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Future sea-level rise from tidewater and ice-shelf tributary glaciers of the Antarctic Peninsula

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ABSTRACT

Iceberg calving and increased ice discharge from ice-shelf tributary glaciers contribute significant amounts to global sea-level rise (SLR) from the Antarctic Peninsula (AP). Owing to ongoing ice dynamical changes (collapse of buttressing ice shelves), these contributions have accelerated in recent years. As the AP is one of the fastest warming regions on Earth, further ice dynamical adjustment (increased ice discharge) is expected over the next two centuries. In this paper, the first regional SLR projection of the AP from both iceberg calving and increased ice discharge from ice-shelf tributary glaciers in response to ice-shelf collapse is presented. An ice-sheet model forced by temperature output from 13 global climate models (GCMs), in response to the high greenhouse gas emission scenario (RCP8.5), projects AP contribution to SLR of 28 ± 16 to 32 ± 16 mm by 2300, partitioned approximately equally between contributions from tidewater glaciers and ice-shelf tributary glaciers. In the RCP4.5 scenario, sea-level rise projections to 2300 are dominated by tidewater glaciers (~8–18 mm). In this cooler scenario, 2.4 ± 1 mm is added to global sea levels from ice-shelf tributary drainage basins as fewer ice-shelves are projected to collapse. Sea-level projections from ice-shelf tributary glaciers are dominated by drainage basins feeding George VI Ice Shelf, accounting for ~70% of simulated SLR. Combined total ice dynamical SLR projections to 2300 from the AP vary between 11 ± 2 and 32 ± 16 mm sea-level equivalent (SLE), depending on the emission scenario used. These simulations suggest that omission of tidewater glaciers could lead to a substantial underestimation of the ice-sheet's contribution to regional SLR.

1. Introduction

The Antarctic Peninsula (AP) is a mountainous and heavily glaciated region, dominated by glaciers flowing directly into the sea (henceforth tidewater glaciers) and into floating ice-shelves (henceforth ice-shelf tributary glaciers). In response to the rapid warming experienced by this region over the last 50 years (Vaughan et al., 2003), glaciers have contributed at an accelerated rate to global sea-level rise (SLR) in recent years (Cook et al., 2005; Wouters et al., 2015). In addition to an increase in near-surface air temperatures, surface waters of the surrounding ocean have warmed (Meredith and King, 2005). This ocean warming has been accompanied by an acceleration (Pritchard and Vaughan, 2007) and retreat (Cook et al., 2016) of tidewater glaciers, leading to increased ice discharge to the ocean.

Climatological changes have also affected ice-shelf tributary glaciers. Unlike tidewater glaciers, ice-shelf tributary glaciers do not flow directly into the ocean, but into a floating ice-shelf. This extension of the grounded ice exerts backstress (buttressing force) on the grounded glacier upstream and thus restrains ice flow. If this buttressing force is reduced or removed, the grounded ice upstream will speed up, thin and discharge more ice into the ocean. This behaviour has been observed at several locations in the AP region (Rott et al., 2002; Scambos et al., 2004; Rignot et al., 2004). Glaciers draining into the Prince–Gustav–Channel and Larsen A embayments are still adjusting to ice-shelf removal, some 20 years after ice-shelf collapse (Rott et al., 2014; Scambos et al., 2014), and are providing a significant portion to the region's SLR (McMillan et al., 2014).

Abrupt ice-shelf collapse events in the past have been linked to a combination of atmospheric warming (Vaughan and Doake, 1996; Scambos et al., 2000) and structural weakening as a result of increased basal melting (Pritchard et al., 2012; Holland et al., 2015). Ice-shelves are thought to be structurally weakened prior to collapse by: i) hydrofracture of surface crevasses; and,

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ii) basal melting at the ice–ocean interface. In the latter process, warm ocean water erodes the underside of the ice shelf, thinning it and thus leaving the ice shelf more vulnerable to the process of hydrofracturing (Shepherd et al., 2003). Hydrofracture of surface crevasses occurs primarily when sufficient meltwater is available at the surface of the ice shelf and can wedge open crevasses to cause catastrophic ice-shelf disintegration (Scambos et al., 2004). Recent studies suggest that other ice-shelf weakening processes such as fracturing and weakening of shear margins may also be important and lead to a progressive weakening of the ice shelf prior to disintegration (Khazendar et al., 2015; Borstad et al., 2016). A prime example of this is the progressive mechanical weakening of the remnant Larsen B Ice Shelf over the last 15 years (Borstad et al., 2016). The importance of these processes may, however, vary for individual ice shelves.

While projections of the surface mass balance are forecasted to provide a negative contribution to sea level, this is expected to be offset by sea-level rise contributions from ice dynamical changes (Barrand et al., 2013a). Owing to their short response times to ice dynamical perturbations (e.g. ice-shelf removal) in comparison to the rest of the Antarctic Ice Sheet (Barrand et al., 2013a), AP glaciers are projected to play an important role in the global SLR budget over the next century (Barrand et al., 2013a; Schannwell et al., 2015). Hitherto, ice-sheet modelling studies of the AP have focused on SLR projections from ice-shelf tributary glaciers, ignoring any contributions from tidewater glaciers (Barrand et al., 2013a; Schannwell et al., 2015). Given the observed acceleration and retreat of most tidewater glaciers (Cook et al., 2005; Pritchard and Vaughan, 2007), this may lead to a substantial underestimation of the SLR contribution from the AP. In this paper, we present the first comprehensive modelling study of SLR projections from both tidewater and ice-shelf tributary glaciers of the AP. Building on the work of Schannwell et al. (2015), ice-shelf collapse timing is not determined by thermal viability limits, but is instead based on the total number of melt days—a more direct and physically-based link to the process of hydrofracture. Daily, rather than monthly near-surface temperature projections are used to provide more sensitive timing estimates of future ice-shelf collapse events. To estimate grounding-line retreat in response to ice-shelf removal, a new statistical framework is introduced that builds on previous work by Schannwell et al. (2015), improving their statistical parameterisation by relating expected grounding-line retreat to the degree of buttressing. Buttressing at the grounding line of each drainage basin is calculated by dividing the normal pressure in presence of an ice shelf by the ocean pressure acting when no ice shelf is present. The combined SLR contribution over the next 300 years is computed, including for the first time the largest 235 tidewater glaciers throughout the northern AP. In addition to this, volume responses of the largest 215 ice-shelf tributary glaciers are also simulated. These 450 drainage basins cover a total of 77% of the AP's area, providing a comprehensive coverage of the Antarctic Peninsula Ice Sheet (APIS).

2. Data and methods

2.1. Climate data and preprocessing

In order to estimate the timing of future ice-shelf collapse events, daily near-surface temperature fields from 13 GCMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2011) were selected using the Representative Concentration Pathway (RCP)4.5 and RCP8.5 emission scenarios (Vuuren et al., 2011). The selection of the GCM forcings are provided in Fig. A.6 and follows Schannwell et al. (2015). Temperature projection fields were bias-corrected against monthly ERA-Interim data from the European Centre for Medium Range Weather Forecasts (ECMWF; Dee et al., 2011), by shifting the future temperature fields by the average bias for each month between the GCM and ERA-Interim temperatures over the period 1979–2005 (Radić et al., 2014). The bias-corrected temperatures were then compared to surface station data (Table B.2) from the AP. The remaining temperature difference between bias-corrected temperature fields and surface station data is attributed to an inaccurate height representation in the temperature fields caused by the relatively coarse spatial resolution of the models ($\sim 0.75°$). Owing to the rugged topography of the AP, this can introduce significant temperature differences (Jones and Lister, 2014). To correct for this, temperature fields were shifted by a temperature-height correction factor derived for each month from every station. As most surface stations are clustered in the north of the AP, temperature data from automatic weather stations were additionally included to improve spatial coverage. A list of stations is provided in the appendix (Table B.2). Height correction factors were then bi-linearly interpolated and extrapolated to provide an ice-sheet wide correction map for each month.

The same sample of GCMs was selected for monthly ocean surface temperature fields which were bias-corrected against the Extended Reconstructed Sea Surface Temperature (ERSST) v4 reanalysis product (Huang et al., 2015) using the same methods as for the surface temperature fields. A plot of the bias for each GCM is provided in the appendix (Fig. B.7).

2.2. Tidewater glaciers

A substantial portion of the mass loss of ice sheets and near-polar glaciers comes from calving (Rignot and Kanagaratnam, 2006; Benn et al., 2007a; Barrand et al., 2013b). While the importance of iceberg calving has been recognised and a number of empirical calving laws have been proposed (Brown et al., 1982; van der Veen, 1996; Benn et al., 2007b; Alley et al., 2008; Luckman et al., 2015), modelling iceberg calving remains a major source of uncertainty in ice-sheet models (O'Leary and Christoffersen, 2013). Unlike the rest of the Antarctic Ice Sheet, the AP is located in a maritime climate, experiencing significant surface melt during the austral summer (Barrand et al., 2013c). These characteristics, combined with small- to medium-size calving fronts, demonstrate strong similarity to tidewater glacier systems in Alaska, Svalbard, and coastal Greenland. In the absence of a universal calving law, a scenario-type approach was employed utilising three different types of calving criteria which have been used to successfully simulate calving front retreat in at least one of these regions (Brown et al., 1982; van der Veen, 1996; Luckman et al., 2015). Each calving criterion is assessed in a separate simulation.

The first criterion (henceforth, water depth) relates calving rate to water depth (e.g. Brown et al., 1982), using the updated formula from Pelto and Warren (1991)

$$V_c = 70 + 8.33 D_w, \tag{1}$$

where V_c is the calving rate in $\mathrm{m\,yr^{-1}}$ and D_w is the water depth in m at the calving front.

The second criterion (henceforth, flotation criterion) follows van der Veen (1996), who argues that the calving front position is controlled by water depth and ice thickness, following the relationship:

$$H_c = \frac{\rho_w}{\rho_i} D_w + H_0, \tag{2}$$

where H_c is the critical thickness, ρ_w and ρ_i are water and ice densities, respectively, and H_0 represents the minimum thickness above the flotation thickness. Based on modelling studies from