ARTICLE IN PRESS

Deep-Sea Research II ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Changing distributions of sea ice melt and meteoric water west of the Antarctic Peninsula

Michael P. Meredith [a,*], Sharon E. Stammerjohn [b], Hugh J. Venables [a], Hugh W. Ducklow [c], Douglas G. Martinson [c], Richard A. Iannuzzi [c], Melanie J. Leng [d,e], Jan Melchior van Wessem [f], Carleen H. Reijmer [f], Nicholas E. Barrand [g]

[a] British Antarctic Survey, Cambridge, UK
[b] Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO, USA
[c] Lamont-Doherty Earth Observatory, Columbia University, New York, USA
[d] NERC Isotope Geosciences Facilities, British Geological Survey, Keyworth, UK
[e] Centre for Environmental Geochemistry, University of Nottingham, UK
[f] Institute for Marine and Atmospheric Research, Utrecht, Netherlands
[g] School of Geography, Earth and Environmental Sciences, University of Birmingham, UK

ARTICLE INFO

Keywords:
Ocean–ice–atmosphere system
Meltwater
Ocean circulation
Sea ice
West Antarctic Peninsula

ABSTRACT

The Western Antarctic Peninsula has recently undergone rapid climatic warming, with associated decreases in sea ice extent and duration, and increases in precipitation and glacial discharge to the ocean. These shifts in the freshwater budget can have significant consequences on the functioning of the regional ecosystem, feedbacks on regional climate, and sea-level rise. Here we use shelf-wide oxygen isotope data from cruises in four consecutive Januaries (2011–2014) to distinguish the freshwater input from sea ice melt separately from that due to meteoric sources (precipitation plus glacial discharge). Sea ice melt distributions varied from minima in 2011 of around 0 % up to maxima in 2014 of around 4–5%. Meteoric water contribution to the marine environment is typically elevated inshore, due to local glacial discharge and orographic effects on precipitation, but this enhanced contribution was largely absent in January 2013 due to anomalously low precipitation in the last quarter of 2012. Both sea ice melt and meteoric water changes are seen to be strongly influenced by changes in regional wind forcing associated with the Southern Annular Mode and the El Niño–Southern Oscillation phenomenon, which also impact on net sea ice motion as inferred from the isotope data. A near-coastal time series of isotope data collected from Rothera Research Station reproduces well the temporal pattern of changes in sea ice melt, but less well the meteoric water changes, due to local glacial inputs and precipitation effects.

1. Introduction

The freshwater system of the Southern Ocean is a critical factor in determining the time-evolving ocean circulation and properties, and in structuring the marine ecosystem and its response to climatic change (e.g. Dierssen et al., 2002; Jullion et al., 2013; Rye et al., 2014). Partly this is a consequence of the very strong dependence of seawater density on salinity at low temperatures, with implications for geostrophic flows, stratification, mixing, and so on. Each of the contributors to the freshwater budget of the Southern Ocean (sea ice, glacial melt from Antarctica, iceberg calving and subsequent melt, precipitation) has the capacity to influence marine ecology and biodiversity, not only by shaping the physical environment, but also by influencing habitat suitability and the biogeochemistry of the marine system (Boyd and Ellwood, 2010; Ducklow et al., 2012; Raiswell, 2011; Venables et al., 2013).

Climatic change around Antarctica and the Southern Ocean is complex and spatially very heterogeneous (Turner et al., 2005). The most rapidly warming sector is West Antarctica, within which the Western Antarctic Peninsula (WAP) has been the fastest-warming region in the Southern Hemisphere (Vaughan et al., 2003). During the second half of the twentieth century, annual-mean atmospheric warming at WAP stations averaged 3.7 ± 1.6 °C/century, with the strongest warming occurring in the autumn and winter (Smith et al., 1996; Van Wessem et al., 2015; Vaughan et al., 2003).

At the WAP, sea ice is known to be especially significant in influencing local climate (King, 1994; Meredith and King, 2005). Unlike other sectors of Antarctica, the winds have a significant

* Corresponding author.
E-mail address: mmm@bas.ac.uk (M.P. Meredith).

http://dx.doi.org/10.1016/j.dsr2.2016.04.019
0967-0645/

Please cite this article as: Meredith, M.P., et al., Changing distributions of sea ice melt and meteoric water west of the Antarctic Peninsula. Deep-Sea Res. II (2016), http://dx.doi.org/10.1016/j.dsr2.2016.04.019

onshore component here, and hence air masses cross the sea ice before encountering land (Harangozo, 2006; King and Harangozo, 1998). Consequently, the extent of sea ice adjacent to the WAP is a critical factor in determining local atmospheric temperatures (Smith and Stammerjohn, 2001; Turner et al., 2013). The ocean adjacent to the WAP has been marked by a rapid loss of sea ice in recent decades, comprised of a moderate trend toward earlier retreat in spring, coupled with a more pronounced trend toward later advance in autumn (Stammerjohn et al., 2008a).

Concurrent with the atmospheric warming, and strongly linked with the sea ice changes, the upper ocean at the WAP warmed significantly during the second half of the twentieth century (Meredith and King, 2005). It has also been shown that the delivery of heat to the WAP shelf via the intrusion of deep waters from the Antarctic Circumpolar Current (ACC) increased over similar timescales (Martinson, 2011a; Schmidtko et al., 2014). The ACC is the major oceanographic current system that inhabits the Southern Ocean; unlike other sectors, it lies immediately adjacent to the Antarctic shelf at the WAP, enabling the warm, saline waters from its mid-layers to intrude onto the shelf in relatively unmodified form (Klinck et al., 2004; Martinson et al., 2008).

In regions of West Antarctica that are exhibiting rapid loss of ice shelves, the warming and greater penetration of deep waters from the ACC onto and across the shelf has been invoked as the major proximal cause of the ice loss (Pritchard et al., 2012; Schmidtko et al., 2014). At the WAP, the role of atmospheric warming has also been implicated in glacial ice loss, since it is the one region of Antarctica where temperatures are sufficiently high to enable significant melt and runoff to occur (Vaughan et al., 2003). The annual duration of the melt season at the WAP has increased in recent decades, which is suggested to have contributed to ice shelf collapse (Scambos et al., 2000; van den Broeke, 2005) and the acceleration and thinning of glaciers (Pritchard and Vaughan, 2007) and although most of the meltwater will percolate down and refreeze within the firn layer, there is still the potential for an increase in runoff to the ocean (Barrand et al., 2013b; Vaughan, 2006). Overall, 80% of the glaciers at the WAP are known to have retreated during the second half of the twentieth century, with a recent tendency toward accelerated retreat (Cook et al., 2005). Recent modeling studies have suggested that the currently observed trends of glacier melting, recession and thinning are expected to continue at the peripheries of the Antarctic Peninsula (Davies et al., 2014), while the interior ice sheet may thicken in response to increased accumulation (Barrand et al., 2013a).

Discharge of ice from glaciers can be in the form of direct melt to the ocean, or via the calving of icebergs. The WAP is typically not characterized by the presence of large icebergs (> 18 km in length), though smaller icebergs are present due to local calving and advection into the region from other sectors. The distribution of these is such that the southern WAP shows greater volumes than the north (e.g. Fig. 9 of Tournadre et al., 2016).

Precipitation at the WAP is known to have increased in recent decades, with station data showing more precipitation events and an increasing tendency for rainfall rather than snowfall (Kirchgäßner, 2011; Turner et al., 1997). Shallow ice cores also indicate increasing precipitation over the last century, with a doubling inferred for some locations (Thomas et al., 2008).

Such changes in the freshwater system can have profound effects on the upper ocean at the WAP, and the regional ecosystem. One manifestation of this is the role of freshwater in stabilising the water column: a thin layer of ice melt will act to enhance stratification, and thus create an environment more favourable for phytoplankton blooms, whereas processes that reduce stratification (e.g. strong ice production in winter) can have the opposite effect (Dierssen et al., 2002; Mitchell and Holm-Hansen, 1991). In northern Marguerite Bay (adjacent to Adelaide Island; Fig. 1a), decreases in sea ice cover since 1998 have resulted in deeper winter mixed layers, and consequently reduced stratification and phytoplankton concentration in spring (Venables et al., 2013).

At Palmer Station (Anvers Island; Fig. 1a), positive anomalies in summer chlorophyll-a have been related to positive anomalies in the preceding winter sea ice extent followed by anomalously later ice edge retreats, weaker winds and less cloud cover in spring (Montes-Hugo et al., 2009; Saba et al., 2014). Years with positive chlorophyll-a anomalies were associated with the initiation of a robust cohort of krill the following summer, as evidenced in the diets of Adélie penguins (Saba et al., 2014). On the Peninsula scale, phytoplankton biomass along the WAP decreased overall since the late 1970s (Montes-Hugo et al., 2009) with strong negative trends occurring in the now mostly ice-free region north of 63°S (i.e., north of Palmer Station), concurrent with positive trends in the far southern region where the sea ice cover transitioned from quasi-perennial to seasonal.

Glacial discharge can also influence the WAP marine ecosystem due to the capacity of glaciers to supply micronutrients such as iron to the ocean, the low levels of which limit productivity across large regions of the open Southern Ocean away from such sources (Edwards and Sedwick, 2001; Raiswell, 2011). Scouring of the underlying rock and sediment, in addition to accumulation from atmospheric deposition, can result in glacial ice being significantly enriched in such micronutrients (Boyd and Ellwood, 2010). It has been suggested that an increase in freshwater input to the ocean from glaciers could result in a greater injection of such micronutrients (Hawkings et al., 2014), a shift in phytoplankton assemblage composition, and an increase in biomass in the waters influenced (Dierssen et al., 2002).

Understanding the full effects of these changes on the diverse aspects of the marine biogeochemical and biological systems requires detailed measurements that are very difficult to obtain on a circumpolar scale. A different approach to achieving progress is to study the system in a region of known rapid climate change, so that a mechanistic understanding can be developed, and can give insight into the future of other sectors as their climates evolve. Here, we explore in detail the time-varying freshwater distributions in a region of recent rapid change, and elucidate the processes responsible for the changes and their impacts.

2. Background

2.1. Water masses, circulation and variability at the WAP

The presence of the southern edge of the ACC adjacent to the WAP shelf leads to a northeastward flow along the shelf break. The mid-layer waters of the ACC, termed Circumpolar Deep Water (CDW) are consequently brought into close proximity with the shelf break, and the glacial canyons that dissect the shelf (Fig. 1a) provide efficacious conduits for the intrusion of this CDW and its flow toward land. Eddy dynamics are believed to be significant in these processes (Martinson, 2011b; Moffat et al., 2009). This CDW mixes upwards on the shelf, providing heat and macronutrients to the upper layers of the water column. The locations and processes that enable this mixing are thought to be heterogeneously distributed, with coastal upwelling and internal tides highlighted previously (Wallace et al., 2008).

In winter, the CDW is overlain by a thick (50–150 m) mixed layer with temperatures close to the freezing point and salinities up to 34.0 (Klinck, 1998; Meredith et al., 2004). In summer, the surface of this layer is warmed by insolation and freshened by ice melt, leading to the existence of a subsurface temperature-minimum layer termed Winter Water (WW; Mosby, 1934). The

Please cite this article as: Meredith, M.P., et al., Changing distributions of sea ice melt and meteoric water west of the Antarctic Peninsula. Deep-Sea Res. II (2016), http://dx.doi.org/10.1016/j.dsr2.2016.04.019