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Biological Sciences - Short Note

Extreme summer marine heatwaves increase chlorophyll *a* in the Southern Ocean

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Introduction

Extreme marine heatwaves (MHWs; i.e. temperatures exceeding four time the 90th percentile of the climatological sea-surface temperature (SST) for > 5 days) (Hobday *et al.* 2018) can have dramatic impacts on the structure and functioning of ecosystems (Hobday *et al.* 2018, Smale *et al.* 2019; Thomsen *et al.* 2019). A recent meta-analysis indicated that phytoplankton may be negatively impacted by MHWs (Smale *et al.* 2019), but none of the underpinning studies were from polar regions. It is essential to understand how phytoplankton in polar regions respond to MHWs because phytoplankton control biogeochemical cycles and form the base of food webs (Thomas *et al.* 2012, Deppeler & Davidson 2017). We therefore tested how 19 extreme summer MHWs affected chlorophyll *a* (chl *a*) concentration (a proxy for phytoplankton abundance) in the Southern Ocean (SO).

Methods

We identified 19 extreme summer MHWs (Fig. 1a) between 2002 and 2018 using the MHW tracker (http://www.marineheatwaves.org/tracker.html) where we had access to corresponding high-quality satellite images for chl *a*. For each MHW, we extracted basic attributes, including the MHW duration, intensity, spatial centre, etc. (Table SI). The MHWs were grouped into sub-Antarctic zone (SAZ), permanently open ocean zone (POOZ), seasonal sea-ice zone (SSIZ) or coastal zone (CZ), where SSIZ and CZ are more influenced by sea ice and have significantly colder waters (see Supplemental Material). Aqua MODIS satellite images with low cloud and ice cover that coincided with the MHWs were analysed by comparing derived surface chl *a* concentration at the centre of the MHW with multiple control areas 250 and 500 km away. Unfortunately, high-quality recurring images were not available for all 19 MHWs, ruling out analysis of lag effects (i.e. we may underestimate total impacts). Factorial analysis of variance, conducted separately on the 250 and 500 km control data, tested for the effects of the MHWs (presence/absence), climatic SST (cold *vs* warmer waters) and zones (nested within climatic SST) on chl *a* (log-transformed to remove or, in one case, reduce variance heterogeneity). Furthermore, $r_{Spearman}$ correlation analyses, conducted on log-response ratio effect sizes (i.e. ln(chl a_{impact}/chl $a_{control}$)), tested whether the MHW attributes modified the impacts on chl *a*.

Results

We found significant single-factor and MHW × SST interactions on chl *a* concentration ($P < 0.05$ for both 250 and 500 km control site data; see Supplemental Material). Specially, chl *a* was significantly greater at the centre of the MHWs at the cold sites (2.76 ± 0.73 SE mg m^{-3}) compared to the centres of the MHWs at the warmer sites (0.51 ± 0.14 SE mg m^{-3}) and the controls at both the cold (0.55 ± 0.15 SE mg m^{-3} for 250 km; 0.56 ± 0.26 SE mg m^{-3} for 500 km) and warmer (0.30 ± 0.05 SE mg m^{-3} for 250 km; 0.21 ± 0.03 SE mg m^{-3} for 500 km) sites (Fig. 1b). We also found significant negative correlations between log-response ratios and the temperature at the impacted site (250 and 500 km), the MHW maximum intensity (250 km) and the MHW mean intensity (250 km; see Supplemental Material).

Discussion

Extreme summer MHWs increased chl *a* concentration by ~80% compared to control sites, with a stronger effect in colder regions. Specifically, chl *a* increased by up to 2.76 mg m^{-3} at coldest sites, exceeding a 1 mg m^{-3} threshold that represents blooms in the SO (Moore & Abbott 2000). Changes to phytoplankton communities associated with slow and gradual temperature increases have been studied much more than impacts following MHWs (Deppeler & Davidson 2017, Boyd 2019, Smale *et al.* 2019), but our results support Dunstan *et al.* (2018), who argued that without assessment of short-term variability, we may fail to identify punctuated and smaller-scale impacts. Many

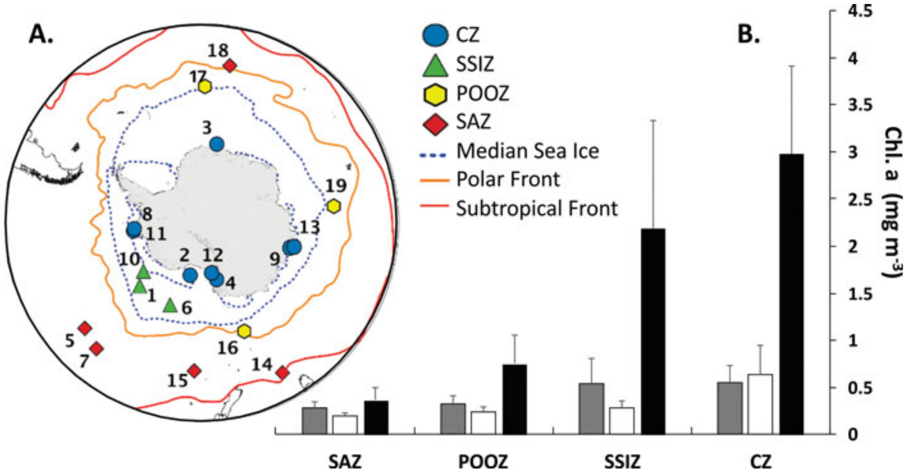

Fig. 1. a. Location of extreme summer marine heatwaves (MHWs) (2002–18) grouped into coastal zone (CZ), seasonal sea-ice zone (SSIZ), permanently open ocean zone (POOZ) and sub-Antarctic zone (SAZ). The CZ and SSIZ have colder waters and are more influenced by sea ice. **b.** Mean chl *a* concentration (+ SE) for impacted (black) and non-impacted control sites positioned 250 km (grey) and 500 km (white) away from the centre of extreme MHWs. See Supplemental Material for details.

SO phytoplankton species are adapted to sub-zero temperatures, so this region is expected to experience dramatic changes from gradual ocean warming (Thomas *et al.* 2012, Deppeler & Davidson 2017, Boyd 2019). For example, under a predicted gradual increase in mean SST of 1.5°C by 2100, polar diatoms such as *Pseudonitzschia* spp., *Proboscia* spp. and *Nitzschia stellata* and nanoplankton such as *Phaeocystis antarctica* will be near their thermal summer maximum (Boyd 2019). Here, we suggest that superimposed MHWs will accelerate changes, further inhibiting cold-water species.

In conclusion, extreme summer MHWs increased surface chl *a* in the SO, with the strongest effects in the coldest regions, potentially increasing SST above optimum ranges for cold-water phytoplankton species and with unknown cascading impacts on food webs. To better understand the impacts of MHWs on SO phytoplankton, we require detailed remote-sensing analyses (e.g. analyses of lag effects, bloom persistence, currents, nutrient concentrations and vertical stratification) combined with ground truth sampling and MHW simulations in laboratory and field experiments.

Author contributions

SM analysed the data and wrote the draft. MST, WR and PAB helped with analysis and manuscript revisions.

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Supplemental material

A methods description, three supplemental tables and three supplemental figures can be found at https://doi.org/10.1017/S0954102020000401.

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