SIDEBAR 6.1: RETURN OF THE MAUD RISE POLYNYA: CLIMATE LITMUS OR SEA ICE ANOMALY?—S. SWART, E. C. CAMPBELL, C. H. HEUZÉ, K. JOHNSON, J. L. LIESER, R. MASSOM, M. MAZLOFF, M. MEREDITH, P. REID, J.-B. SALLÉE, AND S. STAMMERJOHN

The Maud Rise polynya is a persistent area of open water within the sea ice cover of the Southern Ocean, which overlies an area of elevated topography called Maud Rise (66°S, 3°E) located in the eastern sector of the Weddell Sea (Fig. SB6.1a). It is termed a "Weddell polynya" if it grows and migrates westward into the central Weddell Sea. This larger sized polynya was first observed in satellite data in 1974 and recurred for each of the two subsequent austral winters (Zwally and Gloersen 1977; Carsey 1980). Its large size, ~300 000 km^2, meant that it could contribute strongly to the transfer of heat from the ocean to the atmosphere in winter and, hence, instigate dense water production and the renewal of deep ocean waters in the Weddell Sea (Gordon 1978). The amount of deep water formed via this route was estimated at 1–3 Sverdrups (Martinson et al. 1981). The 1974–76 polynya may have been responsible for up to 34% of observed warming of the deep Southern Ocean (Zanowski et al. 2015). Smaller features, perhaps associated with topographically driven upwelling of warm waters, have been observed subsequently (Comiso and Gordon 1987), but a large polynya had not re-appeared until recently and unexpectedly during austral winters 2016 and 2017.

Following the Maud Rise polynya development in 2016 (Mazloff et al. 2017), mid-September 2017 saw the opening of a longer lived and larger polynya over the same region. The 2017 polynya grew quickly but its size remained quite static at approximately 50 000 km^2 until 3 November, after which it more than tripled in size over a period of a week. The sudden expansion is possibly the result of a considerable change in atmospheric circulation due to the development of a La Niña in early November (Section 6e), combined with an anomalously earlier spring ice edge retreat (see Section 6e). The polynya continued to expand over the following month (Fig. SB6.1b) and reached its maximum size of 295 000 km^2 (larger than New Zealand) on 2 December 2017 before coalescing with the open ocean. Overall, it contributed to a significantly large negative anomaly in sea ice concentration (see Section 6e).

Two under-ice biogeochemical profiling floats from the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project were present at Maud Rise before, during, and after the 2016 and 2017 polynyas. Both floats surfaced and transmitted data within the 2017 polynya (Fig. SB6.1b). These data show the appearance of cold and fresh subsurface anomalies in late 2016 (extending from ~100 to 300 m depth in Figs. SB6.2a,b), indicating that deep ventilation may have occurred during the brief 2016 polynya. This modified subsurface water mass persisted into 2017 and was punctuated in October and November by warm and salty intrusions indicative of deep mixing during the 2017 polynya event. Additionally, enhanced biogeochemical responses to the polynya's presence were observed with approximately a 2-month earlier (September 2017) increase in chlorophyll fluorescence (phytoplankton) and pH (Figs. SB6.2c,d) compared to the two previous years, which were ice covered. Hydrographic measurements collected near Maud Rise during two research expeditions on the R/V *S.A.*

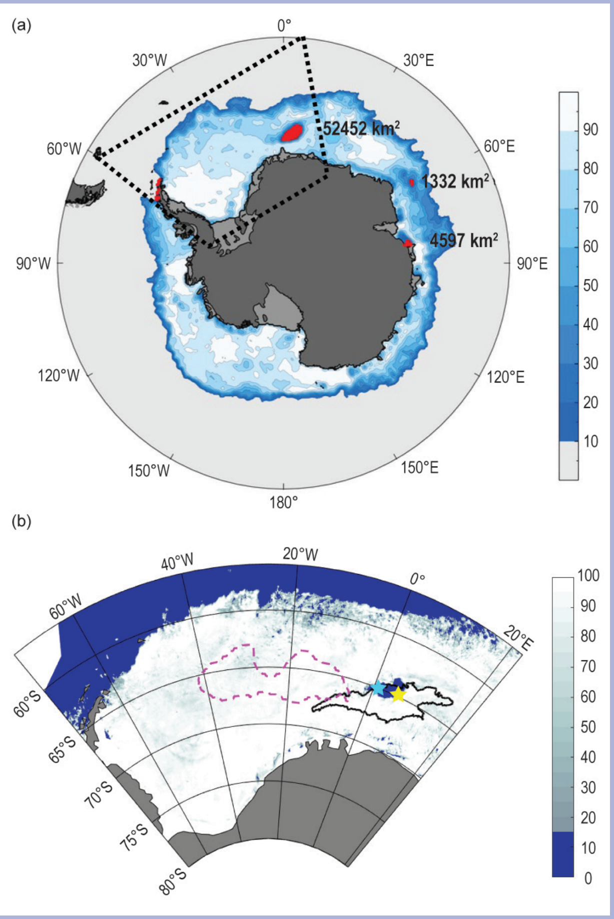

FIG. SB6.1. (a) Circumpolar map of AMSR2 sea ice concentration (in %) on 8 Nov 2017, with the red shading marking polynya locations, including the largest—the Maud Rise polynya. (b) Location of the polynya on 14 Oct 2017 from AMSR2 sea ice concentration (Spreen et al. 2008). The black line represents the polynya size on 29 Nov 2017, at its largest extent just prior to coalescing with the open ocean. The yellow and cyan stars represent the location of the SOCCOM floats 5904471 and 5904468, respectively. The magenta contour shows a 20-yr mean location of the polynya as depicted in the MPI-ESM-LR model.

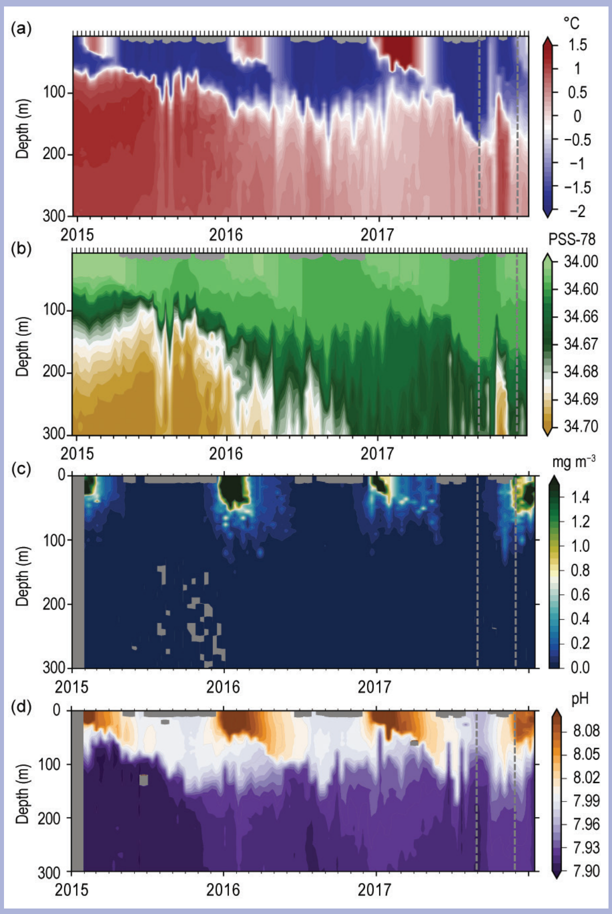

Fig. SB6.2. Sections of (a) potential temperature (°C), (b) salinity (PSS-78) from SOCCOM float 5904471, (c) chlorophyll-*a* (mg m^{-3}), and (d) pH from SOCCOM float 5904468, from within the polynya over 3 years. Gray dashed lines represent the start and end dates of the 2017 polynya. Gray shading indicates absence of data.

Agulhas II and R/V *Polarstern* in December 2017 and January 2018, respectively, when fully processed and analyzed, may lend additional insights regarding the ocean impacts from the 2016 and 2017 polynyas.

The research community continues to speculate on the causes of the 2017 polynya and whether it is related to the 2016 event. It is possible that the 2017 polynya was caused by persistent subsurface ocean conditions that were initiated during the 2016 polynya, and/or it was caused by preconditioning that resulted from anomalous sea ice divergence occurring late spring 2016 (Schlosser et al. 2018). Preconditioning mechanisms may include a build-up of subsurface heat (Martin et al. 2013), a precipitation deficit caused by prolonged negative SAM (Gordon et al. 2007), and/or reduced sea ice concentration and upper-ocean instability from upwelling of warm and salty waters on the flanks of Maud Rise (Gordon and Huber 1995; Lindsay et al. 2004; de Steur et al. 2007; Cheon et al. 2014, 2015). Triggering mechanisms remain less clear but may include transient eddies or other topography–mean flow interactions associated with Maud Rise (Holland 2001) or small positive salinity anomalies at the surface caused by anomalous wind and/or sea ice conditions (Cheon et al. 2014; Heuzé et al. 2015; Kjellsson et al. 2015). A prolonged period of strong westerly winds (coincident with positive SAM) might also explain the 2016 and 2017 openings that may have responded to the wind-induced Ekman transport and associated upwelling of warmer water (Cheon et al. 2014; Ferreira et al. 2015). In the lead-up to the 2016 and 2017 polynyas, the SAM index was indeed strongly positive with three of its ten highest monthly values since 1957 recorded in 2015 and 2016, including the largest value in February 2015—coinciding with the annual sea ice minimum. It is quite possible that strong winds and an associated enhanced Weddell Gyre were the catalyst for these polynya events. A contributing mechanism during both years may be anomalously warm waters advecting south from the Indian and western Atlantic sectors of the Southern Ocean. More research is needed to better understand the respective roles of large-scale modes (SAM) versus regional circulation anomalies, in addition to needing more highly resolved data in space and time (e.g., Schlosser et al. 2018).

Global coupled models generally exhibit a greater frequency of Maud Rise polynya occurrence compared to observations (e.g., Heuzé et al. 2013; Fig. SB6.1b) and have thus been a valuable source of information regarding their causes and occurrences. Models suggest a preconditioning is needed by the slow accumulation of subsurface heat over several decades (Martin et al. 2013; Dufour et al. 2017), heat that would be lost after years of the polynya remaining open, possibly explaining why polynyas on the scale of the 1974–76 event have not been seen in 40 years. Alternatively, models also suggest that increased freshening at the ocean surface, caused by increased ice sheet/iceberg melt for example, may increase stratification and reduce the frequency of polynya formation (Kjellsson et al. 2015). The extent to which such models robustly reproduce the real ocean is largely unknown due to the comparatively short observational record, but such results highlight the need to better understand this intermittent but important mode of deep ocean ventilation.