

SNOW AND ICE PRODUCTS FROM THE MODERATE RESOLUTION IMAGING SPECTRORADIOMETER

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ABSTRACT

Snow and sea ice products, derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument, flown on the Terra and Aqua satellites, are or will be available through the National Snow and Ice Data Center Distributed Active Archive Center (DAAC). The algorithms that produce the products are automated, thus providing a consistent global data set that is suitable for climate studies. The suite of MODIS snow products begins with a 500-m resolution, 2330-km swath snow-cover map that is then projected onto a sinusoidal grid to produce daily and 8-day composite "tile" products. The sequence proceeds to daily and 8-day composite climate-modeling grid (CMG) products at 0.05° resolution. A daily snow albedo product will be available in early 2003 as a beta test product. The sequence of sea ice products begins with a swath product at 1-km resolution that provides sea ice extent and ice-surface temperature (IST). The sea ice swath products are then mapped onto the Lambert azimuthal equal area or EASE-Grid projection to create a daily and 8-day composite sea ice tile product, also at 1-km resolution. Climate-Modeling Grid (CMG) sea ice products in the EASE-Grid projection at 4-km resolution are planned for early 2003.

INTRODUCTION

The Earth Observing System (EOS) Terra and Aqua spacecraft, launched in 1999 and 2002, respectively, each carry a Moderate Resolution Imaging Spectroradiometer (MODIS) instrument. MODIS data are used to produce snow-cover products <http://modis-snow-ice.gsfc.nasa.gov/> from automated algorithms at Goddard Space Flight Center in Greenbelt, Maryland. The products are transferred to the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, where they are archived and distributed via the EOS Data Gateway (EDG) at <http://nsidc.org/imswelcome>.

The MODIS snow-cover maps (Figure 1) complement existing hemispheric-scale snow maps that are available today (e.g., Ramsay, 1998), and provide some advances in spatial resolution and snow/cloud discrimination capabilities, and the data archiving and distribution system provides free Web-based access to the data products. Validation studies are ongoing and several studies show that the MODIS snow maps compare very favorably with operational snow maps (Hall et al., 2002a and b; Klein and Barnett, in press).

The MODIS sea ice maps (Figure 2) of ice extent and ice-surface temperature (IST) complement existing sea ice maps used for operational purposes and passive-microwave-derived sea ice maps (Zwally et al., 1983; Parkinson et al., 1987; Partington et al., submitted). Preliminary validation work on the MODIS IST has begun.

In this paper, we describe the MODIS snow and sea ice products, with a focus on the newest in the suite of MODIS cryospheric products which are the daily snow albedo maps and the daily sea ice climate-modeling grid (CMG) maps.

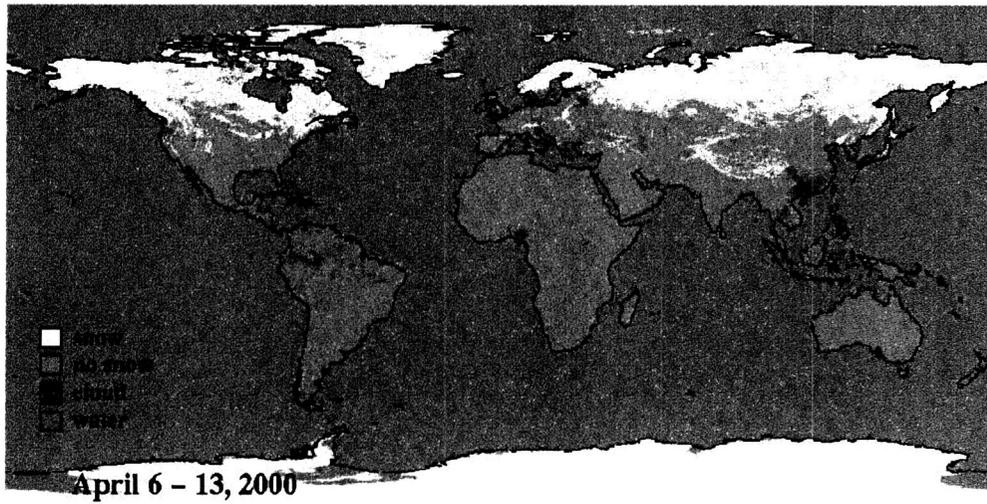


Figure 1. Eight-day composite snow climate-modeling snow-cover product from MODIS.

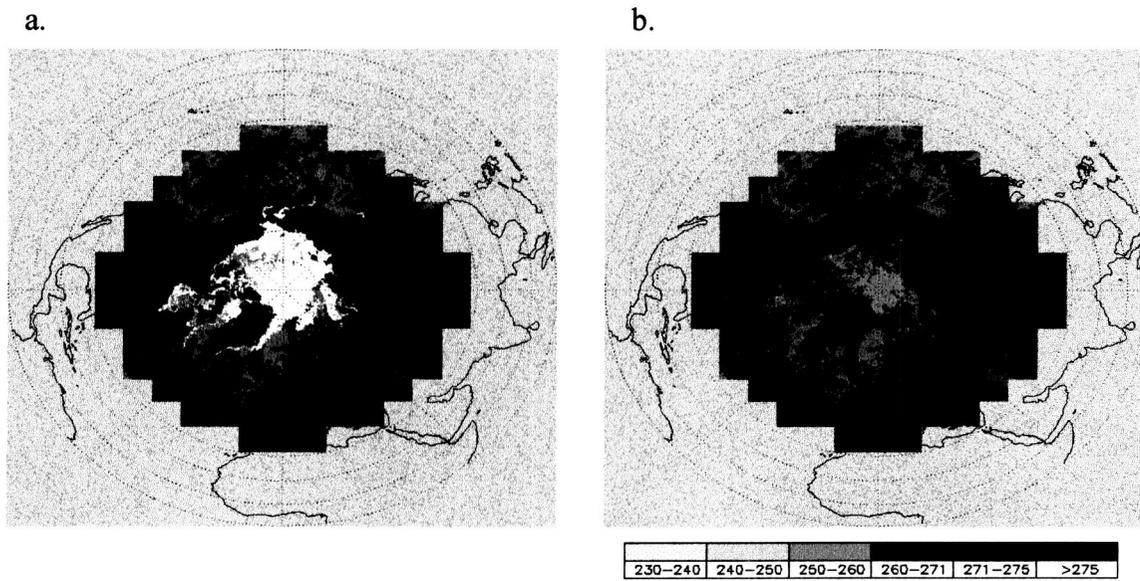


Figure 2. Prototype of the sea ice extent climate-modeling grid (CMG) product of the north polar area (a); and sea ice surface (IST) on the CMG (b).

BACKGROUND

Instrument Description

MODIS is an imaging spectroradiometer that provides imagery of the Earth's surface and clouds in 36 discrete narrow spectral bands from approximately 0.4 to 14.0 μm (Barnes et al., 1998). Key land-surface objectives are to study global vegetation and land cover, global land-surface change, vegetation properties, surface albedo, surface temperature and snow and ice cover on a daily or near-daily basis (Justice et al., 2002). The spatial resolution of the MODIS instrument varies with spectral band and ranges from 250 m to 1 km at nadir.

Description of the MODIS Cryosphere Products

The suite of current MODIS snow and sea ice products and near-future enhancements is shown in Table 1. We have included the "Long Name" and "Earth Science Data Type (ESDT)" as well as spatial resolution information. The Long Name and ESDT are important as they are required for users to order data products from the EDG (see section on ordering, below.)

Table 1. MODIS snow and sea ice data products.

Long Name	Earth Science Data Type (ESDT)	Spatial Resolution
MODIS/Terra Snow Cover 5-Min L2 Swath 500m	MOD10_L2	500-m resolution, swath of MODIS data
MODIS/Terra Snow Cover Daily L3 Global 500m SIN Grid (includes daily snow albedo*)	MOD10A1	500-m resolution, projected, gridded tile data
MODIS/Terra Snow Cover 8-Day L3 Global 500m SIN Grid	MOD10A2	500-m resolution, projected, gridded tile data
MODIS/Terra Snow Cover Daily L3 Global 0.05Deg CMG	MOD10C1	0.05° resolution, lat/lon climate modeling grid
MODIS/Terra Snow Cover 8-Day L3 Global 0.05Deg CMG	MOD10C2	0.05° resolution, lat/lon climate modeling grid
MODIS/Terra Sea Ice Extent 5-Min L2 Swath 1km	MOD29	1-km resolution, swath of MODIS data
MODIS/Terra Sea Ice Extent Daily L3 Global EASE-Grid Day	MOD29P1D	1-km resolution, projected, gridded tile data
MODIS/Terra Sea Ice Extent Daily L3 Global EASE-Grid Night	MOD29P1N	1-km resolution, projected, gridded tile data
MODIS/Terra Sea Ice Daily L3 Global EASE-Grid*	MOD29C1	4-km resolution, gridded
MODIS/Terra Sea Ice 8-Day L3 Global EASE-Grid *	MOD29C2	4-km resolution, gridded

*Future enhancement (see text for explanation).

Cryospheric products from the Terra MODIS are currently available. Aqua MODIS products have not yet been released. Except for the difference in acquisition times, Terra has a 10:30 local time overpass while Aqua has a 13:30 local time overpass, the Terra and Aqua MODIS cryospheric products should be nearly identical in terms of the data-product characteristics.

MODIS snow and sea ice swath products are generated automatically using MODIS sensor radiance data (Guenther et al., 2002), the geolocation product (Wolfe et al., 2002), and the MODIS cloud mask product (Ackerman et al., 1998). The daily products are generated automatically by mapping and gridding the swath products into tiles of a map projection. Data products contain data arrays (maps) of snow or sea ice extent and IST along with quality assessment, and metadata.

Collection 4 processing of the cryospheric products began on 1 January 2003. Collection 4 is the third reprocessing for earlier data and is the current version for forward processing and uses the best available versions of the product algorithms. Specifics of improved algorithms and status of product quality can be found at the MODIS snow and ice project website, <http://modis-snow-ice.gsfc.nasa.gov/>. Collection 4 processing is done in two processing streams, reprocessing and forward. Reprocessing began with data acquired 24 February 2000. Data from Collection 3 are available for dates prior to 1 January 2003 but will be deleted from the archive about six months after Collection 4 data are archived. Dates of Collections 3 and 4 are presented in Table 2. Collection 4 reprocessing is expected to be completed in September 2003.

Snow. The MODIS snow maps provide global, daily coverage at 500-m and, at 0.05° resolution (~5.6 km at the Equator) (Riggs et al., 2003a and Hall et al., 2002b). Eight-day composite maps are also available and provide more cloud-free coverage of snow-covered areas (Table 1). The dates showing the beginning of the data stream for the snow products are shown in Table 2.

MODIS/Terra Snow Cover 5-Min L2 Swath 500 m (MOD10_L2). The snow data-product sequence begins with a 5-minute swath segment (granule) at a nominal pixel spatial resolution of 500 m and with a nominal swath coverage of 2330 km (cross track) by 2030 km (along track). Inputs to the swath snow-cover product (MOD10_L2) are: the MODIS (Level 1B) radiance data product (MOD02) (Guenther et al., 2002), the MODIS geolocation product and the MODIS cloud mask (MOD35) (Ackerman et al., 1998). The algorithm creates a snow cover map that shows snow extent, land, water bodies and other features. Analysis is done on pixels that are land and unobstructed by clouds. Land extent is determined using the 1-km resolution United States Geological Survey (USGS) global land/water mask (USGS, 1997) from the corresponding MODIS geolocation product (Wolfe et al., 2002). Only pixels that are unobstructed by clouds according to the MODIS cloud mask are analyzed. The cloud mask has been useful in the snow algorithm albeit the accuracy of the cloud mask varies with conditions (Riggs and Hall, in press).

MODIS/Terra Snow Cover Daily L3 Global 500m SIN Grid (MOD10A1) and MODIS/Terra Snow Cover 8-Day L3 Global 500m SIN Grid (MOD10A2). The swath product (MOD10_L2) is gridded to a sinusoidal projection to create the daily snow "tile" product. The daily snow map is generated by selecting the observation acquired nearest nadir and having the greatest coverage of the grid cell from the multiple observations acquired during a day. This product (MOD10A1) also has 500-m resolution. An 8-day composite maximum snow-cover product is also produced for each tile on the grid by compositing over eight days using the daily 500-m resolution products (MOD10A2). The 8-day composite product shows maximum snow cover and minimum cloud cover as calculated from the 500-m resolution products for the time period.

Table 2. MODIS cryospheric product availability and validation status for Collection 3 and Collection 4.

Earth Science Data Type (ESDT)	Collection	Begin Date (Julian Day)	End Date (Julian Day)	Validation Status
MOD10_L2	Collection 3	2000 Aug 13 (257)	2002 Dec 31 (365)	Validated Stage 2
	Collection 4	2000 Feb 24 (055) (reprocessing)	*2002 Dec 31 (365)	Validated Stage 2
		2003 Jan 1 (001) (forward processing)	**	Validated Stage 2
MOD10A1	Collection 3	2000 Sept 13 (257)	2002 Dec 31 (365)	Validated Stage 2
	Collection 4	2000 Feb 24 (055) (reprocessing)	*2002 Dec 31 (365)	Validated Stage 2
		2003 Jan 1 (001) (forward processing)	**	Validated Stage 2
MOD10C1	Collection 3	2002 Feb 14 (045)	2002 Dec 31 (365)	Validated Stage 2
	Collection 4	2000 Feb 24 (055) (reprocessing)	*2002 Dec 31 (365)	Validated Stage 2
		2003 Jan 1 (001) (forward processing)	**	Validated Stage 2
MOD10A2	Collection 3	2000 Sept 13 (257)	2002 Dec 31 (365)	Validated Stage 2
	Collection 4	2000 Feb 24 (055) (reprocessing)	ppp2002 Dec 31 (365)	Validated Stage 2
		2003 Jan 1 (001) (forward processing)	**	Validated Stage 2
MOD10C2	Collection 3	2001 Sept 30 (273)	2002 Dec 31 (365)	Validated Stage 2
	Collection 4	2000 Feb 24 (055) (reprocessing)	*2002 Dec 31 (365)	Validated Stage 2
		2003 Jan 1 (001) (forward processing)	**	Validated Stage 2

*In progress with an estimated completion in September 2003.

** In progress with an end date TBD.

Included within the gridded snow-cover product (MOD10A1) will be snow albedo (Figure 3). This enhancement to the daily snow product should be available in early 2003. A broadband snow albedo measurement will be provided for pixels mapped as snow in the MODIS 10A1 product. In addition to the other inputs used in the MOD10A1 product, for determining snow albedo, the MOD09 atmospherically-corrected surface reflectances, MOD12 land cover product as well as local slope and aspect information are used. Following previous work (Stroeve et al., 1997), the reflectance of snow-covered pixels in individual MODIS bands located in non-forested areas are adjusted for anisotropic scattering effects using a discrete ordinates radiative transfer model (DISORT) and snow optical properties. Currently, snow covered forests are considered to be Lambertian reflectors. A narrow-to-broadband conversion scheme (Liang, 2000) is used to combine the MODIS narrow-band albedos into a single broadband albedo estimate (Klein and Stroeve, 2002).

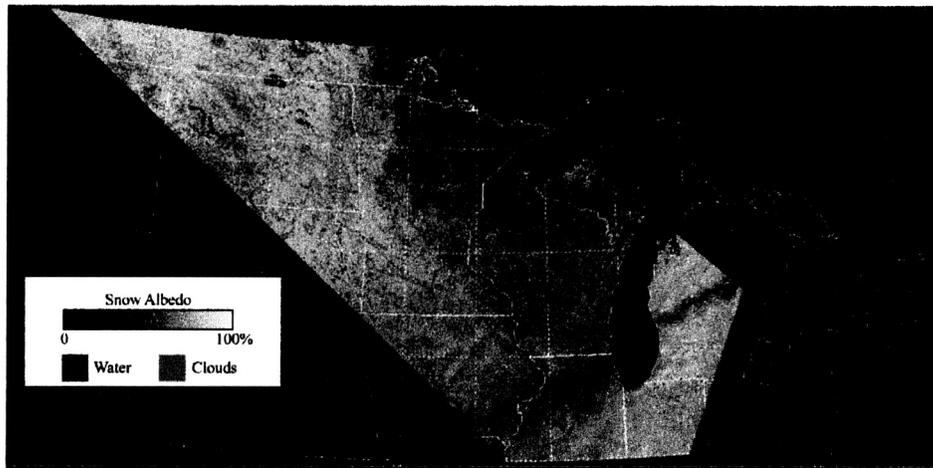


Figure 3: Prototype of snow albedo product - north central United States and southern Canada - February 16, 2001.

MODIS/Terra Snow Cover Daily L3 Global 0.05Deg CMG (MOD10C1) and MODIS/Terra Snow Cover 8- Day L3 Global 0.05Deg CMG (MOD10C2). The climate modeling grid product provides a global view of the Earth's snow cover (Figure 1). It is specifically designed for use by climate modelers with a spatial resolution of 0.05°. Snow-cover fraction for each cell (from 1-100%) and the corresponding cloud obstruction for each cell is available in the products. The fraction of snow cover in each cell is calculated from the 500-m snow maps. Since each 500-m pixel is either "snow" or "non-snow," the binary decision on snow cover is binned into the 0.05° cell, thus providing a fraction of snow cover and a fraction of cloud cover for the cell. Daily CMG browse products are available to view at the National Snow and Ice Data Center (NSIDC) http://nsidc.org/data/modis/cmg_browse/index.html. The daily global snow-cover CMG product is presented in a geographic projection, by assembling MODIS daily data tiles (approximately 320) to include all land areas, of the daily 500-m snow product and binning the 500-m cell observations into the ~5.6-km spatial resolution of the CMG cells. An 8-day composite maximum snow-cover CMG product (MOD10C2) is also produced.

Sea Ice. The sea ice algorithms identify sea ice-covered oceans by reflectance characteristics and by ice-surface temperature (IST) (Riggs et al., 1999). Thus, during the daylight hours, two sea ice extent maps are produced – one using reflectances and the other using IST. Early in 2003, sea ice CMG products (MOD29C1 and MOD29C2) (Table 1) will become available.

Figure 2A is sea ice extent as determined by reflectance, and Figure 2B is an IST map which also shows ice extent because any pixel that has a temperature of $<271.5^{\circ}\text{K}$ is considered to be ice, and any pixel $>271.5^{\circ}\text{K}$ is considered to be open water. Because sea ice is saline, it freezes at a temperature below 273°K , thus 271.5°K was selected as the threshold temperature between liquid water and ice. Sea ice extent as mapped by reflectance by IST do not always agree in terms of their determination of sea ice extent. There will be two CMG sea ice maps – one of the north polar area, as seen in Figure 2, and one of the south polar area.

MODIS/Terra Sea Ice Extent 5-Min L2 Swath 1 km (MOD29). The first product of the sequence of sea ice products is a sea ice extent map at 1-km spatial resolution for a MODIS swath (MOD29). Sea ice extent mapped by reflectance uses the same data inputs and algorithm, with minor variations, as for snow covered land. Inputs are the MODIS (Level 1B) radiance data product (MOD02) (Guenther et al., 2002), the MODIS geolocation product (MOD03) and the MODIS cloud mask (MOD35) (Ackerman et al., 1998). Analysis is constrained to ocean pixels that are unobstructed by clouds. Ocean extent is determined using the 1-km resolution United States Geological Survey (USGS) global land/water mask (USGS, 1997) from the corresponding MODIS geolocation product (Wolfe et al., 2002). Only pixels that are unobstructed by clouds according to the MODIS cloud mask are analyzed. Although it is a significant challenge to identify clouds over sea ice, especially in darkness, and it is known that the accuracy of the cloud mask varies with conditions (Riggs and Hall, in press) the cloud mask is nevertheless very useful in the sea ice algorithm. A particular problem for mapping clouds over sea ice is the identification of thin, low-level fog. Fog often develops in sea ice covered waters when water vapor forms following the formation of leads and polynyas. While it may be possible to see the sea ice, and even map the sea ice through the fog, it may not be possible to retrieve an accurate IST through the fog.

Sea ice surface temperature (IST) is determined with the split-window technique using MODIS instrument channels 31 and 32 centered at approximately 11.0 and $12.0\ \mu\text{m}$, respectively, as input. Several investigators (e.g. Key and Haeffliger, 1992; Massom and Comiso, 1994; Yu et al., 1995; Key et al., 1997) have employed variations of the split-window technique for estimation of IST in polar regions using the Advanced Very High Resolution Radiometer (AVHRR) and other instruments. IST accuracy of $0.5 - 1.5\ \text{K}$ relative to measured or modeled surface temperatures have been reported by investigators using the split-window technique. However, there has not yet been adequate validation on the MODIS-derived IST product to assign accuracies to the retrieved temperatures.

MODIS/Terra Sea Ice Extent Daily L3 Global EASE-Grid Day (MOD29P1D) and MODIS/Terra Sea Ice Extent Daily L3 Global EASE-Grid Night (MOD29P1N). The swath data are gridded onto the EASE-Grid polar projection at 1-km resolution. In the daily product, an algorithm is used to select the observation, from the many acquired during a day, with the highest “score” determined from: observation coverage in a cell, distance from nadir, and solar elevation angle. In the case of night data, solar elevation is omitted from the algorithm.

The content of the sea ice data products is different between day (MOD29P1D) and night (MOD29P1N) because MODIS visible data are not acquired when the sensor is in night mode. The day product (MOD29P1D) contains both day and nighttime data while the night product (MOD29P1N) contains only estimated ice surface temperature (IST) data processed from MODIS thermal data acquired during the night mode operation of the sensor. Further details of the sea ice data products may be found in Riggs et al. (2003b).

MODIS/Terra Sea Ice Daily L3 EASE-Grid (MOD29C1) and MODIS/Terra Sea Ice 8-Day L3 EASE-Grid (MOD29C2). The final product in the sequence of sea ice products is the climate-modeling grid (CMG) map (Fig. 2), which is also projected onto the EASE-Grid at a resolution of 0.5° which is $\sim 4\text{-km}$ resolution. Two CMG maps will be produced daily – one for the north polar region, and one for the south polar region. The daily CMG maps (MOD29C1) will be available in early 2003, while the 8-day composite CMG maps are expected to be available during Collection 5 processing in 2004.

Data archiving and distribution. The NSIDC Distributed Active Archive Center (DAAC) is part of the Earth Observation System Data and Information System (EOSDIS). The EOSDIS utilizes the EOSDIS Core System (ECS) for data management across the DAACs, and the EDG, to facilitate online Web-based user access to data (Scharfen et al., 2000). Users can access information about the MODIS snow products with links to related MODIS

web pages at <http://nsidc.org/NASA/MODIS> . The MODIS products (Table 1) may be ordered through the NSIDC DAAC Earth Observing System (EOS) Data Gateway (EDG) client at <http://nsidc.org/imswelcome>.

CONCLUSION

The suite of MODIS cryospheric products (Table 1) is now becoming available in Collection 4 which is the third version of reprocessing for earlier data and is the current version for forward processing. Data are available in Collection 4 beginning from February 24, 2000, and continuing through the present. Collection 4 reprocessing will be complete by the fall of 2003, and new data products will continue to be processed in Collection 4. With each new version, the products have improved.

Collection 4 is the processing stream containing the most advanced algorithms and is the one that should be ordered when possible. (Collection 4 is known as Version 004, or V4, in the EDG when ordering). However, note that the sea ice CMG products (MOD29C1 and MOD29C2) and the snow albedo enhancement to the snow map (MOD10A1) are not yet available to order, but should be available in early 2003. When Collection 5 is created in 2004, the data will be reprocessed beginning February 24, 2000, and to the present. At that time, all of the CMG and snow albedo maps will be orderable.

Most of the MODIS cryospheric products have been validated to stage 2 which means that the accuracy of the products has been assessed by a number of independent measurements, at a number of locations or times representative of the range of conditions expected for the products. As new data sets are added, e.g. daily snow albedo, they will be released at a beta level of validation. The early release will allow users to gain familiarity with the products with the caveat that there may still be significant errors and that the data are not appropriate for use in quantitative scientific publication. As validation proceeds, and necessary algorithm changes are made, the products will move into "provisional" and then "validated" status.

An important enhancement to the snow product (MOD10A1), daily snow albedo, should be available early in 2003 in the Collection 4 forward-processing mode. A daily, global map of sea ice on the climate-modeling grid (CMG) (MOD29C1), will also be available early in 2003 in the forward-processing mode. When significant algorithm changes warrant it in the future for the entire suite of MODIS land products, Collection 5 processing and reprocessing will begin, probably sometime in 2004.

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Statement of Significant Findings

As a result of the MODIS snow and ice derived products, it is significant that they will be used in General Circulation Models (GCMs) to improve the parameterization of snow and ice. This, in turn, will affect the model output, in particular the Earth's energy balance results.

Popular Summary

Snow and sea ice products, derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument, flown on the Terra and Aqua satellites, are available in a format that is suitable for climate studies. The suite of MODIS snow and ice products, consisting of 10 current or near-future products, is available free of charge. In the paper, the products are described and the reader is provided detailed information on how to order the products.