Technical Memorandum

A 21st century high-resolution glacier and ice sheet fractional area dataset

A.C. Lute, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ, USA

Motivation

Glaciers and ice sheets are an integral part of the climate system due to their strong effect on land surface albedo, regulation of ocean salinity, and unique runoff timing relative to other water sources. In the Seamless System for Prediction and EArth System Research (SPEAR) model, glaciers and ice sheets are considered static, but do have distinct albedo and other land surface properties through which they influence local climate. Glaciers and ice sheets are designated in the model using a fractional glacier area dataset that helps to define sub grid tiles.

The glacier and ice sheet dataset employed in the most recent, highest resolution SPEAR model (SPEAR_HI, 25 km atmosphere and land) had several undesirable characteristics. First, as described in Milly & Shmakin, (2002), the dataset was derived from a 1° resolution soil classification dataset from 1986 (Zobler, 1986) that included an ice category. The 1986 dataset was in turn based on United Nations Food and Agriculture Organization (FAO) soil data from the 1970s. Information about glaciers, especially in remote areas, has improved significantly since the 1970s. Furthermore, global glacier area declined 0.18%/year between 1980 and 2015 (Li et al., 2019) and the decline has likely accelerated since that time. This highlights the relevance of temporal changes in glacier extent, which are currently not represented in the SPEAR models. The current dataset used in SPEAR_HI may most accurately represent glacier extent in the 1970s and overestimate glacier extent thereafter with implications for model simulation accuracy. It is beyond the scope of the present work to address the issue of temporal change and variability, but it is highlighted as a point for future research.

Second, the glacier and ice sheet dataset used in SPEAR_HI was remapped from the original 1° resolution dataset described above to the 25 km SPEAR_HI grid in such a way that large (~1° x 1°) blocks of glaciated area were retained in the finer resolution version (Figure 1). This resulted in what was effectively a 1° (~100 km) resolution glacier layer being used in a 25 km model, negating some of the benefits of the higher model resolution. Through their effects on land surface albedo and other surface properties, these large glacier areas resulted in block-like features in a range of climate variables, including near-surface air temperature (Figure 2). These artifacts were particularly apparent in highly glaciated regions such as High Mountain Asia. Figures in this document focus on the High Mountain Asia region for illustration purposes, however similar issues were found in other global regions.

This document describes the development of a new, higher-resolution fractional glacier and ice sheet area dataset that is based on more recent observations. The dataset is designed for use in SPEAR_HI and subsequent, higher-resolution, SPEAR models. The dataset as well as all code and data needed to recreate the dataset are available at https://doi.org/10.5281/zenodo.6425852 (Lute, 2022).

.

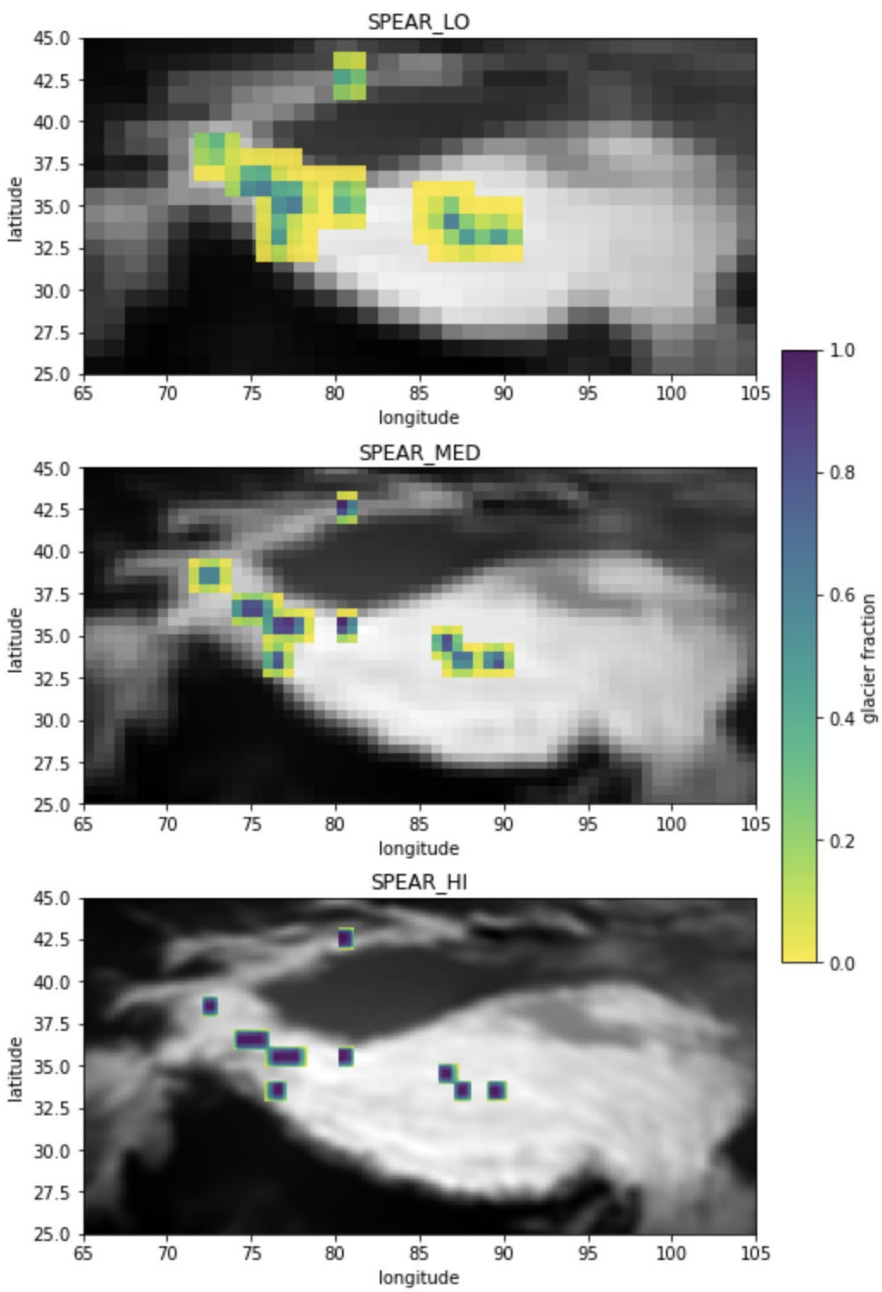

Figure 1: Fraction of land covered by glaciers in the High Mountain Asia region in SPEAR_LO (100 km; top), SPEAR_MED (50 km; middle), and SPEAR_HI (25 km; bottom). Grayscale background shows model land surface elevation with darker colors indicating lower elevations. Colorbar shows glacier fraction.

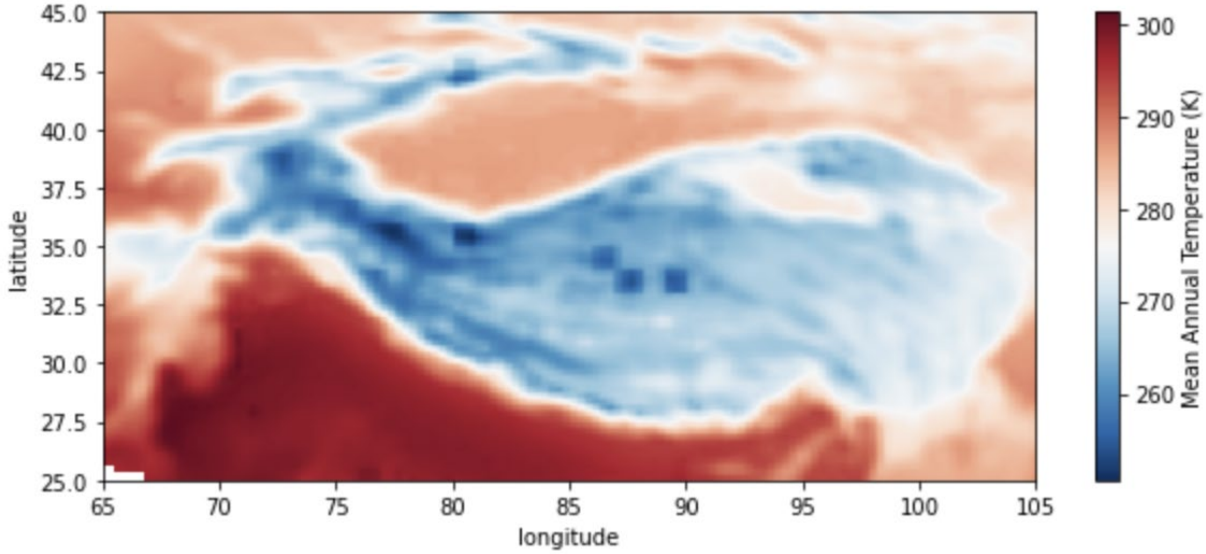

Figure 2. Ensemble average mean annual near-surface air temperature from SPEAR_HI historical runs for the period 1971-2000 over the High Mountain Asia region.

Data and Methods

Existing Data Products

The Randolph Glacier Inventory version 6.0 (RGI 6.0; RGI Consortium, 2017) is the most spatially comprehensive global glacier outline dataset available. It provides a snapshot of glacier outlines around the beginning of the 21st century in shapefile format. The RGI is supplemental to the multitemporal Global Land Ice Measurements from Space (GLIMS) database which includes additional details about global glaciers such as hypsometry and tracks changes over time.

Recognizing the utility of gridded glacier datasets, particularly for climate change applications, Li et al., (2021) recently developed gridded versions of the RGI dataset at multiple spatial resolutions (1° × 1°, 0.5° × 0.5°, 0.25° × 0.25° and 0.1° × 0.1°). Their approach was to create a global grid at the desired spatial resolution, disaggregate the glaciers into the grid cells, reproject the data, and then calculate the glacier area within each grid cell. They showed that, compared to existing gridded glacier area datasets, this approach resulted in a large reduction in glacier area errors relative to glacier areas calculated directly from the RGI shapefiles. The resulting gridded glacier area data and the code to develop the gridded glacier area data from the RGI shapefiles are available at https://github.com/rylanlee/RGI-Gridded.

The Li et al., (2021) datasets provide an excellent starting point for the development of a new glacier and ice sheet fractional area dataset for SPEAR. However, there are two primary modifications that are needed. First, the RGI and the Li et al., (2021) datasets do not include the Greenland and Antarctic ice sheets. These regions need to be represented in the fractional area dataset supplied to SPEAR. Second, the Li et al., (2021) dataset provides glaciated area whereas the SPEAR model requires values representing the fraction of land that is covered by glaciers or ice sheets (hereafter referred to as fractional glacier area).

To address these concerns, supplementary shapefiles for the Greenland and Antarctic ice sheets were identified, the code of Li et al., (2021) was adapted to create gridded glacier area datasets for these regions, a land area dataset was created on a matching grid, and fractional glacier area on the grid was calculated. These steps are described in more detail below. Data processing was performed in Python 3.7 using Jupyter Lab at the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory. The Python environment is described in the environment.yml file. All scripts and datasets mentioned below can be found at https://doi.org/10.5281/zenodo.6425852 (Lute, 2022). Scripts are located in the code subfolder and datasets are located within the data subfolder. Data locations referred to below are subfolders within the data folder of the repository. Required packages are listed at the top of each script.

Step 1: Prepare glacier and ice sheet outlines

Outlines of all glaciers globally are available from the RGI version 6.0. RGI glacier outlines are grouped into 19 regions and a shapefile is available for each one. These shapefiles were downloaded from https://www.glims.org/RGI/rgi60_dl.html and are available in the 00_rgi60/ subfolder.

The RGI includes the glaciers along the Greenland periphery, but does not include the Greenland ice sheet. Shapefiles of glacier catchments covering the Greenland ice sheet were downloaded from https://datadryad.org/stash/dataset/doi:10.7280/D1WT11 (Mouginot & Rignot, 2019) and are available in the doi_10.7280_D1WT11__v1/ subfolder. These shapefiles were merged (i.e. combined) with the RGI Greenland Periphery region (RGI region 5) shapefile and dissolved (aggregated into one feature with internal boundaries removed) to avoid double counting of regions contained in both datasets. The resulting Greenland glacier and ice sheet shapefile (hereafter referred to as Greenland_all) is available in the greenland_merged/ subfolder. To reduce the computational expense of calculating glacier area on a 0.1° grid across the ice sheet, the interior region of the shapefile (hereafter referred to as Greenland_center) was extracted. A buffer operation was used to extract the domain areas that are inside the initial shapefile and at least 15 km from the edge of the initial shapefile. The buffer distance (15 km) was chosen in order to ensure that the region extracted was 100% glaciated. A range of other buffer distances would likely work equally well. This enabled fractional glacier area to be set to 1 for this entire region and glacier area only had to be calculated for the peripheral areas, as described in Step 4. The preparation of the Greenland shapefile is accomplished using make_greenland_ice_shapefile.ipynb.

The RGI includes glaciers in the Antarctic and subantarctic regions, but does not include the Antarctic ice sheet. A shapefile of the Antarctic ice shelf, excluding sea ice, was downloaded from the US National Ice Center (https://usicecenter.gov/Resources/AntarcticShelf, 2019 version) and is available in the USNIC_ANTARC_shelf_2019/ subfolder. The ice shelf shapefile was merged with the RGI Antarctic and Subantarctic region (RGI region 19) shapefile to create a shapefile that includes the Antarctic ice sheet and smaller regional ice bodies. The resulting Antarctic ice sheet and glaciers shapefile is available in antarctica_merged/ subfolder. The preparation of the Antarctic region shapefile is accomplished using make_antarctica_ice_shapefile.ipynb. The modified approach described above for Greenland, in which a center shapefile was created, was not used for Antarctica due to the complications associated with working with shapefile projections over the poles.

Step 2: Develop global grid

The next step was to create a global grid onto which the land and glacier shapefiles could be disaggregated. This was accomplished using a wrapper (create_global_grid.ipynb) around the create_vector_polygon function of Li et al., (2021). The grid resolution parameter was set to 0.1° x 0.1°. This spatial resolution was chosen to balance computational concerns with the goal of creating a gridded layer that was fine enough to summarize well when translated to the native SPEAR grid. The resulting shapefile of the global grid is available in the global_grid_0.1/ subfolder.

Step 3: Calculate land area on global grid

The denominator for the fractional glacier area calculation is the area of land in each grid cell. Land area in each grid cell was calculated using the grid_glacier_area function from Li et al., (2021) which finds the intersection between a shapefile (in this case the land shapefile) and each grid cell in turn, reprojects the intersected portion to the Mollweide projection, and then calculates the intersected area within each cell. The land shapefile used was the 10 m global coastline dataset (version 4.1.0) available from Natural Earth (https://www.naturalearthdata.com/downloads/10m-physical-vectors/10m-land/), which is available in the ne_10m_land/ subfolder. The result of this step is a shapefile of grid cells where each grid cell has a land area value (km^2) (available in the ne_10m_land/ subfolder). This processing was accomplished using calc_land_area_on_global_grid.ipynb.

Step 4: Calculate glacier and ice sheet area on global grid

The numerator for the fractional glacier area calculation is the area of glaciers or ice sheets in each grid cell. This is calculated using the grid_glacier_area function as described in Step 3. For each RGI glacier region, the regional glacier shapefile is imported and then clipped to the land shapefile to ensure that only glacier areas over land are counted. This excludes, for example, floating ice shelves and floating portions of tidewater glaciers. The glacier area within each grid cell is then calculated as described in Step 3. For the Antarctic region, the shapefile created in Step 1, which includes the Antarctic ice sheet, is used instead of the RGI shapefile. This processing was accomplished using calc_glacier_area_on_global_grid.ipynb.

For the Greenland region, a modified approach was used to minimize computation time. The Greenland_all shapefile and Greenland_center shapefile developed in Step 1 were imported, clipped to the land shapefile, and joined to the global grid shapefile. The peripheral regions were then extracted by subtracting the gridded Greenland_center shapefile from the gridded Greenland_all shapefile, resulting in a shapefile of grids covering the Greenland periphery (hereafter referred to as Greenland_outside) for which glacier area was calculated. The gridded Greenland_center shapefile was saved without area calculations. This processing was accomplished using calc_glacier_area_on_global_grid_greenland.ipynb.

The gridded glacier area files for all regions are available in the 00_rgi60_gridded/ subfolder.

Step 5: Calculate glacier fraction

For all regions except central Greenland, the gridded glacier area shapefile was imported and joined with the gridded land area shapefile. The glaciated fraction was calculated by dividing the glaciated area in each grid cell by the land area in each grid cell, resulting in glaciated fractions ranging from 0 to 1. For central Greenland, all cells in the gridded Greenland_center shapefile were assigned a glacier fraction of 1. Glaciated fraction data was then repackaged into a netcdf file (available in the global_gridded_glacier_fraction/ subfolder) following CF conventions for spatial attributes. This processing was accomplished using calc_glacier_fraction_to_netcdf.ipynb.

Discussion

The new fractional glacier area dataset described here provides a much more realistic representation of glacier coverage than the previous dataset employed in SPEAR_HI (Figure 3). The large (~1° x 1°) blocks of glaciated areas that characterize the previous dataset are absent from the new dataset. There are many areas which have no glacier coverage in the previous dataset, but which do have glaciers according to the RGI dataset and other sources. In the new dataset, these areas have non-zero glacier fractions.

While the new glacier fraction dataset represents a substantial improvement over the previous dataset, there remains room for improvement. Many of the glaciers in the RGI dataset have significant debris cover. A more nuanced dataset might differentiate between pure ice glaciers and debris covered glaciers in order to more accurately represent land surface albedo. Given ongoing and projected rapid deglaciation in many global regions (Clarke et al., 2015; Gardner et al., 2013; Radić et al., 2014), the glacier dataset should be updated regularly if the goal is to reflect current conditions. However, for models that treat glaciers in a static matter this may not be important.

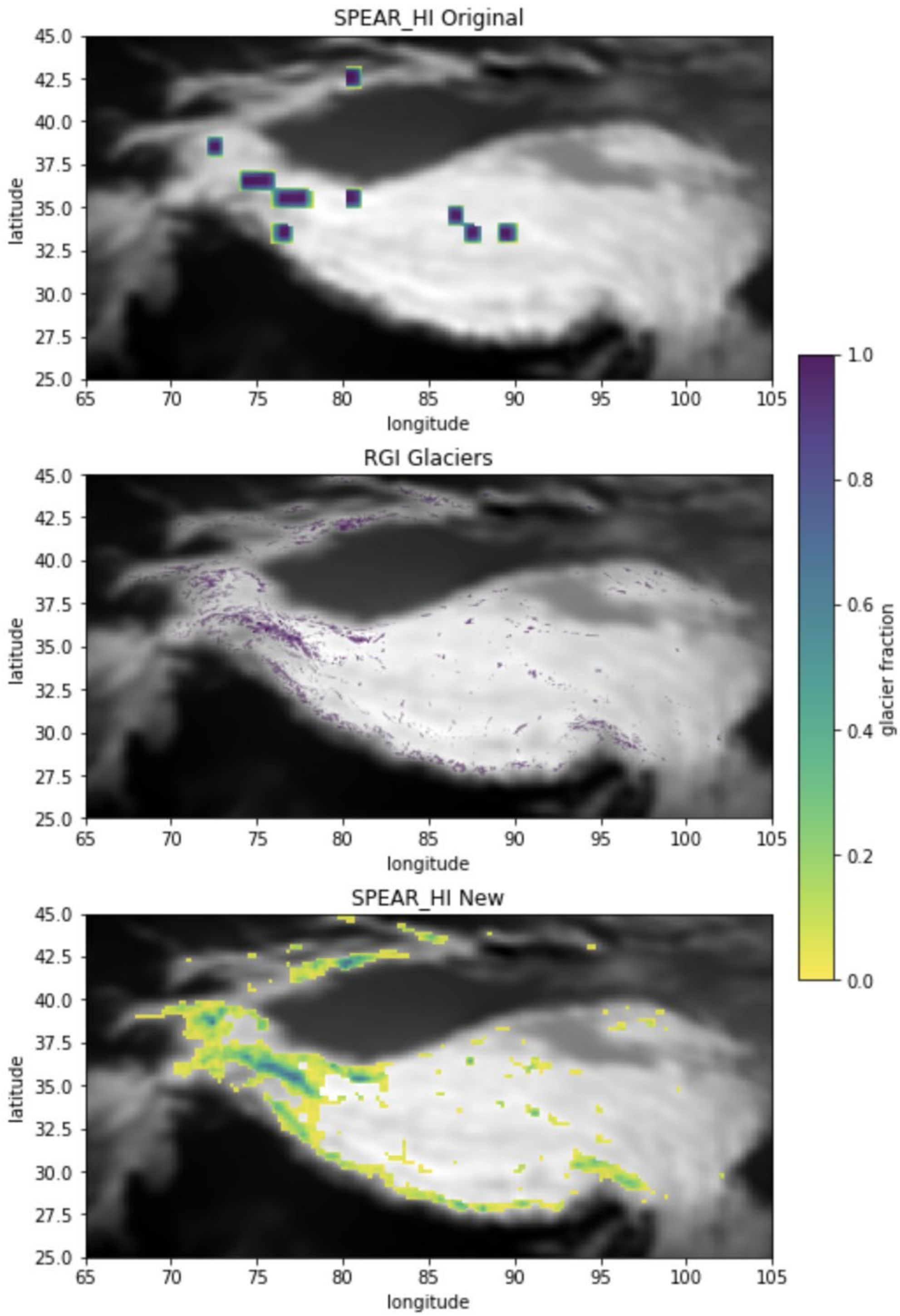

Figure 3. Fractional glacier area in the High Mountain Asia region in the previous SPEAR_HI fractional glacier area dataset (25 km; top), the RGI glacier shapefile (middle), and the fractional glacier area dataset described in this document (25 km; bottom). All glacier polygons in the RGI dataset were assigned a fractional glacier area value of 1. The bottom panel shows the 0.1° resolution dataset described in this document interpolated to the SPEAR_HI grid. Grayscale

background shows the SPEAR_HI land surface elevation with darker colors indicating lower elevations. Colorbar shows glacier fraction.

Acknowledgements

I acknowledge GFDL resources made available for this research.

Funding support for this work was provided through Interagency Agreement Number 80HQTR21T0015 from NASA Earth Science Division's High Mountain Asia program.

Drs. William Cooke and Sergey Malyshev are acknowledged for their comments and suggestions on an internal review of the manuscript.

References

Clarke, G. K. C., Jarosch, A. H., Anslow, F. S., Radić, V., & Menounos, B. (2015). Projected deglaciation of western Canada in the twenty-first century. *Nature Geoscience*, *8*(5), 372–377. https://doi.org/10.1038/ngeo2407

Food and Agriculture Organization (FAO) of the United Nations, 1970-78, Soil map of the world, scale 1:5,000,000, volumes I- X: United Nations Educational, Scientific, and Cultural Organization, Paris.

Gardner, A. S., Moholdt, G., Cogley, J. G., Wouters, B., Arendt, A. A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W. T., Kaser, G., Ligtenberg, S. R. M., Bolch, T., Sharp, M. J., Hagen, J. O., van den Broeke, M. R., & Paul, F. (2013). A Reconciled Estimate of Glacier Contributions to Sea Level Rise: 2003 to 2009. *Science*, *340*(6134), 852–857. https://doi.org/10.1126/science.1234532

Li, Y., Li, F., Shangguan, D., & Ding, Y. (2021). A new global gridded glacier dataset based on the Randolph Glacier Inventory version 6.0. *Journal of Glaciology*, *67*(264), 773–776. https://doi.org/10.1017/jog.2021.28

Li, Y.-J., Ding, Y.-J., Shangguan, D.-H., & Wang, R.-J. (2019). Regional differences in global glacier retreat from 1980 to 2015. *Advances in Climate Change Research*, *10*(4), 203–213. https://doi.org/10.1016/j.accre.2020.03.003

Lute, A.C. (2022). A 21st century high-resolution glacier and ice sheet fractional area dataset: Code and Data (v1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.6425852

Milly, P. C. D., & Shmakin, A. B. (2002). Global Modeling of Land Water and Energy Balances. Part I: The Land Dynamics (LaD) Model. *Journal of Hydrometeorology*, *3*(3), 283–299. https://doi.org/10.1175/1525-7541(2002)003<0283:GMOLWA>2.0.CO;2

Mouginot, J., & Rignot, E. (2019). *Glacier catchments/basins for the Greenland Ice Sheet* (Version 1, p. 4137543 bytes) [Data set]. Dryad. https://doi.org/10.7280/D1WT11

Radić, V., Bliss, A., Beedlow, A. C., Hock, R., Miles, E., & Cogley, J. G. (2014). Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models. *Climate Dynamics*, *42*(1–2), 37–58. https://doi.org/10.1007/s00382-013-1719-7

RGI Consortium (2017). Randolph Glacier Inventory (RGI) – A Dataset of Global Glacier Outlines: Version 6.0. Technical Report, Global Land Ice Measurements from Space, Boulder, Colorado, USA. Digital Media. doi:10.7265/N5-RGI-60

Zobler, L. (1986). A world soil file for global climate modeling. National Aeronautics and Space Administration Tech. Memo. 87802, 33 pp.