# MEaSUREs MODIS Mosaic of Greenland (MOG) 2005, 2010, and 2015 Image Maps, Version 2

## USER GUIDE

**How to Cite These Data**

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

Haran, T., J. Bohlander, T. Scambos, T. Painter, and M. Fahnestock. 2018. *MEaSUREs MODIS Mosaic of Greenland (MOG) 2005, 2010, and 2015 Image Maps, Version 2.* [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/9ZO79PHOTYE5. [Date Accessed].

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National Snow and Ice Data Center

# TABLE OF CONTENTS

# 1 DETAILED DATA DESCRIPTION

This data set consists of two image maps each for the years 2005, 2010, and 2015 (MOG2005, MOG2010, and MOG2015). The two image maps are:

1. Surface morphology derived from high-pass filtered Moderate-resolution Imaging Spectroradiometer (MODIS) Band 1 (red light) images;
2. Snow grain-size inferred from the MODIS Band 1 and Band 2 (near-infrared light) normalized difference.

For MOG2005, the image maps were assembled from 104 MODIS scenes (five-minute segments of swath data). In the case of MOG2010 and MOG2015, the image maps consist of 88 MODIS scenes and 98 MODIS scenes, respectively. For each of the three MOGs, the goal is to create a mosaic with complete cloud-free coverage of Greenland. The number of scenes varies between the years due to the presence of clouds and shadows. The scenes were selected from the MODIS/Aqua and MODIS/Terra Calibrated Radiances 5-Min L1B Swath 250m data sets (MYD02QKM and MOD02QKM). The scenes used for MOG2005 are a mix of Collection 4 and Collection 5 MYD02QKM and MOD02QKM data, whereas the scenes for MOG2010 are from Collection 5 and the scenes for MOG2015 are from Collection 6. Scenes were mosaicked using: a) a stacking technique (data cumulation) that allows multiple images to contribute to a single grid cell's representation; and b) a weighting scheme that favors near-nadir views and feathers the edges of contributing images.

Both image maps are provided at 100 m and 500 m spacings. In addition, the following ancillary files are available:

1. Scene counts and average weights for grid cells in the 100 m and 500 m image maps;
2. Scene counts, average weights, and standard deviations of unweighted values for grid cells in the 500 m grain size image map[1].

Lastly, this data set includes ESRI shapefiles with outlines of the Greenland coastline and ice edges suitable for overlaying on the 100 m and 500 m MOG image maps. However, these files only contain data for Greenland and not areas west of the mainland including Ellesmere Island, Axel Heiberg Island, Devon Island, Baffin Island, and the Labrador Peninsula.

[1]Scene counts and weights are not provided for the 100 m grain size image map. The investigators felt these data offered no additional value compared with the 500 m grid.

## 1.1 Format

The image maps and corresponding ancillary data are available in the Geographic Tagged Image File Format (GeoTIFF, 16-bit).

Maps of the Greenland coastline and ice edges are available as ESRI shapefiles. One complete shapefile consists of four file types: .shp, .shx, .dbf, and .prj. For details about the shapefile format, see the ESRI Shapefile Technical Description white paper (pdf, 124 KB).

## 1.2 File and Directory Structure

Data are available via HTTPS in the following directory:

https://n5eil01u.ecs.nsidc.org/MEASURES/NSIDC-0547.002/

Within this directory, there are three folders, organized by date: /2005.03.12/, /2010.03.15/, and /2015.03.12/.

All three folders contain 11 GeoTIFF (.tif) files, with four files at 100 m resolution and seven files at 500 m resolution (see Table 1 for a list of GeoTIFF files and the 1.3 section for more information on the file names). In addition, the /2005.03.12/ folder includes four shapefiles (.shp), plus auxiliary files (.shx, .dbf, .prj) of the coastlines and ice edges.

Table 1 lists the GeoTIFF files in the folders /2005.03.12/, /2010.03.15/, and /2015.03.12/.

Table 1. List of GeoTIFF Files with Descriptions

| File Name [1] | Description |
|---|---|
| mog100_YYYY_grn_v02.tif | 100 m weighted optical grain size image; 16-bit unsigned integer little-endian flat binary. |
| mog100_YYYY_hct_v02.tif | 100 m count of MODIS scenes contributing to each mog100_YYYY_hp1 grid cell; 8-bit unsigned integer flat binary. |
| mog100_YYYY_hp1_v02.tif | 100 m high-pass band 1 surface morphology image; 16-bit unsigned integer little-endian flat binary. |
| mog100_YYYY_hwt_v02.tif | 100 m average weight applied to computed hp1 values to determine composited mog100_YYYY_hp1 values; 16-bit unsigned integer little-endian flat binary; divide by 50000 to get true hwt decimal value. |
| mog500_YYYY_gct_v02.tif | 500 m count of MODIS scenes contributing to each mog500_YYYY_grn grid cell; |
| mog500_YYYY_grn_v02.tif | 500 m weighted optical grain size image; 16-bit unsigned integer little-endian flat binary. |
| mog500_YYYY_gsd_v02.tif | 500 m standard deviation of unweighted optical grain size values contributing to each valid mog500_YYYY_gmn cell; 16-bit unsigned integer little-endian flat binary; a value of 1 indicates there were less than 2 valid contributing unweighted grain size values; otherwise divide by 10 to get true gsd decimal value. |
| mog500_YYYY_gwt_v02.tif | 500 m average weight applied to computed grain size values to determine composited mog500_YYYY_grn values; 16-bit unsigned integer little-endian flat binary; divide by 50000 to get true gwt decimal value. |
| mog500_YYYY_hct_v02.tif | 500 m count of MODIS scenes contributing to each mog500_YYYY_hp1 grid cell; 8-bit unsigned integer flat binary. |
| mog500_YYYY_hp1_v02.tif | 500 m high-pass band 1 surface morphology image; 16-bit unsigned integer little-endian flat binary. |
| mog500_YYYY_hwt_v02.tif | 500 m average weight applied to computed hp1 values to determine composited. mog500_YYYY_hp1 values; 16-bit unsigned integer little-endian flat binary; divide by 50000 to get true hwt decimal value. |
| [1] YYYY is 2005, 2010, or 2015 | |

## 1.3 File Naming Convention

This section explains the GeoTIFF and shapefile naming conventions with examples.

### 1.3.1 GeoTIFF

#### 1.3.1.1 Example File Names

mog100_2005_hp1_v02.tif

mog500_2010_grn_v02.tif

#### 1.3.1.2 Naming Convention

mog[res]_YYYY_[map]_v02.tif

Refer to Table 2 for descriptions of the variable strings used in the GeoTIFF file naming convention.

Table 2. Descriptions for Variable Strings in GeoTIFF File Names

| String | Values | Description |
|---|---|---|
| `mog` | — | Mosaic of Greenland |
| `res` | `100 or 500` | Resolution: 100 m or 500 m |
| `YYYY` | `2005, 2010, or 2015` | 4-digit year: 2005, 2010, or 2015 |
| `map` | `hp1` | Surface morphology (high-pass filtered Band 1) image map (for 100 m and 500 m) |
| | `grn` | Grain size image map (for 100 m and 500 m) |
| | `hct` | Scene count for each cell in the surface morphology (`hp1`) image map (for 100 m and 500 m) |
| | `hwt` | Average weight applied to each cell in the surface morphology (`hp1`) image map (for 100 m and 500 m) |
| | `gct` | Scene count for each cell in the grain size image map (for 500 m only) |
| | `gwt` | Average weight applied to each cell in the grain size image map (for 500 m only) |
| | `gsd` | Standard deviation of unweighted values for each cell in the grain size image map (for 500 m only) |

### 1.3.2 Shapefiles

#### 1.3.2.1 Example File Name

mog100_geus_coastline_v02.dbf

mog100_gimp_coastline_v02.prj

mog500_geus_coastline_v02.shp

mog500_gimp_coastline_v02.shx

#### 1.3.2.2 Naming Convention

mog[res]_[src]_[map]_v02.[ext]

Refer to Table 3 for descriptions of the variable strings used in the shapefile file naming convention.

Table 3. Naming Convention Variables for Shapefiles Files

| String | Values | Description |
|---|---|---|
| `mog` | — | Mosaic of Greenland |
| `res` | `100, 500` | Resolution: 100 m or 500 m |
| `src` | `GEUS, GIMP` | Map source:<br>GEUS: Geological Survey of Denmark and Greenland<br>GIMP: Greenland Ice Mapping Project<br>See 3.3 for details. |
| `map` | `coastline, iceedge` | Coastline or ice edges map. Note: these maps do not cover areas in the MOG west of Greenland, including Ellesmere Island, Axel Heiberg Island, Devon Island, Baffin Island, and the Labrador Peninsula |
| `ext` | `.dbf, .prj, .shp, .shx` | File extension. A complete shapefile comprises four files with the following extensions: `.dbf` (database file), `.prj` (projection information), `.shp` (spatial data), and `.shx` (shape indices). |

## 1.4 File Size

The 100 m surface morphology and grain size GeoTIFFs are approximately 520 MB and 235 MB, respectively. The 500 m surface morphology and grain size GeoTIFFs are approximately 22 MB and 12 MB, respectively. Ancillary data files range from about 1 MB to 550 MB, depending on grid spacing and the parameter of interest. Shapefiles range from approximately 5 MB to 50 MB.

Each of the three years contains approximately 1.4 GB of GeoTIFF files, for a total of 5.2 GB. The total data volume including ancillary and shapefiles is approximately 6 GB.

## 1.5 Spatial Coverage

Northernmost Latitude: 85° N

Southernmost Latitude: 57° N

Easternmost Longitude: 11° E

Westernmost Longitude: 109° W

### 1.5.1 Spatial Resolution

Image maps are provided at 100 m and 500 m spacings. The underlying MODIS Band 1 and 2 swath data have a nominal resolution of 250 m; however, the image stacking scheme used to assemble the mosaics increases the resolution of the final product beyond that of individual MODIS scenes to between 150 m and 250 m, depending on the number of images that were stacked and how the images were weighted. See the 3.3.4 section of this document for information on Compositing via Data Cumulation.

### 1.5.2 Projection Description

- Projection: Polar Stereographic
- Spheroid: WGS-84
- Rotation: 45°, that is 45° W longitude extending down from pole
- Longitude of Central Meridian: 0°
- Latitude of True Scale: 70° N
- EPSG code: 3413

### 1.5.3 Grid Description

Table 4 lists the dimensions (in pixels) for the 100 m and 500 m grids and the locations (in meters from the origin) of the upper left corner of the upper left cell:

Table 4. Grid Dimensions

| Grid | x | y | Upper left corner, upper left cell |
|---|---|---|---|
| 100 m | 21000 px | 28000 px | -1200000.0 m from origin |
| 500 m | 4200 px | 5600 px | -600000.0 m from origin |

**Note**: Grids do not include the North Pole.

## 1.6 Temporal Coverage

The MOG2005 scenes were acquired between 12 March 2005 and 30 April 2005.

The MOG2010 scenes were acquired between 15 March 2010 and 14 May 2010.

The MOG2015 scenes were acquired between 12 March 2015 and 30 April 2015.

## 1.7 Parameter or Variable

### 1.7.1 Parameter Description

The MOG image maps report two parameters:

- Surface morphology, derived from brightness variations in MODIS Band 1 red light images;
- Snow grain size, inferred from the normalized difference radiance ratio of red to near-infrared light.

### 1.7.2 Surface Morphology

Many processing steps were required to create a seamless and uniform surface morphology mosaic from the numerous images that contributed to each grid cell. As such, the image values no longer have a clearly quantifiable relationship to the top-of-atmosphere, red light reflectances from which they were derived. Instead, the image map provides a semi-quantitative but highly consistent approximation of the surface shape and reflectivity for the entire continent, as illuminated by the sun across all surface types.

### 1.7.3 Snow Grain Size

Processing for the grain size mosaic was reduced compared with the surface morphology image map. While this approach sacrifices seamlessness, it produces a truer quantitative map of radiance ratios that approximate mean snow grain size in dust-free, non-shadowed areas with snow, firn, and ice. Values from 10 through 1100 represent mean optical snow grain size in microns; values of 5 and 1105 indicate grain sizes which lie outside of this range or grid cells for which a grain size could not be computed.

# 2 SOFTWARE AND TOOLS

## 2.1 Software and Tools

GeoTIFF files are most easily accessed using GIS software such as QGIS and ArcGIS.

# 3 DATA ACQUISITION AND PROCESSING

**Note:** The image maps in this data set were generated using the same procedures as in the MODIS Mosaic of Antarctica 2003-2004 (MOA2004) Image Map and the MODIS Mosaic of Antarctica 2008-2009 (MOA2009) Image Map data sets. The following sections outline the key steps used to create the mosaics, ancillary data, and corresponding coastline and ice edge maps for Greenland. Additional detail is available in the Data Acquisition Methods section of the MOA2004 documentation.

## 3.1 Theory of Measurements

Since the 1990s, a host of studies have demonstrated that carefully processed satellite radiometry, most notably from the Landsat series and NOAA's AVHRR instruments, can reveal unprecedented details about the surface morphology of ice sheets. Furthermore, subsequent research has demonstrated that the red-infrared normalized difference radiance ratio can be used to map surface snow grain size, because snow reflectivity decreases in the infrared as grain size increases.

The twin MODIS instruments on board NASA's Terra and Aqua satellites provide an opportunity to exploit two active sensors during the compilation period with a higher spatial and radiometric resolution than AVHRR. In addition, this data set improves the accuracy, detail, and seamlessness of the final products by combining new methods with several preexisting techniques.

## 3.2 Data Acquisition Methods

The MOG2005 image maps were composited from MODIS scenes acquired between 12 March 2005 and 30 April 2005. In the case of MOG2010 and MOG2015, the scenes were acquired between 15 March 2010 and 14 May 2010, and between 12 March 2015 and 30 April 2015, respectively. Scenes were selected from a specific time window to restrict solar illumination to a range of azimuths and to ensure that all scenes were illuminated from approximately the same direction.

## 3.3 Derivation Techniques and Algorithms

### 3.3.1 Geolocation and Processing

Band 1 and Band 2 scenes from NASA's MYD02QKM and MOD02QKM products, together with illumination and viewing angles from the MYD03[1] and MOD03[2] products, were geolocated and resampled onto the projection grid using NSIDC's MODIS Swath-to-Grid Toolbox (MS2GT). The software interpolated the MYD03 and MOD03 latitude/longitude data from 1 km resolution to 250 m and then resampled the MODIS/Aqua and MODIS/Terra Level-1B calibrated radiances to the grid using a forward elliptical weighted average algorithm (Greene et al. 1986).

Each mog100_YYYY_*.tif file was created directly from 250 m resolution swath data that were gridded to 100 m grid scale. The mog500_YYYY_g*.tif files were created by resampling the corresponding 100 m file using a nearest neighbor algorithm, and the mog500_YYYY_h*.tif files were created by resampling the corresponding 100 m file using a drop-in-the-bucket averaging algorithm.

1MODIS Level 1A Geolocation Fields from EOS Aqua
2MODIS Level 1A Geolocation Fields from EOS Terra

### 3.3.2 Destriping of MODIS Image Data

The MS2GT algorithm was modified to remove MYD02QKM and MOD02QKM striping artifacts, a known problem with all Terra and Aqua MODIS 250 m Level-1B data, by adding a Lambertian solar zenith angle normalization on the swath data for both bands. Telemetry noise and line drops, which have the appearance of chads in the projected images, were reset to zero (treated as masked cloud areas). This procedure is discussed in detail in the Destriping of MODIS Image Data section of the MOA2004 documentation.

### 3.3.3 Cloud Masking

The geolocated scenes were manually masked to remove clouds, cloud shadows, fog, blowing snow, and heavy surface frost. Refer to the Cloud Masking section of the MOA 2004 documentation. The final image maps are nearly perfectly cloud-cleared, except for some areas of thin clouds, cirrus cloud shadows, and fog or low-lying small clouds.

### 3.3.4 Surface Morphology Image Map

Geolocated, destriped Band 1 images were high-pass filtered to reduce non-Lambertian illumination and to reset the mean grayscale range to a common value for compositing. Then for each gridded image the investigators created a corresponding weight image, in which each non-masked pixel is assigned a scalar value (or weight). Weights were computed based on proximity to the nadir track, favoring near-nadir areas, and proximity to an image or mask edge to feather the edges of the component images. Weight images were then combined using stacking techniques called image super-resolution or data cumulation. These techniques allow multiple images to contribute to how a single grid cell is represented in the final composite.

The algorithms used to compute and combine the weight images into the final mosaics are provided in the MOA2004 Compositing the Image Swaths documentation.

### 3.3.5 Snow Grain Size

The snow grain size image map was generated from MODIS Band 1 and Band 2 imagery using the following normalized difference ratio:

(Band1 - Band2)/(Band1 + Band 2)

This ratio exploits the decreasing reflectivity of snow in the infrared range to create an image that is sensitive to grain-size variations (Warren 1982) (Fily et al. 1997). To maintain the quantitative relationship, images were not pre-processed beyond geolocation, calibration, and destriping.

Intermediate images of grain size were generated by applying a model-derived lookup table to computed normalized differences and solar zenith angles. These images were then composited using the same approach as the surface morphology image map, except that computed grain sizes of <10 µm and >1100 µm were treated like missing data and set to 5 µm and 1105 µm, respectively. Count and weight images for the grain size composites were slightly different from the corresponding surface morphology count and weight images because of these additional missing values. In cases where all images gave out-of-range grain size results, the grid cell value was set to either 5 µm or 1105 µm. For additional details, including algorithms and snow grain size validation measurements, see the Optical Mean Snow Grain Size section in the MOA2004 documentation.

### 3.3.6 Greenland Coastlines and Ice Edges

Greenland coastline shapefiles, suitable for overlaying on the 100 m and 500 m MOG image maps, were derived from 500,000:1 and 2,500,000:1 (complex UTM) shapefiles, respectively, which were graciously provided by Willy Lehmann Weng of the Geological Survey of Denmark and Greenland (GEUS). The investigators opted to approach GEUS to address the apparent gelocation problem over northern Greenland found in all public domain coastline data sets (Henriksen 2000). The GEUS source files were imported into Esri ArcMap 10.0 and reprojected to the MOG projection.

The ice edge shapefiles were derived from 90 m and 180 m ice masks developed by the Greenland Ice Mapping Project (GIMP) at the Byrd Polar and Climate Research Center. The 90 m and 180 m masks (Version 1, downloaded 02 December, 2011) were first nearest-neighbor resampled to the 100 m and 500 m MOG grids, respectively. Using the ENVI raster-to-vector function, the resampled masks were then converted to ENVI vector files which were exported to the GIMP Greenland ice edge shapefiles (Howat 2014).

The data for the mog100_geus_coastline_* shapefiles were collected between 1979 and 2010, whereas the data for the mog500_geus_coastline_* shapefiles were collected in 1995. The data for both the mog100_gimp_iceedge_* and the mog_500_gimp_iceedge_* shapefiles were collected between 1999 and 2001.

### 3.3.7 Version History

In Version 2 of this data set, MOG2010 and MOG2015 data were added to the collection to extend the MOG2005 data.

### 3.3.8 Error Sources

Wolfe et al, 2002 estimated the accuracy of the MYD03/MOD03 Level-1A geolocation data to be 50 m, considerably better than the MYD02QKM/MOD02QKM ground-equivalent nadir pixel size of 250 m. The accuracy and precision of this geolocation was also tested for the MOA2004 using known surface sites, such as South Pole Station, Vostok Station, Siple Dome camp and traverse trail, and areas of well-mapped coastline such as Ross Island and the northern Antarctic Peninsula. The investigators did not find discrepancies greater than 125 m in the projected location of any fixed object.

In general, the MOG quality is higher in areas with both high counts and high weights. The mean image weight and image count ancillary data are provided for users to assess image quality in various regions of the MOG image maps.

The MOG snow grain size error is approximately ±50 µm, as estimated for the MOA by comparing in situ spectra of varying snow grain sizes with near-simultaneous MODIS images processed in the same manner. However, snow grain size varies greatly over the period of image acquisition. As such, large ranges of snow grain sizes were averaged together in certain areas. Additional details are provided in the 3.3.8 section in the MOA2004 documentation.

## 3.4 Sensor or Instrument Description

The MODIS instruments collect 12-bit radiometric data in 36 spectral bands, ranging from 0.4 µm to 14.4 µm in wavelength. Bands 1 and 2 are imaged at a nominal resolution of 250 m at nadir. The Terra satellite crosses the equator from north to south (descending node) at 10:30 a.m. local time; Aqua crosses from south to north (ascending node) at 1:30 p.m. local time. Both satellites occupy sun-synchronous, near-polar, circular orbits at an altitude of 705 km. The MODIS instruments' ±55 degree scanning pattern produces a 2330 km cross-track by 10 km along-track swath with nearly complete global coverage every one to two days.

# 4 REFERENCES AND RELATED PUBLICATIONS

Bindschadler, R. A. and P. L. Vornberger. 1990. AVHRR Imagery reveals Antarctic ice dynamics. EOS 71(23), 741-742.

Bohlander, J., T. Scambos, T. Haran, M. Fahnestock. 2004. A New MODIS-based Mosaic of Antarctica: MOA. EOS, *Transactions, American Geophysical Union* 85(47). F452.

Bourdelles, B., and M. Fily. 1993. Snow grain-size determination from Landsat imagery over Terre Adélie, Antarctica. *Annals of Glaciology* 17, 86-92.

Cooper, A. P. R. 1994. A simple shape-from-shading algorithm applied to images of ice-covered terrain. IEEE Transactions on Geoscience and Remote Sensing 32(6), 1196-1198.Dowdeswell, J. A., and McIntyre, N. F. 1987. The surface topography of large ice masses from Landsat imagery. *Journal of Glaciology* 33(133), 16-33.

Fahnestock, M. A., R. Bindschadler, R. Kwok, and K. Jezek. 1993. Greenland Ice Sheet surface properties and ice dynamics from ERS-1 SAR imagery. *Science* 262, 1530-1534.

Ferrigno, J. G., J. L. Mullins, J. A. Stapleton, R. A. Bindschadler, T. A. Scambos, L. B. Bellisime, J. A. Bowell, and A. V. Acosta. 1994. Landsat TM image maps of the Shirase and Siple Coast ice streams, West Antarctica. *Annals of Glaciology* 20, 407-412.

Fily, M, B. Bourdelles, J. P. Dedieu, and C. Sergent. 1997. Comparison of in situ and Landsat Thematic Mapper derived snow grain characteristics in the Alps. *Remote Sensing of Environment* 59. 452-460.

Greene, N. and P. S. Heckbert. 1986. Creating Raster Omnimax Images from Multiple Perspective Views Using the Elliptical Weighted Average Filter. *IEEE Computer Graphics and Applications* 6(6). 21-27.

Haran, T. M., M. A. Fahnestock, and T. A. Scambos. 2002. De-striping of MODIS optical bands for ice sheet mapping and topography. EOS, Transactions, *American Geophysical Union* 88(47). F317.

Haran, T. M, T. A. Scambos, J. A. Bohlander. 2011. Updated MODIS-Derived Ice Sheet Data Sets for Antarctica and Greenland: MOA 2009, MOG 2010 Mosaics and Products, Abstract C31A-0606 presented at 2011 Fall Meeting, AGU, San Francisco, CA, 05 - 09 December 2011.

Henriksen, N., A. K. Higgins, F. Kalsbeek, T. Christopher, R. Pulvertaft. 2000. Greenland from Archaean to Quaternary. Descriptive text to the Geological map of Greenland, 1:2 500 000. *Geology of Greenland Survey Bulletin*, Volume 185, Copenhagen.

Howat, I. M., A. Negrete, B. E. Smith. 2014. The Greenland Ice Mapping Project (GIMP) land classification and surface elevation datasets. *The Cryosphere*, 8, 1509-1518, doi:10.5194/tc-8-1509-2014

Jezek, K. 1999. Glaciological properties of the Antarctic ice sheet, from Radarsat-1 Synthetic Aperture Radar Imagery. *Annals of Glaciology* 29, 286-290.

Massom, R., and 17 others (2006). ARISE (Antarctic Remote Ice Sensing Experiment) in the East 2003: Validation of satellite-derived sea-ice data products. *Annals of Glaciology*, 44, 288-296.

Merson, R. H., 1989. An AVHRR mosaic image of Antarctica. *International Journal of Remote Sensing* 10, 669.

Nolin, A. W., and J. Dozier. 2000. A hyperspectral method for remotely sensing the grain size of snow. *Remote Sensing of Environment* 74(2), 207-216.

Orheim, O. and B. Lucchitta. 1988. Numerical analysis of Landsat thematic mapper images of Antarctica: surface temperatures and physical properties. *Annals of Glaciology* 11, 109.

Orheim, O., and B. Lucchitta. 1990. Investigating climate change by digital analysis of blue ice extent on satellite images of Antarctica. *Annals of Glaciology* 14, 211-215.

Painter, T., and J. Dozier. 2004. Measurements of the hemispherical-directional reflectance of snow at fine spectral and angular resolution. *Journal of Geophysical Research* 109, D18115, doi:10.1029/2003JD004458.

Parish, T. R. and D. H. Bromwich. 1991. Continental-scale simulation of the Antarctic katabatic wind regime. *Journal of Climate* 4(1), 135-146, doi: 10.1175/1520-0442(1991)004<0135:CSSOTA>2.0.CO;2

Ricchiazzi, P., S. Yang, C. Gautier, and D. Sowle. 1998. SBDART: A research and teaching software tool for plane-parallel radiative transfer in the Earth's atmosphere. *Bulletin of American Meteorological Society* 79(10), 2101-2114.

Scambos, T. A., and R. A. Bindschadler. 1991. Feature map of Ice Streams C, D, and E, West Antarctica. *Antarctic Journal of the United States* 26(5), 312-314.

Scambos, T., G. Kvaran, and M. Fahnestock. 1999. Improving AVHRR resolution through data cumulating for mapping polar ice sheets. *Remote Sensing of Environment* 69. 56-66.

Scambos, T. A., and M. A. Fahnestock. 1998. Improving digital elevation models over ice sheets using AVHRR-based photoclinometry. *Journal of Glaciology* 44, 97-103.

Scambos, T. A., Dutkiewitcz, M. J., Wilson, J. C., and R. A. Bindschadler. 1992. Application of image cross-correlation software to the measurement of glacier velocity using satellite image data. Remote Sensing of Environment 42, 177-186.

Scambos, T., T. Haran, M. Fahnestock, T. Painter, and J. Bohlander. 2007. MODIS-based Mosaic of Antarctica (MOA) data sets: continent-wide surface morphology and snow grain size. *Remote Sensing of Environment* 111(2): 242-257, doi:10.1016/j.rse.2006.12.020.

Seko, K., Furukawa, T., Nishio, F., and Watanabe, O. 1993. Undulating topography on the Antarctic ice sheet revealed by NOAA AVHRR images. *Annals of Glaciology* 17, 55-62.

Swithinbank, C., K. Brunk, and J. Sievers. 1988. A glaciological map of Filchner-Ronne Ice Shelf, Antarctica. *Annals of Glaciology* 11, 150–155.

USGS. 1991. Satellite Image Map of Antarctica, 1:5,000,000. Miscellaneous Map Investigation Series I-2284.

USGS. 1996. Satellite Image Map of Antarctica, 1:5,000,000. Miscellaneous Map Investigation Series I-2560.

Warren, S. 1982. Optical properties of snow. *Reviews of Geophysics and Space Physics* 20(1), 67-89.

Winther, Jan-G., M. N. Jespersen and G. E. Liston. 2001. Blue-ice areas in Antarctica derived from NOAA AVHRR satellite data. *Journal of Glaciology* 47(157), 325–334.

Wolfe, R. E., M. Nishihama, A. J. Fleig, J. A. Kuyper, D. P. Roy, J. C. Storey and F. S. Patt. 2002. Achieving sub-pixel geolocation accuracy in support of MODIS land science. *Remote Sensing of the Environment* 83 (1-2), 31-49.

## 4.1 Related Data Collections

- MODIS Mosaic of Antarctica 2003-2004 (MOA2004) Image Map
- MODIS Mosaic of Antarctica 2008-2009 (MOA2009) Image Map
- MODIS/Aqua Calibrated Radiances 5-Min L1B Swath 250m
- MODIS/Terra Calibrated Radiances 5-Min L1B Swath 250m
- MODIS/Aqua Geolocation Fields 5-Min L1A Swath 1km
- MODIS/Terra Geolocation Fields 5-Min L1A Swath 1km
- MEaSUREs MODIS Mosaic of Antarctica 2009 Image Map
- Digital SAR Mosaic and Elevation Map of the Greenland Ice Sheet
- MEaSUREs Greenland Ice Mapping Project (GIMP) Land Ice and Ocean Classification Mask

## 4.2 Related Websites

- NSIDC
    - MODIS Data
    - MODIS Swath-to-Grid Toolbox (MS2GT)
- Byrd Polar and Climate Research Center
    - Greenland Ice Mapping Project
    - Glacier Dynamics Research Group Data & Software
- NASA
    - MODIS | Moderate Resolution Imaging Spectroradiometer
    - NASA MODIS Characterization Support Team

# 5 CONTACTS AND ACKNOWLEDGMENTS

**Terry Haran**

National Snow and Ice Data Center

449 UCB, University of Colorado

Boulder, CO 80309-0449 USA

**Jennifer Bohlander**

Polar Science Consulting

200 Merry Hill Drive

Cary, NC 27518 USA

**Ted Scambos**

National Snow and Ice Data Center

449 UCB, University of Colorado

Boulder, CO 80309-0449 USA

**Thomas Painter**

Jet Propulsion Laboratory

4800 Oak Grove Drive

Pasadena, CA 91109

**Mark Fahnestock**

Institute for the Study of Earth, Oceans, and Space

University of New Hampshire

Morse Hall

8 College Road

Durham, NH 03824-3525 USA

## 5.1 Acknowledgments

This work was supported by NASA grants NNG04GM10G and NAG5-7760. GIMP ice masks were developed by the Greenland Ice Mapping Project Two: Measuring Rapid Changes in Ice Flow (MEAS-06-0071). The investigators also wish to thank R. Bindschadler, W. Abdalati, and J. Ferrigno for their interest and support initiating this project.

# 6 DOCUMENT INFORMATION

## 6.1 Publication Date

February 2018

## 6.2 Date Last Updated

29 December 2020