MERGING THE MODIS AND RUCL MONTHLY SNOW-COVER RECORDS

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Abstract-**Monthly time series from two satellite snow-cover records are merged to study the construction of a climate-data record for the Northern Hemisphere, and its limitations.**

I. INTRODUCTION AND BACKGROUND

A. Snow-cover mapping of the Northern Hemisphere

Satellite-derived maps of snow cover for the Northern Hemisphere have been generated using a variety of satellites, sensors and techniques. NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) began to generate Northern Hemisphere Weekly Snow and Ice Cover analysis charts in November 1966 using manual techniques from NOAA satellite data, at a spatial resolution of 190 km. Since 1997 the Interactive Multi-Sensor Snow and Ice Mapping System (IMS) has been used by NESDIS analysts to produce products daily at a spatial resolution of about 25 km, utilizing a variety of satellite data [1]. This snow-cover record has been studied carefully [2], [3] and has been reconstructed by the Rutgers University Climate Lab (RUCL) using adjustments for inconsistencies that were discovered in the early part of the data set [4], [5]. Results show that the Northern Hemisphere annual snow-covered area has decreased [2], [6], [7], [8], [9], [5], [10] about 0.2% per year from 1978 - 1999 [9].

With the launch of NASA's Earth Observing System (EOS) Terra satellite, snow maps have been produced globally, using automated algorithms, on a daily and 8 day composite basis from the Moderate-Resolution Imaging Spectroradiometer (MODIS) instrument since February 24, 2000. The MODIS snow products http://modis-snow-ice.gsfc.nasa.gov, are provided at a variety of different resolutions and projections to serve different user groups [11] and [12]. In the near future, monthly MODIS snow products will also be produced automatically.

The period of overlap of the MODIS and RUCL monthly snow maps, March 2000 to the present, presents an opportunity to compare the maps with the intent of producing a climate-data-record (CDR) quality product for the Northern Hemisphere. In this paper, we explore some of the problems and limitations of this process.

B. MODIS monthly snow-cover algorithm and maps

The monthly snow-cover product is being developed at Goddard Space Flight Center and will become a standard EOS product in 2005. Currently, monthly snow maps from MODIS are available only from September 2003 through March of 2004. This prototype product is created using the 0.05° daily, global climate-modeling grid (CMG) snow maps which provide fraction of snow and cloud in each cell. Monthly snow-cover maps are computed in a two-step process that includes a daily data-quality filter and a low-snow-fraction filter applied to the monthly snow cover. Daily data are accepted if the Confidence Index (CI), a measure of the quality of the data (good quality data defined as clear view daytime data) is ≥70. Daily snow "average" is computed for cells with CI ≥70 as follows,

$$ds\ \% = (\text{snow}\ \% / CI) * 100 \qquad (1)$$

Daily snow percentage (ds) is calculated this way so that in a cell where there is a small percentage of cloud reported an inference is made as to fraction of snow obscured by the cloud. Cells in which the CI <70 are designated as "cloud," "nighttime" or "no decision."

The monthly snow (ms) for each cell is computed as follows,

$$ms = ({}_0^n\Sigma\ ds) / n \qquad (2)$$

where, n = number of days in month where CI ≥ 70, and n ≤ days in the month. A low-snow (ls) fraction filter calculated as follows,

$$ls = ({}_0\Sigma\ ds) / s \qquad (3)$$

where, s = number days that snow was found and s ≤ n

If ls ≤10 then no snow is reported for the cell. Also, if ls <70 and s ≤3, then no snow is reported for the cell. The objective of the low-snow filter is to remove erroneous low-snow fractions that are caused by snow/cloud confusion in the swath snow algorithm and that are then carried into the daily snow product.

Monthly snow is the average percentage of snow from all days with a CI>70%, and with low-snow-percentage data filtered from the output. This technique allows for snowstorm events that leave a transient snow cover to be included in the monthly snow map. Because of cloudcover, it is impossible to calculate a true monthly "average" snow cover for each cell.

C. Rutgers University Climate Lab (RUCL) monthly snow-cover frequency maps

The raw NOAA gridded 89x89 data and the RUCL reanalysis gridded data are both utilized in creating a unique Northern Hemisphere snow cover product. Weekly and monthly 89 x 89 grid cell charts are generated at RUCL. In this procedure, weekly areas are calculated from digitized snow files, and monthly values are calculated by weighting the weekly areas according to the number of days of a map week falling in the given month. The result is an accurate grid cell product which details Northern Hemisphere snow cover data over the last 36 years. Weekly maps are based primarily on image analyses from the last day or two of the week.

II. METHODOLOGY

Monthly snow maps derived from the daily MODIS CMG products (MOD10C1) were reprojected to polar stereographic projection with the resolution of 5 km for both the latitude and longitude (25 km^2 per pixel). The 28-km RUCL monthly snow-cover frequency maps (http://climate.rutgers.edu/snowcover/) were then registered to the MODIS maps by using about 70 "ground control points" and a 3rd order for image-to-image registration. The root-mean square (RMS) error is approximately 0.25 of a pixel. In order to make an accurate comparison, clouds and lakes that are shown on the MODIS maps were transferred to the RUCL maps; and the coastlines and political boundaries were transferred from RUCL maps to the MODIS maps.

To make the MODIS maps potentially more useful for modelers, and for improved comparison with the RUCL maps, land cells containing "night" or "cloud" on the MODIS maps were replaced with 100% snow cover in the following way for the months of October through March. All nighttime or cloud land-based cells above 80°N (for October), 65°N (for November) and 60°N (for December) were replaced with 100% snow. Additionally, Greenland is mapped as 100% snow covered year 'round for this preliminary work. (Only the parts of Greenland that are snow covered with be shown as snow covered in the MODIS monthly product when it is produced.)

III. RESULTS

Comparison of the MODIS and RUCL maps was very favorable, with the RUCL maps in all cases (except September of 2003 in Eurasia) showing greater snow extent than the MODIS maps (see Tables 1 and 2).

Figures 1 and 2 show the difference graphically. Note that October of 2003 and February of 2004 represent the months with the greatest and least discrepancy, respectively, in snow-covered area. In October, the snow cover expands greatly, sometimes more than 100,000 km^2 in 24 hours. (Some of those discrepancies are due to transient snow covers of early season storms. MODIS and the RUCL maps may differ on how transient snow covers are handled.) Thus even slight differences in compositing techniques can provide different monthly snow-cover values.

TABLE 1
COMPARISON OF SNOW EXTENT (km^2) MAPPED FROM THE MODIS AND RUCL PRODUCTS FOR NORTH AMERICA

Month & Year	MODIS snow extent km^2	RUCL snow extent km^2	Percent difference
Sep 2003	3,974,775	4,211,700	5.6
Oct 2003	7,932,850	12,533,200	36.7
Nov 2003	14,881,750	15,320,550	2.9
Dec 2003	17,355,200	18,001,150	3.6
Jan 2004	17,444,475	18,485,650	5.6
Feb 2004	18,411,075	18,497,400	0.5
Mar 2004	14,863,225	15,569,675	4.5

TABLE 2
COMPARISON OF SNOW EXTENT (km^2) MAPPED FROM THE MODIS AND RUCL PRODUCTS FOR EURASIA

Month & Year	MODIS snow extent km^2	RUCL snow extent km^2	Percent difference
Sep 2003	2,792,875	2,365,725	18.0
Oct 2003	15,130,925	21,649,100	29.3
Nov 2003	23,840,725	27,091,425	12.0
Dec 2003	28,108,975	31,658,200	11.2
Jan 2004	31,655,650	36,161,550	12.5
Feb 2004	30,035,650	33,171,050	9.5
Mar 2004	25,723,300	27,824,800	7.6

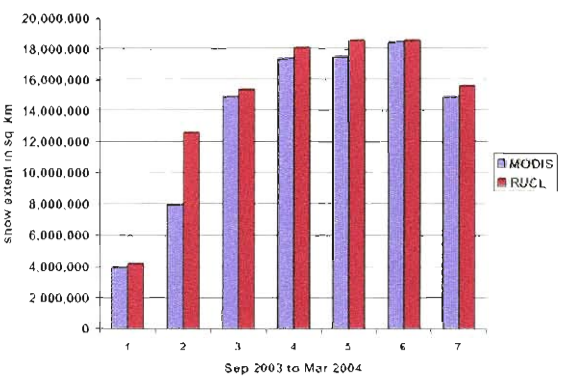

Figure 1. Comparison of snow extent derived from MODIS and RUCL monthly maps of North America.

For example, there was a significant snowstorm on 30 October 2003 that covered nearly all of Montana, North Dakota, northern Minnesota, northwestern South Dakota, and most of Wyoming. Because it was cloudy during the storm, the MODIS algorithm did not capture that snow event; assuming the last day of the month was clear, the effects of the storm

would be seen only on the last day of the month and snow cover is not mapped for the month [Eq. 1, 2 & 3] if only one day is snow covered. Alternatively, the RUCL maps would be more likely to capture the effects of the snowstorm because of their mapping techniques. Further investigation into these possible errors in the MODIS maps will be undertaken.

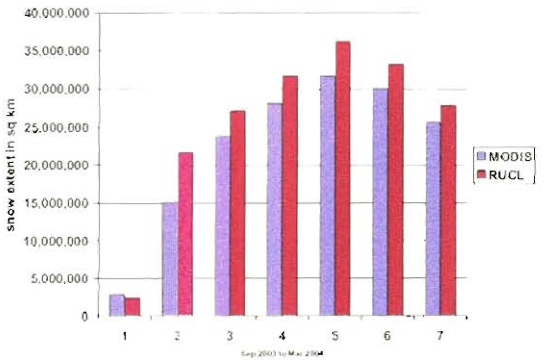

Figure 2. Comparison of snow extent derived from MODIS and RUCL monthly maps of Eurasia.

Additionally, analysis of the frequency of snow cover on the RUCL monthly maps indicates that only the very low frequency of snow cover (meaning that snow may have been present in many areas only ~15% of the month) is mapped by RUCL in those areas where the MODIS and RUCL maps disagree. Furthermore, the cells with less than 11% snow cover are not shown on the MODIS maps and when those areas are included, the difference between the MODIS and RUCL maps is even less.

October and November of 2003 were anomalous for snow cover in the Northern Hemisphere as the extent of snow cover was much greater than the climatic average. Snow cover was very low at the beginning of October and there was a rapid increase in snow cover at the end of the month. Because of cloud cover obscuration, and the compositing technique used to develop the monthly MODIS maps, errors may be more likely to occur in the MODIS products especially during times in the snow season when snow conditions are changing rapidly.

In February of 2004, the main areas of disagreement are at the edges of the snow-covered areas in both North America and Eurasia (Figure 3). Small differences at the edges of snow-covered areas are expected due to the difference in resolution of the maps, and the differences in the algorithms. Again, as discussed for the October comparison, the differences in the snow maps generally stem from the areas on the RUCL maps showing snow cover with frequencies <15%.

Standardization of the monthly snow maps that are being developed using MODIS data is necessary in order to ensure that the maps can be compared quantitatively with the RUCL monthly snow-cover maps. The period of overlap of the two maps, March 2000 to the present, represents an opportunity to compare the maps. The complete stream of MODIS monthly snow-cover maps will be in production in 2005.

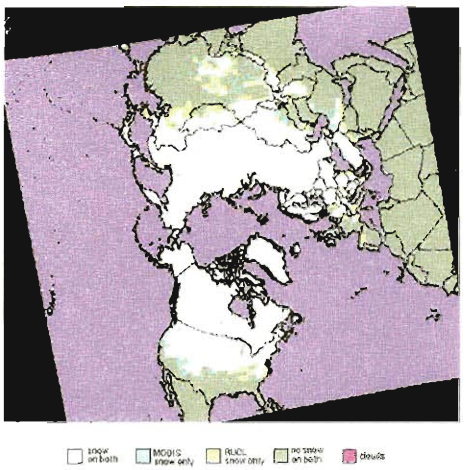

Figure 3. Difference map from February 2004. February 2004 is the month with the least difference in monthly snow cover between the MODIS and RUCL maps.

IV. DISCUSSION AND CONCLUSION

In this limited and preliminary study, we have shown that the maps are very similar in terms of the extent of snow cover. In September and October 2003, the buildup of snow cover can occur rapidly, and since different algorithms are used to map monthly snow cover, differences in the areal extent of snow mapped are more likely. When new snow falls near the end of the month, and if clouds do not clear until early the following month, then the MODIS algorithm will not map snow in those cells obscured by clouds.

As the length of the satellite record increases through the MODIS era, and into the National Polar-Orbiting Environmental Satellite System (NPOESS) era, it should become easier to identify trends in areal extent of snow cover, if present, that may have climatic significance. Thus it is important to study the validity of merging the NESDIS and MODIS, and, in the future, the NPOESS snow datasets for determination of long-term continuity in measurement of Northern Hemisphere, and ultimately, global snow cover. In this preliminary study, we have identified some of the issues relating to comparing two snow-cover data sets. A

continuation of this work is planned when a longer monthly snow-cover record from MODIS can be utilized.

ACKNOWLEDGMENTS

The authors thank Nick DiGirolamo/SSAI for programming and help developing the MODIS monthly snow algorithm, Janet Chien/SAIC for image-processing analysis of the MODIS and RUCL data sets, and Thomas Estilow/Rutgers for generation of NOAA monthly maps. This work is supported in part by NOAA grant NA06GP0566 and NASA grant NAG511403, and by NASA's EOS Program.

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