Submitted: 2023-10-22

Proposal for an

IACS Working Group on the delineation of glaciers, ice sheets, and ice sheet basins

Co-chairs:
Ken Mankoff, NASA GISS, New York, USA
Fabien Maussion, University of Bristol, Bristol, UK

Steering committee:
Regine Hock, University of Oslo, Norway
Sophie Nowicki, University of Buffalo, USA
Celia Baumhoer, German Aerospace Center (DLR), Germany
Bertie Miles, Edinburgh University, UK
Frank Paul, University of Zurich, Switzerland
Heiko Goelzer, Bjerknes Centre for Climate Research, Norway
Mathieu Morlighem, Dartmouth College, USA
Will Kochtitzky, University of New England, USA
Rachel Oien, University at Buffalo, USA
Niels J. Korsgaard, Geological Survey of Denmark and Greenland, Denmark

1. EXECUTIVE SUMMARY

Mass and volume changes of the ice sheets in Greenland and Antarctica and the Earth's glaciers are typically studied separately, not only for historic reasons but also because the types of suitable observing systems and models used are generally different. However, the definitions of the main ice sheets and peripheral ice bodies in Greenland and Antarctica are not uniformly recognized across diverse groups and stakeholders. This ambiguity has led to peripheral ice masses in Greenland and Antarctica being either omitted or double-counted in global assessments of their mass changes, introducing errors in our estimation of mass loss and sea level rise. Despite the care taken when summarizing values it is probable that the use of different datasets have impacted recent IPCC reports, but to what extent is not yet quantified. While it may seem trivial, the challenge of establishing and agreeing upon consistent geographical and hydrological boundaries between the different ice masses is highly challenging. Each interested community (e.g., observations, remote sensing, modeling) and domain (e.g., ice sheets, peripheral glaciers) often uses distinct boundaries. Even within some of these communities, there is no universally agreed-upon standard.

We propose an effort aiming (a) to build a community standard product defining what is considered the 'main' ice sheet and what is a 'peripheral glacier', and (b) to define standardized drainage basins within the ice sheets as well as for the peripheral glaciers. This should include developing and making available both the rule-set and tools used for separating glaciers from

ice sheets and defining ice sheet basins as well as ice divides for glaciers along with recommendations to facilitate comparison between studies. To ensure broad acceptance, this standardized reference should be developed through an open, democratic process, enabling future revisions.

2. CONTEXT AND MOTIVATION

2.1 BACKGROUND

Glaciers vs Ice sheet

The group of researchers focusing on glaciers work with a widely adopted standard: the Randolph Glacier Inventory (RGI), available since 2012 and regularly updated since then (RGI Consortium, 2017, 2023). Almost all large-scale studies use the RGI as reference, and deviations from this standard in the peer-reviewed literature – even if they intended to represent an improvement to the RGI – have often led to confusion (Hock et al., 2023). The RGI, however, is not always used as a standard in the ice sheet community, and existing ice sheet products (volume or mass change estimates) often overlap with the RGI (Table 1; Figure 1), especially in Antarctica where only a few studies have tried to clearly delineate analysis domains across research communities (Bliss et al. 2013, Cook et al. 2014, Huber et al. 2017). Ice bodies inventoried in the RGI are categorized as part of the ice sheet in various other products, leading to double counting.

Preliminary attempts to address this problem have been made in Greenland, with the introduction of the concept of "connectivity level", describing the strength of the dynamical connection of peripheral glaciers to the ice sheet (Rastner et al., 2012). Still, challenges and inconsistencies remain. Even recent community efforts to produce consensus estimates of mass changes of the Greenland ice sheet cannot unambiguously define over which domain these estimates are valid (e.g., Otosaka et al., 2023). Finally, there are additional challenges in maintaining such a dataset in the face of rapid change, where the connectivity between peripheral glaciers and the ice sheet may be different after decades of retreat.

Basins within the ice sheets

Within the ice sheet community, similar issues exist with internal basin boundaries as with external boundaries. A few common products define large-scale regions (e.g., NW Greenland, East Antarctica), but these products do not necessarily reflect the complete extent of the ice sheets (i.e., the edges of the ice sheet are not always included in the reference geospatial data set). These products also use different areas to define labeled regions, making it challenging to compare results that use different products. For example the Zwally et al. (2012) region 7.1 covering Sermeq Kujalleq (Jakobshavn Isbræ) is 95,458 km^2, while the Mouginot et al. (2019) basin covering the same glacier is 78,155 km^2, or nearly 20 % smaller. This area discrepancy does not impact ice discharge, but significantly impacts the accumulation area, and therefore estimates of Jakobshavn Isbræ mass balance.

The issues are compounded when working with individual basins, where the signal-to-noise ratio increases due to smaller areas and the relatively larger impact of changing basin boundaries. There is a growing interest and need in basin-scale mass balance estimates. However, basin-scale mass-balance estimates are highly sensitive to the basin area (e.g., Hermann et al., 2018), making individual results challenging to interpret, and multiple results using different basin definitions impossible to compare.

Table 1: non-exhaustive list of products used to define ice boundaries in Greenland and Antarctica.

Name	Purpose	Timespan	Comments	Data Citation
BedMachine Greenland v5	Bed topography	1993-2021	Ice boundary is provided in mask but is not primary product	doi:10.5067/GMEVBWFLWA7X
BedMachine Antarctica v3	Bed topography	1970-2019	Ice boundary is not primary product	doi:10.5067/C2GFER6PTOS4
GEUS	Greenland boundary	Nominal 1978-1987	Has “main”, “local”, and “disconnected”	doi:10.5194/tc-7-445-2013
GIMP	Land Ice/Ocean delineation	Two ice masks with nominal years 2000 and 2015.	Year 2000 ice mask compiled from data from 1999-2002 and 2015 ice mask compiled from data from the years 2013 and 2015.	doi:10.5067/B8X58MQBFUPA
RGI	Outlines of glaciers outside of the ice sheets	2000 (deviations frequent)	Widely accepted standard, but overlaps with ice sheet products in this table	doi:10.7265/4m1f-gd79
“AutoTerm” Ice Masks	Land Ice/Ocean delineation	2018, 2019, 2020	The GIMP 2015 ice mask with termini from 295 (?) marine terming outlet glaciers grafted on for the years 2018-2020.	doi:10.5194/tc-17-3485-202 Data not yet released by the NSIDC
Greene 2022	Land Ice/Ocean delineation	1997-2021	24 annual coastlines of Antarctica masked on a 240 m grid.	doi:10.5281/zenodo.5903643
MEaSUREs Antarctic Boundaries v2	Land Ice/Ocean delineation & Antarctic	IPY 2007-2009	Maps of Antarctic ice shelves, basins and coastline from radar satellite data.	https://nsidc.org/data/nsidc-0709/versions/2

Name	Purpose	Timespan	Comments	Data Citation
	Basins			
MODIS Mosaic of Antarctica	Land Ice/Ocean delineation	2004, 2009, 2014	Antarctic coastline manually delineated, Methods defined in Scambos et al. (2007)	doi:10.5067/4ZL43A4619AF; doi:10.5067/RNF17BP824UM; doi:10.5067/68TBT0CGJSOJ
Radarsat Coastline	Land Ice/Ocean delineation	1997, 2000	Antarctic coastline from Radarsat. Methods in Liu & Jezek (2004)	https://research.byrd.osu.edu/rsl/radarsat/data/
Baumhoer 2021	Land Ice/Ocean delineation	2018	Antarctic coastline automatically extracted from Sentinel-1 imagery, 40 m resolution	https://download.geoservice.dlr.de/icelines/ files/
"Mouginot"	Glacier catchments/basins for the Greenland Ice Sheet	2009– (slow ice) & 2013– (fast ice)	Commonly used by community (e.g., IMBIE)	doi:10.7280/d1wt11
"Rignot Basins"	Antarctic & Greenland drainage systems		Commonly used by community (e.g., IMBIE)	No DOI. See http://imbie.org/imbie-3/drainage-basins/
"Zwally Basins"	Antarctic & Greenland drainage systems		Commonly used by community (e.g., IMBIE)	No DOI. Maybe http://imbie.org/imbie-3/drainage-basins/
Krieger 2023	Internal Greenlandic basins	TBD	Methods defined in Krieger et al. (2020)	In progress & unpublished

2.2 MOTIVATION

The lack of a widely accepted standard across communities in delineating ice sheet vs glaciers (Fig. 1) and defining basins within ice sheets has hampered comparisons between studies and most likely has also led to errors of accounting, for example, in recent IPCC reports, such as

AR5, AR6, and the Special Report on the Ocean and Cryosphere in a Changing Climate.

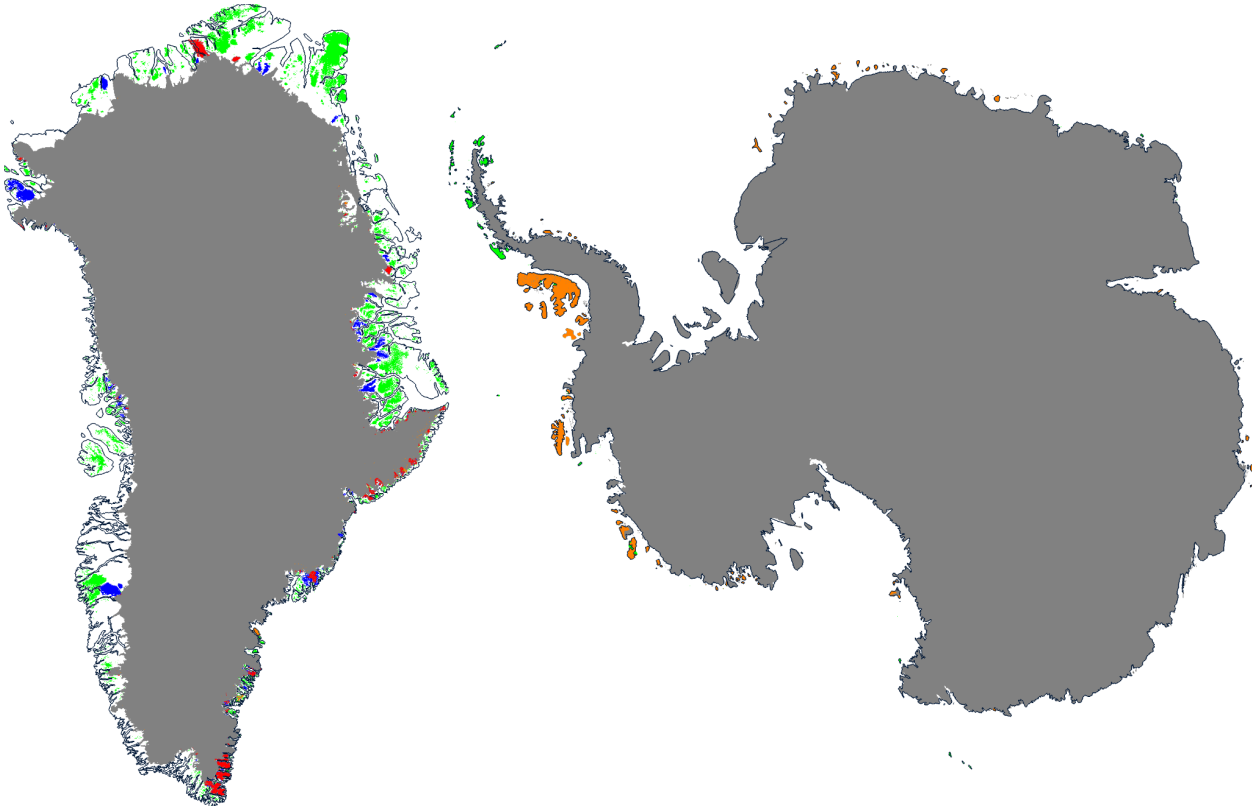

Figure 1: Ice sheet, glaciers, and overlap. Greenland: Mouginot ice sheet excluding 'ice caps' (solid gray), RGI 7.0 peripheral glacier with non-overlapping connectivity level 0/1 (green/blue) and overlapping connectivity level 0/1 (orange/red). Antarctica: IMBIE2 "Rignot" ice sheet (solid gray), RGI 7.0 glaciers (green) and overlap (orange)

Hence, the research community needs an authoritative source for defining analysis domains in Greenland and Antarctica. This source should allow the separation of peripheral glaciers from the two ice sheets. If possible, it should also define analysis domains within the ice sheet and glacier domains ("sub-basins" or "sub-regions"), standardizing and uniformizing intercomparison efforts, greatly simplifying the work of review studies such as from the IPCC.

This new effort should prioritize wide acceptance over perfectionism or correctness. The complexity of the system increases with the number of use cases, and the product generated by this effort will likely never be perfect. The RGI, for example, has had several known flaws since its creation, yet its wide acceptance as a community standard has dramatically advanced our understanding of glaciers, and has increased community engagement in improving the dataset further.

3. OBJECTIVES

The proposed WG will have the following general objectives:

A. **Make a community standard agreement on which ice masses in and around Greenland and Antarctica fall into the "glacier" category and which are part of the main ice sheets**
    a. Provide outlines of the Greenland and Antarctic ice sheets, so that various stakeholders can work with the same domains
    b. Provide outlines of glaciers and ice caps outside of the two ice sheets, and if necessary update the RGI to take these into account.
    c. Provide outlines of ice shelves and other objects where necessary to help models and other tools to work appropriately with the outlines.
    d. Add attributes to the outlines, for example if an ice mass is marine-terminating
B. **Make a community standard agreement on internal ice sheet basins, subregions and boundaries**
    a. Identify suitable variables for basin delineation such as surface velocity, surface hydrology, surface topography, etc.
    b. Build on existing delineation techniques to select and implement an open source algorithm(s) for basin delineation.
    c. Calculate ice drainage basins using the selected algorithm(s).
    d. Select regional grouping of basins
C. **Develop methods and tools to support mass change estimates that avoid under- or over-counting**
    a. Provide Methods & tools to convert from the highest resolution product generated by this effort to lower resolutions and/or on different grids and projections.
    b. Provide Methods & tools to remap model results at different grid resolutions.
    c. Provide Methods & tools to remap mass-change assessments from GRACE.
D. **Engage a sustainable community**
    a. Provide the rule-set, the datasets and the tools used to realize in open online repositories, in order to encourage code reviews, dataset adjustments, and improvements from the community.
    b. Open a discussion platform for users and developers to come together and discuss issues around the working group. This platform should be inclusive and ideally replace private emails for all discussions related to the dataset itself: it can take the form of open meetings, open meeting notes, and a low-maintenance online forum (e.g., GitHub issues).
    c. Regularly invite members of the broader communities to contribute to this effort with improvement to rule-set or products. Provide educational material about the project and related products.
    d. Communicate with universities, research centers, employers, funding agencies and scientific journals to raise awareness about the usefulness of the products and to encourage their sustainable development.

4. DELIVERABLES

D1 Review report outlining the current situation, extracting the relevant information and suspected double counting in previous studies and IPCC report and proposed solutions to improve the situation.
D2 Publication of a GIS standard data set defining the ice sheet and glacier domain in vector format, and at various resolutions in raster format along with a rule-set to create them
D3 Publication of algorithms used to accomplish D2, if there is an algorithmic definition
D4 Publication of rule-sets, data sets and algorithms for ice sheet ice drainage basins boundaries

5. EXPECTED CHALLENGES AND CONTINGENCY PLANS

- A clear definition of the boundary between the two ice sheets and their peripheral glaciers is not yet available and will depend on the spatial resolution used to assess/simulate a certain variable. Before starting the separation, a survey of the community should be done to help defining the rule-set and facilitate the mapping work.
- We anticipate the workload to be unevenly distributed between WG members. The absence of funding will make certain tasks difficult to realize (e.g., algorithm development, product generation and correction, etc.). The WG should attempt to convince members and stakeholders to fund part of the work via projects and/or on permanent staff. The first months of the WG should focus on that aspect.
- It will likely be challenging to define the ice sheet vs glacier for the Antarctic Peninsula. However, a physically correct definition is not a requirement to avoid double-counting, as long as both communities use the same definition. Nonetheless, we will aim for physically plausible definitions. The contingency plan will be to include more data. That is, not just visible imagery and elevation information, but also radar, and velocity, possibly covering longer time periods, to try to elucidate the boundaries of the peripheral ice masses.
- Internal basins - of any type (velocity, hydrologic, etc.) are likely to have many small basins at the ice sheet edge. These may not be physically realistic or meaningful, due to data fidelity. An aggregation method will need to be defined and implemented.
- Neither ice sheets nor glaciers are steady state. The system changes in time. We will pick one timestamp for the initial result. Products that do not exist at that time will be treated carefully and with larger uncertainty. Workflow architecture will aim easy updating to generate output products with different timestamps.

6. WORKING GROUP ORGANISATION AND MEMBERSHIP

1. Two co-chairs (Mankoff, Maussion)
2. A steering committee (co-chairs + additional members; See top of document)
3. Additional members (to be determined following an open call for participation)

4. Observers (invited to annual meetings and kept informed of progress; no expected contribution)

Including those currently listed as steering committee members, 35 people have expressed interest in contributing as steering committee members, members, or observers of the WG in response to a November 2022 email to CRYOLIST (link).

The **co-chairs** will oversee the overall work of the WG, serve as liaisons to IACS and are responsible for reporting back to IACS (including annual reports). The **steering committee** will discuss day-to-day business, decide the specifics and next steps to meet the WG's goals, and contribute to the deliverables. The steering committee will discuss WG business roughly every month via teleconference. **Members** are expected to contribute actively to one or several deliverables and provide feedback, and participate in the annual business meetings. They are also encouraged to contribute with ideas about how to meet the WG's goals and deliverables. Membership will be open and we will invite members through international calls (e.g., through CRYOLIST, CLIMLIST) once the WG is approved. **Observers** are community members who have expressed an interest in the project but do not plan to actively contribute. An annual online meeting will be held with all WG members and the steering committee to discuss plans and progress. Observers will also be invited. In addition in-person meetings will be organized when possible at suitable international conferences open to all members or other interested conference delegates. The WG will strive for wide international participation and diversity.

The steering committee will also establish specific focus groups to reach our goals. **The purpose of these groups is not to reproduce existing barriers for collaborations, but rather to make sure that each community is properly represented in the WG and achieve broad acceptance.**

Specific groups:

WG leadership (co-chairs, steering committee) Management of milestones, organization of meetings, communication with IACS.

Glaciers (at least one member of the steering committee and any relevant members) Glacier mapping methods, rule-sets for entity division and with the ice sheets and ice shelves, mapping of missing glaciers and problematic regions (e.g., permanent snowfields and ice without movement) .

Ice Sheets (at least one member of the steering committee and any relevant members)
Ice sheet mapping methods, mapping of internal basins.

Observations (at least one member of the steering committee and any relevant members)
Development of the necessary tools to extract recent ice sheet and glacier delineation from remote sensing observations.

Models (at least one member of the steering committee and any relevant members)
Interface between ice sheet/glacier products and model domains. Definition of "main" versus "peripheral" from a model domain / structure perspective.

Communication and outreach (all members)
Online tutorials, workshops, website, community engagement, scientific publications.

International collaborations (all members)
Contact with international collaborators and institutions (see Section 7).

7. INTERNATIONAL COLLABORATIONS

The WG will work closely with related international groups such as the IACS WG on the "Randolph Glacier Inventory (RGI) and its role in future glacier monitoring and GLIMS", the IACS WG on "Regional Assessments of Glacier Mass Change (RAGMAC)" and the IACS standing group "Global Terrestrial Network for Glaciers (GTN-G)", the Ice Sheet Model Intercomparison Project (ISMIP), the Glacier Model Intercomparison Project (GlacierMIP), the Ice sheet Mass Balance Inter-comparison Exercise (IMBIE), and the Glacier Mass Balance Intercomparison Exercise (*GlaMBIE*). Interaction with these communities will be essential to the success of the WG.

REFERENCES

Bliss, A., Hock, R., and Cogley, J. G. (2013). A new inventory of mountain glaciers and ice caps for the Antarctic periphery. *Annals of Glaciology*, 54, 191–199, doi:10.3189/2013AoG63A377.

Cook, A. J., Vaughan, D. G., Luckman, A. J., and Murray, T. (2014). A new Antarctic Peninsula glacier basin inventory and ob- served area changes since the 1940s. *Antarctic Science*, 26, 614–624, doi:10.1017/S0954102014000200

Greene, C.A., Gardner, A.S., Schlegel, NJ. *et al.* Antarctic calving loss rivals ice-shelf thinning. *Nature* **609**, 948–953 (2022). https://doi.org/10.1038/s41586-022-05037-w

Hermann, M., Box, J. E., Fausto, R. S., Colgan, W. T., Langen, P. L., Mottram, R., et al. (2018). Application of PROMICE Q-transect in situ accumulation and ablation measurements (2000-2017) to constrain mass balance at the southern tip of the Greenland ice sheet. *Journal of Geophysical Research: Earth Surface*. https://doi.org/10.1029/2017jf004408

Hock, R., Maussion, F., Marzeion, B., & Nowicki, S. (2023). What is the global glacier ice volume outside the ice sheets? *Journal of Glaciology*, 1–7. https://doi.org/10.1017/jog.2023.1

Huber, J., Cook, A. J., Paul, F., and Zemp, M. (2017). A complete glacier inventory of the Antarctic Peninsula based on Landsat 7 images from 2000 to 2002 and other preexisting data sets. *Earth System Science Data*, 9, 115–131, https://doi.org/10.5194/essd-9-115-2017

Krieger, L., Floricioiu, D., & Neckel, N. (2020). Drainage basin delineation for outlet glaciers of Northeast Greenland based on Sentinel-1 ice velocities and TanDEM-X elevations. *Remote Sensing of Environment*, *237*, 111483. https://doi.org/10.1016/j.rse.2019.111483

Liu, H. and Jezek, K. C.(2004). A complete high-resolution coastline of Antarctica extracted from orthorectified Radarsat SAR imagery, Photogrammetric Engineering & Remote Sensing, 70, 605–616, https://doi.org/10.14358/pers.70.5.605.

Mankoff, K. D., Fettweis, X., Langen, P. L., Stendel, M., Kjeldsen, K. K., Karlsson, N. B., et al. (2021). Greenland ice sheet mass balance from 1840 through next week. *Earth System Science Data*, *13*(10), 5001--5025. https://doi.org/10.5194/essd-13-5001-2021

Mouginot, J., & Rignot, E. (2019). Glacier catchments/basins for the Greenland ice sheet. UC Irvine. https://doi.org/10.7280/d1wt11

Rastner, P., Bolch, T., Mölg, N., Machguth, H., Le Bris, R., & Paul, F. (2012). The first complete inventory of the local glaciers and ice caps on Greenland. *The Cryosphere*, *6*(6), 1483–1495. https://doi.org/10.5194/tc-6-1483-2012

RGI Consortium, 2017. Randolph Glacier Inventory - A Dataset of Global Glacier Outlines, Version 6. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: https://doi.org/10.7265/4m1f-gd79.

RGI 7.0 Consortium, 2023. Randolph Glacier Inventory - A Dataset of Global Glacier Outlines, Version 7.0. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi:10.5067/f6jmovy5navz. Online access: https://doi.org/10.5067/f6jmovy5navz

Scambos, T. A., Haran, T. M., Fahnestock, M. A., Painter, T. H., and Bohlander, J.: MODIS-based Mosaic of Antarctica (MOA) data sets (2007): Continent-wide surface morphology and snow grain size, Remote Sensing of Environment, 111, 242–257, https://doi.org/10.1016/j.rse.2006.12.020.

Zwally, H. J., Giovinetto, M. B., Beckley, M. A., & Saba, J. L. (2012). Antarctic and Greenland drainage systems. Retrieved from http://icesat4.gsfc.nasa.gov/cryo_data/ant_grn_drainage_systems.php