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Distributed ice thickness and glacier volume in southern South America

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ABSTRACT

South American glaciers, including those in Patagonia, presently contribute the largest amount of meltwater to sea level rise per unit glacier area in the world. Yet understanding of the mechanisms behind the associated glacier mass balance changes remains unquantified partly because models are hindered by a lack of knowledge of subglacial topography. This study applied a perfect-plasticity model along glacier centre-lines to derive a first-order estimate of ice thickness and then interpolated these thickness estimates across glacier areas. This produced the first complete coverage of distributed ice thickness, bed topography and volume for 617 glaciers between 41°S and 55°S and in 24 major glacier regions. Maximum modelled ice thicknesses reach 1631 m ± 179 m in the South Patagonian Icefield (SPI), 1315 m ± 145 m in the North Patagonian Icefield (NPI) and 936 m ± 103 m in Cordillera Darwin. The total modelled volume of ice is 1234.6 km^3 ± 246.8 km^3 for the NPI, 4326.6 km^3 ± 865.2 km^3 for the SPI and 151.9 km^3 ± 30.38 km^3 for Cordillera Darwin. The total volume was modelled to be 5955 km^3 ± 1191 km^3, which equates to 5458.3 Gt ± 1091.6 Gt ice and to 15.08 mm ± 3.01 mm sea level equivalent (SLE). However, a total area of 655 km^2 contains ice below sea level and there are 282 individual overdeepenings with a mean depth of 38 m and a total volume if filled with water to the brim of 102 km^3. Adjusting the potential SLE for the ice volume below sea level and for the maximum potential storage of meltwater in these overdeepenings produces a maximum potential sea level rise (SLR) of 14.71 mm ± 2.94 mm. We provide a calculation of the present ice volume per major river catchment and we discuss likely changes to southern South America glaciers in the future. The ice thickness and subglacial topography modelled by this study will facilitate future studies of ice dynamics and glacier isostatic adjustment, and will be important for projecting water resources and glacier hazards.

1. Introduction and rationale

The southern South America glaciers and Patagonian Icefields (Fig. 1) are sensitive to climate change due to their relatively low latitude location, low-elevation termini and rapid response times (Oerlemans and Fortuin, 1992). They are the largest temperate ice masses in the Southern Hemisphere outside Antarctica and are sustained by the large volume of orographic precipitation that falls over the Andes under the prevailing Westerly winds (Carrasco et al., 2002; Casassa et al., 2002). Most of these ice masses are presently experiencing a negative mass balance, especially tidewater and lacustrine-terminating glaciers, but some glaciers, such as Pio XI, Moreno and Garibaldi, are presently displaying a positive mass balance (Schaefer et al., 2015). The general and dominant trend of ice mass loss is manifest in pronounced glacier recession (Davies and Glasser, 2012) and the largest contribution to sea level rise per unit area in the world (Ivins et al., 2011; Mouginot and Rignot, 2015; Willis et al., 2012). Indeed this sea level contribution is ~10% of that from all glaciers and ice caps worldwide (Rignot et al., 2003). Over the next two centuries, mass loss from these glaciers has implications for sea level rise (Braithwaite and Raper, 2002; Gardner et al., 2013; Glasser et al., 2011; Levermann et al., 2013), for increased hazards from glacial lake outburst floods (Anacona et al., 2014; Dussaillant et al., 2009; Harrison et al., 2006; Loriaux and Casassa, 2013), and for water resources.

Recent analysis of southern South America glaciers has yielded data regarding glacier area, areal and volume change since the Little Ice Age (LIA) (Davies and Glasser, 2012; Glasser et al., 2011), ice surface velocity (Rivera et al., 2012; Jaber et al., 2014; Mouginot and Rignot, 2015), surface mass balance (Koppes et al., 2011; Mernild et al., 2015; Schaefer et al., 2015; Willis et al., 2011) and surface thinning and elevation changes (dh/dt) (Rivera et al., 2007; Willis et al., 2012). These analyses are largely reliant on satellite observations due to the inherent difficulties in accessing large parts of the ice surface (cf. Paul and Mölg, 2014). There are few in situ observations (the few examples include Gourlet et al., 2016; Rivera and Casassa, 2002, and they target only the NPI and SPI) and none that cover all glaciers at a catchment-scale across the NPI, SPI, Cordillera Darwin, Grand

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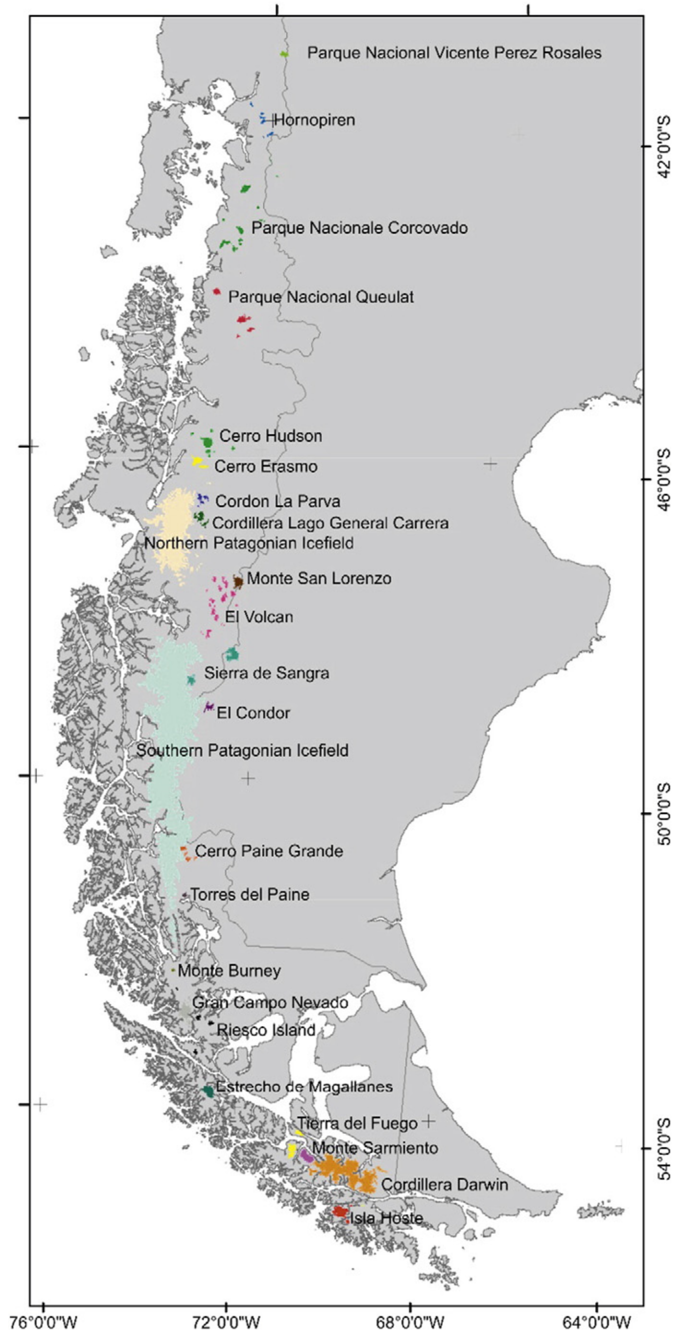

Fig. 1. Southern South America with the 24 major glacier regions of this study displayed in unique colours.

Campo Nevado and outlying small glaciers and icefields. As a result, directly observed data on bed topography and ice thicknesses are sparse. Yet, these data are essential for calculations of ice volume, potential sea level contribution, and are a key input parameter in numerical modelling studies (Huybrechts, 2007), particularly when it is the smaller outlying glaciers and icefields with fast response times that will respond most rapidly to climate change (Meier et al., 2007; Raper and Braithwaite, 2009). This study aims to provide the first complete regional calculation and assessment of distributed glacier ice thickness and catchment-scale ice volume of all southern South America glaciers (Fig. 1).

2. Southern South America: ice fields and volcanoes

Our study area extends along the axis of the Andean mountain chain from Isla Hoste at 55°S to Parque Nacional Vicente Perez Rosales at 41°S (Fig. 1). The highest peaks nearly reach 4000 m·asl and the terrain is generally steep. The area is characterised by a highly maritime climate with a pronounced east-west precipitation gradient (cf. Fig. 1), influenced by the westerly airflow over the Andes (Aravena and Luckman, 2009; Garreaud et al., 2009). The steep orographically-driven precipitation gradient produces precipitation on the western side of the Andes that is 100% to 300% higher than on the eastern side. At 49°S the precipitation totals are 7220 mm·yr^{-1} east of the Andes, and 209 mm·yr^{-1} at Lago Argentino on the western side. Firn cores on the NPI confirm the east-west gradient in accumulation (Rasmussen et al., 2007).

In Northern and Central Patagonia, precipitation has steadily decreased since around the 1960s (Aravena and Luckman, 2009). Garreaud et al. (2013) found a 300 mm to 800 mm per decade decrease in precipitation in north-central Patagonia, and a 200 mm to 300 mm per decade increase south of 50°S, which may account for generally positive glacier mass balances south of 50°S (Schaefer et al., 2015), decreasing rates of glacier recession south of 50°S after 2001 and faster rates of recession north of 50°S (cf. Davies and Glasser, 2012). There is also evidence of widespread air temperature warming in Patagonia (Garreaud et al., 2013). Warming of the upper atmosphere (850 hPa; ca. 1400 m·asl) has been ~0.5 °C from 1960 to 1999, both in winter and summer and this warming has caused a decreased in the amount of precipitation falling as snow and increased ablation, exacerbating glacier recession (Rasmussen et al., 2007).

Some of these changes in precipitation have been related to variations in the strength of the prevailing Southern Hemisphere Westerlies, with stronger westerlies augmenting local precipitation. Stronger westerlies will also result in a decreased amplitude of the local air temperature annual cycle, whilst weaker westerlies result in a colder winter and warmer summer, increasing temperature seasonality (Garreaud et al., 2013). The core of the Southern Hemisphere Westerlies is currently 50 to 55°S, but through the Holocene latitudinal variations in these winds periodically brought increased precipitation to the area, driving glacier advance and recession (Boex et al., 2013; Lamy et al., 2010; Moreno et al., 2012) but with a pronounced east-west shift (Ackert et al., 2008).

The study area (Fig. 1) includes 617 glaciers (mapped by Davies and Glasser, 2012; data available from the GLIMS database: http://nsidc.org/glims/). These glaciers are found predominantly within four key icefields: the North Patagonian Icefield (NPI), the South Patagonian Icefield (SPI), Gran Campo Nevado (Schneider et al., 2007) and Cordillera Darwin (Bown et al., 2014), but also on numerous outlying mountains and volcanoes (Rivera and Bown, 2013) (Fig. 1).

In 2011, the total glacierised area of the study region was 22,717.5 km^2, with the SPI covering 13,218 km^2, the NPI covering 3976 km^2, Cordillera Darwin covering 1832.7 km^2 and Gran Campo Nevado covering 236.9 km^2 (Davies and Glasser, 2012). The large western outlet glaciers of the SPI mostly extend down to sea level and calve into fjords, whilst those on the eastern slide largely terminate in large proglacial lakes (Warren and Sugden, 1993; Rasmussen et al., 2007). The NPI glaciers have mean elevations of 1000 m to 1500 m, with one glacier (San Rafael) terminating in a tidal lagoon, whilst the rest are lacustrine- or terrestrial-terminating glaciers. The ELA of outlet glaciers of the NPI ranges from ~700 m·asl on the west and 1200 m·asl on the east (Kerr and Sugden, 1994; Barcaza et al., 2009). Snowline mapping in the SPI suggested that ELAs ranged from ~800 m to 1400 m·asl (De Angelis, 2014).

3. Previous ice-thickness measurements in southern South America

Although the total ice area of the Patagonian Icefields is well constrained, the total ice volume is poorly known. Most studies have