., Feely, R. A., ... Yool, A. (2005). Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, 437, 6812–7686. <https://doi.org/10.1038/nature04095>
- Poloczanska, E. S., Burrows, M. T., Brown, C. J., Molinos, J. G., Halpern, B. S., Hoegh-Guldberg, O., ... Sydeman, W. J. (2016). Response of marine organisms to climate change across oceans. *Frontiers in Marine Science*, 3, 62. <https://doi.org/10.3389/fmars.2016.00062>
- Porter, M., Dale, A. C., Jones, S., Siemerling, B., & Inall, M. E. (2018). Cross-slope flow in the Atlantic Inflow Current driven by the on-shelf deflection of a slope current. *Deep-Sea Research Part I: Oceanographic Research Papers*, 140, 173–185. <https://doi.org/10.1016/j.dsr.2018.09.002>
- Puerta, P., Johnson, C., Carreiro-Silva, M., Henry, L.-A., Kenchington, E., Morato, T., ... Orejas, C. (2020). Influence of water masses on the biodiversity and biogeography of deep-sea benthic ecosystems in the North Atlantic. *Frontiers in Marine Science*, 7, 239. <https://doi.org/10.3389/fmars.2020.00239>
- Ramírez, F., Afán, I., Davis, L. S., & Chiaradia A. (2017). Climate impacts on global hot spots of marine biodiversity. *Science Advances*, 3, e1601198. <https://doi.org/10.1126/sciadv.1601198>

- Rix, L., de Goeij, J. M., Mueller, C. E., Struck, U., Middelburg, J. J., van Duyl, F. C., ... van Oevelen, D. (2016). Coral mucus fuels the sponge loop in warm- and cold-water coral reef ecosystems. *Scientific Reports*, 6, 18715. <https://doi.org/10.1038/srep18715>
- Roberts, J. M., Brown, C. J., Long, D., & Bates, C. R. (2005). Acoustic mapping using a multibeam echosounder reveals cold-water coral reefs and surrounding habitats. *Coral Reefs*, 24, 654–669. <https://doi.org/10.1007/s00338-005-0049-6>
- Roberts, J. M., Davies, A. J., Henry, L.-A., Dodds, L. A., Duineveld, G. C. A., Lavaleye, M. S. S., ... van Haren, H. (2009). Mingulay reef complex: An interdisciplinary study of cold-water coral habitat, hydrography and biodiversity. *Marine Ecology Progress Series*, 397, 139–151. <https://doi.org/10.3354/meps08112>
- Roberts, J. M., Murray, F., Anagnostou, E., Hennige, S., Gori, A., Henry, L.-A., ... Foster, G. L. (2016). Cold-water corals in an era of rapid global change: Are these the deep ocean's most vulnerable ecosystems? In S. Goffredo, & Z. Dubinsky (Eds.), *The Cnidaria, past, present and future* (pp. 593–606). Springer International Publishing.
- Roberts, J. M., Wheeler, A. J., & Freiwald, A. (2006). Reefs of the deep: The biology and geology of cold-water coral ecosystems. *Science*, 312, 543–547. <https://doi.org/10.1126/science.1119861>
- Rupp, J. H. (1973). Effects of temperature on fertilization and early cleavage of some tropical echinoderms, with emphasis on *Echinometra mathaei*. *Marine Biology*, 23, 183–189. <https://doi.org/10.1007/BF00389483>
- Savini, A., Vertino, A., Marchese, F., Beuck, L., & Freiwald, A. (2014). Mapping cold-water coral habitats at different scales within the northern Ionian Sea (Central Mediterranean): an assessment of coral coverage and associated vulnerability. *PLoS ONE*, 9, e87108. <https://doi.org/10.1371/journal.pone.0087108>
- Sundahl, H., Buhl-Mortensen, P., & Buhl-Mortensen, L. (2020). Distribution and suitable habitat of the cold-water corals *Lophelia pertusa*, *Paragorgia arborea*, and *Primnoa resedaeformis* on the Norwegian Continental Shelf. *Frontiers in Marine Science*, 7, 213. <https://doi.org/10.3389/fmars.2020.00213>
- Selmoni, O., Vajana, E., Guillaume, A., Rochat, E., & Joost, S. (2020). Sampling strategy optimization to increase statistical power in landscape genomics: A simulation-based approach. *Molecular Ecology Resources*, 20, 154–169. <https://doi.org/10.1111/1755-0998.13095>
- Simon, C., San Martin, G., & Robinson, G. (2014). Two new species of *Syllis* (Polychaeta: Syllidae) from South Africa, one of them viviparous, with remarks on larval development and vivipary. *Journal of the Marine Biological Association of the UK*, 94, 729–746.
- Smith, K. L. Jr, Ruhl, H. A., Bett, B. J., Billett, D. S. M., Lampitt, R. S., & Kaufmann, R. S. (2009). Climate, carbon cycling, and deep-ocean ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, 106, 19211–19218. <https://doi.org/10.1073/pnas.0908322106>
- Sweetman, A. K., Thurber, A. R., Smith, C. R., Levin, L. A., Mora, C., Wei, C.-L., ... Roberts, J. M. (2017). Major impacts of climate change on deep-sea benthic ecosystems. *Elementa Science of the Anthropocene*, 5, 4. <https://doi.org/10.1525/elementa.203>
- Tews, J., Brose, U., Grimm, V., Tielbörger, K., Wichmann, M. C., Schwager, M., & Jeltsch, F. (2004). Animal species diversity driven by habitat heterogeneity/diversity: The importance of keystone structures. *Journal of Biogeography*, 31, 79–92. <https://doi.org/10.1046/j.0305-0270.2003.00994.x>
- Turley, C. M., Roberts, J. M., & Guinotte, J. M. (2007). Corals in deep water: Will the unseen hand of ocean acidification destroy cold-water ecosystems? *Coral Reefs*, 26, 445–448.
- Vergés, A., Steinberg, P. D., Hay, M. E., Poore, A. G. B., Campbell, A. H., Ballesteros, E., ... Wilson, S. K. (2014). The tropicalization of temperate marine ecosystems: Climate-mediated changes in herbivory and community phase shifts. *Proceedings of the Royal Society B: Biological Sciences*, 281, 20140846. <https://doi.org/10.1098/rspb.2014.0846>
- Wei, T., & Simko, V. (2017). R package "corrplot": Visualization of a Correlation Matrix (Version 0.84). Retrieved from <https://github.com/taiyun/corrplot>
- Weinnig, A. M., Gómez, C. E., Hallaj, A., & Cordes, E. E. (2020). Cold-water coral (*Lophelia pertusa*) response to multiple stressors: High temperature affects recovery from short-term pollution exposure. *Scientific Reports*, 10, 1768. <https://doi.org/10.1038/s41598-020-58556-9>
- Woodall, L. C., Robinson, L. F., Rogers, A. D., Narayanaswamy, B. E., & Paterson, G. L. J. (2015). Deep-sea litter: A comparison of seamounts, banks and a ridge in the Atlantic and Indian Oceans reveals both environmental and anthropogenic factors impact accumulation and composition. *Frontiers in Marine Science*, 2. <https://doi.org/10.3389/fmars.2015.00003>
- Zettler, M. L., Friedland, R., Gogina, M., & Darr, A. (2017). Variation in benthic long-term data of transitional waters: Is interpretation more than speculation? *PLoS One*, 12, e0175746. <https://doi.org/10.1371/journal.pone.0175746>

BIOSKETCH

Georgios Kazanidis is a marine zoologist who studies the impacts of human activities and changing environmental conditions on the structure and functioning of marine ecosystems. Since 2012, he has focussed on the ecology of deep-sea ecosystems. The authors of the present study (affiliated with ATLAS and iAtlantic projects) formed a multidisciplinary team and advanced human knowledge about the effects of interannual variability of regional oceanography and seafloor terrain on the biodiversity and biogeography of cold-water coral reefs. This serves the assessment of cold-water coral reefs health status and their conservation for the future.

Author contributions: LAH and JMR collected samples. GK and LAH sorted and identified macrofauna. LAH, JMR, CJ, JV and LDC provided data on the environmental variables. GK and JV analysed the data and made the graphs. GK wrote the manuscript with editorial help from LAH, JV, CJ, LDC and JMR.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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