



MEaSURES Greenland Annual Ice Sheet Velocity Mosaics from SAR and Landsat, Version 5

USER GUIDE

How to Cite These Data

As a condition of using these data, you must include a citation:

Joughin, I. 2023. *MEaSURES Greenland Annual Ice Sheet Velocity Mosaics from SAR and Landsat, Version 5*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. <https://doi.org/10.5067/USBL3Z8KF9C3>. [Date Accessed].

Literature Citation

As a condition of using these data, we also request that you acknowledge the author(s) of this data set by referencing the following peer-reviewed publications:

Joughin, I., B. Smith, I. Howat, T. Scambos, and T. Moon. 2010. Greenland flow variability from ice-sheet-wide velocity mapping, *Journal of Glaciology*. 56. 415-430.
<https://doi.org/10.3189/002214310792447734>

Joughin, I., B. Smith, and I. Howat. 2018. Greenland Ice Mapping Project: ice flow velocity variation at sub-monthly to decadal timescales, *The Cryosphere*. 12. 2211-2227. <https://doi.org/10.5194/tc-12-2211-2018>

FOR QUESTIONS ABOUT THESE DATA, CONTACT NSIDC@NSIDC.ORG

FOR CURRENT INFORMATION, VISIT <https://nsidc.org/data/NSIDC-0725>



National Snow and Ice Data Center

TABLE OF CONTENTS

1	DATA DESCRIPTION.....	2
1.1	Parameters	2
1.2	File Information.....	2
1.2.1	Format	2
1.2.2	File Contents.....	2
1.2.3	Naming Convention.....	2
1.3	Spatial Information.....	4
1.3.1	Coverage	4
1.3.2	Resolution.....	5
1.3.3	Geolocation.....	5
1.4	Temporal Information	7
1.4.1	Coverage	7
1.4.2	Resolution.....	7
2	DATA ACQUISITION AND PROCESSING.....	7
2.1	Acquisition.....	7
2.1.1	Annual Variation in Data Acquisition	7
2.2	Processing	8
2.3	Baseline Fits.....	8
2.3.1	Aggregation and Weighting	9
2.3.2	Submergence/Emergence Velocity.....	9
2.3.3	Temporal Offset Calculation	9
2.3.4	Interpolated Points	10
2.3.5	Areas with No Data	10
2.3.6	GDAL-Generated Cloud Optimized GeoTIFFs	11
2.4	Quality, Errors, and Limitations	11
2.5	Instrumentation.....	12
3	SOFTWARE AND TOOLS.....	12
4	VERSION HISTORY	13
5	RELATED DATA SETS	14
6	RELATED WEBSITES.....	14
7	CONTACTS AND ACKNOWLEDGMENTS	14
7.1	Contacts.....	14
7.2	Acknowledgements	15
8	REFERENCES	15
9	DOCUMENT INFORMATION	16
9.1	Publication Date	16
9.2	Date Last Updated.....	16

1 DATA DESCRIPTION

This data set, part of the NASA Making Earth System Data Records for Use in Research Environments (MEaSURES) program, contains annual ice velocity mosaics for the Greenland Ice Sheet posted at 200 m. Velocities are estimated using Synthetic Aperture Radar (SAR) data from TerraSAR-X/TanDEM-X (TSX/TDX) and Sentinel-1A and -1B and optical imagery from Landsat 8 and 9.

1.1 Parameters

Velocity estimates, in meters per year, are provided as velocity magnitude (v_v), x and y component velocities (v_x , v_y), and x and y component velocity errors (e_x , e_y). In addition, to assess potential temporal skew in the velocity estimates, a temporal offset parameter (dT) is included that reports the number of days between the measurement date¹ and the midpoint date of the measurement period.

1.2 File Information

1.2.1 Format

Data are provided as cloud optimized GeoTIFFs (.tif) and shapefiles. TIFF and JPEG browse files are also available.

1.2.2 File Contents

Data files are available for each data year. Each of the parameters listed above in “Section 1.1 | Parameters” is provided as a separate GeoTIFF file. Annual shapefiles are also available that indicate the source of the image pairs (SAR or Landsat 8/9) used to produce the mosaics.

1.2.3 Naming Convention

1.2.3.1 GeoTIFF

Naming Convention:

[product name]_[start date]_[end date]_[parameter]_[version].[ext]

Example:

GL_vel_mosaic_Annual_01Dec16_30Nov17_vv_v05.0.tif

¹Because of the data aggregation process, the true date represented by the data may differ from the nominal midpoint date of the measurement period. See “2.3.3 | Temporal Offset Calculation” for details.

GL_vel_mosaic_Annual_01Dec16_30Nov17_vx_v05.0.tif
 GL_vel_mosaic_Annual_01Dec16_30Nov17_vy_v05.0.tif
 GL_vel_mosaic_Annual_01Dec16_30Nov17_ex_v05.0.tif
 GL_vel_mosaic_Annual_01Dec16_30Nov17_ey_v05.0.tif
 GL_vel_mosaic_Annual_01Dec16_30Nov17_dT_v05.0.tif

Table 1. GeoTIFF File Naming Convention

Variable	Description
product name	GL_vel_mosaic_Annual (Greenland Annual Ice Sheet Velocity Mosaics)
start date	Start date of measurement period (DDMMYY)
end date	End date of measurement period (DDMMYY)
parameter	vv (velocity magnitude) vx, vy (component velocity) ex, ey (component velocity error) dT (temporal offset)
version	Two digit version, plus release number (when applicable). E.g., V04.0 = Version 4 (initial release).
ext	File extension (.tif)

1.2.3.2 Shapefile

Naming Convention:

[product name]_[start date]_[end date]_[source]_[version].[ext]

Example:

GL_vel_mosaic_Annual_01Dec16_30Nov17_LS_v05.0.dbf
 GL_vel_mosaic_Annual_01Dec16_30Nov17_LS_v05.0.prj
 GL_vel_mosaic_Annual_01Dec16_30Nov17_LS_v05.0.shp
 GL_vel_mosaic_Annual_01Dec16_30Nov17_LS_v05.0.shx

The following table describes the variables in the shapefile file naming convention:

Table 2. Shapefile File Naming Convention

Variable Name	Description
product name	GL_vel_mosaic_Annual (Greenland Annual Ice Sheet Velocity Mosaics)
start date	Start date of measurement period (DDMMYY)
end date	End date of measurement period (DDMMYY)
source	SAR or LS (Landsat 8/9)
version	Two digit version, plus release number (when applicable). E.g., V05.0 is the initial release of Version 5.
ext	File extension. For this data set, a complete shapefile consists of four file types: <ul style="list-style-type: none"> .dbf (dBASE table file) .shp (main file) .shx (index file) .prj (projection definition file)

1.2.3.3 Browse Images

Browse images follow the same naming convention described above, but include the word “browse” in the file name and terminate with either the “tif” or “jpg” file extension.

1.3 Spatial Information

1.3.1 Coverage

Data span the Greenland Ice Sheet as follows:

Northernmost Latitude: 83° N

Southernmost Latitude: 58.5° N

Easternmost Longitude: 8.32° W

Westernmost Longitude: 90.9° W

1.3.2 Resolution

Data are posted at 200 m. JPEG browse files are 500 m resolution.

Note that this resolution does not reflect the true "on the ground" resolution. The velocities are derived from source data with spatially varying averages that range from a few hundred meters to 1.5 km, making it difficult to specify the resolution at any point.

For example, some estimates represent the average of 30 or more individual measurements. While this enhances the final resolution to some degree relative to the individual source products, the amount is not well quantified.

For work requiring finer resolution, users may prefer the individual DLR TerraSAR-X (TSX)/TanDEM-X (TDX) and USGS Landsat data where available (see [MEaSURES Greenland Ice Velocity: Selected Glacier Site Velocity Maps from InSAR](#) and [MEaSURES Greenland Ice Velocity: Selected Glacier Site Velocity Maps from Optical Images](#)).

1.3.3 Geolocation

The following tables provide information for geolocating this data set:

Table 3. NSIDC Sea Ice Polar Stereographic North (EPSG:3413)

Geographic Coordinate System	WGS 84
Projected Coordinate System	WGS 84 / NSIDC Sea Ice Polar Stereographic North
Longitude of True Origin	-45
Latitude of True Origin	70
Scale factor at longitude of true origin	1
Datum	WGS 1984
Ellipsoid/spheroid	WGS 84
Units	meter
False Easting	0
False Northing	0
EPSG Code	3413
PROJ4 String	+proj=stere +lat_0=90 +lat_ts=70 +lon_0=-45 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m +no_defs
Reference	https://epsg.org/crs_3413/WGS-84-NSIDC-Sea-Ice-Polar-Stereographic-North.html

Table 4. World Geodetic System 1984 (EPSG:4326)

Geographic Coordinate System	WGS 84
Projected Coordinate System	N/A
Longitude of True Origin	0°
Latitude of True Origin	N/A
Scale factor at longitude of true origin	N/A
Datum	World Geodetic System 1984
Ellipsoid/spheroid	WGS 84
Units	degree
False Easting	N/A
False Northing	N/A
EPSG Code	4326
PROJ4 String	+proj=longlat +datum=WGS84 +no_defs
Reference	https://epsg.org/crs_4326/WGS-84.html

1.4 Temporal Information

1.4.1 Coverage

1 December 2014 – 30 November 2023

1.4.2 Resolution

Annual

2 DATA ACQUISITION AND PROCESSING

2.1 Acquisition

The velocity mosaics in this data set were produced from data acquired by the European Space Agency (ESA) Sentinel-1A and Sentinel-1B satellites, supplemented with TSX/TDX data for coastal outlets. The data were acquired in either 12-day (through Sept 2016) or 6-day repeat cycles (October 2016 forward). In cases of missing acquisitions, the repeat periods may be longer (integer multiples of 6 or 12 days) for some of the image pairs.

In addition, during periods with sufficient daylight, SAR-derived velocities were supplemented with velocities derived from optical imagery acquired by Landsat 8 and Landsat 9.

2.1.1 Annual Variation in Data Acquisition

2015 (Dec 1, 2014 – Nov 30, 2015)

Sentinel-1A data acquisitions began in 2015, but the acquisition rates were not as regular as later years. As a result, these data tend to be somewhat noisier than the 2016 data, particularly in the middle of the ice sheet. In addition, the sampling of coastal regions is more irregular (there are gaps in the temporal coverage where TSX/TDX data were not acquired by the satellite for a month or more), which reduces the averaging of seasonal variation.

2016 (Dec 1, 2015 – Nov 30, 2016)

For this year, the six Sentinel-1A tracks that image the majority of the Greenland coast were collected for almost every 12-day satellite repeat cycle. Beginning in October 2016, Sentinel-1B started acquiring data over Greenland in an orbit that lags Sentinel-1A by six days, providing better coverage and thus more correlations in the data. As a result, the accuracy for these mosaics is considerably better than the mosaics for 2015 for most regions.

2017 (Dec 1, 2016 – Nov 30, 2017)

These products are similar to the earlier 2015 and 2016 products. The major difference is that this is the first year that regular 6-day coverage occurred throughout the year, which should improve performance on fast moving glaciers. In addition, the Copernicus Sentinel mission improved coverage for the southern part of Greenland in mid-2017, so the results should be improved for areas south of 67.5 degrees.

2018 (Dec 1, 2017 – Nov 30, 2018)

These products follow the same specifications as the previous year's release, with the following minor differences: some data using a few scenes from the COnstellation of small Satellites for the Mediterranean basin Observation (COSMO-SkyMed) were included; some of the glaciers which were monitored by TSX in past years are covered by other instruments during this year.

2019 (Dec 1, 2018 – Nov 30, 2021)

No changes. See specifications for previous releases.

2023 (Dec 1, 2021 – Nov 30, 2022)

Data in the interior are slightly noisier for this year due to the reduced Sentinel-1 acquisitions following the failure of Sentinel-1B. In addition, from Jan 1, 2022 onward, these products utilize Landsat 9 observations when available.

2.2 Processing

These mosaics were computed as averages of all available data at each point, weighted by their respective errors following Joughin, 2002. In addition to speckle/feature tracking, interferometric phase data are utilized when possible to improve accuracy (Joughin et al., 2017).

With Sentinel-1 TOPS mode, azimuth motion introduces phase discontinuities at burst boundaries (roughly every 20 km) because the radar squint angles differ at the fore and aft edges of each burst. These errors were corrected by using an existing velocity map² to model and remove burst discontinuities similar to the procedure described by Andersen et al. (2020). Phase discontinuities introduced by the ionosphere were reduced by processing the interferograms using the InSAR Computing Environment (ISCE) with the ionospheric correction enabled (Fattahi et al., 2017).

2.3 Baseline Fits

Each azimuth and range offset swath product used to produce the mosaics must be calibrated to determine parameters related to the relative positions of the satellites when the images in a pair

²MEaSURES Multi-year Greenland Ice Sheet Velocity Mosaic, Version 1 (NSIDC-0670)

were collected. As such, regressions are used to construct baseline fits to sets of control points with known velocity and elevation, thus capturing the along-track variation in the parameters.

Along the slow-moving ice divides, where speeds are < 5 m/y, the data are calibrated using balance velocities³ (Bamber et al., 2000), estimated by computing surface mass balance (SMB) as the average of two models—the Regional Atmospheric Climate Model, Version 2.3 (RACMO2.3) and the Modèle Atmosphérique Régionale, Version 3.12 (MAR3.12)—both averaged over the period from 1958 to 2021.

Because greater reliance can be placed on parameters derived from Sentinel-1 orbital state vectors, the data are calibrated by using a fitting process to determine a constant for each parameter, rather than a quadratic function, allowing the along-track dependence to be determined directly from the state vectors.

For years where data are not well controlled (sparse ground control points), control points from other years with adequate controls are used as a substitute. This greatly improves consistency of the data from year to year, and while it could mask some true change, the errors without this procedure are far larger than any change likely to occur.

2.3.1 Aggregation and Weighting

For each year, all available data are aggregated and combined in an error-weighted method to achieve an optimal estimate with respect to error reduction. Due to limited coverage or lack of unsuccessful matches, some data gaps exist such that the full annual period may not be sampled uniformly.

2.3.2 Submergence/Emergence Velocity

The submergence/emergence velocity (i.e., the vertical motion of the ice surface) is removed using an average of RACMO2.3 and MAR3.12 SMB for the period 1958 to 2021.

2.3.3 Temporal Offset Calculation

As a measure of temporal skew, a mean temporal offset (dT) is provided which reports the number of days between the measurement date—the dates of the image pairs, adjusted by any weighting applied when computing the component velocities—and the midpoint date of the measurement period.

³Balance velocities represent depth-averaged speeds in the downslope direction that would result if the amount of snow added annually to a volume of the ice sheet equaled the amount of mass lost from that volume via advection or melting.

In estimating velocity, different weights are used for the v_x and v_y components, so an intermediate weight is used for the individual dTs. In the final mosaicking step, any data with dT greater than one-half the output interval was discarded. As a result, for the annual product, the time stamp error is less than or equal to approximately 183 days.

In detail, dT is computed as follows:

1. Using a Day of the Year (DOY) calendar, determine the midpoint for the measurement period i.e., quarterly, monthly, or annual.
2. For each pixel, identify the image pairs used as input for velocity and calculate the central DOY date.
3. Calculate a weighted average central date for that pixel by using an intermediate weight, based on the weights used to compute the v_x and v_y components.
4. $dT = \text{weighted average central date} - \text{midpoint}$.

Although the averaged dT value provides some idea of the deviation from nominal date, users should be cautious when using dT to correct dates.

For example, if the mosaic covers the period from 1 December 2014 to 30 November 2015, the nominal midpoint would be 31 May 2015, and thus a value of $dT = 5$ would indicate that 05 June better represents the midpoint. However, users should note that data gaps can lead to some convoluted cases in which, e.g., $dT = 5$ despite no observation having been acquired five days after the midpoint date.

The data providers recommend using dT to flag potential time skew issues rather than for date correction. In cases where a large temporal skew exists, other GrIMP products with finer temporal sampling are likely better suited for analyzing temporally varying behavior.

2.3.4 Interpolated Points

Small gaps in the final maps have been filled via interpolation. These points can be identified as those that have valid velocity data but no corresponding error estimate. See Joughin et al. (2002) for more detail on errors and how they were computed.

2.3.5 Areas with No Data

Areas with no data correspond either to regions where no data were acquired or where the interferometric or optical correlation was insufficient to produce an estimate. This occurs most often in areas with high snow accumulation. The no data value for v_v , e_x , and e_y files is -1. The no data value for v_x , v_y , and dT is -2e9.

2.3.6 GDAL-Generated Cloud Optimized GeoTIFFs

The GeoTIFFs were generated using Geospatial Data Abstraction Library (GDAL), to make them compatible with the latest cloud optimized GeoTIFF format. GDAL generates previews for Cloud Optimized GeoTIFFs; however, the software uses cubic interpolation that results in minor artifacts around the lower resolution previews. Averaging is used to avoid this issue.

 When GDAL creates cloud optimized GeoTIFFs, it writes image statistics directly to the file header.

2.4 Quality, Errors, and Limitations

Recalibrations used to create this data set substantially improve the accuracy of the products, especially in the interior of the ice sheet, with errors well under 1 m/yr. However, as with previous versions, these data do not represent true annual averages due to the weighting schemes. For example, in some places mid-summer may be weighted more heavily than mid-winter due to the seasonal availability of Landsat 8 data. Similarly, clouds or large snow accumulation events may affect the seasonal distribution of the data.

As a result, these data should not be used to determine inter-annual change for interior regions of the ice sheet (roughly defined as areas above 2,000 m). In outlet glaciers close to the coast where the baselines are well constrained by bedrock, the velocity mosaics are better suited to this task. However, care should be exercised in interpreting any change observed in intermediate regions (roughly 1000 m to 2000 m), i.e., avoid areas where the observed changes seem to follow a satellite swath boundary (Refer to Figure 5 in Phillips et al., 2013, for an example.).

In general, the error estimates represent the average behavior of the data. This means that errors may be much lower than reported in some areas and much greater in others; care should be taken when assigning statistical significance based on the errors, especially given that the errors can be correlated over large areas. For example, even if the errors are correct in a global sense, one might compare two mosaics and find a large difference over 5% of the ice sheet. However, because errors can be spatially correlated over broad areas, one should not assume significance at the 95% confidence level; this might be precisely the 5% that statistically should exceed the errors because the errors are not uniformly distributed. By contrast, if the errors were completely uncorrelated one could average over neighborhoods to reduce the error.

While the data are posted at 200 m, the true resolution varies between a few hundred meters to 1.5 km. *Posting* represents the spacing between samples and should not be confused with the resolution at which the data were collected. Many small glaciers are resolved outside the main ice sheet, but for narrow (<1 km) glaciers, the velocity represents an average of both moving ice and stationary rock. As a result, while the glacier may be visible in the map, the actual speed may be

underestimated. For smaller glaciers, interpolation produces artifacts where the interpolated value is derived from nearby rock, causing apparent stationary regions in the middle of otherwise active flow. The data have been screened to remove most of these artifacts, but should be used with caution.

In areas where Sentinel-1A and -1B ascending and descending crossing orbit data were available, an error-weighted range-offset-only solution was included in the velocity algorithm. Where these data are included, the errors are generally substantially lower than solutions with azimuth offsets, which can be subject to large errors due to ionospheric streaking. However, by virtue of the error weighting, the range-offset-only solutions tend to dominate the aggregate output and yield more accurate results.

Regarding the correction for ice-equivalent submergence/emergence velocity, recent increases in melt may impact these estimates. However, this parameter should evolve at decadal or greater timescales for much of the ice sheet.

In addition, this correction does not account for firn compaction due to the large uncertainties in penetration depth and compaction rates. For the bare-ice zone where the correction tends to be the largest, this omission should have no effect. For firn covered areas, the correction may underestimate the true submergence/emergence velocity by up to a few tens of centimeters per year. However, the results still represent an overall improvement in accuracy.

Finally, this product uses a variation of the GrIMP DEM (see [NSIDC-0715](#)) which has a lower resolution of 270 m and utilizes geoidal heights for the ocean. The DEM also contains a correction to a 15m horizontal shift that was identified previously.

2.5 Instrumentation

- European Space Agency (ESA)
 - [Sentinel-1](#)
- Deutsches Zentrum für Luft- und Raumfahrt (DLR)
 - [TerraSAR-X \(TSX\)](#)
 - [TanDEM-X \(TDX\)](#)
- U.S. Geological Survey (USGS)
 - [Landsat 8](#)
 - [Landsat 9](#)

3 SOFTWARE AND TOOLS

GeoTIFF files and shapefiles can be viewed with a variety of Geographical Information System (GIS) software packages including [QGIS](#) and [ArcGIS](#).

4 VERSION HISTORY

📌 Version 1 of this data set was published in October 2017 and updated annually thereafter. In April 2020, the data access location was changed and the data files renamed to conform to NASA's version-numbering standard.

Table 5. Version History

Version	Date	Description of Changes
5.0	Sep 2024	<ul style="list-style-type: none"> Added coverage from 1 Dec 2022 through 30 Nov 2023. An update to the Python library used to generate this data set's ShapeFiles has resulted in field names being truncated to 10 characters instead of 11. As such, the "PercentGood" field name appears as "PercentGoo" in all ShapeFiles added after Dec 2023.
5.0	Dec 2023	<ul style="list-style-type: none"> Improved correction for submergence/emergence velocity using an average of RACMO2.3 and MAR3.12 SMB for the period from 1958 to 2021. Calibration improved by using an improved balance velocity estimate, computed as the average of RACMO2.3 and MAR3.12, and by excluding GPS points >2000 m from the 1990s. Solid Earth tides corrected using PySolid (https://github.com/insarlab/PySolid) Includes Landsat 9 data from 2022 onward Landsat-specific data files now designated by "LS" in the file name (instead of "LS8" as in previous versions).
4.0	Aug 2022	<ul style="list-style-type: none"> Temporal coverage extended Data recalibrated relative to previous versions to reduce biases imposed by quadratic fits to control points Correction added for the submergence/emergence velocity Addition of interferometric phase data where available.
3.0	Jun 2021	<ul style="list-style-type: none"> GDAL (3.2.1) used to create cloud optimized GeoTIFFs Temporal coverage updated Data reprocessed utilizing a corrected DEM.

Version	Date	Description of Changes
2.0	Feb 2020	<ul style="list-style-type: none"> • New file naming convention. • Data set temporal range increased by one year from: 01 December 2014 to 30 November 2019. • Application of a new DEM, NSIDC-0715; prior versions relied on NSIDC-0645 • Addition of dT GeoTIFFs, a temporal offset parameter. • All files have a 200 m resolution with the exception of the browse.jpg which is at 500 m; 500 m resolution velocity files no longer available • A more rigorous culling of the data removed bad data and added previously overlooked data. As a result, mosaics show more areas with no data, the min/max ex and ey values are lower, and SAR/LS8 feature counts differ from Version 1. • The no data value for vv changed from -0.1 to -1; the no data value for ex and ey changed from -2e9 to -1. • Newly available are cloud-optimized GeoTIFFs along with tif.aux.xml, and jpg.aux.xml files
1.0	Oct 2017	Initial release

5 RELATED DATA SETS

- [MEaSURES Greenland Quarterly Ice Sheet Velocity Mosaics from SAR and Landsat](#)
- [MEaSURES Greenland Monthly Ice Sheet Velocity Mosaics from SAR and Landsat](#)
- [MEaSURES Greenland Ice Velocity: Selected Glacier Site Velocity Maps from InSAR](#)
- [MEaSURES Greenland Ice Sheet Velocity Map from InSAR Data](#)

6 RELATED WEBSITES

- [MEaSURES Data | Overview](#)
- [Alaska Satellite Facility](#)
- [Greenland Ice Mapping Project \(GrIMP\)](#)

7 CONTACTS AND ACKNOWLEDGMENTS

7.1 Contacts

Ian Joughin

University of Washington
Applied Physics Laboratory
Seattle, WA

7.2 Acknowledgements

This project was supported by a grant from the NASA Making Earth System Data Records for Use in Research Environments (MEaSURES) Program.

Contains modified Copernicus Sentinel data (2014–2016), acquired by the ESA, distributed through the Alaska Satellite Facility, processed by Joughin, I. and from the TanDEM-X and TerraSAR-X missions processed by DLR, as well as results derived from optical images collected by Landsat-8 processed by USGS.

8 REFERENCES

- Andersen, J. K., A. Kusk, J.P.M. Boncori, C.S. Hvidberg, and A. Grinsted. (2020). Improved Ice Velocity Measurements with Sentinel-1 TOPS Interferometry. *Remote Sens*, 12, 2014. <https://doi.org/10.3390/rs12122014>.
- Fattahi, H., M. Simons, and P. Agram. (2017). InSAR Time-Series Estimation of the Ionospheric Phase Delay: An Extension of the Split Range-Spectrum Technique. *IEEE T Geosci Remote*, 55, 5984–5996. <https://doi.org/10.1109/tgrs.2017.2718566>.
- Fettweis, X., J.E. Box, C. Agosta, C. Amory, C. Kittel, C. Lang, D. van As, H. Machguth, and H. Gallée. (2017). Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR model. *Cryosphere*, 11, 1015–1033, <https://doi.org/10.5194/tc-11-1015-2017>.
- Joughin, I., R. Kwok, and M. Fahnestock. (1998). Interferometric estimation of three-dimensional ice-flow using ascending and descending passes. *IEEE*, 36, 25–37, 1998. <https://doi.org/10.1109/36.655315>
- Joughin, I. (1995). Estimation of ice-sheet topography and motion using interferometric synthetic aperture radar. *PhD Dissertation*, University of Washington.
- Joughin, I. (2002). Ice-sheet velocity mapping: a combined interferometric and speckle-tracking approach. *Annals of Glaciology*, 34, 195–201. <https://doi.org/10.3189/172756402781817978>
- Joughin, I., Tulaczyk, S., Bindshadler, R., & Price, S. F. (2002). Changes in west Antarctic ice stream velocities: Observation and analysis. *Journal of Geophysical Research: Solid Earth*, 107(B11), EPM 3-1-EPM 3-22. <https://doi.org/10.1029/2001jb001029>
- Joughin, I., Abdalati, W., & Fahnestock, M. (2004). Large fluctuations in speed on Greenland's Jakobshavn Isbræ glacier. *Nature*, 432(7017), 608–610. <https://doi.org/10.1038/nature03130>

Joughin, I., Smith, B. E., Howat, I. M., Scambos, T., & Moon, T. (2010). Greenland flow variability from ice-sheet-wide velocity mapping. *Journal of Glaciology*, 56(197), 415–430. <https://doi.org/10.3189/002214310792447734>

Joughin, I., Smith, B. E., & Howat, I. M. (2017). A complete map of Greenland ice velocity derived from satellite data collected over 20 years. *Journal of Glaciology*, 64(243), 1–11. <https://doi.org/10.1017/jog.2017.73>

Moon, T., & Joughin, I. (2008). Changes in ice front position on Greenland's outlet glaciers from 1992 to 2007. *Journal of Geophysical Research*, 113(F2). <https://doi.org/10.1029/2007jf000927>

Phillips, T., Rajaram, H., Colgan, W., Steffen, K., & Abdalati, W. (2013). Evaluation of cryo-hydrologic warming as an explanation for increased ice velocities in the wet snow zone, Sermeq Avannarleq, West Greenland. *Journal of Geophysical Research: Earth Surface*, 118(3), 1241–1256. <https://doi.org/10.1002/jgrf.20079>

Rignot, E. (2006). Changes in the Velocity Structure of the Greenland Ice Sheet. *Science*, 311(5763), 986–990. <https://doi.org/10.1126/science.1121381>

9 DOCUMENT INFORMATION

9.1 Publication Date

August 2022

9.2 Date Last Updated

September 2024