The importance of local settings: within-year variability in seawater temperature at South Bay, Western Antarctic Peninsula

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The Western Antarctic Peninsula (WAP) has undergone significant changes in air and seawater temperatures during the last 50 years. Although highly stenotherm Antarctic organisms are expected to be severely affected by the increase of seawater temperature, high-resolution datasets of seawater temperature within coastal areas of the WAP (where diverse marine communities have been reported) are not commonly available. Here we report on within-year (2016-2017) variation in seawater temperature at three sites on Doumer Island, Palmer Archipelago, WAP. Within a year, Antarctic organisms in South Bay were exposed to water temperatures in excess of 2° C for more than 25 days and 2.5° C for more than 10 days. We recorded a temperature range between -1.7° to 3.0° C. Warming of seawater temperature was 3.75 times faster after October 2016 than it was before October. Results from this study indicate that organisms at South Bay are already exposed to temperatures that are being used in experimental studies to evaluate physiological responses to thermal stress in WAP organisms. Continuous measurements of short to long-term variability in seawater temperature provides important information for parametrizing meaningful experimental treatments that aim to assess the local effects of environmental variation on Antarctic organisms under future climate scenarios.

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3 **Bay, Western Antarctic Peninsula**

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17 **Abstract**

18 The Western Antarctic Peninsula (WAP) has undergone significant changes in air and seawater

19 temperatures during the last 50 years. Although highly stenothermal Antarctic organisms are

20 expected to be severely affected by the increase of seawater temperature, high-resolution datasets

21 of seawater temperature within coastal areas of the WAP (where diverse marine communities

22 have been reported) are not commonly available. Here we report on within-year (2016-2017)

23 variation in seawater temperature at three sites on Doumer Island, Palmer Archipelago, WAP.

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26 range between -1.7° to 3.0° C. Warming of seawater temperature was 3.75 times faster after

27 October 2016 than it was before October. Results from this study indicate that organisms at

28 South Bay are already exposed to temperatures that are being used in experimental studies to

29 evaluate physiological responses to thermal stress in WAP organisms. Continuous measurements

30 of short to long-term variability in seawater temperature provides important information for

31 parametrizing meaningful experimental treatments that aim to assess the local effects of

32 environmental variation on Antarctic organisms under future climate scenarios.

33

34 **Introduction**

35 Although there is an absence of continent-scale warming over Antarctica over the last 100 years

36 (Stenni et al., 2017), during the last 50 years the Western Antarctic Peninsula (WAP) has

37 undergone significant warming in air and seawater temperatures, with the later increasing by ~

38 2° C (Cook et al., 2016; Meredith & King, 2005; Stenni et al., 2017). Warming has contributed

39 to the range expansion of various marine flora (e.g., Convey & Smith, 2006; Smith, 1994; Hill et

40 al., 2011), the loss of glacier mass, the retreat of ice shelves, and summer melting, with the latter

41 being unprecedented over the past 1,000 years (Abram et al., 2013; Paolo, Fricker & Padman,

42 2015). Increased snowfall on the Antarctic Peninsula has been linked to warming sea surface

43 temperatures in the western Pacific (Thomas et al., 2015, 2017) and the warming of WAP mid-

44 ocean depths (rather than the warming of air temperatures) has been proposed as the primary

45 driver of glacier retreat (e.g., Cook et al., 2016). These changes highlight the complexity of

46 environmental change occurring at the WAP and the need for high-resolution information on

47 regional- to local-scale patterns of climate change, to address its implications for marine polar

48 ecosystems (e.g., Clarke et al., 2007; Meredith, Stefels & van Leeuwe, 2017).

49   Many Antarctic species are not well adapted to sudden temperature change because they

50 have evolved in one of the most stable environments on Earth (e.g., Peck, 2005; Morley et al.,

51 2016; Peck, Webb & Bailey, 2014). Some Antarctic species are sensitive to even small changes

52 in temperature (2 - 3°C above the annual average), losing the ability to perform essential

53 functions (Ingels et al., 2012; Peck, Morley & Clark, 2010; Peck, Webb & Bailey, 2004; Peck,

54 2005; Pörtner, Peck & Somero, 2007). For example, the Antarctic scallop *Adamussium colbecki*

55 loses its ability to perform essential activities (Peck, 2005) with increases in seawater

56 temperature of 2-3 °C, and attempts to acclimate individuals to temperatures above 2°C have

57 failed for this species (Bailey, Johnston & Peck, 2005). Experiments using the Antarctic clam

58 *Laternula elliptica*, have shown that half of the individual died in 60 days at 3°C, and for the

59 brittle star *Ophionotus victoriae* half of the individuals died in less than 30 days at 3°C (Turner et

60 al., 2009). In contrast others organisms, such as the sea urchin *Sterechinus neumayeri,* are

61 comparatively resistant to increases in seawater temperature (Ericson et al., 2012; Suckling et al.,

62 2015). Recent studies have highlighted the dramatic effects of warming waters on Antarctic

63 organisms at the community level (Ashton et al., 2017), where small increases in temperature (1°

64   C) altered community composition by reducing overall species diversity and evenness. The study

65   of resistance, adaptation and tolerance to environmental variation has become a key focus of

66   evaluating how Antarctic ecosystems respond to climate change (Gutt et al., 2012; Ingels et al.,

67   2012; Peck, 2005). Research to date has focused on identifying how Antarctic organisms respond

68   to the expected seawater temperature increase at community (Ashton et al., 2017), assemblage

69   (Peck et al., 2009) and species (physiological and molecular) levels (Cascella et al., 2015;

70   Ericson et al., 2012; Foo et al., 2016; González et al., 2016; Kapsenberg & Hofmann, 2014; Peck

71   et al., 2009, 2014; Schram et al., 2015; Suckling et al., 2015), with the latter being the most

72   studied. To inform the design of studies that are relevant to future climate scenarios high-

73   resolution records of local to regional patterns of water temperature are required.

74   Due to the physical constraints that the Antarctic continent imposes on equipment and

75   sampling, obtaining long-term high-resolution water temperature data is often logistically

76   challenging. The urgent need to increase the spatio-temporal coverage of surface seawater

77   temperature data, with a focus on coastal areas, has been highlighted by several authors (Gutt et

78   al., 2017; Stenni et al., 2017). Although a number of moorings have been deployed along

79   channels and open waters in the WAP (See www.soos.aq/activities/soos-at-sea/moorings), there

80   remains a lack of long-term, high-resolution temperature data from shallow waters in coastal

81   zones dominated by diverse communities of sessile organisms with limited behavioral

82   thermoregulatory ability (Ashton et al., 2017). Fine-scale temporal (daily) data can be crucial for

83   inferring climatic impacts on survival, growth and reproduction (Kearney, Matzelle & Helmuth,

84   2011), while monthly data is better suited to studying relationships between population dynamics

85   and climatic conditions (Gutt et al., 2017; Jan et al., 2017; Kennicutt et al., 2016). Observational

86   gaps in surface seawater temperature leave fractionated information that does not provide a

87   coherent and robust picture of the current and future conditions occurring in Antarctic

88   ecosystems. In order to fill some of these gaps, high-resolution temporal observations are

89   required to advance ecosystem modelling and projections (Gutt et al., 2017).

90   Here we report for the first time extreme changes in shallow seawater temperature around

91   Doumer Island, Palmer Archipelago (WAP). We present shallow seawater temperatures recorded

92   over one year at high temporal resolution (hours), which can be used to parameterize future

93   physiological experiments.

94

95   **Material and Methods**

96   This study was conducted from the Chilean Yelcho Scientific Station in South Bay, Doumer

97   Island, Palmer Archipelago, WAP (Fig. 1), where diverse benthic communities have been

98   described (Cárdenas et al., 2016; Zamorano, 1983) (Fig. 2). Three HOBO pendant

99   temperature/light data loggers (Part #UA-002-XX; Onset Computer Corp; accuracy: ± 0.5° C at

100   0° C, resolution: 0.1° C at 0° C) were deployed in January 2016 and recovered in February 2017

101   at three sites in South Bay (Fig. 1). Sites were separated by ~1.5 km and are part of a research

102   project assessing the responses of Antarctic sponge assemblages to climate change. Data loggers

103   from two of the three sites (PY1; 64°52'28.1"S; 63°34'36.0"W and PY4; 64°51'58.6"S;

104   63°37'46.7"W) were at 10 m depth, whereas the third data logger (PY2; 64°52'15.3"S;

105   63°33'52.2"W) was at a depth of 20 m. Data was recorded every 2 hours at sites PY2 and PY4,

106   and every 1 hour at PY1. Sites PY1 and PY2 were located inside the bay and were characterized

107   by dense beds of *Himantothallus grandifolius* with a sub-canopy of crustose calcareous algae

108   and sponges on a boulder/gravel substrate (Fig. 2). PY4 was located at Cape Kemp, which is

109   regularly exposed to swell and is dominated by a mix of *H. grandifolius*, *Desmarestia* spp. and

110   *Ascoseira mirabilis* on a bedrock substrate. Benthic coverage of sponges at PY4 was higher than

111   in sites inside the bay (Bravo, 2017). The data loggers at PY1, PY2 and PY4 recorded data for

112   404, 374 and 312 days, respectively. Data from PY4 stopped by late November (2016),

113   presumably after being damaged by an iceberg. The study was conducted under the permit

114   806/2015 granted by the Chilean Antarctic Institute (INACH).

115   In order to describe non-linear, site-specific variability in the within-year patterns of

116   seawater temperature, we fit separate Generalized Additive Models (GAMs) to each of the three

117   sites, as they do not prescribe any particular form for the trend (Ferguson et al., 2008; Hastie &

118   Tibshirani 1990; Orr et al., 2015). We chose GAMs instead of other techniques (e.g. linear

119   regression) because: (1) GAMs do not assume linearity and allow specification of the mean value

120   of the response and the systematic component using a link-function (Wood, 2006; Zuur, Ieno &

121   Smith, 2007); (2) GAMs allow the application of an autoregressive structure to account for

122   dependency of serial correlations in time series data; and (3) GAMs allow the use of thin-plate

123   shrinkage smoothers to model temporal trends (recommended in Wood, 2006). The estimated

124   smooth trends are described by: (i) the shape of the estimated curve, (ii) a hypothesis test for no

125   variation over time, and (iii) *edf*, which describes effect complexity and corresponds to the

126   amount of information used by each smoother. An *edf* of 0 indicates no variation, an *edf* of 1

127   indicates a linear relationship between the response and the covariate, and higher values

128   correspond to more complex non-linear relationships; and (4) GAMs allow the use of finite

129   differences (Curtis & Simpson, 2014; Monteith et al., 2014) to estimate periods where the rate of

130   change (slope) is statistically different from zero (i.e., periods where the temperature is either

131   increasing or decreasing in a significant manner). This was achieved by computing the first

132   derivatives of the fitted trend. Uncertainty estimates were also calculated for the derivatives to

133   form approximate 95% confidence intervals.

134   All models were fit using the R-programming language (version 3.3.3 by R Foundation

135   for Statistical Computing, 2017) and the package mgcv (Wood, 2004; Wood, 2006). The R code

136   and scripts are available in the supplemental material.

137

138   **Results**

139   All seawater temperature records showed significant seasonality (p-value < 0.01; Fig. 3), with

140   clear minima in winter (July – September) and maxima in summer (January-March). Although

141   data loggers were located at different sites and depths (Fig. 1) they showed a similar seasonal

142   pattern throughout the year (Fig. 4), implying that the three sites are representative of broader

143   shallow waters temperatures in South Bay. In addition, sea surface temperatures within the same

144   time frame from Port Arthur (Palmer Station, ~25 km from Yelcho Station) show similar

145   temperature ranges and patterns suggesting that the temperature variability reported could be

146   representative of the wider Palmer Archipelago. Mean daily temperatures ranged from -1.7° to

147   3.0° C (range = 4.7° C, SD = 1.1) at PY1 (the longest record, 404 days), from -1.6° to 1.00° C

148   (range = 2.6° C, SD = 0.8) at PY4 (the shortest record, 312 days), and from -1.8° to 1.8° C

149   (range = 3.6 ° C, SD = 0.8) at PY2. Seawater temperature differed between the 2016 (max 0.8°

150   C) and 2017 (max 3.0 °C) summers at PY1 (p-value < 0.01; Figs. 5 and S1).

151   To identify periods of statistically significant change in the time series of seawater

152   temperature at PY1 we calculated the first derivative method from a second GAM model (k = 58,

153   *edf* = 55.7, p-value < 0.001, Figs. 5 and S2), which allowed a closer examination of the

154   temperature variability at PY1 site. Figure 5 shows there were 26 periods of statistically

155   significant change throughout the year, 12 increases and 13 decreases. From all periods of

156   significant increasing temperatures, the rate of temperature increase (°C day^{-1}) to which marine

157   organisms were subjected varied between 0.11 to 0.15 °C day^{-1} (mean 0.13, SD = 0.01) after

158   October 2016. In contrast, the rate of increase before October 2016 ranged between 0.04 and

159   0.07 °C day^{-1} (mean = 0.05, SD = 0.02; Table 1).

Discussion

161   In recent years, several studies have focused on assessing how Antarctic organisms will adapt to

162   future environmental conditions (e.g., Cascella et al., 2015; Ericson et al., 2012; Peck, 2011,

163   2016; Peck et al., 2014; Schram et al., 2015). Existing studies have used different species,

164   methodologies and warming rates, which sometimes make comparing species-specific responses

165   and treatment effects difficult (Clark et al., 2017). In addition, most experimental studies have

166   used standard scenarios of climate change that are not necessarily relevant to nearshore areas that

167   may be affected by a higher degree of temperature variability than other marine environments

168   (e.g., Vargas et al., 2017). It is therefore important to incorporate realistic scenarios of

169   temperature change into evaluations of ecosystem responses to climate change across multiple

170   spatial and temporal scales (Gutt et al., 2017).

171   The present work provides the first yearlong record of shallow seawater temperatures

172   around Doumer Island and one of the few on the Palmer Archipelago, WAP. Results show short-

173   term variability and significant warming events. This constitutes important baseline information

174   that could be used to assess long-term trends in local seawater temperature, and inform future

175   physiological and molecular experimental studies in the area. Although HOBO data loggers have

176   an accuracy of ± 0.5° C at 0° C which could increase the temperature range reported in our

177   study, our results are in accordance with those obtained from 24-hour CTD measurements

178   carried out in parallel by other researchers during certain days of the field season. Results

179   demonstrate that marine organisms, at least in some coastal areas of Antarctica, are already

180   exposed seawater temperatures that have been widely used in physiological tolerance

181   experiments to evaluate the effects of future climate scenarios. For example, observed

182   temperatures in this study of more than 2.0 °C for more than 25 days or 2.5 °C for more than ten

183   days within a year, have been used experimentally to test responses to acute heat stress (e.g. Peck

184   et al., 2009). Further, Waller et al. (2017) reported for the first time the presence of the bivalve

185   *Laternula elliptica* (has been used as a model to test the responses of Antarctic organisms to

186   warming sea temperatures) in intertidal habitats were sediment and air temperature reached more

187   than 7 to 10 °C, respectively. That study (Waller et al., 2017) and the continuous records of

188   water temperature reported here suggest that we may need to rethink the temperature ranges used

189   in experimental setups to better reflect local conditions, as organisms occurring on different

190   regions of Antarctica might respond differently to environmental variation.

191   Short-term variability in water temperature is relatively low in Antarctic coastal

192   environments, with a mean annual temperature range of ~3.1° C at some places such as Anvers

193   Island (Barnes et al., 2006); hence, it is expected to have very little impact on ecology (e.g.,

194   Clarke, 2001). However, recent work highlights the importance of environmental variability at

195   different scales, with acute thermal stress events and even timing of seasonal events being

196   suggested as critical factors driving physiological, ecological and evolutionary processes (See

197   Fordham et al., 2017 and references therein). Although our time-series of continuous, directly-

198   measured sea temperatures is limited to a year, it shows the complete annual pattern and

199   existence of dynamic variations within South Bay, Doumer Island. Our results are in accordance

200   with sea surface temperature data from Port Arthur, Palmer Station in Anvers Island

201   (http://pal.lternet.edu), which is approximately 25 km west of Doumer Island, suggesting this

202   pattern occurs at least throughout the Palmer Archipelago (Fig. 4). Additionally, there are some

203   long-term data sets at WAP for a few areas (e.g. Palmer LTER, Rothera Station-BAS Database)

204   that allowed comparison.

205   Our results show that marine organisms at South Bay were exposed to a broad annual

206   temperature range from -1.7° to 3.0° C with a range of 4.7° C. Antarctic marine organisms are

207   recognized as the most stenothermal on Earth (i.e., organisms only capable of surviving over a

208   narrow range of temperature). For example, some species such as the brittlestar *Ophionotus*

209   *victoriae* cannot tolerate acclimation temperatures of more than 2 - 3° C (Peck et al., 2009).

210   Based on an experimental approach using 3.5° C seawater temperatures (representative of

211   current summer transient peaks of sea surface recorded at Port Arthur, Anvers Island), Schram et

212   al. (2015) suggested that an increase in the frequency and peaks of warning events may affect

213   feeding preferences of amphipod species. Considering the observed within-year trends in water

214   temperature recorded at South Bay, it is important to assess and monitor the potential effects on

215   physiological and ecological processes due to rising water temperatures. The effects of increased

216   seawater in sessile organisms, such as sponges, which form diverse assemblages in the shallows

217   (Cárdenas et al., 2016), have not been well studied in Antarctica. Evidence from other latitudes

218   suggests some sponge species might be highly vulnerable to small increases in seawater

219   temperature (Lopez-Legentil et al., 2011), however this remains to be tested in Antarctic species.

220   Previous work has shown that even small variations in environmental condition can have

221   significant effects on the physiology of some organisms (Morley et al. 2010). This is highly

222   relevant considering thermal limits cannot only vary spatially but also between years and even

223   seasons (Morley et al., 2012, 2016). Laboratory studies have used rapid warming rates, which are

224   100 -10,000 times faster than those observed here and predicted for seawater temperatures (Peck

225   et al., 2009). Our HOBO data loggers recorded a significant change in the warming rates before

226 and after October 2016 (3.75 times higher after October 2016, Table 1, Fig. 4). Warming rates

227 are positively correlated with Critical Thermal Maximum (CTMax), which is used to describe

228 the effects of heat tolerance on different organisms (Bilyk & DeVries, 2011; Cascella et al.,

229 2015; Mora & Maya, 2006; Peck et al., 2009; Peck et al., 2014; Terblanche et al., 2007). Lower

230 CTMax results from slower warming rates and consequently poorer thermal tolerance. Our

231 results suggest that caution must be applied when interpreting CTMax derived from laboratory

232 experiments because some of those values were obtained by using warming rates that are far

233 faster than that experienced by organisms in their natural habitats (in this study between 0.03 and

234 0.15º C per day). In addition, differences in warming rates before and after October 2016 (0.05

235 [SD: 0.01] vs. 0.13 [SD: 0.02] º C day) can have a significant impact on the mechanisms

236 dictating the survival limits of benthic organisms (see Peck et al., 2009).

237   Recent studies have shown the importance of including natural local variability (with

238 several treatment levels) in experimental designs to avoid exposing organisms to unrealistic

239 scenarios (Vargas et al., 2017). Local conditions should be taken into account since organisms

240 occurring in areas where high variability occurs, might show different responses to stressors

241 compared to those from areas where environmental variability is lower. For instance, it is

242 possible that organisms inhabiting zones that have more stable temperatures (e.g., East

243 Antarctica) might show different responses to warming than those inhabiting areas exposed to

244 higher temperature variability such as the WAP. The use of continuous measurements of

245 temperature and other environmental data constitute a valuable tool to identify long- and short-

246 term variability in coastal waters. This type of information can provide more realistic scenarios

247 based on local conditions in future studies assessing the effect of environmental variation on

248 Antarctic organisms.

249

Conclusions

250

251   The use of continuous measurements of environmental data such as seawater temperature, can

252   provide key information to identify current patterns of long- and short-term variability in

253   Antarctic coastal waters. Such information is important in informing realistic scenarios for

254   experimental work assessing the local effect of environmental variation on Antarctic organisms.

255   Our results show that benthic organisms at South Bay were exposed to high local variability in

256   seawater temperature (range: -1.7° to 3.0°), rates of warming (0.04 to 0.15 °C day^{-1}), and

257   duration of elevated temperatures (more than 25 days over 2 °C). These results demonstrate that

258   seawater temperatures at depths of 10 to 20 m during summer in South Bay already reach those

259   predicted temperatures for 2100. Although our data was collected in a relatively short period (1

260   year), due to scarcity of sea temperature data at WAP environments, especially in coastal areas, it

261   represents an important source of baseline information, that along with future high-resolution

262   temporal observations on local temperature, will help us to better understand and forecast climate

263   impacts on Antarctic marine organisms and ecosystems.

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269

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Figure 1

Study site

Locations of HOBO temperature/light data loggers deployments for studying sponge assemblages at Doumer Island (Palmer, Archipelago), WAP.

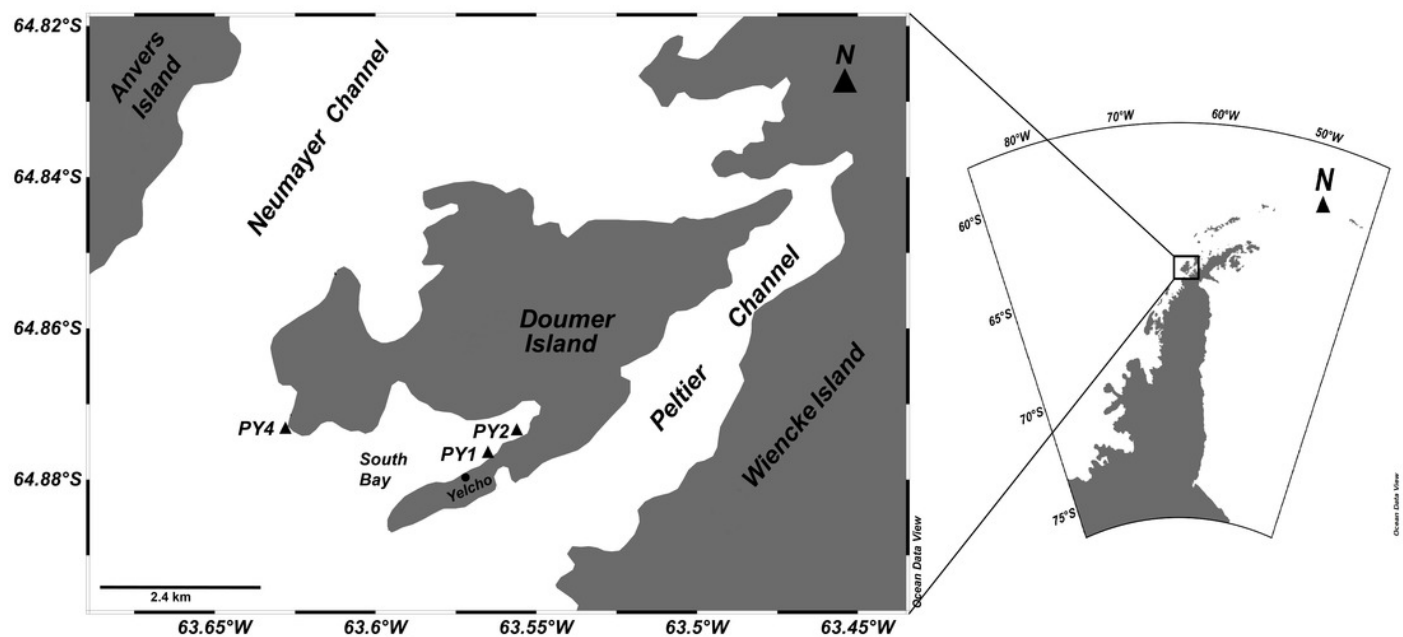



Figure 2

Benthic communities at Doumer Island (Palmer Archipelago), WAP

A) algae-dominated zones (10 m depth), where B) diverse sponge assemblages have been identified underneath the algal canopy. The area showed in B is approximately 80 cm x 50 cm.

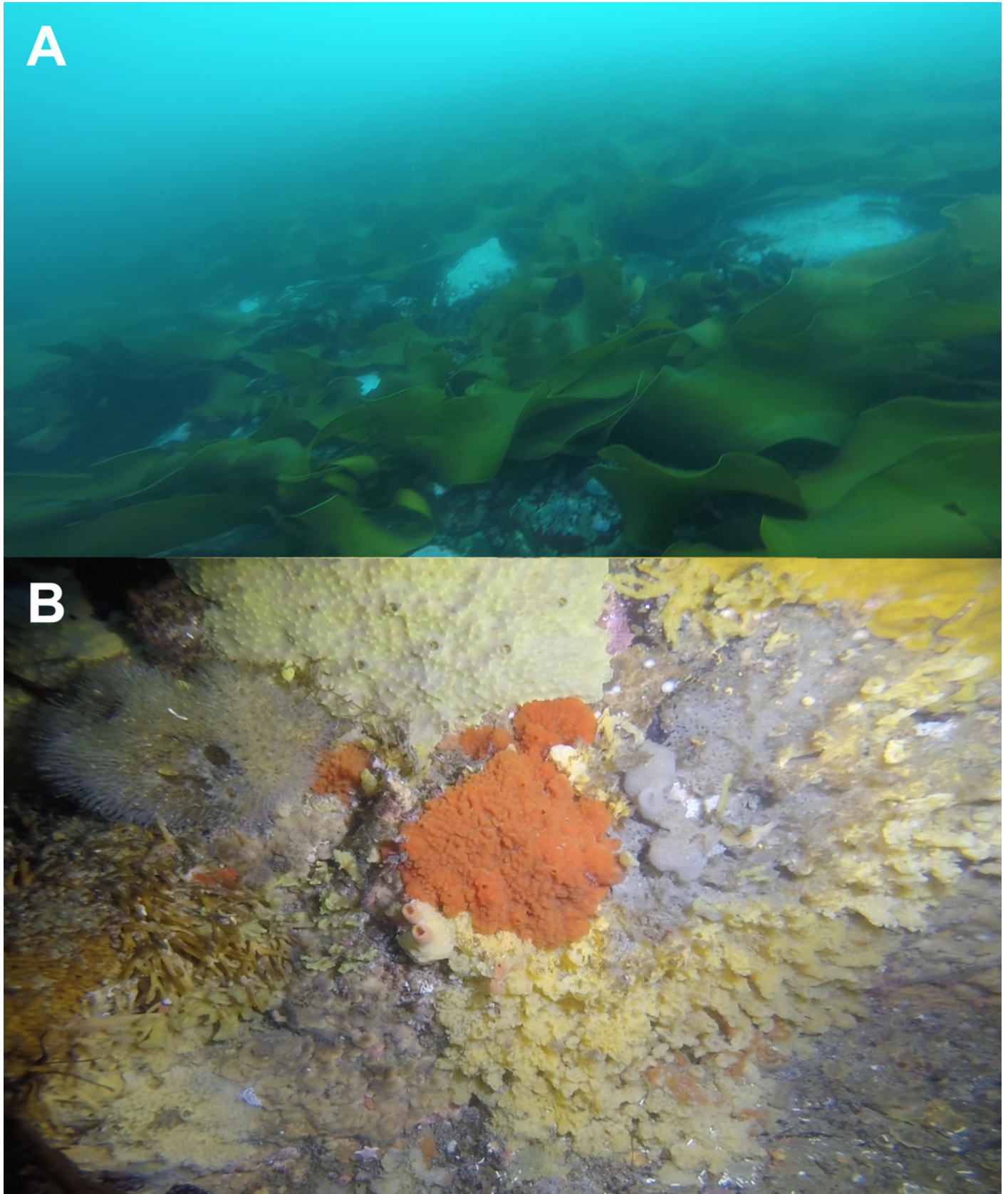



Figure 3

Daily mean seawater temperature

Within-year GAM (solid line) of daily mean seawater temperature (°C) in (A) PY1-10m (edf = 6.7, p-value < 0.001, 404 days), (B) PY4-10 m (edf = 5.7, P<0.001, 312 days) and (C) PY2-20 m (edf= 7.1, P<0.001, 374 days), respectively, at South Bay, Doumer Island, WAP. Black solid curves are the fitted seasonal model from the GAM. Colored areas correspond to 95% confidence bands and the colored thin lines are the observational data (temperature daily means).

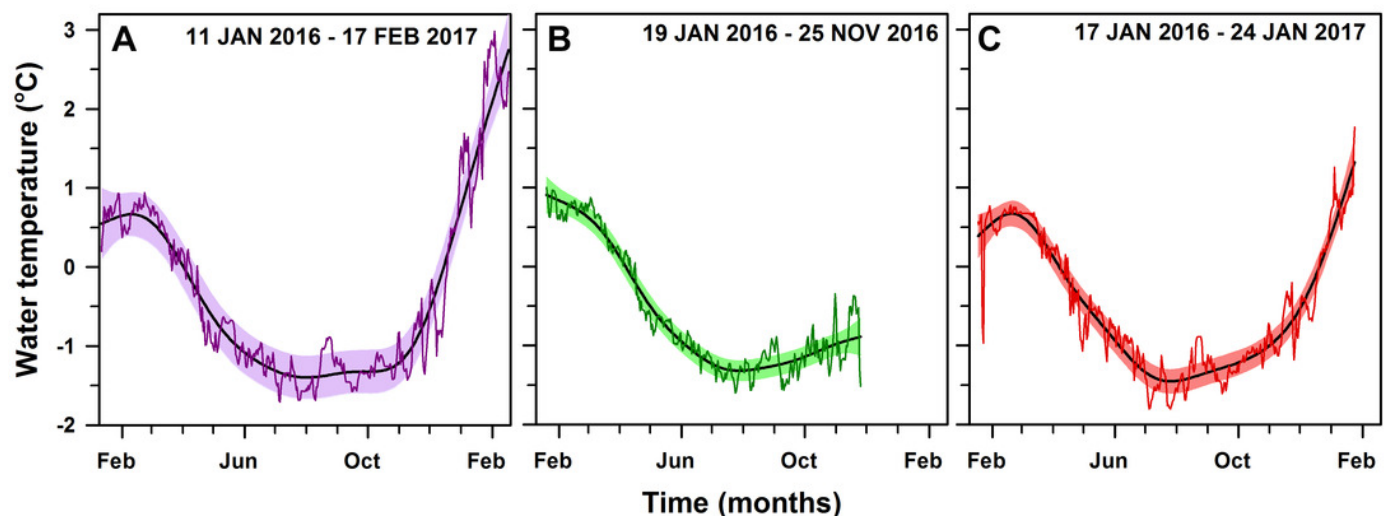



Figure 4

Shallow sea water temperatures recorded at Doumer Island

Full records of shallow sea water temperatures recorded every 2 hours at PY2- 20 m (red dots) and PY4-10 m (green dots), and every 1 hour at PY1-10 m (violet dots). Grey diamonds represent sea surface temperature average for the day, taken from Port Arthur (Palmer Station) in Anvers Island (http://pal.lternet.edu).

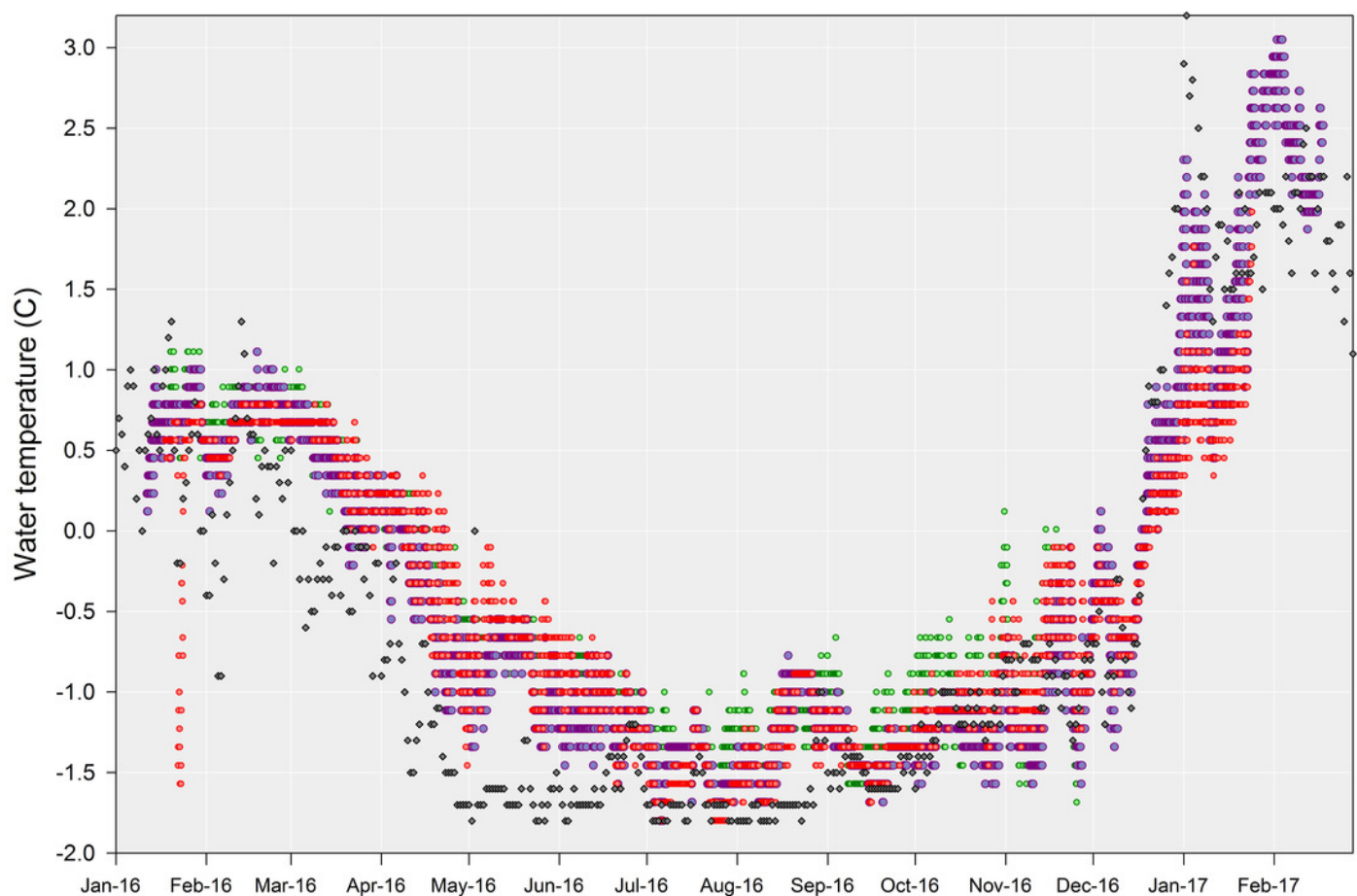
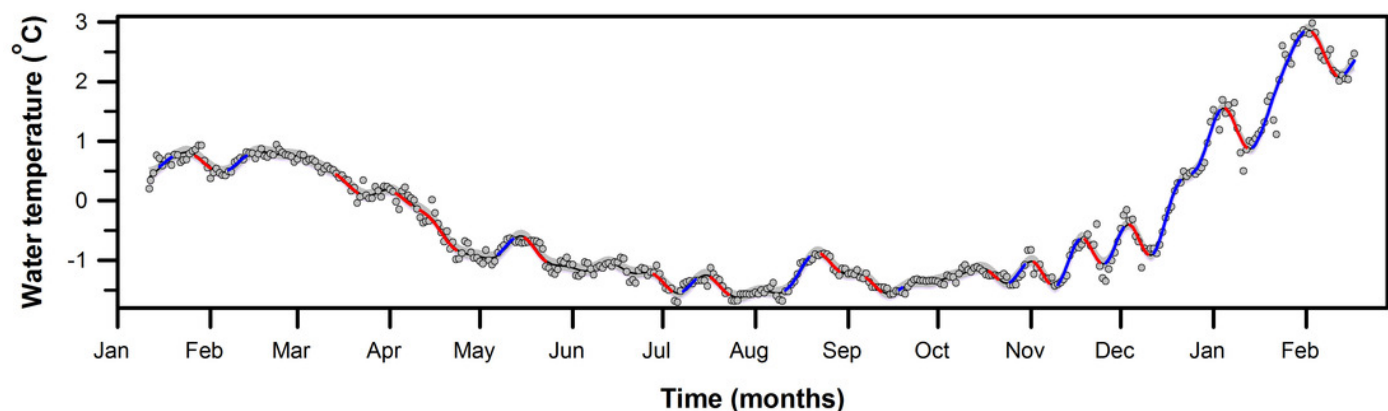



Figure 5

First derivative of seawater temperature trend from PY1 (10 m)

Fitted GAM trend (k = 58) showing estimate time intervals with significant rates of change in seawater temperature. Periods of significant change in the fitted trend, determined by derivative analysis, are highlighted by the thickened colored sections of the trend (red=decrease; blue=increase). Grey areas around the black line (fitted trend) indicate 95% confidence limits, and the dots are the daily mean seawater temperature recorded at PY1 from January 11th, 2016 to February 17th, 2017 in South Bay, Doumer Island, WAP.

Periods of significant temperature increase

Calculated warming rates (°C day^{-1}) of periods of significant temperature increase from PY1

fitted GAM (k = 58, edf = 55.7, p-value< 0.001, Fig. 2).

Periods of significant temperature increase	Rates (°C day^{-1})
15 - 19 Jan 2016	0.04
7 - 13 Feb 2016	0.04
7 - 13 May 2016	0.05
8 - 12 Jul 2016	0.05
11 - 19 Aug 2016	0.07
18 - 19 Sep 2016	0.03
25 - 30 Oct 2016	0.06
10 - 17 Nov 2016	0.12
26 Nov – 2 Dec 2016	0.11
12 -21 Dec 2016	0.15
25 Dec 2016 – 3 Jan 2017	0.13
14 - 31 Jan 2017	0.12