

Supplementary Material

to

The Foundations of the Patagonian Icefields

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S1 - THICKNESS OBSERVATIONS

The two primary sources for the 1.4 million thickness measurements are direct or indirect observations, roughly comprising a two and one-third share of the total data amount, respectively.

S1.1 - DIRECT OBSERVATIONS

Overview. Direct thickness measurements were collected by four survey techniques: gravimetry, radio echo sounding (RES), seismic sounding and boreholes (Table S1). Seismics and boreholes are labour-intensive and mostly provide point information or single profiles. These techniques were only used on Perito Moreno Glacier in the SPI. Largest spatial coverage is achieved by the gravimetric and radar surveys. In principle, we can distinguish two campaigns types: icefield-wide coverage or single outlet glacier focus. Airborne gravimetric surveys covered large parts of the icefields, primarily aiming at plateau areas, where thickness values locally exceed 1000m. As the icefields are assumed temperate [76], the plateau areas are unfavourable for ground-penetrating radar (GPR) measurements beyond 800m. GPR measurements therefore mainly focussed on the lower trunks of individual outlet glaciers. Exceptional spatial GPR coverages were achieved on Nef and Colonia glaciers in the NPI [77] as well as for Tyndall and Grey in the SPI.

If surface or bed elevation information is provided alongside the thickness value, it is transferred to the Earth Gravitational Model 1996 (EGM96) [78]. As the target time stamp for the thickness mapping is February 2000 (reference SRTM, cf. Data & Methods), thickness values are homogenised to this point in time. If information on bed elevation is available, it is subtracted from the SRTM to infer thicknesses in 2000. For this purpose, the 30-m SRTM is bi-linearly interpolated to the measurement location. If no elevation information was provided, thickness values are corrected by scaling the annual mean elevation change rates (2000/2011-2016) with the elapsed time between measurement acquisition and February 2000. On account of the high spatial correlation in thickness measurements, a sub-sampling was applied discarding records within 200m.

Specific information on individual campaigns. In this section, we want to highlight a few particularities in (1) the data usage of the airborne gravimetric surveys [16, 25] and (2) in the pre-processing of the 2012 GPR measurements on San Rafael, Nef and Colonia glaciers in the NPI [85].

(1) Information on ice thickness over the plateau areas of both icefields are almost exclusively acquired by airborne gravimetric surveys (cf. Table S1). Yet the recorded gravity anomalies at a certain point along the flight path do not give direct measurements of local nadir ice thickness. These anomalies only allow inference of the thickness distribution within a certain area of influence. For mapping ice thickness, the available gravity measurements enter an inverse approach to infer a three-layer bedrock model, comprising water, ice and rock [25]. Ice thickness values are therefore already available as a map product. Here, we refrain from using the gridded map as input because it is highly unconstrained away from actual gravity measurements, nunataks or rock outcrops. However, we consider it a great loss to ignore these measurements as no other survey techniques gives information on the interior ice thickness. We therefore decided to extract the thickness values for each

gravity point measurement along the actual survey flight path in 2012 and 2016 by bi-linear interpolation of the associated thickness map. The point information on ice thickness along the flightlines is then used as actual thickness measurement.

(2) The 2012 airborne radar campaign, jointly organised by the ‘Centro de Estudios Científicos’ (CECs) and the ‘Dirección General de Aguas’ (DGA), targeted three glaciers of the NPI [85], namely San Rafael, Nef and Colonia. Aside from the bedrock identification, they measured the respective surface elevation. After geoid correction, we noticed a systematic offsets between the point elevation measurements and the SRTM. As such a bias enters into the final thickness map, we decided for an a-priori removal. We therefore quantified the bias for each of the glaciers at the uppermost measurements locations normally above the equilibrium line altitude. No elevation bias was found for Nef, whereas for San Rafael and Colonia, elevation measurements were corrected by -67m and -43m, respectively.

S1.2 - INDIRECT OBSERVATIONS

Overview. The second source of thickness information relates to glacier retreat as defined by the glacier outlines in 2001 and 2016 together with DEMs in 2000 and 2019 (Data & Methods). In this time period, areal changes indicate a 5%-reduction for NPI (-181 of 3856km^2 in 2000) and 2% for SPI (-282 of 12514km^2 in 2000). The retreat volume is extracted by differencing to the SRTM reference DEM. This choice implies that inferred thickness values have the timestamp February 2000. Retreat along land-terminating sections of the icefields represent the majority of past thickness values, with roughly 450'000 entries. These measurements show a large spatial coverage. The remaining $\sim 10\%$ were derived for marine- and lake-terminating (MALT) glaciers with bathymetric measurements in previously ice-covered area. The latter information is exclusively available for a few glaciers of the SPI. In the following, the pre-processing of these retreat observations is specified for these two cases.

Land-termination. For the extraction of past thickness values in areas that retreated over land since 2000, the first step is to accurately delineate a valid retreat mask. For this purpose, we first decreased the dissolved RGI outlines by 15m, to avoid artefacts from digitisation differences. Afterwards, we infer the spatial difference between the RGI6.0 in 2001[3, 4] and more recent outlines from 2016 [47]. As this retreat mask also holds information for marine- and lake termination, we further remove areas that are either labelled as ocean in the DEM (below geoid) or as lakes in the HydroLAKES database [92]. Then, frontal areas of glaciers labelled as MALT are discarded if they fall within the lower 5% of the full elevation range of each drainage basin as given by RGI6.0. In this way, near-front retreat of MALT glaciers are efficiently masked out. In the final step, DEM differences between 2000 and 2019 are computed within this retreat mask on 30-m resolution. These point values serve as past thickness information in the reconstruction. The influence of bed erosion between 2000 and the 2019 on these thickness estimates is considered negligible.

Marine/lake termination. An overview of available bathymetric information in the vicinity of the glacier fronts of NPI and SPI is given in Table S2. The thickness reconstruction ingests observations that fall into the RGI6.0 outlines. Bathymetry of the Laguna San Rafael [93], Perito Moreno [49, 51, 50] as well as west-coast measurements of the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA) fell outside and remained unconsidered. The remaining observations are exclusively from the east side of SPI. Only exception is HPS12 which showed an exceptional retreat. To infer past thickness values, water depth measurements were subtracted from SRTM (linearly interpolated). This implies a February 2000 timestamp for this marine retreat information on ice thickness. Also here, erosion of the sea or lake bed between 2000 and the acquisition dates of the bathymetric surveys is considered negligible.

S1.3 - ERRORS IN THICKNESS OBSERVATIONS

Direct measurements. Some of the surveys did provide an error estimate for their thickness products (cf. Table S1). For the majority of surveys, no error was provided. In this case, we pursued a formalised strategy for thickness error estimation of GPR measurements ($\epsilon_{H,GPR}$) [79].

$$(S1) \quad \epsilon_{H,GPR} = \frac{1}{2} \sqrt{\tau^2 \epsilon_c^2 + c^2 \epsilon_\tau^2}$$

The error computation accounts for the uncertainties in the radio-wave propagation velocity c (ϵ_c) as well as in the picking of the bed reflection (in terms of two-way travel time τ) in each trace of the radio-echo sounding (ϵ_τ). In this way, the error estimate primarily depends on the operation frequency of the radar system and the local ice thickness. However, the error component of the measurement positioning remains unaccounted for. As the gravimetric campaigns in 2012 and 2016 as well as the WISE radar survey in 2014 assume bulk errors, relative values are often very high where measured thickness values are small. Therefore, we additionally cap relative measurement errors to not exceed 50% of the local thickness measurements.

Indirect measurements. For land-terminating retreat, we assume a relative error of 20% in the past thickness values. For the marine-retreat thickness information, we assume a baseline 9-m uncertainty stemming from SRTM and add, if available, any given measurement error (cf. Table S2). As above, we cap the relative error to 50% of the respective thickness value.

S2 - MODEL DEVELOPMENTS

S2.1 - Weighting of gravimetric measurements. As gravimetric measurements have a dense spatial coverage, they often dominate the thickness solution over individual observations from other surveying techniques (e.g. GPR). We therefore decided to decrease the weighting of gravimetry measurements in the cost function (Equation 13 in reference [38]). The rationale is as follows: First, the weight of the mismatch between modelled and gravimetric measurements is globally lowered by a factor of hundred ($w_0 = 10^{-2}$). Second, we anticipate that the reliability of gravimetric measurements decreases downglacier towards the narrow outlet trunks. This is confirmed by direct comparison of radar and gravimetric measurements. The latter often show smaller values. As many outlet glaciers either reach the ocean or low-elevated lakes, we decided for the following elevation scaling.

$$(S2) \quad w = w_0 \cdot \exp(-w_1 \frac{z_1 - z}{z_1 - z_0})$$

Here, the lower reference elevation $z_0 = 0$ m a.s.l. is set to sea-level. The upper reference elevation $z_1 = 1200$ m a.s.l. is chosen as a compromise between the median icefield elevation (~ 1330 m a.s.l.) and the mean equilibrium line altitude of both icefields (~ 1050 m a.s.l.). Above z_1 , the weighting is fixed to w_0 . The remaining free parameter in the exponent $w_1 = \ln(10^{-3})$ results in an additional downgrade by a factor of one thousand at sea-level (z_0). The most sensitive parameters w_0, w_1 have been determined as a compromise between domination either of gravimetric or GPR measurements in regions of overlap (e.g. San Rafael, Jorge Montt).

S2.2 - Directional scaling. Concerning the regularisation of the thickness solution in the cost function for the second step reconstruction (Eq. 6 in reference [39]), we follow the suggestions on distinguishing across- and along-flow variation for an ice-sheet-wide application of a similar mass conservation approach on Greenland [95]. We therefore replace the regularisation cost term J_{reg} as follows:

$$(S3) \quad J_{\text{reg}} = \lambda_{\text{reg}} \cdot \int_{\Omega} \left[(\nabla H \cdot n_{\parallel})^2 + \lambda_{\text{reg},\perp} (\nabla H \cdot n_{\perp})^2 \right]$$

Thickness variations across- and along flow are therefore penalised differently. Calibration of this parameter over both icefields showed an optimal result for $\lambda_{\text{reg},\perp} = 0.1$ in agreement with the Greenland-wide application. In this way, along-flow thickness variations result in increased costs and are thus smoothed more efficiently.

S3 - EXTENDED DISCUSSION

S3.1 - Outlet-glacier showcases. In the following, selected showcases for typical glacier beds are discussed and compared to previous estimates. Starting with the NPI, San Rafael Glacier is one of the fastest and most prolific calving glaciers in the region reaching a lagoon at sea-level [11]. Thickness values are well-constrained by gravimetric measurements over the entire drainage basin. Towards lower elevations there are additional GPR profiles (cf. Table S1). Results show an elongated trough that reaches -200 m below sea-level near the ice front. On the lake side away from the ice, unconsidered bathymetric measurements on Laguna San Rafael indicate a depth of ~ 250 m. Except for the most recent velocity-based map [2], previous estimates generally suggested land-termination (Fig. S2). Turning to San Quintín Glacier, no observations were available for its majestic 30-km long and 5-10-km wide tongue. Recent GPR cross-profiles [81] finally shed light on its ice thickness, mostly away from the central flowline. This valuable information is ingested in our approach and the final map shows a trough not deeper than 400 m below sea-level (away from the highly crevassed frontal area). San Quintín is therefore prone to important retreat into overdeepened areas up to 15 km from its current front position. In comparison to previous estimates, the perfect plasticity approach [24] shows a much deeper and more elongated over-deepening (Fig. S2). Other reconstructions produce a more patchier bed topography beneath San Quintín. In the Northeast, Exploradores Glacier currently terminates on land and all reconstructions agree on a deeply incised over-deepening. Considering an overspill elevation of about 150 m, the potential pro-glacial lake could grow to 10 km^2 and show water depths of more than 300 m. Currently, there is only a small lake near the spillway and a lateral lake damned by the glacier itself. Turning to the SPI, Pío XI Glacier is to this day unsurveyed in terms of ice thickness and there is strong disagreement between our approach and the other available bed maps (Fig. S3). The latter show that Eyre Fjord in the South could extend far upglacier, often connecting to Lago Greve (187 km^2 [96]) at the current northern front via a bathymetric section that reaches down to 300 m below sea-level. However, our mapping results suggest a rather shallow bathymetry - in many parts not deeper than 50 m below sea-level. The bed topography even emerges above sea level at the junction between the northern and southern branch. Aerial photographs from the 1940s (Fig. 2), when the glacier was in a retreated stage (by about 10 km from present), suggest that Eyre Fjord extends to this junction but is disconnected from Lake Greve by an out-wash plane. In our reconstruction, the areal extent of this land-area is somewhat overestimated. Admittedly, we expect that during the recent advance, the glacier has likely removed sediments in these areas [97].

S3.2 - Valley Shapes. Another observation is that cross-profiles of outlet glacier troughs have a single deepest point near the centreline for two approaches, i.e. again the gravimetric [25] and the perfect-plasticity approach [24]. Despite the fact that the depth is often much deeper (e.g. San Quintín, Colonia, Pío XI), the bed linearly increases from this deepest point towards the lateral margin producing V-shaped valleys. This characteristic valley form stems from the fact that the perfect plasticity approach was applied along centrelines and then interpolated to the margin [24]. Along outlet glaciers, the latter map was also spliced to the gravimetry map [25]. This V-shape is less expressed in the consensus and velocity-based estimates

as well as in our estimate (Fig. 3a, d, e and Suppl. Fig. S1a, d, e). For all of them, valleys generally appear wider (U-shaped). Although the participant approaches in the consensus estimate often pursue the reconstruction along flow lines or elevation bands, the final map interpolation depends on local slopes [57, 58, 1]. Although advantageous in this respect, this slope dependence introduces a patchy pattern of the ice thickness distribution. On NPI, San Rafael and San Quintín glaciers are prime examples (Fig. 3d). Also the velocity-based approach (Fig. 3e) shows this erratic pattern because it relies on the SIA, which is equally sensitive to surface slope. Our estimate is less affected (Fig. 3a). The reason is that for the fast-flowing glacier units, it exclusively builds on mass conservation and is thereby independent of local slopes. Again, the San Rafael setup is representative showing that mass conservation suggests an elongated glacier trunk thicker than 500 m that almost reaches the ice front. Only over the last few kilometres thickness values quickly decrease to 200 m. For most other approaches, frontal thickness falls beneath 200 m. In a similar way, Upsala Glacier in the SPI funnels ice export through an equally thick glacier trunk (Fig. S1a). More recent approaches do not support such deeply incised valleys (Fig. S1c, d, e). Yet for both glaciers, near front thickness observations were assimilated into our map. Away from direct observations, there is good agreement in thickness values between the modelling studies for Exploradores and Pared Norte glaciers of NPI, as well as Europa Glacier of SPI.

S3.3 - Measured vs. Modelled Thickness Values. A point-by-point comparison of all measurements against existing thickness maps (Fig. S4) is dominated by the gravimetric surveys. The latter were the basis of the gravimetric map product [25], for which the median and mean almost vanish (Fig. S4d). Yet the standard deviation remains at about 100 m because of interpolation effects. Biases for large thickness values are visible for all other map products. Withholding the gravimetric measurements together with the retreat observations from this comparison, a more unbiased picture emerges (Fig. 4). Admittedly, the approach presented here (Fig. 4a) was informed by all measurements and therefore shows small median and mean differences. Nonetheless, a positive bias is observed for the SPI, which is likely related to the weighting compromise between different measurement types (Suppl. Sect. 2.1). Standard deviations remain below 150 m. Other thickness maps did not a-priori see any measurements, which is reflected in the more elevated standard deviations. It is noteworthy that median and mean values are comparable for all but one approach, being the early perfect-plasticity approach [24] (Fig. 4b).

S3.4 - Frontal ablation from flux gate methods. On a glacier-by-glacier level, the flux-gate estimates show a systematic divergence. While values from Schaefer et al. (2015) [8] are generally smaller than from Minowa et al. (2021) [21], our estimates often fall between these extremes while uncertainty ranges overlap. Yet there are also exceptions like the well surveyed San Rafael, Jorge Montt, O’Higgins and Upsala or the unsurveyed Amalia, HPS 13 and Pío XI icefronts. Anyhow, some aspects need highlighting. On NPI (Fig. 5a), San Quintín is identified as much less prolific in frontal 2012 ice discharge than San Rafael. For San Quintín, it is the first time that a discharge estimate is based on near-front thickness measurements from 2019 [81]. Admittedly, associated uncertainties remain large. For San Rafael, cross-profile GPR measurements near the snout allow however a well-constrained discharge estimate of $1.26 \text{ km}^3 \text{ yr}^{-1}$ with mere $\sim 15\%$ uncertainty. For the latter

glacier, our ice discharge supports the lower end of previously reported values in the range from 0.8 to $2.22 \text{ km}^3 \text{ yr}^{-1}$ [98, 99, 6, 100]. On Nef and Colonia glaciers, a high-density thickness survey has been acquired and discharge values can also be constrained well. With regard to Minowa et al. (2021)[21], we confirm the estimate on Colonia but have to lower frontal discharge from Nef. Turning to SPI (Fig. 5b), four glaciers explain half of the mass loss, namely Jorge Montt, HPS13, Penguin and Upsala. The previous flux-gate estimate also forward equally large discharge for Europa and O’Higgins, which we no longer confirm. Our results suggest half as much discharge for these glaciers. For Glaciar O’Higgins, frontal ice discharge is well constrained by gravimetry surveys over the glacier trunk. For Jorge Montt, frontal ice discharge is $1.94 \text{ km}^3 \text{ yr}^{-1}$. This prolific loss rate agrees well with independent flux-gate estimates [44] range from 1 to $4 \text{ km}^3 \text{ yr}^{-1}$ during the 2012-2017 retreat years.

SUPPLEMENTARY REFERENCES

REFERENCES

- [1] Farinotti, D. *et al.* A consensus estimate for the ice thickness distribution of all glaciers on Earth. *Nature Geoscience* **12**, 22–28 (2019).
- [2] Millan, R., Mouginot, J., Rabatel, A. & Morlighem, M. Ice velocity and thickness of the world’s glaciers. *Nature Geoscience* **15**, 124–129 (2022). URL <https://doi.org/10.1038/s41561-021-00885-z>.
- [3] RGI Consortium (ed.) *Randolph Glacier Inventory ? A Dataset of Global Glacier Outlines: Version 6.0: Technical Report* (Global Land Ice Measurements from Space, Colorado, USA. Digital Media, 2017).
- [4] Randolph Glacier Inventory - A Dataset of Global Glacier Outlines, Version 6 (2017). URL <https://doi.org/10.7265/4m1f-gd79>.
- [5] Garreaud, R. D. The Andes climate and weather. *Advances in Geosciences* **22**, 3–11 (2009). URL <https://adgeo.copernicus.org/articles/22/3/2009/>.
- [6] Schaefer, M., Machguth, H., Falvey, M. & Casassa, G. Modeling past and future surface mass balance of the Northern Patagonia Icefield. *Journal of Geophysical Research: Earth Surface* **118**, 571–588 (2013). URL <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/jgrf.20038>.
- [7] Lenaerts, J. T. M. *et al.* Extreme Precipitation and Climate Gradients in Patagonia Revealed by High-Resolution Regional Atmospheric Climate Modeling”. *Journal of Climate* **27**, 4607–4621 (2014). URL <https://journals.ametsoc.org/view/journals/clim/27/12/jcli-d-13-00579.1.xml>.
- [8] Schaefer, M., Machguth, H., Falvey, M., Casassa, G. & Rignot, E. Quantifying mass balance processes on the Southern Patagonia Icefield. *The Cryosphere* **9**, 25–35 (2015). URL <https://tc.copernicus.org/articles/9/25/2015/>.
- [9] Mernild, S. H., Liston, G. E., Hiemstra, C. & Wilson, R. The Andes Cordillera. Part III: Glacier surface mass balance and contribution to sea level rise (1979–2014). *International Journal of Climatology* **37**, 3154–3174 (2017). URL <https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.4907>.
- [10] Sauter, T. Revisiting extreme precipitation amounts over southern South America and implications for the Patagonian Icefields. *Hydrology and Earth System Sciences* **24**, 2003–2016 (2020). URL <https://hess.copernicus.org/articles/24/2003/2020/>.
- [11] Mouginot, J. & Rignot, E. Ice motion of the Patagonian Icefields of South America: 1984–2014. *Geophysical Research Letters* **42**, 1441–1449 (2015). URL <http://dx.doi.org/10.1002/2014GL062661>.
- [12] Rignot, E., Mouginot, J. & Scheuchl, B. Ice Flow of the Antarctic Ice Sheet. *Science* **333**, 1427–1430 (2011).
- [13] Rignot, E. & Mouginot, J. Ice flow in Greenland for the International Polar Year 2008–2009. *Geophysical Research Letters* **39**, 7 pp. (2012).
- [14] Joughin, I., Smith, B., Howat, I., Scambos, T. & Moon, T. Greenland flow variability from ice-sheet-wide velocity mapping. *Journal of Glaciology* **56**, 415–430 (2010).
- [15] Mouginot, J., Rignot, E. & Scheuchl, B. Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013. *Geophysical Research Letters* **41**, 1576–1584 (2014). URL <http://dx.doi.org/10.1002/2013GL059069>.
- [16] Gourlet, P., Rignot, E., Rivera, A. & Casassa, G. Ice thickness of the northern half of the patagonia icefields of south america from high-resolution airborne gravity surveys. *Geophysical Research Letters* **43**, 241–249 (2016). URL <http://dx.doi.org/10.1002/2015GL066728>.
- [17] Braun, M. *et al.* Constraining glacier elevation and mass changes in South America. *Nature Clim Change* **9**, 130–136 (2019).
- [18] Dussaillant, I. *et al.* Two decades of glacier mass loss along the andes. *Nature Geoscience* **12**, 802–808 (2019).
- [19] Zemp, M. *et al.* Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature* **568**, 382–386 (2019). URL <https://doi.org/10.1038/s41586-019-1071-0>.
- [20] Hugonnet, R. *et al.* Accelerated global glacier mass loss in the early twenty-first century. *Nature* **592**, 726–731 (2021). URL <https://doi.org/10.1038/s41586-021-03436-z>.

- [21] Minowa, M., Schaefer, M., Sugiyama, S., Sakakibara, D. & Skvarca, P. Frontal ablation and mass loss of the Patagonian icefields. *Earth and Planetary Science Letters* **561**, 116811 (2021). URL <https://www.sciencedirect.com/science/article/pii/S0012821X21000704>.
- [22] Welty, E. *et al.* Worldwide version-controlled database of glacier thickness observations. *Earth System Science Data* **12**, 3039–3055 (2020). URL <https://essd.copernicus.org/articles/12/3039/2020/>.
- [23] GlaThiDa Consortium. Glacier Thickness Database 3.1.0. (2020). URL <https://doi.org/10.5904/wgms-glathida-2020-10>.
- [24] Carrivick, J., Davies, B., James, W., Quincey, D. & Glasser, N. Distributed ice thickness and glacier volume in southern South America. *Global and Planetary Change* **146**, 122–132 (2016). URL <http://www.sciencedirect.com/science/article/pii/S0921818116301515>.
- [25] Millan, R. *et al.* Ice Thickness and Bed Elevation of the Northern and Southern Patagonian Icefields. *Geophysical Research Letters* **46**, 6626–6635 (2019). URL <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019GL082485>.
- [26] Gruber, S. & Haeberli, W. Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change. *Journal of Geophysical Research: Earth Surface* **112** (2007). URL <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2006JF000547>.
- [27] Huss, M. & Hock, R. Global-scale hydrological response to future glacier mass loss. *Nature Climate Change* **8**, 135–140 (2018).
- [28] Cauvy-Fraunié, S. & Dangles, O. A global synthesis of biodiversity responses to glacier retreat. *Nature Ecology & Evolution* **3**, 1675–1685 (2019).
- [29] Farinotti, D., Round, V., Huss, M., Compagno, L. & Zekollari, H. Large hydropower and water-storage potential in future glacier-free basins. *Nature* **575**, 341–344 (2019).
- [30] Immerzeel, W. W. *et al.* Importance and vulnerability of the world’s water towers. *Nature* **577**, 364–369 (2020).
- [31] Ultee, L., Coats, S. & Mackay, J. Glacial runoff buffers droughts through the 21st century. *Earth System Dynamics* **13**, 935–959 (2022). URL <https://esd.copernicus.org/articles/13/935/2022/>.
- [32] Zekollari, H., Huss, M., Farinotti, D. & Lhermitte, S. Ice-dynamical glacier evolution modeling - A review. *Reviews of Geophysics* **60** (2022).
- [33] Rounce, D. R. *et al.* Global glacier change in the 21st century: Every increase in temperature matters. *Science* **379**, 78–83 (2023). URL <https://www.science.org/doi/abs/10.1126/science.abo1324>.
- [34] Shugar, D. H. *et al.* Rapid worldwide growth of glacial lakes since 1990. *Natural Hazards* **10**, 939–945 (2020).
- [35] Iribarren Anaconda, P., Mackintosh, A. & Norton, K. Hazardous processes and events from glacier and permafrost areas: lessons from the Chilean and Argentinean Andes. *Earth Surface Processes & Landforms* **40**, 2–21 (2014).
- [36] Giesecke, R., Höfer, J., Vallejos, T. & González, H. Death in southern Patagonian fjords: Copepod community structure and mortality in land- and marine-terminating glacier-fjord systems. *Progress in Oceanography* **174**, 162–172 (2019). URL <https://www.sciencedirect.com/science/article/pii/S007966111830065X>.
- [37] Rivera, A., Aravena, J., Urra, A. & Reid, B. *Chilean Patagonian glaciers and environmental change* (In: Conservation in Chilean Patagonia: Assessing the state of knowledge, opportunities, and challengers. Springer Serie Integrated Science, 2021).
- [38] Fürst, J. *et al.* Application of a two-step approach for mapping ice thickness to various glacier types on svalbard. *The Cryosphere* **11**, 2003–2032 (2017).
- [39] Fürst, J. *et al.* The Ice-Free Topography of Svalbard. *Geophysical Research Letters* **45**, 11,760–11,769 (2018).
- [40] Hutter, K. *Theoretical glaciology. Material science of ice and the mechanics of glaciers and ice sheets* (Publishing Company/Tokyo, Terra Scientific Publishing Company, Dordrecht, Boston, Tokyo, Japan, and Hingham, 1983).
- [41] Farr, T. *et al.* The Shuttle Radar Topography Mission. *Reviews of Geophysics* **45** (2007). URL <http://dx.doi.org/10.1029/2005RG000183>.
- [42] Briner, J., Bini, A. & Anderson, R. Rapid early Holocene retreat of a Laurentide outlet glacier through an Arctic fjord. *Nature Geoscience* **2**, 496–499 (2009).

- [43] Rivera, A., Koppes, M., Bravo, C. & Aravena, J. C. Little Ice Age advance and retreat of Glaciar Jorge Montt, Chilean Patagonia. *Climate of the Past* **8**, 403–414 (2012). URL <https://cp.copernicus.org/articles/8/403/2012/>.
- [44] Bown, F. *et al.* Recent ice dynamics and mass balance of Jorge Montt Glacier, Southern Patagonia Icefield. *Journal of Glaciology* **65**, 732–744 (2019).
- [45] Koppes, M., Hallet, B. & Anderson, J. Synchronous acceleration of ice loss and glacial erosion, Glaciar Marinelli, Chilean Tierra del Fuego. *Journal of Glaciology* **55**, 207–220 (2009).
- [46] Davies, B. & Glasser, N. Accelerating shrinkage of Patagonian glaciers from the Little Ice Age (AD 1870) to 2011. *Journal of Glaciology* **58**, 1063–1084 (2012).
- [47] Meier, W., Griesinger, J., Hochreuther, P. & Braun, M. An Updated Multi-Temporal Glacier Inventory for the Patagonian Andes With Changes Between the Little Ice Age and 2016. *Front. Earth Sci.* **6**, 1–21 (2018).
- [48] Rivera, A. *et al.* Estudio de la profundidad del lago Viedma, Parque Nacional Los Glaciares, Argentina. *GEOACTA* **42**, 4–6 (2018).
- [49] Huthal, R. *Gletscherbilder aus der argentinischen Cordillere*, vol. 35 (Zeitschrift des Deutschen und Österreichischen Alpenvereins, 1904).
- [50] Lodolo, E. *et al.* The submerged footprint of Perito Moreno Glacier. *Scientific Reports* **10**, 16437 (2020). URL <https://doi.org/10.1038/s41598-020-73410-8>.
- [51] Sugiyama, S. *et al.* Thermal structure of proglacial lakes in Patagonia. *Journal of Geophysical Research: Earth Surface* **121**, 2270–2286 (2016). URL <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016JF004084>.
- [52] Sugiyama, S. *et al.* Subglacial discharge controls seasonal variations in the thermal structure of a glacial lake in Patagonia. *Nature Communications* **12** (2021).
- [53] Minowa, M., Schaefer, M. & Skvarca, P. Effects of topography on dynamics and mass loss of lake-terminating glaciers in southern Patagonia. *Journal of Glaciology* 1–18 (2023).
- [54] Weidemann, S. *et al.* Glacier Mass Changes of Lake-Terminating Grey and Tyndall Glaciers at the Southern Patagonia Icefield Derived From Geodetic Observations and Energy and Mass Balance Modeling. *Frontiers in Earth Sciences* **6** (2018).
- [55] Temme, F. *et al.* Strategies for regional modeling of surface mass balance at the monte sarmiento massif, tierra del fuego. *The Cryosphere* **17**, 2343–2365 (2023). URL <https://tc.copernicus.org/articles/17/2343/2023/>.
- [56] Zekollari, H. & Huybrechts, P. On the climate-geometry imbalance, response time and volume-area scaling of an alpine glacier: insights from a 3-D flow model applied to Vadret da Morteratsch, Switzerland. *Annals of Glaciology* **56**, 51–62 (2015).
- [57] Huss, M. & Farinotti, D. Distributed ice thickness and volume of all glaciers around the globe. *Journal of Geophysical Research* **117**, 10 pp. (2012).
- [58] Maussion, F. *et al.* The Open Global Glacier Model (OGGM) v1.1. *Geoscientific Model Development* **12**, 909–931 (2019).
- [59] Schwikowski, M., Schläppi, M., Santibañez, P., Rivera, A. & Casassa, G. Net accumulation rates derived from ice core stable isotope records of Pío XI glacier, Southern Patagonia Icefield. *The Cryosphere* **7** (2013).
- [60] Sommer, C., Fürst, J., Huss, M. & Braun, M. Constraining regional ice thickness with glacier retreat observations in the European Alps. *The Cryosphere* (2022).
- [61] Linsbauer, A., Paul, F. & Haeberli, W. Modeling glacier thickness distribution and bed topography over entire mountain ranges with GlabTop: Application of a fast and robust approach. *Journal of Geophysical Research* **117**, n/a–n/a (2012). URL <http://dx.doi.org/10.1029/2011JF002313>. F03007.
- [62] Hindmarsh, R. The role of membrane-like stresses in determining the stability and sensitivity of the Antarctic ice sheets: back pressure and grounding line motion. *Philosophical Transactions of the Royal Society A* **364**, 1733–1767 (2006).
- [63] Rivera, A., Benham, T., Casassa, G., Bamber, J. & Dowdeswell, J. Ice elevation and areal changes of glaciers from the Northern Patagonia Icefield, Chile. *Global and Planetary Change* **59**, 126–137 (2007). URL <https://www.sciencedirect.com/science/article/pii/S0921818106003031>.
- [64] De Angelis, H. Hypsometry and sensitivity of the mass balance to changes in equilibrium-line altitude: the case of the Southern Patagonia Icefield. *Journal of Glaciology* **60**, 14–28 (2014).

- [65] Danielson, J. & Gesch, D. Global multi-resolution terrain elevation data 2010 (GMTED2010). *USGS Earth Resources Observation and Science (EROS) Center* **2011-1073** (2011).
- [66] Krieger, G. *et al.* TanDEM-X: A radar interferometer with two formation-flying satellites. *Acta Astronautica* **89**, 83–89 (2013).
- [67] Malz, P. *et al.* Elevation and Mass Changes of the Southern Patagonia Icefield Derived from TanDEM-X and SRTM Data. *Remote Sensing* **10** (2018). URL <https://www.mdpi.com/2072-4292/10/2/188>.
- [68] Kalnay, E. *et al.* The NCEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society* **77**, 437–472 (1996). URL https://journals.ametsoc.org/view/journals/bams/77/3/1520-0477_1996_077_0437_tnyrp_2_0_co_2.xml.
- [69] EU & ESA. *Copernicus DEM - Global and European Digital Elevation Model (COP-DEM)* (DLR e.V. 2010-2014 and Airbus Defence and Space GmbH 2014-2018 provided under COPERNICUS by the European Union (EU) and the European Space Agency (ESA), 2019). URL <https://spacedata.copernicus.eu/collections/copernicus-digital-elevation-model>.
- [70] IANIGLA & CONICET. *Inventario Nacional de Glaciares (ING)*. IF-2018-23356401-APN-DNGAAYEA#MAD (Ministerio de Ambiente y Desarrollo Sustentable - Presidencia de la Nación, Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA) & Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), 2018). URL https://www.glaciaresargentinos.gob.ar/wp-content/uploads/resultados_finales/informe_resumen_ejecutivo_APN_11-05-2018.pdf.
- [71] DGA. *Inventario Público de Glaciares 2014* (Ministerio de Obras Públicas, Dirección General de Aguas (DGA), Unidad de Glaciología y Nieves, 2014). URL <https://snia.mop.gob.cl/repositoriiodga/handle/20.500.13000/125854>.
- [72] Farinotti, D. *et al.* How accurate are estimates of glacier ice thickness? Results from ITMIX, the Ice Thickness Models Intercomparison eXperiment. *The Cryosphere* **11**, 949–970 (2017). URL <https://www.the-cryosphere.net/11/949/2017/>.
- [73] Farinotti, D. *et al.* Results from the Ice Thickness Models Intercomparison eXperiment Phase 2 (ITMIX2). *Frontiers in Earth Science* **8** (2021). URL <https://www.frontiersin.org/articles/10.3389/feart.2020.571923>.
- [74] Liboutry, L. *Nieves y glaciares de Chile. Fundamentos de Glaciología* (Universidad de Chile, 1956).
- [75] Mercer, J. *Southern Hemispheres glacier atlas [in Technical Report W-67-76-ES.]* (Earth Science Laboratory, Natick Laboratories, United States Army, Natick, MA, USA, 1967).
- [76] Rivera, A. & Casassa, G. *Ice Thickness Measurements on the Southern Patagonia Icefield [In: The Patagonian Icefields.]* (Series of the Centro de Estudios Científicos. Springer, Boston, MA, 2002).
- [77] Blindow, N., Salat, C. & Casassa, G. Airborne GPR sounding of two deep temperate glaciers in the Northern Patagonia Icefield. *Proceedings of the 14th International Conference on Ground Penetrating Radar (GPR 2012), Shanghai, China: Tongji University* 664–669 (2012).
- [78] Lemoine, F. *et al.* The Development of the Joint NASA GSFC and NIMA Geopotential Model EGM96. *NASA Goddard Space Flight Center, Greenbelt, Maryland. 20771 USA*, (1998). URL <https://cddis.nasa.gov/926/egm96/nasatm.html>.
- [79] Lapazarán, J., Otero, J., Martín-Español, A. & Navarro, F. On the errors involved in ice-thickness estimates I: ground-penetrating radar measurement errors. *Journal of Glaciology* **62**, 1008–1020 (2016).
- [80] Casassa, G. Ice thickness deduced from gravity anomalies on Soler Glacier, Nef Glacier and the Northern Patagonian Icefield. *Bulletin of Glacier Research* **4**, 43–57 (1987).
- [81] Pętylicki, M. *et al.* Frontal collapse of San Quintín glacier (Northern Patagonia Icefield), the last piedmont glacier lobe in the Andes. *The Cryosphere Discussions* **2023**, 1–25 (2023). URL <https://tc.copernicus.org/preprints/tc-2023-10/>.
- [82] DGA. *Línea de base glaciológica del sector norte de Campo de Hielo Sur: Glaciares Jorge Montt, Témpano, y O’Higgins*. (Centro de Estudios Científicos (CECs) and Dirección General de Aguas (DGA), Ministerio de Obras Públicas, Chile, 2016).

- [83] Rignot, E., Mouginot, J., Larsen, C. F., Gim, Y. & Kirchner, D. Low-frequency radar sounding of temperate ice masses in Southern Alaska. *Geophysical Research Letters* **40**, 5399–5405 (2013). URL <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2013GL057452>.
- [84] Mouginot, J., Rignot, E., Gim, Y., Kirchner, D. & Meur, E. L. Low-frequency radar sounding of ice in East Antarctica and southern Greenland. *Annals of Glaciology* **55**, 138–146 (2014).
- [85] DGA. *Variaciones recientes de glaciares en respuesta al cambio climático: Características glaciológicas de los glaciares San Rafael, Nef y Colonia, Campo de Hielo Norte* (Centro de Estudios Científicos (CECSs) and Dirección General de Aguas (DGA), Ministerio de Obras Públicas, Chile, 2012).
- [86] Raymond, C. *et al.* Retreat of Glaciar Tyndall, Patagonia, over the last half-century. *Journal of Glaciology* **51**, 239–247 (2005).
- [87] Casassa, G. & Rivera, A. Digital radio echo sounding at Tyndall Glacier, Patagonia. *Anales del Instituto de la Patagonia, Serie Ciencias Naturales (Chile)* **26**, 129–135 (1998).
- [88] Casassa, G. Radio-echo sounding of Glaciar Tyndall, southern Patagonia. *Bulletin of Glacier Research* **10**, 69–74 (1992).
- [89] Stuefer, M. Investigations on Mass Balance and Dynamics of Moreno Glacier based on Field Measurements and Satellite Imagery. *Leopold-Franzens-Universität Innsbruck (PhD thesis)* (1999). URL https://www.uibk.ac.at/acinn/theses/dissertations/stuefer.m_1999_investigations-on-mass-balance.pdf.
- [90] Sugiyama, S. *et al.* Hot-water drilling at Glaciar Perito Moreno, Southern Patagonia Icefield. *Bulletin of Glaciological Research* **28**, 27–32 (2010).
- [91] Sugiyama, S. *et al.* Ice speed of a calving glacier modulated by small fluctuations in basal water pressure. *Nature Geoscience* **4**, 597–600 (2011). URL <https://doi.org/10.1038/ngeo1218>.
- [92] Messenger, M., Lehner, B., Grill, G., Nedeva, I. & Schmitt, O. Estimating the volume and age of water stored in global lakes using a geo-statistical approach. *Nature Communications* **7** (2016).
- [93] Koppes, M., Sylwester, R., Rivera, A. & Hallet, B. Variations in Sediment yield Over the Advance and Retreat of a Calving Glacier, Laguna San Rafael, North Patagonian Icefield. *Quaternary Research* **73**, 84–95 (2010).
- [94] Piret, L. *et al.* Gridded bathymetry (GMT netCDF format) of the Baker-Martinez fjord complex (Chile, 48S) v2. *IEDA* (2019). URL https://www.marine-geo.org/tools/search/Files.php?data_set_uid=24862.
- [95] Morlighem, M., Rignot, E., Mouginot, J., Seroussi, H. & Larour, E. Deeply incised submarine glacial valleys beneath the Greenland ice sheet. *Nature Geoscience* **7**, 418–422 (2014). URL <http://dx.doi.org/10.1038/ngeo2167>.
- [96] Hata, S., Sugiyama, S. & Heki, K. Abrupt drainage of Lago Greve, a large proglacial lake in Chilean Patagonia, observed by satellite in 2020. *Communications Earth & Environment* **3**, (2022).
- [97] Hata, S. & Sugiyama, S. Changes in the Ice-Front Position and Surface Elevation of Glaciar Pío XI, an Advancing Calving Glacier in the Southern Patagonia Icefield, From 2000-2018. *Frontiers in Earth Sciences* **8**, (2021).
- [98] Koppes, M., Conway, H., Rasmussen, L. & Chernos, M. Deriving mass balance and calving variations from reanalysis data and sparse observations, Glaciar San Rafael, northern Patagonia, 1950-2005. *The Cryosphere* **5**, 791–808 (2011).
- [99] Willis, M., Melkonian, A., Pritchard, M. & Ramage, J. Ice loss rates at the Northern Patagonian Icefield derived using a decade of satellite remote sensing. *Remote Sensing of Environment* **117**, 184–198 (2012). URL <http://www.sciencedirect.com/science/article/pii/S0034425711003440>.
- [100] Collao-Barrios, G. *et al.* Ice flow modelling to constrain the surface mass balance and ice discharge of San Rafael Glacier, Northern Patagonia Icefield. *Journal of Glaciology* **64**, 568–582 (2018).

TABLE S1. Available direct thickness surveys sorted by measurement technique and time. Measurement uncertainties were either estimated by the data holders or relying on a standardised procedure [79], disregarding the positioning error.

region/ glaciers	acquisition date	survey method	measurement uncertainty	references/ comments
GRAVIMETRY				
NPI & SPI	01.08.2016, 31.07.2016, 22.07.2016	airborne	159 m (overall σ)	[25]
NPI & SPI	03.06.2012, 30.05.2012, 11.05.2012, 04.05.2012	airborne	159 m (overall σ)	[16, 25]
Nef, Soler	29.11.1985	terrestrial	15 – 35%	[80]
RADAR SURVEYS				
San Quintín, Soler	19.-20.05.2019	airborne (20 MHz)	[79]	[81] (data link)
Grey	24.01.2016 09.03.2015	terrestrial (10 MHz)	[79]	comm. G. Gacitúa
ice plateau betw. Viedma, Jorge Montt, Occidental	28.09.2015, 20.-21.09.2015, 03.&06.09.2014, 27.08.2014	airborne (20 MHz)	[79]	[82]
NPI & SPI	11.2014	airborne WISE radar (1-5 MHz)	25, 50 & 100 m (quality categ. 1, 2 & 3)	[83, 84]
San Rafael, Nef, Colonia	27.04.2012 24.08.2012	airborne (20 MHz)	[79]	[85] surface ele- vation corrected
Nef, Colonia	01.11.2010	airborne (30 MHz)	[79]	[77]
Tyndall, Grey	28.-29.03.2008	airborne (25 MHz)	[79]	comm. N. Blindow
Tyndall	1999 17.&22.03.2002	terrestrial	-	[86] not used (no picking)
Chico, Viedma, O'Higgins	10.1997	terrestrial (2.5 MHz)	[79]	[76]
Tyndall	9.-14.12.1993	terrestrial (1.25-5 MHz)	[79]	[87]
Tyndall	12.1990	terrestrial (1.25-2.5 MHz)	[79]	[88]
SEISMIC SURVEYS				
Perito Moreno	22.11.1996 19.11.1996	seismics	20%	[89]
BOREHOLES				
Perito Moreno	05.03.2010	hot-water	5 m	[90, 91]

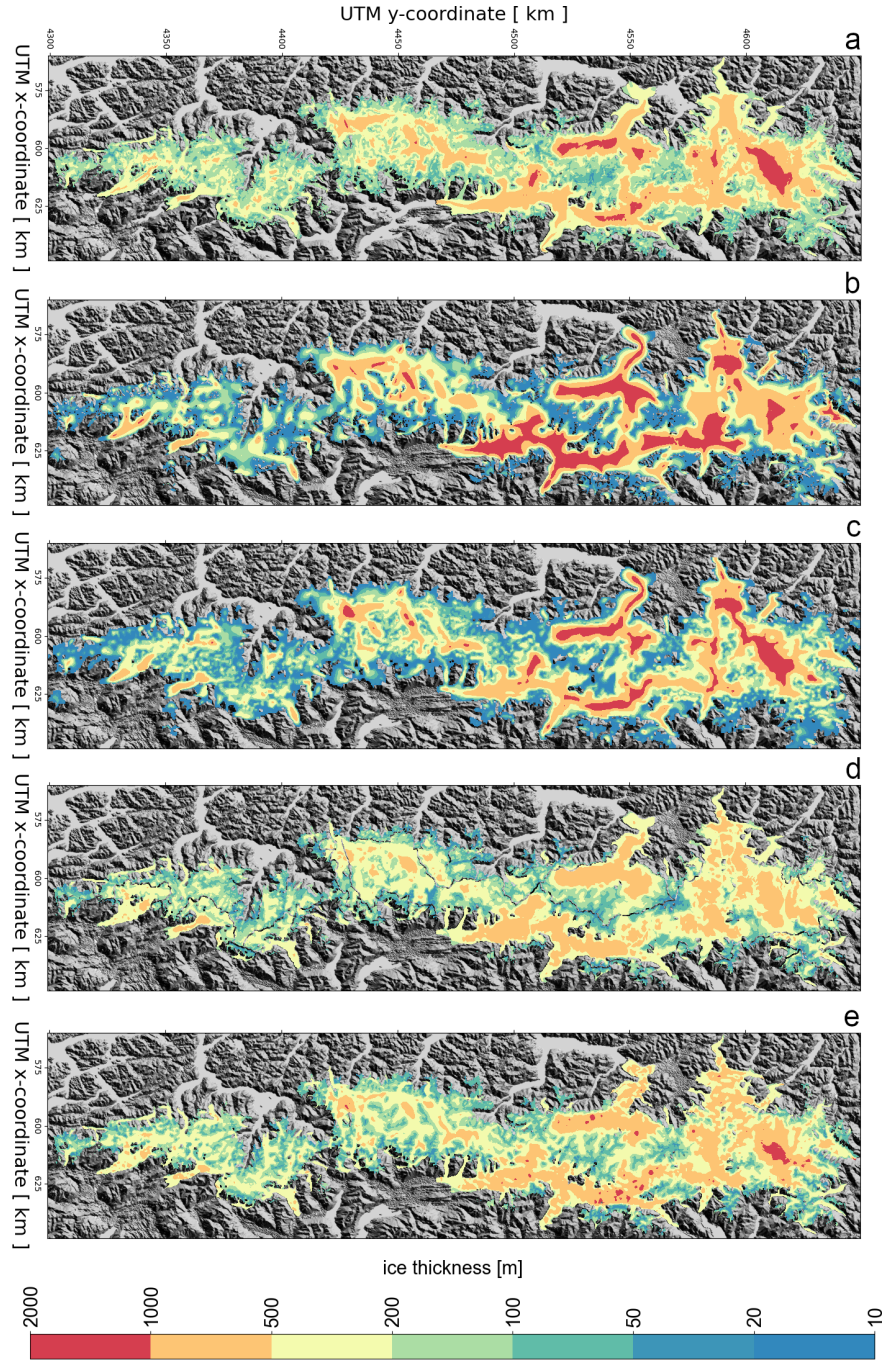
TABLE S2. Bathymetric measurements/information. Grey shading indicates unused data because of no overlap with RGI6.0. Lake-level information was taken from SRTM.

region/ glaciers	acquisition date	survey method	ref. sea/ lake-level (obs. error)	references/ comments
NPI				
San Rafael (Laguna S.R.)	April 2006	Datasonics Bubble Pulser (1 hydrophone)	0 m a.s.l. (unspecified)	[93] not used (no overlap)
SPI				
Pío XI - Amalia (Fiordos Eyre - Peel)	2003 - - 2008	Atlas Fansweep, medium-depth Hydrosweep (MD2)	0 m a.s.l. (unspecified)	*SHOA not used (no overlap)
Jorge Montt (Fiordo Baker)	02.2010	single-beam echo sounder	0 m a.s.l. (unspecified)	[94, 43]
HPS12	01.2020	single-beam echo sounder	0 m.a.s.l. (3.7%)	comm. Minowa
Viedma (Lago Viedma)	01.2017, 11.2018, 11.2019, 06.2020	single-beam echo sounder	252 m.a.s.l. (3.7%)	comm. Minowa
Viedma (Lago Viedma)	12.2012, 12.2013	single-beam echo sounder	252 m.a.s.l. (3.7%)	[51]
Upsala (Brazo Upsala)	11.2019, 03.2020	single-beam echo sounder	179 m.a.s.l. (3.7%)	comm. Minowa
Upsala (Brazo Upsala)	10.2014 12.2013	single beam echo sounder	179 m.a.s.l. (3.7%)	[51]
Perito Moreno (Canal de los Témpanos, Brazo Sur)	04.2019, 11.2017 2002, 2009,	sesismic & echo sounder (2 or 8 hydrophones)	179 m.a.s.l. (unspecified)	[50] not used (no overlap)) mask)
Perito Moreno (Canal de los Témpanos, Brazo Sur)	12.2013	single-beam echo sounder	179 m.a.s.l. (3.7%)	[51] not used (no overlap)
Perito Moreno (Brazo Sur)	15.3.1900	lead line	179 m.a.s.l. (unspecified)	[49] not used (no overlap)
Tyndall (Lago Geikie)	10.2019	single-beam echo sounder	46 m.a.s.l. (3.7%)	comm. Minowa
Tyndall (Lago Geikie)	2001	-	46 m.a.s.l. (unspecified)	[86]
Grey (Lago Grey)	01.-02.2016, 03.2017, 11.2018	single beam echo sounder	45 m a.s.l. (5 m or 5%)	[52]

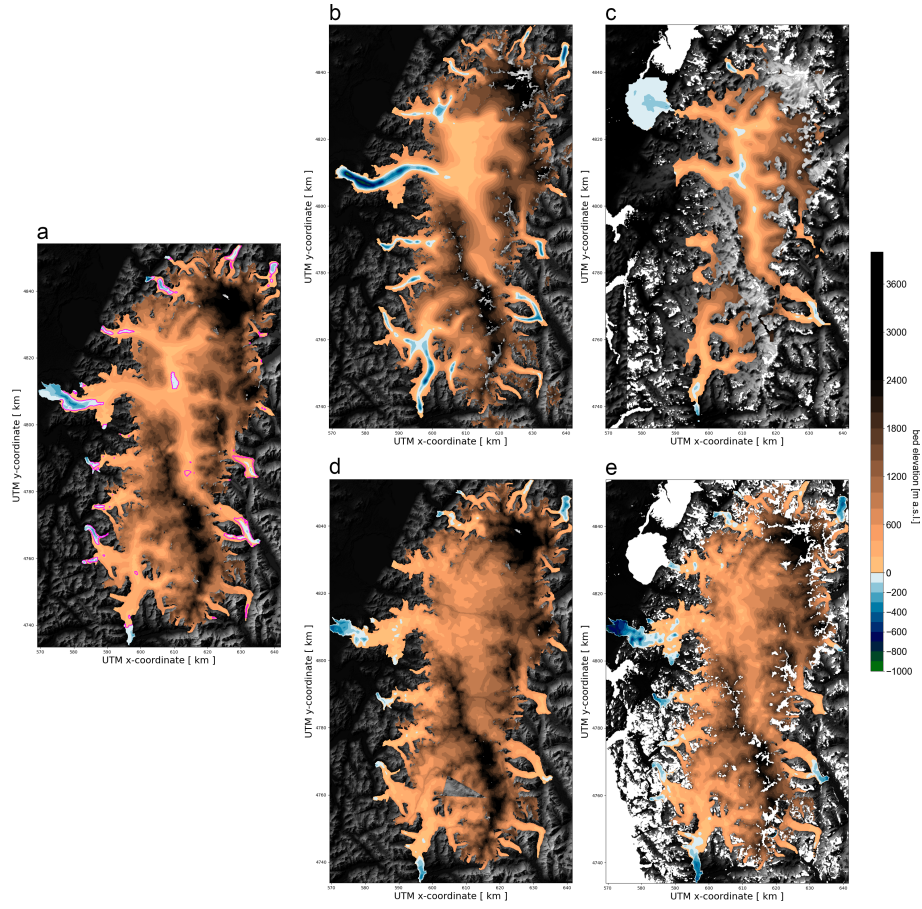
(*) SHOA: Hydrographic and Oceanographic Service of the Chilean Navy

TABLE S3. Model parameter settings as defined in [38, 60].

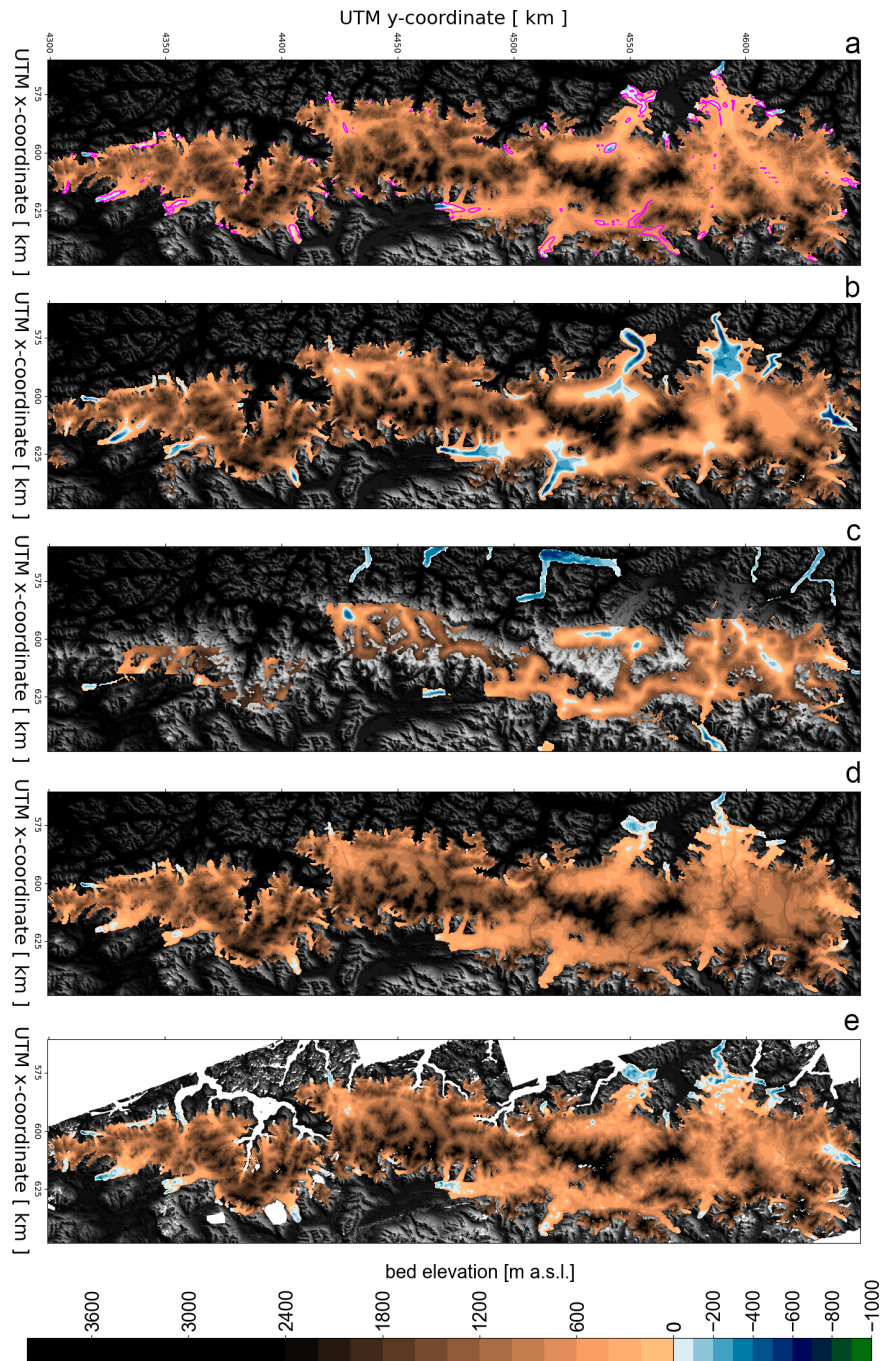
symbol	value	unit	description
GENERAL			
ρ_i	917	kg m^{-3}	<i>ice density</i>
g	9.18	m s^{-2}	<i>gravitational acceleration</i>
FIRST STEP			
l	3	—	<i>coupling length</i>
α_0	1	$^\circ$	<i>slope threshold</i>
cost function			
λ_{pos}	10^{+2}	—	<i>weighting multiplier for positive flux</i>
λ_{reg}	10^{+1}	—	<i>weighting multiplier for flux regularisation</i>
$\lambda_{\hat{a}}$	10^{+1}	—	<i>weighting multiplier restraining control parameter</i>
viscosity scaling [60]			
h_{min}	4	—	<i>multiplier for scaling w.r.t. the distance to the margin</i>
h_{max}	0	m a.s.l.	<i>minimum DEM elevation</i>
$h_{\text{max}}^{\text{slope}}$	2552/2337	m a.s.l.	<i>98% percentile of DEM over ice-covered area of NPI/SPI</i>
α_B^{slope}	52.54404	$^\circ$	<i>reference slope</i>
γ_B^{slope}	−0.08143	$(^\circ)^{-1}$	<i>slope scaling factor</i>
$h_B^{\text{elevation}}$	0.67263	—	<i>reference elevation</i>
$\gamma_B^{\text{elevation}}$	−1.62608	—	<i>elevation scaling factor</i>
SECOND STEP			
cost function			
	0.05	—	<i>weighting of cost derivatives between control parameters</i>
λ_{pos}	10^{+2}	—	<i>weighting multiplier for positive thickness</i>
λ_{obs}	10^{+0}	—	<i>weighting multiplier for thickness mismatch</i>
λ_{marine}	0	—	<i>weighting multiplier for near-front thickness obs.</i>
λ_{reg}	10^{+0}	—	<i>weighting multiplier for thickness regularisation</i>
$\lambda_{\text{reg},\perp}$	10^{-1}	—	<i>weighting between across- and along-flow regularisation</i>
$\lambda_{\hat{a}}$	10^{-4}	—	<i>weighting multiplier restraining apparent mass balance</i>
λ_U	10^{-8}	—	<i>weighting multiplier restraining velocities</i>
Weighting of gravimetry measurements			
z_0	0	m a.s.l.	<i>lower reference elevation</i>
z_1	1200	m a.s.l.	<i>upper reference elevation</i>
w_0	10^{-2}	—	<i>weighting function multiplier</i>
w_1	$\ln(10^{-3})$	—	<i>weighting exponent multiplier</i>



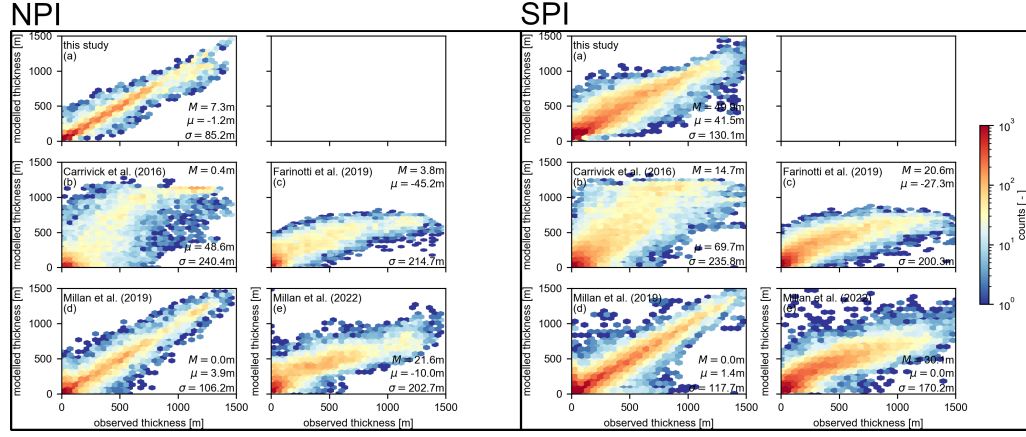
SUPPLEMENTARY FIGURE S1. **SPI thickness distribution for various reconstructions.** (a) this study and (b) the perfect-plasticity estimate [24] as well as the (c) gravimetry-based [25], (d) global consensus [1] and (e) global velocity based estimates [2]. Background: SRTM hillshade.



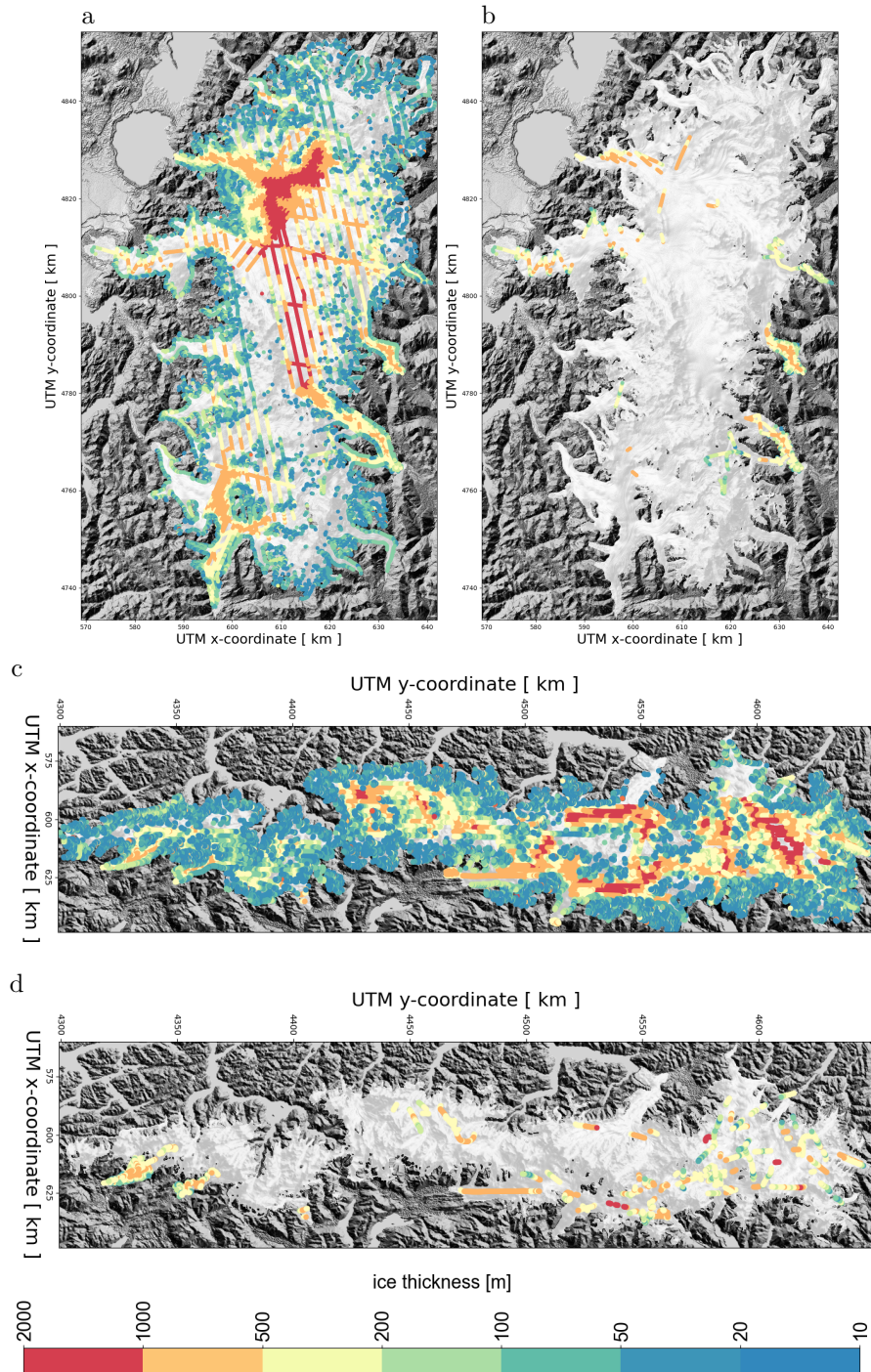
SUPPLEMENTARY FIGURE S2. NPI bedrock topography for various reconstructions. Distributions are shown for (a) this study and (b) the perfect-plasticity estimate [24] as well as the (c) gravimetry-based [25], (d) global consensus [1] and (e) global velocity based estimates [2]. Background: SRTM hillshade.



SUPPLEMENTARY FIGURE S3. SPI bedrock topography for various reconstructions. (a) this study and (b) the perfect-plasticity estimate [24] as well as the (c) gravimetry-based [25], (d) global consensus [1] and (e) global velocity based estimates [2]. Background: SRTM hillshade.



SUPPLEMENTARY FIGURE S4. Observed vs. reconstructed ice thickness. The comparison distinguishes between NPI and SPI. For the point-by-point comparison, respective thickness maps are bi-linearly interpolation to the measurement locations. For this figure, all available measurements were considered. Thickness comparison is conducted for the map products from (a) this study, (b) the perfect-plasticity [24], (c) the global consensus [1], (d) the gravimetry-based [25] and (e) the global velocity-based estimates [2]. Moreover, values for mean (M), median (μ) and standard deviations (σ) are given.



SUPPLEMENTARY FIGURE S5. Ice thickness observations. Locations and thickness values of measurement record for the NPI (a, b) and SPI (c,d). Panels (a, c) show all available measurements, whereas panels (b, d) exclude both gravimetric surveys and retreat information. The latter comprises seismic, GPR and borehole surveys (cf., Table S1). Background: SRTM hillshade. White shading indicates RGI outline.