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Characteristics of the modelled meteoric freshwater budget of the western Antarctic Peninsula

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ABSTRACT

Rapid climatic changes in the western Antarctic Peninsula (WAP) have led to considerable changes in the meteoric freshwater input into the surrounding ocean, with implications for ocean circulation, the marine ecosystem and sea-level rise. In this study, we use the high-resolution Regional Atmospheric Climate Model RACMO2.3, coupled to a firn model, to assess the various contributions to the meteoric freshwater budget of the WAP for 1979–2014: precipitation (snowfall and rainfall), meltwater runoff to the ocean, and glacial discharge. Snowfall is the largest component in the atmospheric contribution to the freshwater budget, and exhibits large spatial and temporal variability. The highest snowfall rates are orographically forced and occur over the coastal regions of the WAP (>2000 mm water equivalent (w.e.) y^{-1}) and extend well onto the ocean up to the continental shelf break; a minimum (~500 mm w. e. y^{-1}) is reached over the open ocean. Rainfall is an order of magnitude smaller, and strongly depends on latitude and season, being large in summer, when sea ice extent is at its minimum. For Antarctic standards, WAP surface meltwater production is relatively large (> 50 mm w. e. y^{-1}), but a large fraction refreezes in the snowpack, limiting runoff. Only at a few more northerly locations is the meltwater predicted to run off into the ocean. In summer, we find a strong relationship of the freshwater fluxes with the Southern Annular Mode (SAM) index. When SAM is positive and occurs simultaneously with a La Niña event there are anomalously strong westerly winds and enhanced snowfall rates over the WAP mountains, Marguerite Bay and the Bellingshausen Sea. When SAM coincides with an El Niño event, winds are more northerly, reducing snowfall and increasing rainfall over the ocean, and enhancing orographic snowfall over the WAP mountains. Assuming balance between snow accumulation (mass gain) and glacial discharge (mass loss), the largest glacial discharge is found for the regions around Adelaide Island (10 Gt y^{-1}), Anvers Island (8 Gt y^{-1}) and southern Palmer Land (12 Gt y^{-1}), while a minimum (< 2 Gt y^{-1}) is found in Marguerite Bay and the northern WAP. Glacial discharge is in the same order of magnitude as the direct freshwater input into the ocean from snowfall, but there are some local differences. The spatial patterns in the meteoric freshwater budget have consequences for local productivity and carbon drawdown in the coastal ocean.

1. Introduction

During the second half of the twentieth century, the western Antarctic Peninsula (WAP) warmed more rapidly than any other region in the Southern Hemisphere. Since 1950, the lower atmosphere above the WAP warmed by 3 °C (King, 1994; Vaughan et al., 2003). This, in combination with increased ocean heat content (Schmidtko et al., 2014), led to the loss of multiple ice shelves (Cook and Vaughan, 2010), a retreat for 90% of its marine terminating glaciers (Cook et al., 2014, 2016), an increase in precipitation (Thomas et al., 2008), and the disappearance of most of the perennial sea ice (Stammerjohn et al., 2011). All these changes affect the freshwater input (sea-ice melt and meteoric water, the latter combining precipitation and glacial discharge) into the surrounding ocean, significantly influencing the ecosystem, and, ultimately, the WAP contribution to regional and global sea-level rise (Ivins et al., 2013; Rye et al., 2014). Rising atmospheric temperatures increase snow melt-rates and meltwater runoff into the ocean (Vaughan, 2006). Intrusion of warm Circumpolar Deep Water (CDW) originating from the Antarctic Circumpolar Current (ACC) onto and across the continental shelf has been identified as the main cause of glacial ice loss in the Amundsen Sea and likely in the Bellingshausen Sea (Martinson, 2012; Pritchard et al., 2012),

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culminating in the retreat and calving of marine terminating glaciers (Wouters et al., 2015; Cook et al., 2016). Together with the (partial) disintegration of WAP ice shelves, such as Wilkins Ice Shelf (Scambos et al., 2009), large icebergs are formed that drift across the open ocean, releasing freshwater into the ocean as they melt (Silva et al., 2006). Spatial and temporal changes in sea-ice volume will significantly alter ocean temperature, salinity and stratification in the vicinity of the WAP (Stammerjohn et al., 2008; Meredith et al., 2013). The marine ecology of the upper ocean adjacent to the WAP responds to these changes in the freshwater budget (Meredith and King, 2005): freshening of the upper ocean stabilizes the water column and enhances phytoplankton blooms (Montes-Hugo et al., 2009); it also alters the ocean circulation by changing the geostrophic flow (Martinson, 2012).

Measurements of stable isotopes of oxygen in seawater enable a quantitative separation of the contributions of sea-ice melt and meteoric water to the total freshwater budget (Meredith et al., 2008, 2010). Several studies used oxygen isotope data from the Palmer Long-Term Ecological Research programme (Pal-LTER; http://pal.lternet.edu/) and the Rothera Oceanographic and Biological Time Series (RaTS; Clarke et al., 2008), as part of more comprehensive suites of physical, biogeochemical and biological measurements (Fig. 1). Some of these studies have found that, as a result of the contributions of both glacial meltwater (Dierssen et al., 2002) and precipitation (Meredith et al., 2008), the meteoric water flux is the dominating freshwater source overall. However, a new study found that sea ice melt contributions can be comparable to the meteoric water flux in specific years because of the large interannual variability of the latter (Meredith et al., 2016).

It is thus clear that quantifying the spatial and temporal variability of the meteoric freshwater input is important for interpreting current and future changes in the WAP. Meteoric freshwater fluxes depend on atmospheric forcing, including the direction and magnitude of atmospheric water vapour transport (Meredith et al., 2010). The are linked to subannual and interannual climate variability as expressed in e.g. the Southern Annular Mode (SAM; Marshall, 2003; Thomas et al., 2008), and the El Niño/Southern Oscillation phenomenon (ENSO, Wolter and Timlin, 1993; Turner, 2004) and their interconnection (Clem and Fogt, 2013). Moreover, model studies have found that precipitation rates over the WAP and the adjacent ocean are extremely high due to strong orographic uplift (Van Wessem et al., 2016). This affects both the direct (precipitation) and indirect (glacial discharge) meteoric freshwater fluxes. Partitioning the contributions of these fluxes is important as they affect the ecosystem in different ways: unlike precipitation, glacial discharge can transport micronutrients and trace metals such as iron to the ocean as the glaciers scour the underlying rock and sediment (Hawkings et al., 2014). However, making this distinction from observations is difficult, especially in the coastal areas where these fluxes are largest, as both water sources have a similar isotopic composition and can be comparable in magnitude (Meredith et al., 2013). An additional complication is the challenge of distinguishing basal melting from iceberg calving on the basis of ocean tracer data alone (Meredith et al., 2013).

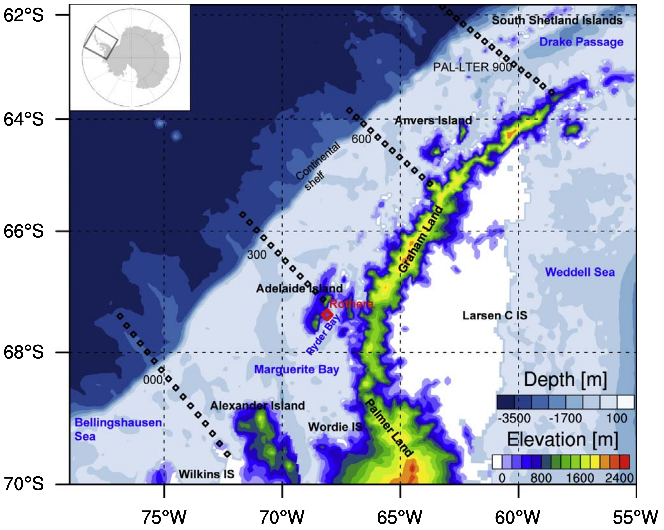

Fig. 1. The northern (> 70°S) Antarctic Peninsula (AP) domain (black box in inset map of Antarctica shows the full AP RACMO2.3 model domain and boundaries, which extends to 75°S) with model surface topography [m] and ocean depth [m] of the AP. White areas represent floating ice shelves and regions over land with elevations <40 m, colours represent the elevation of the grounded ice sheet and ocean depth. Locations of four transects are shown (black diamonds), coinciding with survey lines from the Pal-LTER program, as used in Section 3.1. Some locations as used througout the text are marked. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Atmospheric models provide information about meteoric freshwater input, but are generally limited in horizontal resolution and hence do not resolve the large spatial variability of WAP precipitation rates (Van Wessem et al., 2014a), are limited in simulation length (Van Lipzig et al., 2004; Bromwich, 2004), or have limitations in their ability to resolve atmospheric and/or snow related processes (Nicolas and Bromwich, 2011). In this study, we use the newest version of the Regional Atmospheric Climate Model RACMO2.3 to address the above issues. The model is run at high horizontal resolution (5.5 km) to properly simulate the large spatial variability of the WAP topography and associated climate variables. The model separately simulates the WAP meteoric freshwater components of snowfall, rainfall and meltwater for the period 1979–2014. The model is forced with ERA-Interim, the most reliable re-analysis data for the Southern Ocean and troposphere (Bracegirdle and Marshall, 2012), and is coupled to a Firn Densification Model (FDM) that calculates processes in the snowpack such as the percolation and refreezing of meltwater; runoff into the ocean is assumed to occur instantaneously at the snow/ice interface (Ettema et al., 2010; Ligtenberg et al., 2011). Multiple studies evaluated the performance of RACMO2.3 by comparing model output to observational data; the model has been proven to realistically simulate the near-surface climate and surface mass balance of Antarctica (Van Wessem et al., 2014a,b), as well as that of the Antarctic Peninsula (Van Wessem et al., 2015, 2016). However, significant model biases remain: there is a cold surface bias related to uncertainties in cloud cover and its relation to short- and longwave radiation (Van Wessem et al., 2014a; King et al., 2015), and associated biases in the melt-fluxes and the interaction of melt in the snowpack (Kuipers Munneke et al., 2012; Barrand et al., 2013b). However, as we have shown in Van Wessem et al. (2016), Antarctic Peninsula melt rates are small compared to the other freshwater fluxes, and these biases do not strongly influence the modelled freshwater budget. First, in Section 2, we introduce the model and methods used. In Sections 3.1 and 3.2 we discuss the spatial and temporal variability of the meteoric freshwater components, and present an indirect estimate of WAP glacial discharge in Section 3.3, based on long-term average surface mass balance fields and detailed glacier catchment outlines. Finally, we discuss the results and present conclusions in Section 4.

2. Methods

2.1. RACMO2.3 and FDM

We use the hydrostatic Regional Atmospheric Climate Model RACMO2.3. Model settings are similar to Van Wessem et al. (2016). We only discuss model output north of 70°S, even though the simulations were conducted for a domain extending as far south as 75°S, in order to focus specifically on the WAP areas that include the RaTS and Pal-LTER field sites. We included Larsen B ice shelf in the model domain, even though it has collapsed during the period of the model run, and will discuss the results accordingly. All further model details and a thorough evaluation of model results are described in Van