Ongoing ocean warming threatens the rich and diverse macrobenthic communities of the Antarctic continental shelf

Enrique Isla^{1*} & Dieter Gerdes²

¹Institut de Ciències del Mar-CSIC, Passeig Marítim de la Barceloneta 37-49, 08003, Barcelona, Spain. isla@icm.csic.es

²Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung, Columbusstrasse, 27568, Bremerhaven, Germany. Dieter.Gerdes@awi.de

*corresponding author

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Highlights

Intrusions of warm water onto the Weddell Sea continental shelf showed periodicities similar to diurnal tides.

Warm water intrusions can increase temperature near the seabed $>2^{\circ}\text{C}$.

The highest temperature variation was recorded in the Filchner-Ronne region, macrobenthic communities here may show the effects of warming earlier than those thriving in other regions of the Weddell Sea shelf.

The high percentage of sessile animals constituting the macrobenthic communities in the southeastern Weddell Sea makes this area the most vulnerable to warming.

Abstract

Global warming is heating the Antarctic circumpolar deep water (CDW), which comes into direct contact with the diverse and abundant macrobenthic communities thriving on the continental shelf of the Weddell Sea (WS). A set of 16 current meters deployed along more than 3000 km coastline revealed that tidal currents drive CDW intrusions onto the WS continental shelf and they can increase the temperature near the seabed by $\sim 2.7^{\circ}\text{C}$. The ongoing ocean warming trend may expose macrobenthic assemblages to ambient temperatures $>2^{\circ}\text{C}$ by the end of the century with dramatic consequences for communities which have evolved during millions of years in near geophysical isolation under rather constant environmental conditions with temperatures $<0^{\circ}\text{C}$. These stenothermal communities have long generation times (therefore, reduced opportunity to mutate) and require hundreds of years for adaptation.

Results from 135 benthic stations along the study area showed that macrobenthic communities in the southeastern section of the WS are the most vulnerable to the increase of temperature near the seabed given their high component of sessile organisms. Besides a dramatic marine biodiversity loss, the eventual demise of these communities, which provide habitat structure for a large number of species that can build up $>87\text{ g C m}^{-2}$, will cause the liberation of thousands of tons of carbon to the environment. Macrobenthic communities colonizing the recently opened shelf in the Larsen A and B bays may not have the chance to reach the type of mature assemblage inhabiting the eastern WS shelf. The highest temperatures derived from CDW intrusions were recorded in the Filchner-Ronne region, suggesting that the consequences of the thermal impact could develop faster here than in the rest of the WS. Thus, these macrobenthic communities may show the effects of warming earlier than those

thriving in other regions of the WS shelf. Global warming seriously threatens the abundant and highly diverse macrobenthic communities of the Antarctic continental shelf.

1. Introduction

Anthropogenic global warming effects are evident worldwide (IPCC Report, 2015). They are easily identifiable in the atmospheric and sea surface temperature increasing trends towards the end of the last century and since the 1980's they are also evident in the deep ocean (Levitus et al., 2000; Gille, 2002; Reichert et al., 2002; Fyfe, 2006; Pierce et al., 2006). It has been estimated that in the period between the 1950's and the 1990's the water temperature in the upper 300 m of the ocean increased approximately 0.31°C (Levitus et al., 2000); whereas in the Southern Ocean, the layer between 700 and 1000 m water depth increased about 0.17°C in approximately the same period (Gille, 2002). This warming seems to be concentrated within the Antarctic Circumpolar Current (ACC), where temperature increments are comparable to those observed in the air above the Southern Ocean (Gille, 2002). As water masses flow across oceanic provinces, e.g., between the continental shelf and slope, the continental slope and the abyssal plain, they also transport heat and mass; thus, playing an important role in global climate regulation (Clark et al., 2002). However, their role in shaping high-latitude benthic communities remains poorly known.

The Antarctic continental shelf is wider and deeper than elsewhere. On average it is 500 m deep and in some regions of the western Weddell Sea (WS) it can extend up to 300 km wide, whereas narrower regions can be found off Austasen and Kapp Norvegia in the southeastern WS (Anderson, 1991, 1999). In the WS, temperature and salinity near the seabed have been considered relatively constant throughout the year (Arntz et al., 1994). Together with other environmental variables (e.g., low annual sediment flux, food availability) they have enabled the development of diverse and abundant macrobenthic communities, which in some areas exhibit higher biomasses than in temperate and subtropical settings (Brey and Gerdes, 1997). However, water mass exchange between the continental shelf and the slope introduce variability into this environment. Episodic (e.g., hours to days) intrusions of Circumpolar Deep Water (CDW) from the ACC onto the Antarctic continental shelf, periodically increase the temperature near the seabed (Dinniman et al., 2004; Thoma et al., 2008; Kohut et al., 2013). The effect of these warm water intrusions (WWI) on the warming beneath the ice shelves and their subsequent collapse has already focused attention in the last years (Dinniman et al., 2012; Hellmer et al., 2012, 2017; Cook et al., 2016). Several mechanisms have been invoked to explain WWI, e.g., wind, shelf break topography, eddy development, general circulation patterns, and Ekman transport. It seems, however, that these warming events are mainly modulated by the local characteristics of each study area (Thoma et al., 2008; Klinck et al., 2010; Martinson and McKee, 2012; Kohut et al., 2013; Wåhlin et al., 2013).

Temperature is a key abiotic factor for the development of organisms. It has a strong influence on metabolic rates, larval development and oxygen availability among other factors, which control the organism performance and success

(Gillooly et al., 2001; O'Connor et al., 2007; Pörtner et al., 2007). Temperature increases lead to higher metabolic rates and oxygen demand, reduced larval dispersal and survival (e.g., higher temperatures lead to earlier hatching and faster larval development) and smaller oxygen concentrations in the water column (O'Connor et al., 2007, Pörtner et al., 2007). All these processes seriously limit the performance and success of Antarctic benthic communities, particularly those structured by sessile organisms, which cannot migrate to avoid thermal stress. Macrobenthic communities living in the WS evolved in near isolation for millions of years under geophysical and thermal circumstances that shaped their present status, which resembles the macrobenthic assemblages of the Cretaceous (Gili et al., 2006). The modern Antarctic macrobenthic assemblages show endemism of 50% to 60% at species level and abundance and diversity values comparable to those found in tropical regions (Arntz et al., 1994; Brey and Gerdes, 1997; Gutt et al., 2004). The conditions favoring the retention of apparently archaic features in the Antarctic macrobenthos remain unknown; however, these are unique communities and deserve special conservation measures due to their fragile evolutionary situation (Gili et al., 2006). Under this frame, the apparently remote and nearly isolated rich macrobenthic communities of the WS shelf seem particularly vulnerable to the ongoing ocean warming trend since they are mainly constituted by sessile organisms (Gutt and Starmans, 1998), which can't escape direct exposure to WWI.

Here we demonstrate that WWI onto the continental shelf take place along the entire WS shelf (>3000 km from 8°W to 61°W and 64°S to 74°S). These intrusions can increase the temperature near the seabed >2°C absolute and show periodicities, which in many cases match with those of the diurnal and spring tides. We also identify the regions and macrobenthic communities where these intrusions, under the ongoing ocean warming scenario, may have the greatest impact.

2. Material and methods

2.1 Oceanography

A set of 16 Aanderaa current meters were installed from board R/V Polarstern (AWI, 2017) during 9 expeditions at 14 stations along the continental shelf of the Weddell Sea at different water depths and distances from the shelf break (Fig. 1, Table 1). Each instrument measured temperature, current velocity and direction. The data sets include a variety of sampling periods from days to months with reading intervals between 5 and 60 minutes. Instruments nomenclature was designed according to the mooring area, namely: SE, southeastern Weddell Sea shelf, DI, Drescher Inlet, FI, Filchner-Ronne continental shelf, LA, Larsen A bay and LB, Larsen B bay. The instruments were tethered 5 m above the sea floor. In two mooring lines, SE4 and SE5, a pair of current meters on each line was tethered at two different depths, 5 m above the sea floor and 390 m above the sea floor.

Temperature, current velocity and direction readings from each instrument were analyzed with the Lomb periodogram spectral analysis method (or least-squares spectral analysis) to explore periodicities in their temporal variation

using the statistical software PAST (Hammer et al., 2001). This method is based on the fact that the signal of the time-series variation (as a function of time) can be decomposed into its constituent frequencies. In this method the units in the x axis, i.e., frequency, represent the inverse of the temporal units (time) in the axis, which in all the cases in the present study were the sampling intervals of each current-meter reading, in minutes. The Y or power axis has dimensionless units proportional to the square of the amplitudes (strength) of the sinusoids (frequency) identified with the spectral analyses. Thus, the higher the value in the Y axis is, the higher the contribution of the correspondent frequency in the X axis (time) to the variation in the water current pattern is.

Progressive vector plots were developed to help visualizing the time-integrated displacement that the fluid particle would follow (or trajectory of the current) based on the sequential progressive (consecutive) reading of current direction and velocities at the depth of the current-meter (without consideration of the vertical variation) on the mooring site.

2.2 Benthos

The description of macrobenthic shelf communities in the WS is based on samples covering the eastern Weddell Sea shelf, the Filchner-Ronne Region and the Larsen A and B bays off the eastern Antarctic Peninsula (Fig. 2, supplementary Table 1). Based on the findings of Gutt and Starman (1998) and our own observations, we divided the Weddell Sea shelf into 6 subregions: Austasen as the easternmost region followed towards the west by Kapp Norvegia, Drescher Inlet, Halley Bay, Filchner-Ronne region, and Larsen A and B bays (for the complete set of station coordinates information, see supplementary Table 1). Benthic samples were obtained with a multi-box corer (Gerdes, 1990) during the expeditions ANT V (1988), ANT VI (1989), ANT XIII (1996), ANT XV (1998), ANT XVII (2000), ANT XXI (2003), ANT XXVII (2011) and ANT XXIX (2014) from onboard the R/V Polarstern, covering a water depth range between 161 m and 850 m (supplementary Table 1). 59 stations were sampled in the Austasen subregion, 31 in the adjacent shelf off Kapp Norvegia, 4 stations off Drescher Inlet, 6 in Halley Bay, 16 in the Filchner-Ronne region, 6 in Larsen A and 13 in Larsen B. All samples were sieved over 500 μm mesh size screens and stored in a 4% formaldehyde seawater solution buffered with hexamethylenetetramine. In the laboratory, the material was separated into 35 taxonomical units (TU; available on request); mean abundance (ind m^{-2}) and mean wet biomass (g m^{-2}) values were determined for each TU and station. Colonial forms like sponges and bryozoans were counted for the abundance calculation as 1 (meaning present). Wet mass data were converted to g C_{org} , using conversion factors for major taxonomic groups derived from Brey (2001). Patterns of diversity in the different sub-regions were described by the Shannon index (H) and Pielou's evenness index (J), using the PRIMER software package v. 6 (Clarke and Corley, 2006). The macrobenthic communities in the subregions were characterized by abundance, biomass (wet weight and organic carbon), composition (TU) and by different feeding guilds, namely suspension feeders, deposit feeders, scavengers and predators. The classification of the taxonomic groups into feeding guilds was done following the recommendations of Younge (1928), Hansen (1978), Fauchald and Jumars (1979), Montiel (2005), and Macdonald et al. (2010). In those cases, which different feeding

types occurred parallel in one taxonomic group, the percentage of contribution of the respective guild to the total assemblage was estimated following the detailed classification scheme presented by Macdonald et al. (2010). On this basis, we calculated the proportion of feeding types in each taxonomic group and the contribution of the different feeding guilds to the macrobenthic communities in each subregion.

3. Results

3.1 Physical parameters

Temperature records varied between 0.81°C at station SE4 and -1.97°C at station LB (Table 1, Fig. 3 and supplementary Fig. 1). The largest amplitude in temperature variation, 2.72°C absolute, was observed at station SE5 at 640 m water depth (~5 meters above the sea floor). Relatively high temperature variations (>1°C absolute) took place in stations SE3, SE4, SE5, SE6 and FI; all of them, with the exception of station FI, were located less than 1 km from the continental shelf break (approximately on the 500 m isobath) and near the seabed (~5 meters above the sea floor). In the case of stations SE4 and SE5, the temperature variation was smaller at mid-depth, ~390 m above the sea floor (Table 1). In all other temperature records, the variability was <0.78°C (supplementary Fig. 1). Warm water intrusion periods lasted in most of the cases for 1 day and up to 20 days at station SE5 at 640 m water depth (supplementary Fig. 1).

The only three annual temperature records (two depths at station SE4 and one at station SE6) showed that at 286 m water depth at station SE4 and at 295 m water depth at station SE6, the temperatures were higher by the end of the summer, whereas no evident annual pattern was observed 5 m above the sea floor at station SE4 (supplementary Fig. 1).

Current velocity varied between 0.01 cm s⁻¹ and 54 cm s⁻¹; the highest velocity and variability (e.g., 0.01 to 54 cm s⁻¹) were registered at station SE6, 5 m above the sea floor and near the continental shelf break (Table 1, Fig. 3 and supplementary Fig. 1). In general, velocity profiles showed oscillatory periods of 24-h together with longer periods of 15 to 17 days; in the year-long records at stations SE4 and SE6, no clear annual patterns were recognized (Table 2, Fig. 4 and supplementary Fig. 2).

The water current progressive vector plots (Fig. 5) from the SE and DI instrument groups showed, with some exceptions, a general common pattern of short-term (1 day) North-South oscillations and a main current flow towards the West, following the main direction of the Weddell Gyre (Orsi et al., 1993). Contrarily, at stations SE8 and SE9 the main current flowed towards the East also describing short-term (1 day) North-South oscillations. The progressive vector plot from station SE7 presented a different pattern; it also showed a main current flow towards the West but constituted by a series of short-term (1 day) East-West oscillations. This was the only station within the SE group, which was not located on the open continental shelf, it was sheltered from the circulation of main current path of the Weddell Gyre by the prominent Kapp Norvegia (Fig. 5a). The progressive vector plot of station FI showed a series of short-term

elliptic oscillations (1 day) and a main current flow towards the South, suggesting tidal movements and a flow from the continental slope onto the shelf (Fig. 5b). The Larsen group records showed a main current flow towards the northwest in the case of station LB and towards the northeast at station LA, both patterns matching with the main direction of the Weddell Gyre current (Fig. 5c). Both plots showed short-term (1 day) North-South oscillations.

Temperature, current velocity and direction temporal series spectral analyses showed several periodicities (Table 2, Fig. 4 and supplementary Fig. 2). In most of the cases there was an evident 1-day frequency, which matched with a diurnal tidal pattern. Other frequencies corresponded to semidiurnal (0.5 day) and weekly (7 to 17 days) periods (Table 2).

3.2 Benthos

The highest mean abundance values corresponded to the communities in the southeastern WS shelf with a maximum value of 4589 ind m⁻² off Kapp Norvegia, whereas lower mean values, between 2230 and 2790 ind m⁻² corresponded to the communities in Austasen, Drescher Inlet and Halley Bay (Table 3, Fig. 6). Lower mean abundances, 1773 ind m⁻², were found in the Filchner-Ronne region and the lowest values in the regions LA and LB with 633 and 774 ind m⁻², respectively.

The highest biomass values, 2790 g wet weight m⁻², corresponded to the dense sponge aggregations living on the shelf off Austasen in the southeastern WS (Fig. 6). The mean biomass decreased towards the western subregions, although a relatively high value of 187.6 g m⁻² was obtained for the Larsen A stations. This high value was mainly due to echiurids; their occurrence at just 2 stations contributed >88% to the observed biomass. The C_{org} pattern matched with the biomass trend (Table 3); with maximum values of 87.6 g m⁻² on the southeastern shelf and minimum values of 2.2 g m⁻² towards the west in the Larsen B bay. A relatively larger community of up to 15.8 g C m⁻² was found in the Larsen A bay, corresponding to the observed biomass pattern.

Taxa numbers and diversity indices indicated that the southeastern WS shelf and FI regions host more diverse assemblages than those observed in the Larsen bays (Table 3). Off Austasen, Kapp Norvegia and Drescher Inlet, where the shelf is narrower (max. 50 km) than in the western regions, sessile and community-structuring organisms, especially sponges, bryozoans and ascidians, dominated the benthic assemblages (Fig. 6). In the western subregions, particularly in the southern part of FI, bryozoans, polychaetes, echinoderms and crustaceans were the main TU, forming an assemblage type described as a Southern Shelf Community (*sensu* Voss, 1988). In all subregions, except the Larsen bays, suspension feeders, mainly represented by sponges, bryozoans and ascidians, were the main constituents of those communities, followed by deposit feeders and predators (Table 3, Fig. 6). Scavengers contributed less than 1% to the benthic assemblages everywhere. In the Larsen bays, deposit feeders were the dominant feeding guild due to the high biomass of echiurids, holothurians, echinoids and polychaetes.

4. Discussion

Warm water intrusions of circumpolar deep water onto the Antarctic continental shelf have been identified elsewhere around the continent but it seems that the mechanisms driving them vary among regions. Such mechanisms comprise both topographic and physical forcing including the action of the wind (Thoma et al., 2008; Klinck and Dinniman, 2010; Martinson and McKee, 2012; Kohut et al., 2013; Wåhlin et al., 2013). However, the association of WWI and tidal force has been rarely described and it has been referred only to shallow coastal stations (Makinson, 2002; Hunt et al., 2003). This is probably because the strongest tidal currents in the Antarctic occur in the Weddell Sea, particularly along the southwestern region, in the vicinity of the Filchner Trough (Makinson and Nicholls, 1999; Padman et al., 2002; Darelius et al., 2014). Our observations, based on a set of stations covering most of the continental shelf of the Weddell Sea, suggest that WWI are strongly related to tides in this part of the Antarctic.

4.1 Tides and warm water intrusions

Studies on the structure of the Weddell Gyre revealed that three different patterns dominate current velocity variations in the Weddell Sea (Fahrbach et al., 1994). One corresponds to annual oscillations, also clearly observed in the temperature profiles (i.e., higher values in the summer) and the spectral analysis frequencies in our records from moorings SE4, SE5 and SE6 (Table 2, Figs. 3 and 4, supplementary Figs. 1 and 2). Another pattern relates to mesoscale fluctuations with periods of days to weeks (e.g. spring tides), especially clear in the FI record and a third pattern that was associated to short-period variations (days) due to tides, inertial oscillations and small eddies, which were also observed in all the records of the present study.

Tides in the Weddell Sea mainly have a diurnal component (Foldvik et al., 1985, 1990; Koentopp et al., 2005; Darelius et al., 2014), which is evident at least from 5 m to 100 m above the sea floor (Middelton et al., 1987). A semidiurnal component has been detected also; however, this signal weakens in the upper water column (Foldvik et al., 1990). Tidal force also presents a velocity gradient with higher magnitude close to the continental shelf edge (Cisewski et al., 2011). The results in the data set of the present study match with all these previous observations. The strength in the frequencies in almost all spectral analyses showed higher values in diurnal signals as compared to the semidiurnal signals (Table 2, Fig. 4 and supplementary Fig. 2). The water current velocities were higher close to the continental shelf break and near the seabed as compared to those measured at shallower depths on the same station (e.g., SE4 and SE5) and tens of kilometers away from the shelf break (e.g., SE7, SE8, SE9 and SE10). The temperature variation coincided with the patterns observed in the current velocities in most of the cases and this coincidence was corroborated by the spectral analyses, indicating that these currents also transport heat (e.g., WWI). In stations SE7, SE8, SE9 and SE10, located several kilometers apart from the shelf break (Table 1), the diurnal signal in the temperature variation was almost absent. Overall, our results suggest two main processes, one is that the warming effect of WWI dilutes towards the sea surface and towards the continent, probably because the diurnal tidal force pushing warm water onto the shelf also weakens in both directions. The other process is that the tides seem to be the main force pushing warm water onto the WS shelf.

Contrasting current directions measured at a single site at different depths (e.g., progressive vector plots at station SE5, see Fig. 5a) corroborated that the water column in the Weddell Sea can have a significant baroclinic component (Fahrbach et al., 1994), which may help diluting the signal of WWI in the upper layers of the water column. The dilution of warm water towards the continent also suggests that there should be strong mixing of CDW coming from the shelf break with the water coming from below the ice sheet and the water derived from local sinking processes triggered by the wind (Fahrbach et al., 2011; Darelius et al., 2016). The progressive vector plot of station SE7 (Fig. 5a), in the lee of the main Weddell Gyre flow blocked by Kapp Norvegia, which obstructs a large portion of the shelf, suggests that also topographic effects on the current flow may modify the spatial extent of WWI.

4.2 Implications for the benthic system

The abundant and diverse Antarctic continental shelf macrobenthic communities are often considered to be isolated from global warming effects due to their remote and deep location, with minimal direct anthropogenic impact as compared to those thriving in lower latitudes. However, here we show that they are directly exposed to the rapid anthropogenic warming of the ocean (Roemmich et al., 2012, 2015; Hausfather et al., 2017; Bereiter et al., 2018) due to WWI of CDW (Levitus et al., 2000; Gille, 2002; Reichert et al., 2002; Fyfe, 2006; Pierce et al., 2006) and consequently, they are facing a serious threat under the frame of the ongoing ocean warming pace (Roemmich et al., 2012, 2015; Hausfather et al., 2017; Bereiter et al., 2018).

Temperature limits the latitudinal distribution of many organisms (Somero, 2005; Helmuth et al., 2006; Wetthey and Woodin, 2008). The establishment of the ACC after the opening of the Tasmanian Gateway approximately 30 million years ago set conditions of near geophysical isolation and low temperatures that characterize extant Antarctic waters and shaped modern Antarctic benthic communities (Gili et al., 2006; Scher et al., 2015). In many regions, circumpolar sea surface temperatures typically vary just a few degrees, i.e., the most variable sites in the maritime Antarctic show ranges of only 3°C to 4°C during the year, which is 5 to 10 times smaller than at lower latitudes (Clarke and Gaston, 2006). According to our results, most of temperature variations close to the seabed are even smaller (i.e., <0.8°C absolute), making this environment comparatively constant (Arntz et al., 1994). However, the observed temperature excursions up to 2.7°C presented in this study reflect substantially higher variability than typically experienced by fauna in these regions.

Antarctic ectotherms have lived in a marine environment with the lowest (around freezing point) and most constant temperatures for millions of years, suggesting that adaptation to relatively short-term (~100 years) temperature variations has not been a challenge in their recent evolution. According to Bereiter et al. (2018), the mean global ocean temperature increased by 2.57 ± 0.24 °C over the last glacial transition (20,000 to 10,000 years ago). It has been estimated that in the period between the 1950's and the 1990's the water temperature in the upper 300 m of the world ocean increased approximately 0.31°C (Levitus et al., 2000); whereas in the Southern Ocean, the layer

between 700 and 1000 m water depth increased about 0.17°C in approximately the same period (Gille, 2002). This means that the warming increment during the second half of the last century, and up to date, was orders of magnitude faster than that developing during the last thousands of years. Bernard et al. (2017) found that the late Cretaceous and Paleogene (approx. 100 million years ago) deep-ocean and high-latitude surface-ocean temperatures were significantly lower than is generally accepted, implying that currently rising ocean temperatures are more anomalous than previously thought.

The ability of benthos to adapt to changes is markedly affected by life history characteristics such as generation times, which is the time required for genetic modification to become effective (Peck, 2005). Many Antarctic species have long generation times (therefore, reduced opportunity to mutate) and they require on average hundreds of years for adaptation; their survival will be dictated by the possession of sufficient phenotypic plasticity to resist for the necessary time (Peck, 2011; Peck et al., 2014). The steady warming of Antarctic CDW (Levitus et al., 2000; Gille, 2002) will cause a warming trend in the WWI events, and thereby expose benthos to increasingly warmer episodes beyond the thermal tolerance for the endemic organisms. Thermal tolerance depends on the warming rate. Peck et al., (2014) highlighted that the upper thermal tolerance (CT_{max}) in Antarctic invertebrates drops significantly with slowing warming rates (CT_{max} of 8°C to 17.5°C at 1°C day⁻¹ vs 1°C to 6°C at 1°C month⁻¹). WWI represent acute thermal stress situations, because WWI increase temperature in short periods of time (hours); likewise, longer temperature variations also occur at least every 7 to 14 days and can persist for time spans of 1 to 20 days (Figs. 3 and 4 and supplementary Figs. 1 and 2) exposing organisms to chronic thermal stress. On top of these variations, the CDW ongoing warming trend also generates chronic thermal stress. Antarctic invertebrates may cope with acute stress exposure but the observed combination of CDW warming rate and periodic WWI onto the shelf, seriously expose the macrobenthic communities thriving there to an unprecedented thermal challenge (Gili et al., 2006).

Model simulations have predicted a >2°C warming scenario developing between 300 m and 1000 m water depth in the Weddell Sea during the second half of the 21st century (Hellmer et al., 2012). Many experiments revealed the inability of modern Antarctic ectotherms to acclimate to small rises in sea temperature, where even 2°C could critically hinder their ability to perform essential functions (Peck et al., 2004). 1°C rise in summer sea temperatures around Antarctica could have severe ecological consequences for populations and communities of marine ectotherms (Peck, 2005b). Most Antarctic benthos brood their offspring and development times are very long; the times required to reach a given developmental stage are greatly extended in comparison with temperate and tropical species (Peck 2018). For example, Hain & Arnaud (1992) showed some broods of Antarctic snails require 2 years to hatch. Peck (2016, 2018) showed that the increase in development rate for species living between -2°C and +2°C for a 1°C rise in temperature is much greater than for any other latitude and so WWI will have large effects on organism development, emphasizing the strong effect of temperature on Antarctic benthos.

Further, temperature stress effects can propagate across generations. A critical developmental window (sensitive period) results from the interaction of exposition time and stressor dose (Burggren and Mueller, 2015). Persistent epigenetic marks, such as DNA methylation, are established during early development and modified by environmental factors such as temperature and they can persist throughout adulthood, regulate gene expression and ultimately the phenotype (Faulk and Dolinoy, 2011; Lighten et al., 2016). These marks can be inherited even in the absence of the environmental factor that triggered them (Gilbert and Epel, 2008; Jablonka and Raz, 2009). This means that even if small temperature increases may not have direct influence on survival, they are most likely to affect the organisms at the molecular level and could be transmitted transgenerationally (Shao et al., 2014; Metzger and Schulte, 2017). Given its high periodicity, the frequent intrusions of warm water observed in our records have a high probability of coinciding with the critical thermal sensitivity windows of Antarctic benthic species (including demersal fishes) and their feasible long-lasting consequences are still unpredictable, especially if they take place at early developmental stages (e.g., eggs, larvae).

Peck (2005b, 2018) proposed that animals have 3 mechanisms for coping with change: 1) physiological flexibility, 2) evolving new adaptations and 3) migration to suitable sites. Antarctic marine species have poor physiological possibilities; long generation times (including long lifetimes, slow development rates with months as embryos in many species, and long gametogenic periods) and comparatively smaller (latitudinal gradient) territories to migrate into than benthos thriving in lower latitudes. These factors make Antarctic macrobenthos less likely to succeed under continued warming than most benthic faunal groups elsewhere.

Being typically stenothermal, most Antarctic species investigated so far showed low thermal tolerance and impacts of increasing temperatures on physiological performance ranging from loss of mobility to mortality. For example, DNA methylation has been observed in the Antarctic polychaete *Spiophanes tcherniai* (Marsh and Pasqualtone, 2014). The limpet *Nacella concinna* lost the motile abilities already at temperatures between 2°C and 3°C (Peck, 1989). The scallop *Adamussium colbecki* lost its capacity to swim already between 1°C and 2°C (Bailey, 2001). The most stenothermal species recognized so far, the brachiopod *Liothyrella uva* and the bivalve mollusk *Limopsis marionensis*, only survived in a temperature window between -2°C and 5°C, when temperatures were raised by around 1.5°C week⁻¹ (Peck, 1989; Pörtner et al., 1999, 2007). The brittle star *Ophionotus victoriae* did not survive more than a few weeks at 2°C (Peck et al. 2009b). The physiological mechanisms identified in setting the short-term temperature tolerance limits, at least in marine ectotherms, were associated with failures in oxygen supply and reductions in whole animal aerobic performance (Pörtner et al., 2006). Studies on temperature effects on whole-animal physiological capacities suggest that with as little as a 2°C rise over current summer maxima in the maritime Antarctic, and 3°C in the high Antarctic, biological functions in a wide range of species could already become compromised (Pörtner et al., 2007). Regarding fishes, temperature increases of even 2°C were sufficient to change the global DNA methylation patterns in European sea bass larvae (Anastasiadi et al. 2017). Further, fish that

experienced temperature increases during the thermosensitive period may undergo temperature dependent sex determination and sex reversal with further implications for population sex ratios (Shao et al., 2014; Sun et al., 2016; Metzger and Schulte, 2017). For Antarctic fishes, perhaps the most harmful effects may take place when they release their eggs on the seabed and remain aside guarding their stationary nests (Hourigan and Radtke, 1989; Kock et al., 2008; Jones and Near, 2012). This is a common behavior in several Antarctic fish species, which makes them temporarily sessile and consequently more sensitive, together with their eggs, to the environmental conditions (and changes) at the seabed. At present, our knowledge is mainly restricted to data from laboratory experiments, which suggest that temperature increase will impair the ability of Antarctic benthic invertebrates to perform vital biological functions critical for their long term survival (Kidawa & Janecki, 2011). However, it can be assumed that, in general, the ability of Antarctic benthos to cope with future environmental change is limited, and that it can successfully perform only within a narrow range of temperatures (Kidawa & Janecki, 2011; Peck, 2018).

Winners and losers

The mollusk *Laternula elliptica* lost ability to rebury after removal from sediment at 5°C, and 50% of the population failed at temperatures of 2°C to 3°C (Peck et al. 2004; Peck 2005a). However, recent observations off the eastern Antarctic Peninsula coast found this mollusk thriving at 7.5°C in the sediment in the intertidal zone, although it was not explained for how long this relatively warm period persisted (Waller et al., 2017). Contrastingly, off the western Antarctic Peninsula coast, the same species was found thriving at maximum temperatures of 1.9°C during the decade 1996-2007 (Woo et al., 2019). On the same flank of the peninsular coast, a dramatic change in the shallow-water benthic community structure was induced after a 1°C *in situ* warming maintained for over a year (Ashton et al., 2017). These findings open important questions on the ability of the Antarctic macrobenthic fauna to cope with a warming environment, especially regarding differences on the effects caused by acute and chronic thermal stress both at the species and community levels. The actual communities will certainly change; however, the trajectory of this change remains obscure because of the variety of potential paths, e.g., extinction, species invasions, resilience, unknown temperature tolerance (Griffiths et al., 2017). There will be “winners and losers” (*sensu* Griffiths et al., 2017), we advocate that the current benthic assemblages will change and this projected change threatens existing rich and diverse Antarctic benthic communities. However, forecasting community-level responses to climate change remains one of the greatest challenges in global ecology, even more based on the still scarce knowledge on the effects of repeated warming on Antarctic benthos. It seems likely that further temperature increases will create ‘winners’, i.e. opportunistic species or ‘r-strategists’ and probably also invaders, but also ‘losers’, i.e. those stenothermal species, which cannot stand this impact and will become eliminated. Peck (2018) stated “The current challenge is to identify which species are being, and will be, negatively impacted in future and how that will affect ecosystem stability and the capacity of the oceans to provide services for human societies...” and “...the data are too poor to be able to identify which

species are most vulnerable to change and if any of these are crucial to continued ecosystem functioning. This is the challenge for the future...”

WWI also threaten the benthic system’s ability to ameliorate global warming by storing carbon in the sediment column. Warmer temperatures may accelerate microbial carbon degradation, reducing the organic carbon content in the sediment for a similar given amount of organic carbon supply from pelagic sources (Nedwell, 1999; Mincks et al., 2005; Isla, 2016); hence, creating a global warming negative feedback effect. In parallel, the potential reduction in the amount of organic carbon available for the continental shelf macrobenthos will negatively impact these communities in the winter. During this season, primary production in the euphotic zone drastically reduces, together with the most labile organic matter content in the sediment (Isla et al., 2011) and feeding on fresh organic matter depends on the summer surplus and the slow organic carbon degradation paced by low temperature.

4.3 Regional differences

According to Ingels et al. (2010), studies of Antarctic organisms have shown that individual species and higher taxa display different degrees of sensitivity to environmental shifts, making it difficult to predict overall community or ecosystem responses. This emphasizes the need for an improved understanding of the Antarctic benthic ecosystem response to global climate change using a multitaxon approach with consideration of different levels of biological organization (Ingels et al., 2010). The observed benthic assemblages are patchily distributed over >200 000 km² of continental shelf; according to our data, these communities can have biomasses between 39 g m² (wet weight) and 2790 g m² (wet weight), which in terms of carbon, depending on the type of community, varied between 2.2 g C m² to 87.6 g C m² (Table 3, Fig. 6). Arntz et al. (1994), summarized that regardless of community composition, the same species pool constitutes the Weddell Sea macrobenthos (extremely wide circumpolar distribution), which evolved in relatively similar environmental circumstances (Gili et al., 2006). Thus, most likely, the Antarctic continental shelf species share thermal physiological limits and adaptive capacity. Based on the projected warming over the shelf (Hellmer et al., 2012) and our observations, the eastern WS shelf, particularly the regions off Austasen and the Drescher Inlet, have to be regarded as the most vulnerable areas to the warming effect of WWI because these regions host the macrobenthic communities with the largest component of sessile organisms (e.g., sponges), which are unable to escape from warming. Together with sponges, bryozoans and ascidians make the macrobenthic communities in this region the most diverse and rich in biomass (Table 3, Fig. 6; Brey and Gerdes, 1997). These organisms perform as community engineers that provide structure for a complex benthic assemblage (Arntz et al., 1994; Gili et al., 2006), which builds up locally >87 g C m⁻² (Table 3), an order of magnitude more organic carbon per unit of area than in the rest of the WS. Losing these archaic and unique communities of the eastern WS shelf will have a cascade of impacts, not only on marine benthic faunal diversity and abundance, but probably also on climate because their demise will liberate thousands of tons of carbon to the water column and in the aftermath, less carbon will be retained in devastated shelf areas. Just the

continental shelf between Austasen and Kapp Norvegia (i.e., from moorings SE1 to SE8) covers more than 3400 km² and based on our results (Table 3), the macrobenthic communities living there would represent a biomass between 68000 tons and 299200 tons of carbon.

In the regions of Halley Bay and in the vicinity of the Filchner Through, sessile animals in the macrobenthic assemblages were less abundant than on the southeastern shelf and more numerous than in the Larsen bays. Based on this composition, these two regions in the south of the WS can be considered to be of intermediate risk. However, the highest temperatures derived from WWI were recorded in these regions, suggesting that the consequences of the thermal impact here could develop faster (earlier) than in the rest of the WS, given that the macrobenthic communities thriving along the entire shelf (regardless of the community composition) share species and most likely homogeneity in their thermal tolerances (Arntz et al., 1994).

The Larsen bays present a contrasting situation. Actual models predict that in the present century, most likely in the Larsen A and B bays, the warming effect will take longer to reach the magnitude predicted for the Filchner-Ronne region (Hellmer et al., 2012, 2017). The collapse and retreat of the Larsen ice shelf sections A and B changed a formerly oligotrophic under-ice-shelf system into one, where fresh organic matter is currently settling (Sañé et al., 2011). The macrobenthic communities there are actually in an early developmental stage and clearly differ in their composition, density and biomass from the mature communities on the southeastern WS shelf (Table 3, Fig. 6; Sañé et al., 2012). The macrobenthic community in Larsen A showed a higher component of sessile suspension feeders, particularly sponges (Gutt et al., 2011; Fillinger et al., 2013), whereas a larger fraction of motile species (44% only by echinoderms, Fig. 6) was observed in the community of Larsen B. If this difference is related to the time span between the earlier collapse of the ice shelf section A relative to B (e.g., 7 y), the question arises whether the communities in LB will have the chance to evolve towards the composition observed in LA, which apparently tends to progress to a community type similar to that thriving on the southeastern WS shelf. This contrast makes this area to emerge as a natural laboratory to explore the evolution of Antarctic continental shelf macrobenthic communities under the pressure of ongoing climate change.

Based on the current thermal adaptation examples, it is very likely that some species will be extremely vulnerable to predicted global warming. However, it should be mentioned that other species may be robust to it and many may thrive between extremes (Morley et al. 2009; Beers and Sidell, 2011; Beers and Jaysundara, 2015). Actually, our knowledge about temperature induced effects on Antarctic ectotherms is based on few studies with very few species. Deeper shelf species, which are virtually unrepresented in physiological experiments and live in greater long-term thermal constancy, are possibly much less able to adapt to rapid changes in projected temperature regimes. Understanding how temperature limitations on physiological capacities affect ecological characters such as competitive interactions, predator/prey relationships, migration or dispersal of species, community structure and reactions to disturbance up to

date has received generally little or no attention and it should be addressed urgently before ongoing ocean warming prevents it.

The heterogeneity of habitats and benthic communities in the WS have encouraged the scientific community to propose a Marine Protected Area (MPA) in the WS to protect this rich and diverse marine ecosystem (Teschke et al. 2016). Our results suggest that the establishment of an MPA perhaps may not be sufficient to protect its biodiversity and habitats given the serious exogenous threat from ongoing global warming. Therefore, in combination with the establishment of MPA's, stronger efforts such as effective actions aimed at reducing the CO₂ concentration in the atmosphere should be implemented on a global scale to preserve benthic communities, even in apparently remote, nearly isolated ecosystems such as the high-latitude Antarctic.

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Figure captions

Figure 1. Location of the current meter stations along the Weddell Sea continental shelf. Not all the stations are labeled due to map scale limitations; the full stations list is available in Table 1.

Figure 2. Location of the benthic stations along the Weddell Sea continental shelf. Not all the stations are labeled due to map scale limitations; due to its length, the full stations list is available in supplementary Table 1.

Figure 3. Regional examples of time-series of temperature and current velocity and direction. The left panels show the complete time series of each record and the panels on the right a detailed series (shorter period, typically 4 days) to show daily oscillations more clearly. The instrument identification is found in the upper right panel. The X axis shows the date of the records. The complete station data set is shown in supplementary Figure 1.

Figure 4. Regional examples of time-series spectral analyses of water temperatures and current direction and velocities. The numbers on top of the grey rectangles indicate the time intervals (in days) correspondent to the frequencies below (x axis). Exact power and frequency numbers are listed in Table 2. The complete station data set is shown in supplementary Figure 2.

Figure 5. Progressive vector plots (PVP) of water current readings for each station. PVP correspondent to the group of instruments moored in a) the southeastern Weddell Sea (SE) b) Drescher Inlet (DI) and Filchner-Ronne region (FI) and c) Larsen embayments A (LA) and B (LB). The map and the PVP are oriented to the North. PVP do not share scale with the map. The black circle denotes the first reading (origin) of the series.

Figure 6. Average biomass and macrobenthic community composition. Pie charts show the community composition based on feeding guilds, whereas the histograms show the percentage composition based on the main taxonomical units.

Supporting information

Supplementary Figure 1. Time-series of temperature and current velocity and direction. The left panels show the complete time series of each record and the panels on the right a detailed series (shorter period, typically 4 days) to show daily oscillations more clearly. The X axis shows the date of the records. The instrument identification is found in the upper right panel and station characteristics in Table 1.

Supplementary Figure 2. Time-series spectral analyses of water temperatures and current direction and velocities. The numbers on top of the grey rectangles indicate the time intervals (in days) correspondent to the frequencies below (x axis). Exact power and frequency numbers are listed in Table 2.

2/22/89 3/24/89 4/23/89 5/23/89 6/22/89 7/22/89 8/21/89 9/20/89 10/20/89 11/19/89 12/19/89

2/22/89 2/23/89 2/24/89 2/25/89 2/26/89

2/9/98 2/11/98 2/12/98 2/14/98 2/16/98

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b

Austasen

Kapp Norvegia

Drescher Inlet

- Suspension Feeder
- Deposit Feeder
- Scavenger
- Predator

220.3 g m⁻²

72.3 %

Halley Bay

Filchner Ronne

145
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147 **others**
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151 **cnidarians**
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154 **echinoderms**
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158 **ascidians**
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162 **polychaetes**
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166 **molluscs**
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169 **bryozoans**
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173 **crustaceans**
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177 **sponges**
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72.1 g m⁻²

Larsen A

187.6 g m⁻²

Larsen B

38.7 g m⁻²

1/4/88 1/7/88 1/10/88 1/13/88 1/16/88 1/19/88 1/22/88 1/25/88 1/28/88 1/31/88 2/3/88 2/6/88 2/9/88 2/12/88 2/15/88 2/18/88 2/21/88 2/24/88 2/27/88

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1/4/88 1/5/88 1/6/88 1/7/88 1/8/88

2/5/96 2/6/96 2/7/96 2/8/96 2/9/96 2/10/96 2/11/96 2/12/96 2/13/96 2/14/96 2/15/96 2/16/96 2/17/96 2/18/96 2/19/96 2/20/96 2/21/96 2/22/96

2/5/96 2/6/96 2/7/96 2/8/96 2/9/96

2/9/98 2/11/98 2/12/98 2/14/98 2/16/98

2/9/98 2/10/98 2/12/98 2/13/98

Table 1. Main results and characteristics of the current meter stations.

St.	deployment dates	latitude (S)	longitude (W)	water depth (m)	instrument depth (m)	expedition	readings (min)	sampling period (days)	temp. range (°C)	absolute temperature range	velocity range (cm s ⁻¹)	distance to shelf break (km)
SE 1	03.12.2003- 05.01.2004	70°32,73'	08°53,10'	407	399	ANT XXI/2	10	35	-1.79/- 1.90	0.11	0-28.4	14
SE 2	09.12.2003- 05.01.2004	70°48,37'	10°45,83'	481	473	ANT XXI/2	10	27	-1.09/- 1.89	0.80	0.3-32.6	0.845
SE 3	20.03.2011- 30.03.2011	70°48.60'	10° 46.08'	481	475	ANTXXVII/3	10	16	-0.83/- 1.84	1.01	0-22.3	0.845
SE 4	22.02.1989- 07.02. 1990	71°02,04'	11°44,61'	676	286	ANT VII/4	60	365	-1.06/- 1.87	0.81	0-54.0	0.655
SE 4	22.02.1989- 07.02. 1990	71°02,04'	11°44,61'	676	671	ANT VII/4	60	296	0.68/- 1.87	2.55	0-53.3	0.655
SE 5	04.01. - 27.02.1988	71°07,80'	12°10,80'	645	250	ANT VI/3	60	53	-1.38/- 1.88	0.50	0-48.5	0.763
SE 5	04.01. - 27.02.1988	71°07,80'	12°10,80'	645	640	ANT VI/3	60	53	0.81/- 1.91	2.72	0-32.2	0.763
SE 6	01.03.1988- 27.01.1989	71°07,70'	12°11,90'	682	295	ANT VI/3	60	331	-0.88/- 1.92	1.04	0-54.3	0.787
SE 7	05.02. - 25.02.1996	71°39,58'	12°07,11'	238	233	ANT XIII/3	5	20	-1.67/- 1.74	0.07	1.5-16.5	58
SE 8	05.02. - 22.02.1996	71°19,29'	12°24,68'	275	270	ANT XIII/3	5	17	-1.80/- 1.88	0.08	1.5-27.8	21
SE 9	25.01. - 03.03. 1998	71°30,66'	13°31,06'	235	230	ANT XV/3	10	37	-1.66/- 1.83	0.17	1.5-30.6	24
SE 10	25.01. - 27.02. 1998	71°44,97'	14°45,19'	462	457	ANT XV/3	10	32	-1.80/- 1.90	0.10	1.5-15.8	16
DI	02.02. - 17.02.1998	72°52,12'	19°25,12'	400	118	ANT XV/3	5	8	-1.02/- 1.80	0.78	1.5-27.8	6

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FI	03.01.2014- 11.02.2014	74°41,88'	29°45,52'	427	421	ANT XXIX/9	10	39	0.06/- 1.71	1.77	0.6-38.1	5
LA	27.02.2011- 13.03.2001	64°56,32'	60°36,04'	303	297	ANTXXVII/3	20	14	-1.83/- 1.89	0.06	0.3-40.8	5
LB	11.01.2007- 20.01.2007	65°57.91'	60°18.65'	442	436	ANT XXIII8	10	9	-1.83/- 1.97	0.14	0.9-32.3	24

Table 2. Periodicity found for water temperatures and current direction and velocities along the Weddell Sea continental shelf. The table lists the frequencies and equivalent days associated to the most evident power peaks (shown in Fig. 4 and supplementary Fig. 2) found in each spectral analysis. Small power signals are not shown (ns).

Station	Direction			Velocity			Temperature		
	frequency	power	days	frequency	power	days	frequency	power	days
SE 1	0.00697	247.1	1.0	0.00042	584.3	16.4	0.0004	852.3	17.4
	0.00035	129.2	19.9	0.007	215.5	1.0	0.0069	151.4	1.0
	0.01343	75.4	0.5	0.0134	160.2	0.5	0.00107	137.8	6.5
	0.02035	51.1	0.3	0.02033	48.7	0.3		ns	
SE 2	0.007	653.0	1.0	0.00052	382.9	13.3	0.00068	616.9	10.1
	0.0014	92.5	5.0	0.007	319.2	1.0	0.00697	253.0	1.0
	0.01339	54.67	0.5	0.01329	85.0	0.5	0.00495	61.5	1.4
SE 3	0.00094	169.1	7.4	0.00133	151.0	5.3	0.00072	679.0	9.6
	0.00689	39.8	1.0	0.01416	71.0	0.5	0.0015	90.6	4.6
	0.01399	39.2	0.5	0.0065	58.6	1.1	0.00661	29.15	1.1
SE 4	0.08049	130.6	0.5	0.0002	352.4	208.8	0.00011	1668.8	365.5
286 m	0.03871	96.7	1.1	0.03871	234.3	1.1	0.00027	679.09	153.9
	0.00023	90.2	182.7	0.00053	186.0	79.0	0.0004	456.2	104.5
	0.00325	81.7	12.8	0.00114	134.0	36.5		ns	
	0.00403	79.7	10.39	0.04176	121.0	1.0		ns	
	0.00115	65.5	36.1	0.08048	100.0	0.5		ns	
SE 4	0.03869	140.3	1.1	0.00016	186.3	263.4	0.00014	500.9	296.4
671 m	0.08046	101.7	0.5	0.0387	161.0	1.1	0.0387	352.5	1.1
	0.08329	61.2	0.5	0.00037	104.3	112.9	0.00037	235.0	112.9
	0.04174	50.1	1.0	0.04178	96.6	1.0	0.04178	126.7	1.0
		ns		0.00176	82.2	23.7	0.00114	125.8	36.5
		ns		0.00322	52.3	13.0	0.08048	85.3	0.5
		ns		0.0805	45.4	0.5		ns	
SE 5	0.00079	89.1	53.0	0.00275	146.0	15.1	0.00108	114.73	38.5
250 m	0.00197	77.5	21.2	0.00157	123.1	26.5	0.00443	97.655	9.4
	0.00049	39.5	84.7	0.00521	26.8	8.0	0.00384	45.304	10.9
	0.00384	38.8	10.9	0.00777	19.5	5.4	0.00767	26.435	5.4
	0.03963	34.1	1.1	0.00885	18.2	4.7		ns	
	0.0832	11.4	0.5	0.01052	16.8	4.0		ns	
	0.00502	10.3	8.3		ns			ns	
	0.01003	8.1	4.2		ns			ns	
SE 5	0.08043	50.7	0.5	0.04212	35.0	1.0	0.00098	294.2	42.6
640 m	0.03733	27.8	1.1	0.00264	28.0	15.8	0.00274	101.2	15.2

Table 3. Summarized community parameters of macrobenthic communities in different sub-regions of the Weddell Sea. Feeding guilds were categorized as: Suspension Feeder (SF), Deposit Feeder (DF) and Predator (P). Scavengers contributed in all subregions <1% and are not specified in the table. TU stands for taxonomical unit.

	Austasen	Kapp Norvegia	Drescher Inlet	Halley Bay	Filchner	Larsen A	Larsen B
No. of stations	59	31	4	6	16	6	13
Water depth range (m)	161 - 568	170 - 574	303 - 485	283 - 702	254 - 835	200 - 352	299 - 850
Mean wet weight (g m ² ±std)	2790 ± 13494	479 ±198	220 ± 305	75 ± 62	72 ± 85	188 ± 342	39 ± 57
Mean abundance (ind m ⁻² ±std)	2789 ± 3271	4589 ± 4784	2230 ± 1387	2505 ± 2079	1773 ± 1780	633 ± 600	774 ± 870
Mean C _{org} (g m ⁻² ±std)	88 ± 449	19 ± 24	8 ± 12	4 ± 6	3 ± 7	16 ± 29	2 ± 5
Number of TU	20 ± 5	20 ± 6	24 ± 1	18 ± 7	19 ± 5	13 ± 5	12 ± 4
Feeding guilds	95.3% SF 2.7% DF 1.9% P	75.7% SF 14.8% DF 9.4% P	87.4% SF 8.4% DF 4.1% P	55.8% SF 27.5% DF 16.6% P	75.1% SF 15.1% DF 9.7% P	4.8% SF 93.2% DF 1.9% P	25.6% SF 67.2% DF 7.1% P
Mean H' (biomass)	1.27 ± 0.62	1.11 ± 0.51	1.58 ± 0.86	1.05± 0.41	1.17± 0.51	0.94 ± 0.55	1.00±0.36
Mean J' (biomass)	0.44 ± 0.22	0.37 ± 0.17	0.50 ± 0.27	0.38 ± 0.10	0.40 ± 0.16	0.37 ± 0.20	0.41± 0.15

Supplementary Table 1. Main characteristics of the benthic stations. AU stands for Austasen, KN for Kapp Norvegia, DI for Drescher Inlet, HB for Halley Bay, FI for Filchner-Ronne, LA for Larsen A and LB for Larsen B embayments.

st. number	latitude	longitude	date	water depth (m)	region
85	70°35,27'	09°03,47'	08/12/2003	482	AU
82	70°31,52'	09°06,28'	08/12/2003	420	AU
80	70°28,27'	09°11,71'	08/12/2003	348	AU
77	70°26,08'	09°15,30'	08/12/2003	318	AU
76	70°22,97'	09°22,31'	08/12/2003	488	AU
47	70°52,15'	10°29,26'	30/01/1998	243	AU
48	70°52,15'	10°29,26'	30/01/1998	245	AU
283	70°58,00'	10°30,30'	29/03/2011	284	AU
197	70°56,29'	10°30,32'	18/12/2003	253	AU
279	70°56,22'	10°30,33'	28/03/2011	250	AU
124	70°56,40'	10°31,47'	11/12/2003	290	AU
125	70°56,40'	10°31,56'	11/12/2003	283	AU
275	70°56,42'	10°31,62'	25/03/2011	283	AU
297	70°56,60'	10°31,63'	31/03/2011	276	AU
185	70°56,61'	10°31,65'	17/12/2003	294	AU
183	70°56,53'	10°31,79'	17/12/2003	301	AU
202	70°56,54'	10°31,84'	18/12/2003	387	AU
288	70°56,56'	10°31,86'	30/03/2011	288	AU
105	70°56,50'	10°32,01'	10/12/2003	295	AU
295	70°56,63'	10°32,01'	31/03/2011	303	AU
187	70°56,60'	10°32,02'	17/12/2003	300	AU
106	70°56,64'	10°32,03'	10/12/2003	304	AU
280	70°56,63'	10°32,08'	28/03/2011	261	AU
230	70°50,94'	10°32,18'	20/02/1998	229	AU
65	70°51,90'	10°32,20'	31/01/1998	227	AU
199	70°56,74'	10°32,25'	18/12/2003	311	AU
289	70°56,77'	10°32,33'	30/03/2011	303	AU
63	70°52,10'	10°32,40'	31/01/1998	234	AU
285	70°56,75'	10°32,40'	29/03/2011	307	AU
116	70°56,81'	10°32,84'	11/12/2003	321	AU
201	70°56,26'	10°33,00'	18/12/2003	322	AU
512	70°47'	10°33'	27/02/1988	270	AU
69	70°51,70'	10°33,70'	01/02/1998	227	AU
121	70°53,63'	10°34,21'	08/04/2000	249	AU
274	70°56, 58'	10°34,27'	25/03/2011	333	AU
224	70°49,79'	10°34,40'	19/02/1998	279	AU
136	70°50,16'	10°34,52'	10/04/2000	256	AU
137	70°50,20'	10°34,70'	10/04/2000	272	AU
225	70°50,15'	10°35,03'	19/02/1998	276	AU
120	70°50,34'	10°35,04'	08/04/2000	271	AU
223	70°50,19'	10°35,39'	19/02/1998	273	AU

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62	67	70°49,90'	10°36,70'	01/02/1998	305	AU
63	113	70°49,91'	10°36,77'	06/04/2000	275	AU
64	228	70°49,83'	10°37,53'	20/02/1998	293	AU
65	68	70°50,30'	10°38,10'	01/02/1998	269	AU
66	227	70°49,32'	10°38,84'	20/02/1998	360	AU
67	114	70°46,18'	10°43,20'	07/04/2000	753	AU
68	298	70°50'	10°51'	17/01/1988	434	AU
69	437	70°58'	11°12'	12/02/1988	370	AU
70	26	71°08,10'	11°31,80'	21/02/1996	119	AU
71	25	71°08,10'	11°32,00'	21/02/1996	119	AU
72	216	71°06,46'	11°32,67'	18/02/1998	180	AU
73	266	71°09'	12° 07'	09/01/1988	331	KN
74	274	71°37,10'	12°10,90'	15/02/1989	211	KN
75	503	71°08'	12°12'	26/02/1988	523	KN
76	108	71°08,64'	12°14,74'	04/04/2000	441	KN
77	4	71°18,20'	12°16,00'	09/02/1996	174	KN
78	5	71°18,10'	12°16,00'	09/02/1996	172	KN
79	6	71°18,00'	12°16,30'	09/02/1996	174	KN
80	28	71°19,18'	12°22,77'	22/02/1996	161	KN
81	27	71°19,81'	12°24,96'	22/02/1996	182	KN
82	418	71°19'	12°25'	09/02/1988	170	KN
83	29	71°18,70'	12°25,40'	22/02/1996	181	KN
84	8	71°34,50'	12°26,00'	10/02/1996	574	KN
85	30	71°19,20'	12°26,90'	22/02/1996	250	KN
86	98	71°10,87'	12°27,95'	03/04/2000	314	KN
87	20	71°41,27'	12°31,02'	20/02/1996	437	KN
88	277	71°39,80'	12°34,90'	16/02/1989	405	KN
89	90	71°12,52'	12°39,64'	02/04/2000	365	KN
90	292	71°03,80'	12°42,10'	19/02/1989	561	KN
91	1	71°40,03'	12°42,41'	06/02/1996	246	KN
92	112	71°06,10'	12°43,10'	06/04/2000	567	KN
93	22	71°40,80'	12°45,60'	20/02/1996	222	KN
94	23	71°40,20'	12°45,60'	20/02/1996	212	KN
95	24	71°39,60'	12°45,50'	20/02/1996	219	KN
96	308	71°14'	12°59'	19/01/1988	190	KN
97	305	71°08'	13°00'	18/01/1988	525	KN
98	12	71°32,63'	13°28,00'	11/02/1996	225	KN
99	9	71°31,90'	13°30,19'	11/02/1996	234	KN
100	188	71°31,50'	13°30,60'	15/02/1998	225	KN
101	38	71°31,90'	13°31,00'	28/02/1996	234	KN
102	37	71°31,90'	13°31,20'	28/02/1996	238	KN
103	36	71°31,90'	13°31,30'	28/02/1996	241	KN
104	10	71°32,05'	13°31,31'	11/02/1996	235	KN
105	11	71°32,27'	13°31,32'	11/02/1996	239	KN
106	35	71°31,69'	13°38,29'	25/02/1996	279	KN
107	396	71°18'	13°46'	07/02/1988	427	KN
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387	71°23'	13°57'	06/02/1988	309	KN
33	71°29,20'	14°16,90'	24/02/1996	217	KN
31	71°23,10'	14°19,70'	23/02/1996	628	KN
90	72°26,63'	17°05,00'	29/01/2016	306	DI
104	72°36,34'	18°02,64'	31/01/2016	308	DI
344	72°48,38'	19°18,13'	14/02/2014	485	DI
331	72°56,13'	19°48,71'	03/01/2004	456	DI
144	74°49,80'	25°07,44'	21/01/2014	702	HB
164	74°53,67'	26°42,48'	24/01/2014	290	HB
125	75°29,48'	27°24,60'	19/01/2014	286	HB
130	75° 20,28'	27°38,48'	20/10/2014	361	HB
163	74°39,94'	28°40,16'	24/01/2014	696	FI
40	76°03,96'	30°16,83'	07/01/2014	472	FI
179	74°29,86'	30°59,01'	25/02/2014	530	FI
33	75°56,83'	31°40,57'	06/01/2014	684	FI
270	74°17,05'	32°47,81'	06/02/2014	835	FI
89	76°59,02'	32°51,05'	14/01/2014	254	FI
79	77°01,92'	33°35,19'	12/01/2014	390	FI
190	74°40,21'	33°40,27'	26/01/2014	591	FI
362	77°15'	34°17'	30/01/1988	402	FI
74	76°59,89'	34°97,71'	11/01/2014	571	FI
98	77°42,76'	35°55,73'	15/01/2014	585	FI
200	74°34,73'	36°23,70'	27/01/2014	426	FI
372	78°60'	36°28'	01/02/1988	557	FI
226	74°21,12'	37°36,14'	31/01/2014	554	FI
236	74°13,23'	37°39,67'	01/02/2014	798	FI
242	74°40,84'	39°04,43'	02/02/2014	436	FI
254	65°00,39'	59°25,71'	11/03/2011	300	LA
231	64°55,35'	60°30,60'	28/02/2011	352	LA
722	64°41,16'	60°32,70'	21/01/2007	202	LA
226	64°55,68'	60°36,84'	26/02/2011	261	LA
725	64°55,66'	60°37,19'	22/01/2007	280	LA
252	64°32,75'	60°41,21'	10/03/2011	200	LA
700	65°55,18'	60°19,74'	11/01/2007	446	LB
237	66°09,89'	60°13,48'	03/03/2011	382	LB
239	66°16,58'	60°15,54'	04/03/2011	379	LB
701	65°56,33'	60°25,12'	12/01/2007	383	LB
248	65°56,20'	60°25,39'	07/03/2011	366	LB
715	65°06,46'	60°45,17'	18/01/2007	321	LB
718	65°08,05'	60°45,97'	19/01/2007	328	LB
247	65°19,92'	60°55,07'	07/03/2011	437	LB
250	65°25,45'	61°25,37'	08/03/2011	808	LB
706	65°26,09'	61°26,52'	15/01/2007	850	LB
709	65°26,10'	61°26,53'	15/01/2007	850	LB
235	65°33,07'	61°37,04'	02/03/2011	299	LB
703	65°33,01'	61°37,05'	13/01/2007	299	LB

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704	65°30,58'	61°41,50'	14/01/2007	357	LB
233	65°30,70'	61°42,01'	01/03/2011	364	LB