



Deposited via The University of Leeds.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/244356/>

Version: Accepted Version

Article:

Mottram, R., Hansen, N., Hogg, A.E. et al. (2025) The Greenlandification of Antarctica. Nature Geoscience, 18. pp. 928-930. ISSN: 1752-0894

<https://doi.org/10.1038/s41561-025-01805-1>

© 2025, Springer Nature Limited. This version of the article has been accepted for publication, after peer review (when applicable) and is subject to Springer Nature's AM terms of use (<https://www.springernature.com/gp/open-research/policies/accepted-manuscript-terms>), but is not the Version of Record and does not reflect post-acceptance improvements, or any corrections. The Version of Record is available online at: <https://doi.org/10.1038/s41561-025-01805-1>.

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

The Greenlandification of Antarctica

Ruth Mottram^{1*}, Nicolaj Hansen¹, Anna E. Hogg²,
Christian B. Rodehacke^{1, 3}, Sebastian B. Simonsen⁴,
Benjamin J. Wallis²

^{1*}National Centre for Climate Research, Danish Meteorological
Institute, Sankt Kjelds Plads 11, Copenhagen Ø, DK-2100, Denmark.
²School of Earth and Environment, University of Leeds, Leeds, LS2 9JT,
UK.

³Paleoclimate Dynamics, Alfred Wegener Institute Helmholtz Centre for
Polar and Marine Research, D-27570, Bremerhaven, Germany.

⁴Geodesy and Earth Observations, DTU Space, Technical University of
Denmark, Elektrovej 327, Kgs. Lyngby, DK-2800, Denmark.

*Corresponding author(s). E-mail(s): rum@dmu.dk;
Contributing authors: nh@dmu.dk; a.e.hogg@leeds.ac.uk; cr@dmu.dk;
ssim@dtu.dk; eebjwa@leeds.ac.uk;

Abstract

Recent and projected changes in the Antarctic cryosphere increasingly mirror those previously observed in Greenland. However, the length of observational records from Antarctica makes it difficult to determine how much of this change reflects internal variability or climate change forcing. The term “Greenlandification” of Antarctica describes these observed ice dynamic changes. It indicates that lessons from the Arctic are a useful proxy for understanding the present-day evolution of Antarctica. Notably, we show that ocean and atmosphere-driven processes over both ice sheets follow similar trajectories, observable already especially in the coastal zone of Antarctica. We identify earth observation (EO) data that allows monitoring of both ice sheets in near real-time, as a potential gamechanger helping to identify important ice, ocean and atmosphere processes driving the Greenlandification of Antarctica.

Keywords: Greenland, Antarctica, Climate, Greenlandification



Fig. 1 Comparison of published EO-derived datasets from Greenland and Antarctica show common features, though different timing and magnitudes as discussed in the text. Data illustrating commonalities including decline in sea ice extent 1980 to 2023 [40], seasonal glacier velocities for two representative marine terminating glaciers in Greenland [54] and Antarctica [60], increasing mass loss measured by GRACE satellites [26], multi-sensor records of ice shelf area loss in Antarctica [16] and calving retreat from Greenland glaciers [25], annual mean ice sheet surface temperature from 1982 to 2021 derived from radiation data in the CLARA-A2.1 climate data record [14] processed by OSISAF[40].

1 Introduction

In the late 1990s and early 2000s remote-sensing glaciologists, began to notice large accelerations in Greenland outlet glaciers. This was unexpected. After a flurry of activity in the 1980s, the large ice sheets were generally considered stable and only slowly responding to climate change [59], unlike Arctic sea ice cover which, already in 1997, had reached a new record low. Antarctic sea ice meanwhile actually increased through the 1990s until as recently as 2016 [50], adding to the consensus of a cold and stable Antarctic.

At this time, satellite data were usually low resolution, and there was often limited access to the data. However, the collapse of the floating tongue of Sermeq Kujalleq (Jakobshavn Isbræ) [33] followed by its acceleration and retreat in 2002 and 2003 led to the mobilisation of significant scientific resources to understand the processes driving these changes. Extreme melt seasons across Greenland in 2010, 2012 and 2019, all identified initially in satellite imagery and confirmed by in-situ observations led to important advances in understanding climate change impacts in Greenland and the Arctic.

A similar, though not identical, pattern of climate and ice sheet change is now appearing in Antarctica [10, 50]. However, now we have the satellites, processing techniques and data streams ready to interpret changes in the continent in near real-time as they occur. The Antarctic continent is also now the focus of increasing scientific scrutiny for early warning signs of ice sheet instabilities, not least due to its importance as a major source of sea level rise. There are already similarities in the pattern of glacier retreat [16]. The recent sudden decline of sea ice in the Southern Ocean also reflects the earlier onset of sea ice loss in Greenland and the Arctic [17]. Surface melt in Antarctica is projected to double by 2050 regardless of emissions scenario [7, 22, 64] increasing in both magnitude and spatial extent and further enhancing the similarities between the two ice sheets. Here, we propose the term “Greenlandification” to

cover these processes and define it as the transition from a cold stable ice mass with negligible surface melt to one surrounded by a warmer atmosphere and ocean, increasing surface melt, more active dynamics and potentially more vulnerable to rapid and sustained retreat.

2 Greenlandification

To our knowledge, the term Greenlandification in a natural science context, though used informally for years, and despite occasional socio-cultural use [9], first appears in [44]. Defining the parallels between Greenland and Antarctica helps to focus research on high-impact processes. It assists in identifying deficiencies in current understanding, including both in models and missing observations and monitoring efforts. This is important given the massive cost and logistical complications of conducting research in Antarctica. We note breakthroughs in EO technology offer the scientific community the possibility to study Greenlandification in near-real time. Hence, the term Greenlandification also promotes the urgency of mobilising scientific and societal resources.

As observed in Greenland, some parts of Antarctica are more vulnerable to climate change impacts than others [10]. Greenlandification is most obvious already on Antarctica’s fringing ice shelves, in the sub-Antarctic islands and on the Antarctic Peninsula (AP), where both surface melt and large heavy wet snowfalls are already enhanced by climate warming [23]. These are analogous to the Atlantic adjacent parts of southern Greenland. EO derived surface temperatures show a warming trend over both ice sheets since the 1980s (see Figure 1), but the cold, dry interior of Antarctica, though also experiencing measurable warming [11, 12], is for now still colder, drier and less vulnerable to climate change than the interior of Greenland. As in Greenland, temperature extremes accompanied by precipitation associated with atmospheric rivers have penetrated far inland, including dramatically in East Antarctica in

March 2022 [13]. Attribution studies show the fingerprint of human-induced warming on weather extremes and in time series of weather station records since at least the 1950s [12], matching its Greenlandic counterparts. As with Greenland, internal variability on the scale of decades can either enhance the anthropogenic warming trend or mask it, emphasising the importance of long and spatially heterogeneous observations. The Southern Annular Mode (SAM), for example, like the North Atlantic Oscillation (NAO) in southern and western Greenland, shows up in temperature and precipitation records on a regional scale [29].

Integrated over the whole continent, satellite data shows that Antarctica has, over at least the last 30 years, contributed (7.6 ± 3.9) mm to global sea levels, about two-thirds of its Northern counterpart [41]. Ice loss is concentrated on the West Antarctic Ice Sheet (WAIS) and AP, where the rate of ice loss quadrupled over this period, respectively. WAIS loss is concentrated in the Amundsen Sea Embayment, where ice flow has accelerated more than 50 % since the 1990s on Pine Island Glacier and since the mid-2000s on Thwaites Glacier. While WAIS is characterized by thick (>800 m), fast-flowing (>4 km per year) and large (~ 25 km) ice streams, the AP is made up of over 200 smaller glaciers (~ 3 km wide), flowing from the 3 km high mountainous spine into the Bellingshausen and Weddell Seas on the west and east, respectively. These glaciers terminate directly in the ocean or flow into one of the eight ice shelves on the AP and are directly analogous to Greenland [60].

In contrast to WAIS and AP, the East Antarctic Ice Sheet (EAIS) was thought to be mostly in equilibrium or even gaining mass [49]. However, recent observations of regions of ice dynamic change in some large marine-based sectors of EAIS (e.g. Totten Glacier), including grounding line retreat and thinning, suggest EAIS may be more dynamic and therefore Greenland-like than previously suspected [30, 36, 51]. A key difference between the ice sheets is that ice shelves enclose three-quarters of the Antarctic coastline. These floating shelves buttress the glacier by slowing ice

flow from the grounded ice sheet [20]. Conversely, the widespread development and drainage of supraglacial lakes have been tied to the collapse of ice shelves through hydrofracturing and ice-shelf flexure [3, 47]. During the 20th and 21st centuries, ice shelf thinning, retreat and collapse have led to a net area loss of 36 700 km² from 1997 to 2021, exceeding what can likely be regained through the natural calving cycle [16]. In Greenland, a series of floating ice tongues, similar to Antarctica’s shelves, though generally confined in narrow fjords, collapsed between the 1980s and the first decade of the 2000s, leaving only three remaining ice tongues in northern Greenland [38], most of the remaining glaciers continue to experience extensive calving retreat [25], a possible future for parts of Antarctica too after the loss of ice shelves. The transition to fjord terminating outlet glaciers without floating shelves contributed to the fourfold increase in ice mass loss from the AP between 1992 to 1997 and 2012 to 2017 [46], and has left significant glaciers, such as Crane and Fleming, sensitive to sea-ice conditions [19] and vulnerable to grounding line retreat as observed at Greenlandic termini [54].

As air and ocean temperatures increase, more ice shelves that are currently stable, will thin and exceed thresholds for melt pond formation, becoming vulnerable to collapse as seen on Sermeq Kujalleq (Jakobshavn Isbræ), Larsen B and Wilkins Ice Shelf [6]. Ice shelves become vulnerable to melt ponding and hence flexural stress changes [2, 3] can lead to hydrofracture, due to the depletion of pore space in the firn (firn air content), a key parameter modulating the impact of surface meltwater on the ice sheet. The future trends in firn air content [1] will depend on whether increases in melt or in snowfall dominate [64]. However, projections indicate ice shelves in high melt regions are most vulnerable in the 21st century under a range of climate scenarios [7, 22]. A lesson from Greenland in this regard is that the expansion of melt into cold and dry interior regions can be driven by circulation and cloud cover mediated radiative forcing changes as observed in Northern Greenland [58]; similar drivers were later pinpointed during Ross ice shelf melt events in 2016 and 2022 [35, 64, 65].

Under the ice, the discovery of widespread subglacial lake networks [18, 52], and their impact on ice dynamics reveal subglacial water systems in Antarctica are far more complex than previously assumed [55]. Greenland outlet glaciers have long exhibited substantial seasonal speed variability, with ice flow increasing by up to 50 % in the summer months due to a combination of processes, including meltwater lubrication at the bed [56], reduced buttressing by seasonal fast ice and melange decomposition. These seasonal velocities were not thought to exist in Antarctica until weekly satellite observations acquired over the last six years revealed widespread variability of up to 22 % on the AP [8, 61], and potentially in places in EAIS [24, 37]. On the AP, seasonal ice speed variability may also be driven by warm ocean temperatures in the austral summer [8, 61] and the loss of land-fast sea ice [57]; however, there are so far no observations of a late-summer slowdown caused by a switch to efficient subglacial drainage. This latter process provides offsetting feedback in Greenland and we speculate the same could be true in Antarctica in the future [53], given expected future increases in melt will likely lead to the development of a snow-free ablation zone that permits the rapid routing of surface meltwater through cracks to the ice bed interface [1].

We define Greenlandification here mostly in relation to ice sheets and atmosphere, but it is also potentially applicable in sea ice processes. After being stable and even increasing for decades, Antarctic sea ice has declined since 2017, with notable record lows in 2022 and 2023 [21]. However, high interannual and decadal variability in sea ice extents [17, 50] makes it difficult to distinguish the long-term signal of climate change forcing from internal variability. Further complexity is introduced by strong regional trends that dominate the integrated picture, although recent analysis suggests that a warming ocean may have shifted to a new state, leading to the Antarctic-wide reduction in sea ice [42]. Similar patterns were also first raised in connection with

the dramatic decline of Arctic sea ice, concentrated initially in the Barents-Kara Sea before becoming more widespread across the Arctic.

Greenlandification of Antarctica also has an ecological application [27], where collapsing ice shelves and iceberg groundings can drastically change vast areas of marine habitats [28], retreating glaciers expose new seabed for colonization by benthic species [5], and freshwater fluxes alter circulation and salinity [4]. Analysis of marine productivity in southern Greenland [39] showed enhanced primary productivity directly attributable to increased glacier runoff and reduced sea ice cover. A more complex picture has however emerged around the ecosystem of the North Water polynya, in North West Greenland, where increasing variability related to sea ice and glacier runoff has started to affect local marine productivity [43]. Reductions in sea ice coverage in Antarctica will likewise have major impacts on primary production, benthic communities [15], and the breeding and foraging success of ice-obligate vertebrates [34] [45]. Similarly, there are indications that supraglacial and snow pack ecosystems, primarily made up of algae and bacteria and widespread in Greenland though currently more limited in extent in Antarctica, will spread as meltwater becomes more extensive in Antarctica, promoting higher melt rates via surface darkening [31, 48]. Sentinel-2 and Worldview satellite data is already being mobilised to observe these ecosystem changes [32].

Some of the recently identified changes in the Antarctic are the results — as in Greenland — of enhanced monitoring, with better data availability, including in-situ observations and machine learning to detect changes at the surface quickly. While Greenland has an integrated network of in-situ weather stations across the ice sheet, the great scale and diversity of actors in Antarctica has led to more fragmented coverage, with some key variables such as snow radar and surface mass balance measurements covering only a tiny fraction of the continent [62]. An even smaller fraction of Antarctic measurements are long time series [63], but daily to weekly updated

datasets from physical models and satellite observations now offer the prospect of monitoring real-time changes to fill in important gaps. Greenlandification offers a frame of reference to interpret and understand these observations.

3 Summary

“Greenlandification” was previously a term occasionally used in a socio-cultural context. However, we argue that the natural sciences can understand and predict changes in the Antarctic environment through the lens of well-observed and understood changes in Greenland. Specifically, the Antarctic cryosphere reflects a dynamic environment strongly influenced by regional atmosphere and ocean changes, more similar to Greenland than previously recognised. Antarctic ice sheet models remain underdeveloped and missing crucial processes such as realistic calving schemes. Earth system models also have significant shortcomings in representing the Southern Ocean, and atmospheric climate models have difficulty reproducing climate extremes around Antarctica [50]. In-situ observations are sparse and often with only short time series. The better-observed Greenland, therefore, offers crucial insights into the likely future of Antarctica as a more “Greenland-like” ice sheet. Hence, the need of a broader definition of the term “Greenlandification”.

4 Acknowledgements

Ideas in this manuscript were developed at a workshop organised and run by R.M. for the OCEAN ICE project. This research was supported by Ocean Cryosphere Exchanges in ANtarctica: Impacts on Climate and the Earth system, OCEAN ICE, which is funded by the European Union, Horizon Europe Funding Programme for research and innovation under grant agreement Nr. 101060452. OCEAN ICE contribution number 21.

Illustration and publishing costs were supported by the Danish Government as part of the National Centre for Climate Research (NCKF). We are grateful to illustrator Dr. Jagoba Malumbres-Olarte for his creative work in producing the figures.

N.H. is supported by the Novo Nordisk Foundation Challenge project PRECISE (NNF23OC0081251). C.R. and S.B.S. acknowledge the support of the Horizon 2020 project PROTECT, grant agreement 869304.

The authors gratefully acknowledge the European Space Agency (ESA) for the acquisition and processing of long-term, multi-decadal satellite datasets which have enabled many of these scientific insights to be developed, particularly in the context of the ESA Climate Change initiative. Funding is provided to A.E.H. by ESA via the ESA Polar+ Ice Shelves project (ESA-IPL-POE-EF-cb-LE-2019-834) and the SO-ICE project (ESA AO/1-10461/20/I-NB) which are both part of the ESA Polar Science Cluster. B.J.W. is supported by the Panorama Natural Environment Research Council (NERC) Doctoral Training Partnership, under grant NE/S007458/1.

5 Conflict of interest

The authors declare no conflicts of interest with the ideas expressed in this manuscript

6 Authors' contributions

R.M., C.R. and A.E.H., came up with the ideas behind this manuscript, S.B.S, N.H. and B.W. developed them further. All authors contributed to the writing of the manuscript. Figure illustration was created by illustrator Dr. Jagoba Malumbres-Olarte to a specification by the authors.

References

- [1] Amory C, Buizert C, Buzzard S, et al (2024) Firm on ice sheets. *Nature Reviews Earth & Environment* 5(2):79–99. <https://doi.org/10.1038/s43017-023-00507-9>,

URL <https://www.nature.com/articles/s43017-023-00507-9>

- [2] Banwell AF, MacAyeal DR, Sergienko OV (2013) Breakup of the Larsen B Ice Shelf triggered by chain reaction drainage of supraglacial lakes: LARSEN B CHAIN REACTION LAKE DRAINAGE. *Geophysical Research Letters* 40(22):5872–5876. <https://doi.org/10.1002/2013GL057694>, URL <http://doi.wiley.com/10.1002/2013GL057694>
- [3] Banwell AF, Willis IC, Macdonald GJ, et al (2019) Direct measurements of ice-shelf flexure caused by surface meltwater ponding and drainage. *Nature Communications* 10(1):730. <https://doi.org/10.1038/s41467-019-08522-5>, URL <https://www.nature.com/articles/s41467-019-08522-5>
- [4] Barnes DKA (2017) Iceberg killing fields limit huge potential for benthic blue carbon in Antarctic shallows. *Global Change Biology* 23(7):2649–2659. <https://doi.org/10.1111/gcb.13523>, URL <https://onlinelibrary.wiley.com/doi/10.1111/gcb.13523>
- [5] Barnes DKA, Sands CJ, Cook A, et al (2020) Blue carbon gains from glacial retreat along Antarctic fjords: What should we expect? *Global Change Biology* 26(5):2750–2755. <https://doi.org/10.1111/gcb.15055>, URL <https://onlinelibrary.wiley.com/doi/10.1111/gcb.15055>
- [6] Bell RE, Banwell AF, Trusel LD, et al (2018) Antarctic surface hydrology and impacts on ice-sheet mass balance. *Nature Climate Change* 8(12):1044–1052. <https://doi.org/10.1038/s41558-018-0326-3>, URL <https://www.nature.com/articles/s41558-018-0326-3>
- [7] Boberg F, Mottram R, Hansen N, et al (2022) Uncertainties in projected surface mass balance over the polar ice sheets from dynamically downscaled EC-Earth

- models. *The Cryosphere* 16(1):17–33. <https://doi.org/10.5194/tc-16-17-2022>, URL <https://tc.copernicus.org/articles/16/17/2022/>
- [8] Boxall K, Christie FDW, Willis IC, et al (2022) Seasonal land ice-flow variability in the Antarctic Peninsula. preprint, *Ice sheets/Remote Sensing*, <https://doi.org/10.5194/tc-2022-55>, URL <https://tc.copernicus.org/preprints/tc-2022-55/tc-2022-55.pdf>
- [9] Breum M (2015) *The Greenland Dilemma: The quest for independence, the underground riches and the troubled relations with Denmark*. Royal Danish Defence College, google-Books-ID: 1v1vCQAAQBAJ
- [10] Broeke MRvd, Munneke PK, Noël B, et al (2023) Contrasting current and future surface melt rates on the ice sheets of Greenland and Antarctica: Lessons from in situ observations and climate models. *PLOS Climate* 2(5):e0000203. <https://doi.org/10.1371/journal.pclm.0000203>, URL <https://journals.plos.org/climate/article?id=10.1371/journal.pclm.0000203>
- [11] Casado M, Hébert R, Faranda D, et al (2023) The quandary of detecting the signature of climate change in Antarctica. *Nature Climate Change* 13(10):1082–1088. <https://doi.org/10.1038/s41558-023-01791-5>, URL <https://www.nature.com/articles/s41558-023-01791-5>
- [12] Clem KR, Fogt RL, Turner J, et al (2020) Record warming at the South Pole during the past three decades. *Nature Climate Change* 10(8):762–770. <https://doi.org/10.1038/s41558-020-0815-z>, URL <https://www.nature.com/articles/s41558-020-0815-z>
- [13] Colomb A, Cammas B, Linden E, et al (????) Coup de chaud en Antarctique Est. *La Météorologie* 2022(117):85–88. <https://doi.org/10.37053/>

lameteorologie-2022-0045, URL <https://lameteorologie.fr/issues/2022/117/meteo.2022.117.85>

- [14] Copernicus Climate Change Service (2020) Surface radiation budget from 1982 to present derived from satellite observations. <https://doi.org/10.24381/CDS.CEA58B5A>, URL <https://cds.climate.copernicus.eu/doi/10.24381/cds.cea58b5a>
- [15] Cummings VJ, Hewitt JE, Thrush SF, et al (2018) Linking Ross Sea Coastal Benthic Communities to Environmental Conditions: Documenting Baselines in a Spatially Variable and Changing World. *Frontiers in Marine Science* 5. URL <https://www.frontiersin.org/articles/10.3389/fmars.2018.00232>
- [16] Davison BJ, Hogg AE, Gourmelen N, et al (2023) Annual mass budget of Antarctic ice shelves from 1997 to 2021. *Science Advances* 9(41):eadi0186. <https://doi.org/10.1126/sciadv.adi0186>, URL <https://www.science.org/doi/10.1126/sciadv.adi0186>
- [17] Fogt RL, Sleinkofer AM, Raphael MN, et al (2022) A regime shift in seasonal total Antarctic sea ice extent in the twentieth century. *Nature Climate Change* 12(1):54–62. <https://doi.org/10.1038/s41558-021-01254-9>, URL <https://www.nature.com/articles/s41558-021-01254-9>
- [18] Fricker HA, Scambos T, Bindshadler R, et al (2007) An Active Subglacial Water System in West Antarctica Mapped from Space. *Science* 315(5818):1544–1548. <https://doi.org/10.1126/science.1136897>, URL <https://www.science.org/doi/10.1126/science.1136897>
- [19] Friedl P, Seehaus TC, Wendt A, et al (2018) Recent dynamic changes on Fleming Glacier after the disintegration of Wordie Ice Shelf, Antarctic Peninsula. *The Cryosphere* 12(4):1347–1365. <https://doi.org/10.5194/tc-12-1347-2018>, URL

<https://tc.copernicus.org/articles/12/1347/2018/>

- [20] Fürst JJ, Durand G, Gillet-Chaulet F, et al (2016) The safety band of Antarctic ice shelves. *Nature Climate Change* 6(5):479–482. <https://doi.org/10.1038/nclimate2912>, URL <https://www.nature.com/articles/nclimate2912>
- [21] Gilbert E, Holmes C (2024) 2023’s Antarctic sea ice extent is the lowest on record. *Weather* p wea.4518. <https://doi.org/10.1002/wea.4518>, URL <https://rmets.onlinelibrary.wiley.com/doi/10.1002/wea.4518>
- [22] Gilbert E, Kittel C (2021) Surface Melt and Runoff on Antarctic Ice Shelves at 1.5°C, 2°C, and 4°C of Future Warming. *Geophysical Research Letters* 48(8):e2020GL091733. <https://doi.org/10.1029/2020GL091733>, URL <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020GL091733>
- [23] González-Herrero S, Barriopedro D, Trigo RM, et al (2022) Climate warming amplified the 2020 record-breaking heatwave in the Antarctic Peninsula. *Communications Earth & Environment* 3(1):1–9. <https://doi.org/10.1038/s43247-022-00450-5>, URL <https://www.nature.com/articles/s43247-022-00450-5>
- [24] Greene CA, Young DA, Gwyther DE, et al (2018) Seasonal dynamics of Totten Ice Shelf controlled by sea ice buttressing. *The Cryosphere* 12(9):2869–2882. <https://doi.org/10.5194/tc-12-2869-2018>, URL <https://tc.copernicus.org/articles/12/2869/2018/>
- [25] Greene CA, Gardner AS, Wood M, et al (2024) Ubiquitous acceleration in Greenland Ice Sheet calving from 1985 to 2022. *Nature* 625(7995):523–528. <https://doi.org/10.1038/s41586-023-06863-2>, URL <https://www.nature.com/articles/s41586-023-06863-2>

- [26] Groh A, Horwath M, Horvath A, et al (2019) Evaluating GRACE Mass Change Time Series for the Antarctic and Greenland Ice Sheet—Methods and Results. *Geosciences* 9(10):415. <https://doi.org/10.3390/geosciences9100415>, URL <https://www.mdpi.com/2076-3263/9/10/415>
- [27] Gutt J, Barratt I, Domack E, et al (2011) Biodiversity change after climate-induced ice-shelf collapse in the Antarctic. *Deep Sea Research Part II: Topical Studies in Oceanography* 58(1):74–83. <https://doi.org/10.1016/j.dsr2.2010.05.024>, URL <https://www.sciencedirect.com/science/article/pii/S0967064510001888>
- [28] Gutt J, Isla E, Xavier JC, et al (2021) Antarctic ecosystems in transition – life between stresses and opportunities. *Biological Reviews* 96(3):798–821. <https://doi.org/10.1111/brv.12679>, URL <https://onlinelibrary.wiley.com/doi/10.1111/brv.12679>
- [29] Hansen N, Langen PL, Boberg F, et al (2021) Downscaled surface mass balance in Antarctica: impacts of subsurface processes and large-scale atmospheric circulation. *The Cryosphere* 15(9):4315–4333. <https://doi.org/10.5194/tc-15-4315-2021>, URL <https://tc.copernicus.org/articles/15/4315/2021/>
- [30] Hansen N, Sørensen LS, Spada G, et al (2023) Revisiting ice sheet mass balance: insights into changing dynamics in Greenland and Antarctica from ICESat-2. *The Cryosphere Discussions* pp 1–28. <https://doi.org/10.5194/tc-2023-104>, URL <https://tc.copernicus.org/preprints/tc-2023-104/>
- [31] Hoham RW, Remias D (2020) Snow and Glacial Algae: A Review ¹. *Journal of Phycology* 56(2):264–282. <https://doi.org/10.1111/jpy.12952>, URL <https://onlinelibrary.wiley.com/doi/10.1111/jpy.12952>

- [32] Khan AL, Dierssen HM, Scambos TA, et al (2021) Spectral characterization, radiative forcing and pigment content of coastal Antarctic snow algae: approaches to spectrally discriminate red and green communities and their impact on snowmelt. *The Cryosphere* 15(1):133–148. <https://doi.org/10.5194/tc-15-133-2021>, URL <https://tc.copernicus.org/articles/15/133/2021/>
- [33] Khazendar A, Fenty IG, Carroll D, et al (2019) Interruption of two decades of Jakobshavn Isbrae acceleration and thinning as regional ocean cools. *Nature Geoscience* 12(4):277–283. <https://doi.org/10.1038/s41561-019-0329-3>, URL <https://doi.org/10.1038/s41561-019-0329-3>
- [34] Le Guen C, Kato A, Raymond B, et al (2018) Reproductive performance and diving behaviour share a common sea-ice concentration optimum in Adélie penguins (*Pygoscelis adeliae*). *Global Change Biology* 24(11):5304–5317. <https://doi.org/10.1111/gcb.14377>, URL <https://onlinelibrary.wiley.com/doi/10.1111/gcb.14377>
- [35] Li W, Wu Y, Hu X (2023) The Processes-Based Attributes of Four Major Surface Melting Events over the Antarctic Ross Ice Shelf. *Advances in Atmospheric Sciences* <https://doi.org/10.1007/s00376-023-2287-3>, URL <https://doi.org/10.1007/s00376-023-2287-3>
- [36] Li X, Rignot E, Mouginot J, et al (2016) Ice flow dynamics and mass loss of Totten Glacier, East Antarctica, from 1989 to 2015. *Geophysical Research Letters* 43(12):6366–6373. <https://doi.org/10.1002/2016GL069173>, URL <https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL069173>
- [37] Liang Q, Zhou C, Howat IM, et al (2019) Ice flow variations at Polar Record Glacier, East Antarctica. *Journal of Glaciology* 65(250):279–287. <https://doi.org/10.1017/jog.2019.6>, URL <https://www.cambridge.org/core/journals/journal-of-glaciology/>

article/ice-flow-variations-at-polar-record-glacier-east-antarctica/
20AE74A1B29173CAD3CD6BE66300356A

- [38] Mottram R, B. Simonsen S, Høyer Svendsen S, et al (2019) An Integrated View of Greenland Ice Sheet Mass Changes Based on Models and Satellite Observations. Remote Sensing 11(12):1407. <https://doi.org/10.3390/rs11121407>, URL <https://www.mdpi.com/2072-4292/11/12/1407>
- [39] Oksman M, Kvorning AB, Larsen SH, et al (2022) Impact of freshwater runoff from the southwest Greenland Ice Sheet on fjord productivity since the late 19th century. The Cryosphere 16(6):2471–2491. <https://doi.org/10.5194/tc-16-2471-2022>, URL <https://tc.copernicus.org/articles/16/2471/2022/>
- [40] OSI SAF (2017) OSICOGBNGlobal Sea Ice Concentration (netCDF) - DMSP. https://doi.org/10.15770/EUM_SAF_OSI_NRT_2004, URL <https://navigator.eumetsat.int/product/EO:EUM:DAT:DMSP:OSI-401-B>
- [41] Otosaka IN, Shepherd A, Ivins ER, et al (2022) Mass Balance of the Greenland and Antarctic Ice Sheets from 1992 to 2020. Earth System Science Data Discussions pp 1–33. <https://doi.org/10.5194/essd-2022-261>, URL <https://essd.copernicus.org/preprints/essd-2022-261/>
- [42] Purich A, Doddridge EW (2023) Record low Antarctic sea ice coverage indicates a new sea ice state. Communications Earth & Environment 4(1):1–9. <https://doi.org/10.1038/s43247-023-00961-9>, URL <https://www.nature.com/articles/s43247-023-00961-9>
- [43] Ribeiro S, Limoges A, Massé G, et al (2021) Vulnerability of the North Water ecosystem to climate change. Nature Communications 12(1):4475. <https://doi.org/10.1038/s41467-021-24742-0>, URL <https://www.nature.com/articles/>

- [44] Rodehacke CB, Pfeiffer M, Semmler T, et al (2020) Future sea level contribution from Antarctica inferred from CMIP5 model forcing and its dependence on precipitation ansatz. *Earth System Dynamics* 11(4):1153–1194. <https://doi.org/10.5194/esd-11-1153-2020>, URL <https://esd.copernicus.org/articles/11/1153/2020/>
- [45] Ropert-Coudert Y, Kato A, Shiomi K, et al (2018) Two Recent Massive Breeding Failures in an Adélie Penguin Colony Call for the Creation of a Marine Protected Area in D’Urville Sea/Mertz. *Frontiers in Marine Science* 5. URL <https://www.frontiersin.org/articles/10.3389/fmars.2018.00264>
- [46] Rott H, Abdel Jaber W, Wuite J, et al (2018) Changing pattern of ice flow and mass balance for glaciers discharging into the Larsen A and B embayments, Antarctic Peninsula, 2011 to 2016. *The Cryosphere* 12(4):1273–1291. <https://doi.org/10.5194/tc-12-1273-2018>, URL <https://tc.copernicus.org/articles/12/1273/2018/>
- [47] Scambos T, Fricker HA, Liu CC, et al (2009) Ice shelf disintegration by plate bending and hydro-fracture: Satellite observations and model results of the 2008 Wilkins ice shelf break-ups. *Earth and Planetary Science Letters* 280(1):51–60. <https://doi.org/10.1016/j.epsl.2008.12.027>, URL <https://www.sciencedirect.com/science/article/pii/S0012821X08007887>
- [48] Segawa T, Matsuzaki R, Takeuchi N, et al (2018) Bipolar dispersal of red-snow algae. *Nature Communications* 9(1):3094. <https://doi.org/10.1038/s41467-018-05521-w>, URL <https://www.nature.com/articles/s41467-018-05521-w>

- [49] Shepherd A, Ivins E, Rignot E, et al (2020) Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature* 579(7798):233–239. <https://doi.org/10.1038/s41586-019-1855-2>, URL <https://www.nature.com/articles/s41586-019-1855-2>, number: 7798 Publisher: Nature Publishing Group
- [50] Siegert MJ, Bentley MJ, Atkinson A, et al (2023) Antarctic extreme events. *Frontiers in Environmental Science* 11. URL <https://www.frontiersin.org/articles/10.3389/fenvs.2023.1229283>
- [51] Smith B, Fricker HA, Gardner AS, et al (2020) Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes. *Science* 368(6496):1239–1242. <https://doi.org/10.1126/science.aaz5845>, URL <https://www.science.org/doi/10.1126/science.aaz5845>
- [52] Smith BE, Fricker HA, Joughin IR, et al (2009) An inventory of active subglacial lakes in Antarctica detected by ICESat (2003–2008). *Journal of Glaciology* 55(192):573–595. <https://doi.org/10.3189/002214309789470879>, URL <https://www.cambridge.org/core/journals/journal-of-glaciology/article/an-inventory-of-active-subglacial-lakes-in-antarctica-detected-by-icesat-20032008/4FD0EAF26D7F8D5808DE257E328619FA>
- [53] Sole A, Nienow P, Bartholomew I, et al (2013) Winter motion mediates dynamic response of the Greenland Ice Sheet to warmer summers: INTERANNUAL GREENLAND ICE FLOW CHANGES. *Geophysical Research Letters* 40(15):3940–3944. <https://doi.org/10.1002/grl.50764>, URL <http://doi.wiley.com/10.1002/grl.50764>
- [54] Solgaard AM, Rapp D, Noël BPY, et al (2022) Seasonal Patterns of Greenland Ice Velocity From Sentinel-1 SAR Data Linked to Runoff. *Geophysical Research Letters* 49(24):e2022GL100343. <https://doi.org/10.1029/2022GL100343>, URL <https://doi.org/10.1029/2022GL100343>

- [55] Stearns LA, Smith BE, Hamilton GS (2008) Increased flow speed on a large East Antarctic outlet glacier caused by subglacial floods. *Nature Geoscience* 1(12):827–831. <https://doi.org/10.1038/ngeo356>, URL <https://www.nature.com/articles/ngeo356>
- [56] Sundal AV, Shepherd A, Nienow P, et al (2011) Melt-induced speed-up of Greenland ice sheet offset by efficient subglacial drainage. *Nature* 469(7331):521–524. <https://doi.org/10.1038/nature09740>, URL <https://www.nature.com/articles/nature09740>
- [57] Surawy-Stepney T, Hogg AE, Cornford SL, et al (2023) The impact of landfast sea ice buttressing on ice dynamic speedup in the Larsen-B Embayment, Antarctica. *The Cryosphere Discussions* pp 1–24. <https://doi.org/10.5194/tc-2023-128>, URL <https://tc.copernicus.org/preprints/tc-2023-128/>
- [58] Van Tricht K, Lhermitte S, Lenaerts JTM, et al (2016) Clouds enhance Greenland ice sheet meltwater runoff. *Nature Communications* 7:10266. URL <https://doi.org/10.1038/ncomms10266>
- [59] Vaughan DG (2008) West Antarctic Ice Sheet collapse – the fall and rise of a paradigm. *Climatic Change* 91(1):65–79. <https://doi.org/10.1007/s10584-008-9448-3>, URL <https://doi.org/10.1007/s10584-008-9448-3>
- [60] Wallis BJ, Hogg AE, Meredith MP, et al (2023) Ocean warming drives rapid dynamic activation of marine-terminating glacier on the west Antarctic Peninsula. *Nature Communications* 14(1):7535. <https://doi.org/10.1038/s41467-023-42970-4>, URL <https://www.nature.com/articles/s41467-023-42970-4>

- [61] Wallis BJ, Hogg AE, Van Wessem JM, et al (2023) Widespread seasonal speed-up of west Antarctic Peninsula glaciers from 2014 to 2021. *Nature Geoscience* 16(3):231–237. <https://doi.org/10.1038/s41561-023-01131-4>, URL <https://www.nature.com/articles/s41561-023-01131-4>
- [62] Wang Y, Ding M, Reijmer CH, et al (2021) The AntSMB dataset: a comprehensive compilation of surface mass balance field observations over the Antarctic Ice Sheet. *Earth System Science Data* 13(6):3057–3074. <https://doi.org/10.5194/essd-13-3057-2021>, URL <https://essd.copernicus.org/articles/13/3057/2021/>
- [63] Wang Y, Zhang X, Ning W, et al (2023) The AntAWS dataset: a compilation of Antarctic automatic weather station observations. *Earth System Science Data* 15(1):411–429. <https://doi.org/10.5194/essd-15-411-2023>, URL <https://essd.copernicus.org/articles/15/411/2023/>
- [64] van Wessem JM, van den Broeke MR, Wouters B, et al (2023) Variable temperature thresholds of melt pond formation on Antarctic ice shelves. *Nature Climate Change* 13(2):161–166. <https://doi.org/10.1038/s41558-022-01577-1>, URL <https://www.nature.com/articles/s41558-022-01577-1>
- [65] Zou X, Bromwich DH, Montenegro A, et al (2021) Major surface melting over the Ross Ice Shelf part II: Surface energy balance. *Quarterly Journal of the Royal Meteorological Society* 147(738):2895–2916. <https://doi.org/10.1002/qj.4105>, URL <https://onlinelibrary.wiley.com/doi/10.1002/qj.4105>