Assessment of the Relative Accuracy of Hemispheric-Scale Snow-Cover Maps

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Abstract

There are several hemispheric-scale satellite-derived snow-cover maps available, but none has been fully validated. For the period October 23 – December 25, 2000, we compare snow maps of North America derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the National Oceanic and Atmospheric Administration (NOAA) National Operational Hydrologic Remote Sensing Center (NOHRSC), which both rely on satellite data from the visible and near-infrared parts of the spectrum; we also compare MODIS and Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) passive-microwave snow maps. The maps derived from visible and near-infrared data are more accurate for mapping snow cover than are the passive-microwave-derived maps, however discrepancies exist as to the location and extent of the snow cover among those maps. The large (~30 km) footprint of the SSM/I data and the difficulty in distinguishing wet and shallow snow from wet or snow-free ground, reveal differences up to 5.32 million km^2 in the amount of snow mapped using MODIS versus SSM/I data. Algorithms that utilize both visible and passive-microwave data, which would take advantage of the all-weather mapping ability of the passive-microwave data, will be refined following the launch of the Advanced Microwave Scanning Radiometer (AMSR) in the fall of 2001.

Introduction

The areal extent of snow cover has been monitored continuously from satellite observations by the National Oceanic and Atmospheric Administration since 1966 (**Matson and others (1986).** Although **Robinson (1993)** has identified several weaknesses in the long-term operational snow product, it is nevertheless the most valuable climatological time series of snow cover available. Passive-microwave maps of snow cover have been produced since 1978, providing information on snow extent as well as some information on snow-water equivalent. In order to improve the snow-cover record to optimize future long-term climate studies, and as input to general circulation models, it is important to develop an objective way of mapping snow globally, if trends, such as those discussed in **Brown (1997),** in snow cover are to be validated. In addition, the accuracy of the snow-cover input data needs to be verified in order to establish the accuracy of the model output (**Derksen and LeDrew, 2000**).

In December of 1999, the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor was launched by the National Aeronautics and Space Administration (NASA) and daily, global maps of snow cover at a spatial resolution of 500 m are available. In this paper, we compare 8-day composite snow maps developed using data from the MODIS sensor, NOAA/National Operational Hydrologic Remote Sensing Center (NOHRSC) operational maps, and passive-microwave-derived maps from the Defense Meteorological Satellite Program (DMSP)/Special Sensor Microwave/Imager (SSM/I). Each map is known to have a unique set of problems or limitations. The 30-m resolution Landsat Enhanced Thematic Mapper Plus (ETM+) and the National Oceanic and Atmospheric Administration (NOAA) operational product, the Interactive Multisensor Snow and Ice Mapping System (IMS), as well as some field measurements, are used as "ground truth."

Background

MODIS-derived snow maps. The MODIS snow-mapping algorithm is fully automated which makes its results consistent from scene to scene. The algorithm uses reflectances in MODIS bands 4 (0.545 - 0.565 μm) and 6 (1.628 – 1.652 μm), uncorrected for atmospheric effects, to calculate the normalized difference snow index (NDSI) (**Hall and others, 1995**). Using reflectance data from the MODIS sensor, snow cover is mapped using a grouped-criteria technique algorithm. A pixel will be mapped as snow if the NDSI is ≥0.4 and reflectance in MODIS band 2 (0.841 - 0.876 μm) is ≥11%. However, if the MODIS band 4 reflectance is <10%, then the pixel will not be mapped as snow even if the other criteria are met. This prevents pixels containing very dark targets from being mapped erroneously as snow. MODIS bands 1 (0.620 - 0.670 μm) and 2 (0.841 – 0.876 μm) are used to calculate the normalized difference vegetation index (NDVI). The NDSI and NDVI are used together to map snow in dense forests **(Klein and others, 1998).** A cloud mask **(Ackerman and others, 1998)**, and a land/water mask are inputs to the MODIS snow-cover maps.

Eight-day composite MODIS maximum snow-cover maps at ¼° x ¼° spatial resolution were developed from the 500-m resolution MODIS binary snow maps that are available on a daily or near-daily basis, if cloudcover permits. The 500- binary snow pixels are binned into a ¼° x ¼° latitude/longitude grid to facilitate comparison with other hemisphere-scale maps. Using this binning technique, a pixel is snow covered if as few as ~1% of the observations in the 1/4 by 1/4 grid cell are snow covered. While this technique may tend to overestimate snow cover, it has the advantage that it shows all of the snow that was present during the 8-day composite period. Maximum snow cover means that if snow cover were present on any of the 8 days of the composite, that pixel will be considered to be snow covered.

NOHRSC snow maps. The National Weather Service (NWS) produces a 1-km-resolution snow-cover product on at least a weekly basis over the United States and parts of southern Canada (**Holroyd and others, 1989; Carroll, 1995**). Data are used operationally by the NWS.

To develop the NOHRSC product, remotely-sensed and interpolated, gridded, snow-water equivalent data products are generated by hydrologists using NOAA Geostationary Orbiting Environmental Satellite (GOES) and Advanced Very High Resolution (AVHRR) as well as ground data. AVHRR data are ingested and radiometrically calibrated, and used to generate a snow/no-snow/cloud cover byte plane image. Data are available on the NOHRSC Web site: http://www.nohrsc.nws.gov/.

SSMI-derived snow maps. The SSM/I sensor was launched in 1987. This instrument has many of the same channels as the prior instrument, the Scanning Multichannel Microwave Radiometer (SMMR), launched in 1978. Different algorithms have been used to map snow using SSM/I data (e.g., **Chang and others, 1987; Grody, 1991; Grody and Basist, 1996**). In this paper, we employ the **Chang and others (1992)** algorithm to map snow cover because it provided a closer match with the MODIS and NOHRSC snow maps than did the **Grody and Basist, 1996)** algorithm.

Other NOAA snow maps. The weekly National Environmental Satellite Data and Information System (NESDIS) operational product was determined from visible satellite imagery from polar-orbiting and geostationary satellites and surface observations. The analysis was performed once a week, using the most recent clear view of the surface. Because the analysis for this product was done only once a week, much snow cover, especially from fleeting/transient storms, was missed. And where cloudcover precluded the analyst's view of the surface for an entire week, the analysis from the previous week was carried forward (**Ramsay, 1998**). The maps were hand drawn, and then digitized using an 89 X 89 line grid overlaid on a stereographic map of the Northern Hemisphere. The older, weekly maps were replaced in 1997, by IMS product. The IMS product provides a daily snow map that is constructed through the use of a combination of techniques including visible, near-infrared and passive-microwave imagery and meteorological-station data (**Ramsay, 1998**). NOAA also produces a daily product, developed by automated techniques, that uses visible, near-infrared and passive-microwave data to map snow cover, and agrees in 85% of the cases studied, with the IMS product (**Romanov and others, 2000).**

Additionally, NOAA provides an experimental automated snow mapping product which is based on a synergy of GOES-Imager, NOAA-AVHRR and DMSP-SSM/I data for the North American continent (http://orbit-et.nesdis.noaa.gov/crad/sat/surf/snow/HTML/snow.htm). The original map is prepared in a Platte Carre (lat-lon) projection with a 1/25 of a degree grid size. This product is considered to be less accurate than the IMS product **(Bruce Ramsay, personal communication, 2001**).

Previous work has shown that, when the visible data from the earlier NESDIS product is compared with passive-microwave data on snow extent, the passive-microwave snow maps consistently underestimate the amount of snow relative to the maps derived from visible and near-infrared data (**Basist and others, 1996; Armstrong and Brodzik, 1999**). For the time period from 1978-1999, **Armstrong and Brodzik (1999)** show a mean difference of 3.5 million km^2 with the SSM/I maps showing consistently less snow cover than the maps derived from visible data. The difference in snow-covered area measured by **Armstrong and Brodzik (1999)** is greatest in the fall months, and least in the summer months. This is because, at the lower elevations across North America, Europe and western Asia the snow is more likely to be shallow (<~3.0 cm) and may often be wet which is difficult to detect using passive-microwave snow-mapping algorithms (**Chang and others, 1987**). Additionally, thin, dry snow cover may be transparent and therefore not be mapped using passive-microwave data.

Relative errors in snow-cover mapping, using both visible/near-infrared and passive-microwave maps are easier to ascertain than are the absolute errors in snow-cover mapping. This is because it is very often impossible, in retrospect, to determine which map is the most accurate. A technique that combines ground measurements with determination of snow-mapping accuracy in different land-cover types (e.g., **Hall and others, 2001)**, is a way to begin to assess absolute accuracy of snow-cover maps.

Methodology

Daily snow maps, while useful for local and regional purposes, are usually so cloud contaminated that it makes them difficult to use on a hemispheric or global scale. Therefore we use 8-day composite maps in this work; only clouds that persisted for all 8 days of the period remain on the MODIS or NOHRSC maps, thus facilitating comparison with the NOHRSC and especially the SSM/I maps. Because the entire 2000-2001 winter of MODIS data are not yet available, we used the following 8-day periods in 2000 for development of the MODIS and other composite maps: October 23-30, October 31-November 7, November 8-15 and 16-23, November 24-December 1, December 2-9, 10-17 and 18-25. Depending on the availability of the satellite data, not all days could be used to calculate the composite snow maps during each 8-day period. For example, during the eight-day periods, there were never eight consecutive NOHRSC snow maps available.

Image-processing software was used to register the NOHRSC image onto the MODIS map at ¼° x ¼° resolution. About 50 ground control points (gcp) were determined from both images and saved as a gcp file. Then a "registration" routine was used to place the NOHRSC snow map (uncorrected) onto the MODIS map (georeferenced) using the gcp file and a curve-fitting technique.

If persistent cloud cover appears on either the MODIS or the NOHRSC 8-day composite maps, it is excluded from the comparison. Similarly, in the MODIS/SSM/I comparisons, if there were cloud cover on the MODIS map, then these areas will be excluded from the comparison.

Only early-morning data (6:00 a.m.) from the SSM/I were used to derive the passive-microwave snow maps used in this paper since the colder nighttime (and early morning) temperatures minimize snowpack wetness. A wet or melting snowpack will cause the microwave brightness temperature to increase (**Hallikainen and Jolma, 1992**) and may cause confusion with adjacent wet, snow-free ground. Whenever possible, dry snow cover is preferred for comparison with the visible-derived snow maps.

A modified version of the **Chang and others (1987)** algorithm was used. The algorithm was modified to act as a snow-mapping algorithm instead of a snow depth algorithm and is as follows:

$$SD = (19H - 37H) * 1.59 \qquad [1]$$

Where SD is snow depth, and 19H and 37H refer to the brightness temperature at 19 GHz horizontal polarization, and the brightness temperature at 37 GHz polarization, respectively. 1.59 is a constant.

If the 37V $T_B < 250K$ and the 37H $< 240K$, and the SD > 8cm, then the algorithm will map snow in a pixel.

Results

MODIS/NOHRSC comparisons. In general, the MODIS maps show more snow cover than do the NOHRSC maps **(Figure 1) (Table 1)**, and the MODIS maps show better agreement with the IMS and Landsat ETM+ data. ETM+ browse images (obtained once every 16 days, cloudcover permitting, may be viewed on the United States Geological Survey EROS Data Center Web page [http://edcsns17.cr.usgs.gov/EarthExplorer/]. For example, on the December 10-17 composite, the MODIS map shows considerably more snow cover in Kansas than does the NOHRSC map **(Figure 1)**. Inspection of ETM+ browse products (for example path/row 30/32 on December 14, 2000), and the IMS product (for example, December 11, 2000), shows that in fact snow is present in most of Kansas at some time during that 8-day period. And thus the MODIS map appears to be more accurately mapping snow cover in this case.

During the period November 8-15, the NOHRSC map agrees better with the IMS and ETM+ data than does the MODIS map in the State of Washington, east of Puget Sound. The MODIS 8-day composite snow map is not mapping snow cover which is known to be present. (Perhaps the area was not snow covered on a clear day during the 8-day composite period, and then snow fell and the area was cloudy thereafter; this would cause the MODIS map to underestimate the snow cover. Inspection of the IMS product reveals that the area was, in fact, snow-free at the beginning of that 8-day period. Thus this is a plausible explanation.) By the November 16-23 time period, the MODIS map shows snow in Washington, Oregon and northern California (and in the Sierra Nevada), and this agrees quite well with the NOAA IMS product and selected ETM+ browse data, but snow is not shown there on the NOHRSC map.

MODIS/SSMI comparisons. The MODIS maps also show more snow cover than do the SSM/I maps **(Figure 2)** and **(Table 2).** For example, over most of the Province of Quebec, the MODIS and IMS maps show snow cover during all of the 8-day periods **(Figure 2)** while the SSM/I map shows much less snow there especially early in the snow season. However, by December 10 through the end of the study period, December 25, there is much better agreement between the MODIS and SSM/I maps.

Meteorological data from three stations in Quebec: La Grande, Schfferville and Kuujjuaq, shown in **Figure 3,** reveal average temperatures during the period from October 23- mid-November, 2000, at or above 0°C. With above-freezing average temperatures, there will be enough moisture in the snowpack to cause the microwave emission to increase and the snow-mapping algorithms cannot distinguish wet snow from wet ground. Also, shallow (<5 cm) snowpacks, characteristic of early season conditions, are transparent to microwave radiation.

Discussion and Conclusion

Analysis of the 8 time periods in 2000, beginning on October 23 and ending on December 25, reveals that the MODIS maps for the periods October 23-30 and October 31-November 7, 2000, show considerably more snow cover than do the NOHRSC maps **(Figure 1)** and **(Table 1**). MODIS, because of its frequent coverage, is mapping some fleeting snowstorms that may be missed (either accidentally or intentionally) in the NOAA operational products (NOHRSC and IMS). Since the NOHRSC and IMS products are subjective, the analysts who construct the maps may use ground data, in addition to satellite data, to refine the snow maps. Some minor snow events, located at the edges of areas mapped as snow by both maps, may not be deemed significant enough to label as snow if the snow cover is not continuous or persistent, a common occurrence especially during the beginning of the snow season. Or, the mapping techniques will miss the effects of these storms if the maps are not produced on a frequent basis. In general, there were only five to eight NOHRSC maps for each 8-day period, while the MODIS maps were produced from 8 days of data (with the exception of October 31, 2000, when there were no MODIS data available). However, NOAA's IMS product is produced daily. The greater temporal resolution of the MODIS maps is advantageous for mapping maximum snow cover.

The binning technique selected to transform the 500-m resolution MODIS maps into ¼° x ¼° resolution maps may overestimate snow cover in some cases when only a small amount of the pixel is snow covered, because the entire ¼° x ¼° pixel will be mapped as snow. The exact binning technique for developing ¼° x ¼° global snow map products from MODIS data is under development.

A modification of the **Chang and others (1987)** algoithm, and the **Grody and Basist (1996)** SSM/I algorithm were studied, and the modified **Chang and others (1987)** algorithm was selected to use in this study because the **Grody and Basist (1996)** algorithm was found to map even less snow cover in the early part of the snow season than did the **Chang and others (1987)** modified algorithm. It was therefore decided that the **Chang and others (1987)** modified algorithm was superior for the purposes of this work.

As the winter progresses, agreement between the MODIS and SSM/I maps improves. This was also noted by **Armstrong and Brodzik (1999)** in their comparison study using the SSM/I maps and the NESDIS weekly maps. As the snow deepens during the winter, and the temperatures are consistently colder, the SSM/I does a better job of mapping it, and the agreement between the visible and passive-microwave maps improves. Areas of discrepancy are still present, however, especially in coastal areas where mixed pixels of SSM/I data erroneously map the coastal areas as snow-free when in fact there is snow. An example of this may be seen in northern Quebec on the December 18-25, 2000 MODIS/SSM/I difference map **(Figure 2)**.

In the future, with the launch of NASA's Aqua satellite in 2001, there will be algorithms developed using the Advanced Microwave Scanning Radiometer (AMSR) sensor (**Chang and Koike, 2000)** that should utilize the superior mapping capabilities of the visible sensors, and the all-weather and capabilities of the passive-microwave sensors (**Tait and others, 2000)**. The improved spatial resolution of the AMSR data (up to 12.5 km) will facilitate comparison with visible and near-infrared snow maps.

While the intent of this work was not to establishe which product is the most accurate, it is quite obvious that the passive-microwave data are less accurate in terms of mapping total snow-covered area. This is due to the poor (~30 km) spatial resolution of the data, and the fact that the wet snow and shallow snow may not be mapped by the existing automated passive-microwave algorithms, especially in the early part of the snow season. MODIS and NOHRSC maps are comparable, except that the MODIS nearly always maps more snow cover than does the NOHRSC **(Table 1)**. MODIS maps show more snow than the NOHRSC maps, in general, especially in the beginning of the snow season when more frequent temporal coverage of MODIS permits mapping of shallow snow deposits from fleeting storms.

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References

Ackerman, S.A., Strabala, K.I., Menzel, P.W.P., Frey, R.A., Moeller, C.C. and Gumley, L.E. 1998. Discriminating clear sky from clouds with MODIS, *Journal of Geophysical Research*, 103(D24):32,141-32,157.

Armstrong, R.L. and M.J. Brodzik. 1999. A twenty year record of global snow cover fluctuations derived from passive microwave remote sensing data. *5th Conference on Polar Meteorology and Oceanography,* American Meteorological Society. Dallas, TX, 113-117.

Basist, A., D. Garrett, R. Ferraro, N. Grody and K. Mitchell. 1996. A comparison between snow cover products derived from visible and microwave satellite observations, *Journal of Applied Meteorology*, 35(2):163-177.

Brown, R.D. 1997. Historical variability in Northern Hemisphere spring snow-covered area, *Annals of Glaciology*, 25:340-346.

Carroll, T.R. 1995. Remote sensing of snow in the cold regions, *Proceedings of the First Moderate Resolution Imaging Spectroradiometer (MODIS) Workshop on Snow and Ice Products,* NASA/GSFC, Greenbelt, Maryland, 13-14 September 1995, pp. 3-14.

Chang, A.T.C., J.L. Foster and D.K. Hall. 1987. Nimbus-7 SMMR derived global snow cover parameters, *Annals of Glaciology*, 9:39-44.

Chang, A.T.C. and T. Koike. 2000. Progress in AMSR snow algorithm development, *Microwave Radiometric Remote Sensing of the Earth's Surface and Atmosphere,* P. Pampaloni and S. Paloscia (Eds.), VSP, 515-523.

Derksen, C. and E. LeDrew. 2000. Variability and change in terrestrial snow cover: data acquisition and links to the atmosphere, *Progress in Physical Geography*, 24(4):469-498.

Grody, N.C. 1991. Classification of snow cover and precipitation using the Special Sensor Microwave Imager, *Journal of Geophysical Research*, 96:7423-7435.

Grody, N.C. and A. Basist. 1996. Global identification of snowcover using SSM/I measurements, *IEEE Transactions on Geoscience and Remote Sensing*, 34(1):237-249.

Hall, D.K., J.L. Foster, V.V. Salomonson, A.G. Klein and J.Y.L. Chien. 2001. Development of a technique to assess snow-cover mapping errors from space, *IEEE Transactions on Geoscience and Remote Sensing*, 39(2):432-438.

Hallikainen, M.T. and P.A. Jolma. 1992. Comparison of algorithms for retrieval of snow water equivalent from Nimbus-7 SMMR data in Finland, *IEEE Transactions on Geoscience and Remote Sensing*, 30:124-131.

Holroyd, E.W., J.P. Verdin and T.R. Carroll. 1989. Mapping snow cover with satellite imagery: comparison of results from three sensor systems, *Proceedings of the Western Snow Conference*, Western Snow Conference, Fort Collins, CO, 59-68.

Klein, A.G., D.K. Hall and G.A. Riggs. 1998. Improving snow-cover mapping in forests through the use of a canopy reflectance model, Hydrological Processes, 12:1723-1744.

Matson, M., C.F. Ropelewski and M.S. Varnadore. 1986. *An Atlas of Satellite-Derived Northern Hemisphere Snow Cover Frequency*, U.S. Department of Commerce, Washington, D.C.

Ramsay, B. 1998. The interactive multisensor snow and ice mapping system, *Hydrological Processes*, 12:1537-1546.

Robinson, D.A. 1993. Hemispheric snow cover from satellites, *Annals of Glaciology,* 17:367-371.

Romanov, P., G. Gutman and I. Csiszar. 2000. Automated monitoring of snow cover over North America using multispectral satellite data, *Journal of Applied Meteorology*, 39:1866-1880.

Tait, A., D.K. Hall, J.L. Foster and R.L. Armstrong. 2000. Utilizing multiple datasets for snow-cover mapping, *Remote Sensing of Environment,* 72:111-126.

Table 1. Snow-covered area in millions km^2 for each eight-day composite snow-cover product, exclusive of cloud cover from MODIS and NOHRSC maps. Numbers refer to the 8-day periods*+.

	1	2	3	4	5	6	7	8
MODIS	0.24	0.92	2.13	2.32	1.56	1.79	1.98	2.99
NOHRSC+	0.04	0.53	1.76	1.98	1.38	1.57	1.99	2.78
Difference	0.20	0.39	0.37	0.34	0.18	0.22	(0.01)	0.21

*Period 1: October 23-30, 2000; period 2: October 31-November 7, 2000; period 3: November 8-15, 2000; period 4:November 16-23, 2000; period 5: November 24-December 1, 2000; period 6: December 2-9, 2000; period 7: December 10-17, 2000; and period 8: December 18-25, 2000.
+Exact numbers would change slightly if watershed boundaries were removed from the NOHRSC maps.

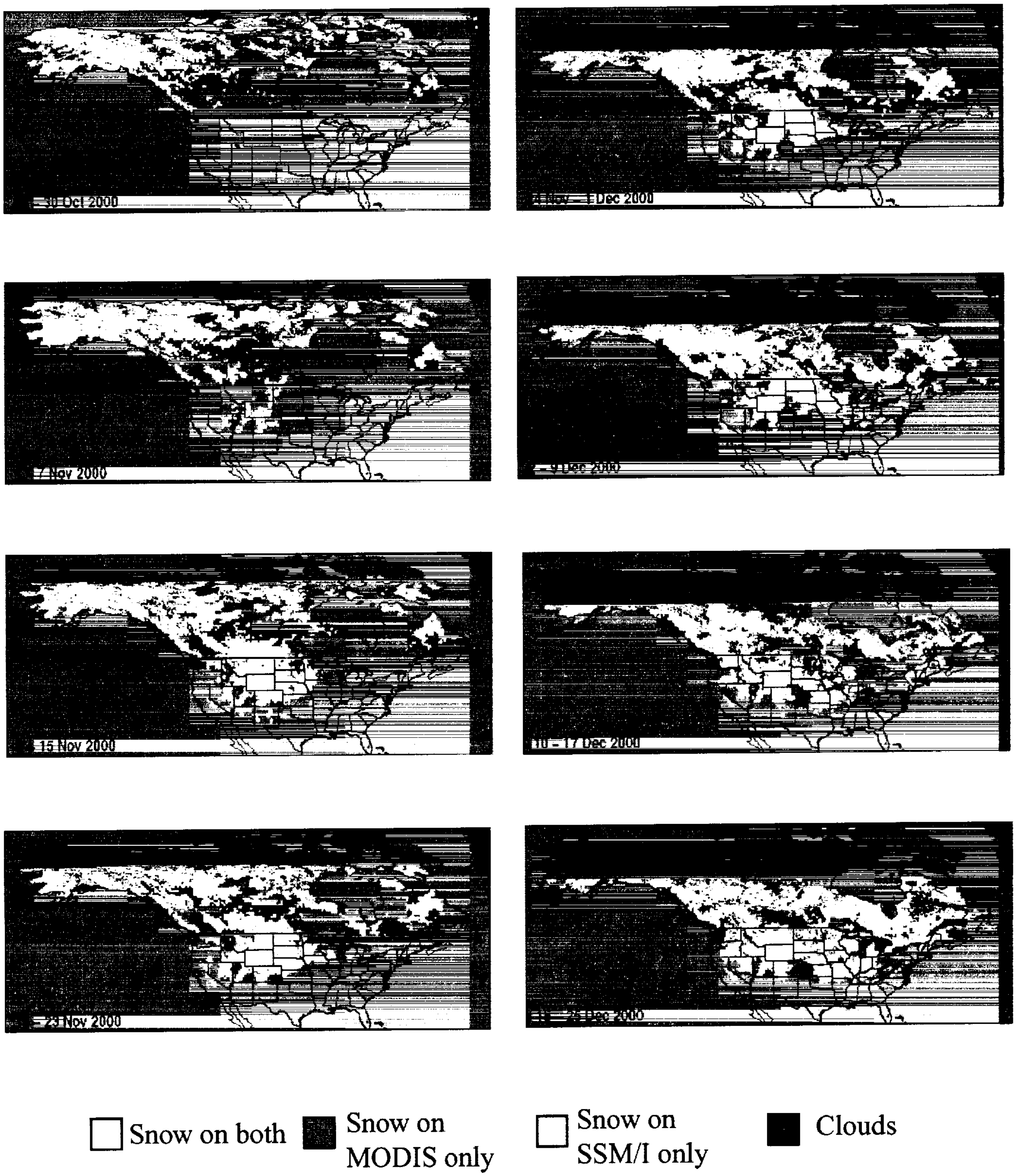
Table 2. Snow-covered area in millions km^2 for each eight-day composite snow-cover product, exclusive of MODIS cloud cover, for MODIS and SSM/I snow maps. Numbers refer to the 8-day periods*.

	1	2	3	4	5	6	7	8
MODIS	6.00	7.84	9.89	10.83	9.67	9.11	8.48	9.44
SSMI	3.00	4.08	5.69	5.50	4.97	5.64	5.45	6.92
Difference	3.00	3.76	4.20	5.33	4.70	3.47	3.03	2.52

*Period 1: October 23-30, 2000; period 2: October 31-November 7, 2000; period 3: November 8-15, 2000; period 4:November 16-23, 2000; period 5: November 24-December 1, 2000; period 6: December 2-9, 2000; period 7: December 10-17, 2000; and period 8: December 18-25, 2000.

Figures

1. MODIS/NOHRSC difference maps.
2. MODIS/SSM/I difference maps.
3. Meteorological station air temperature data from Quebec, Canada.



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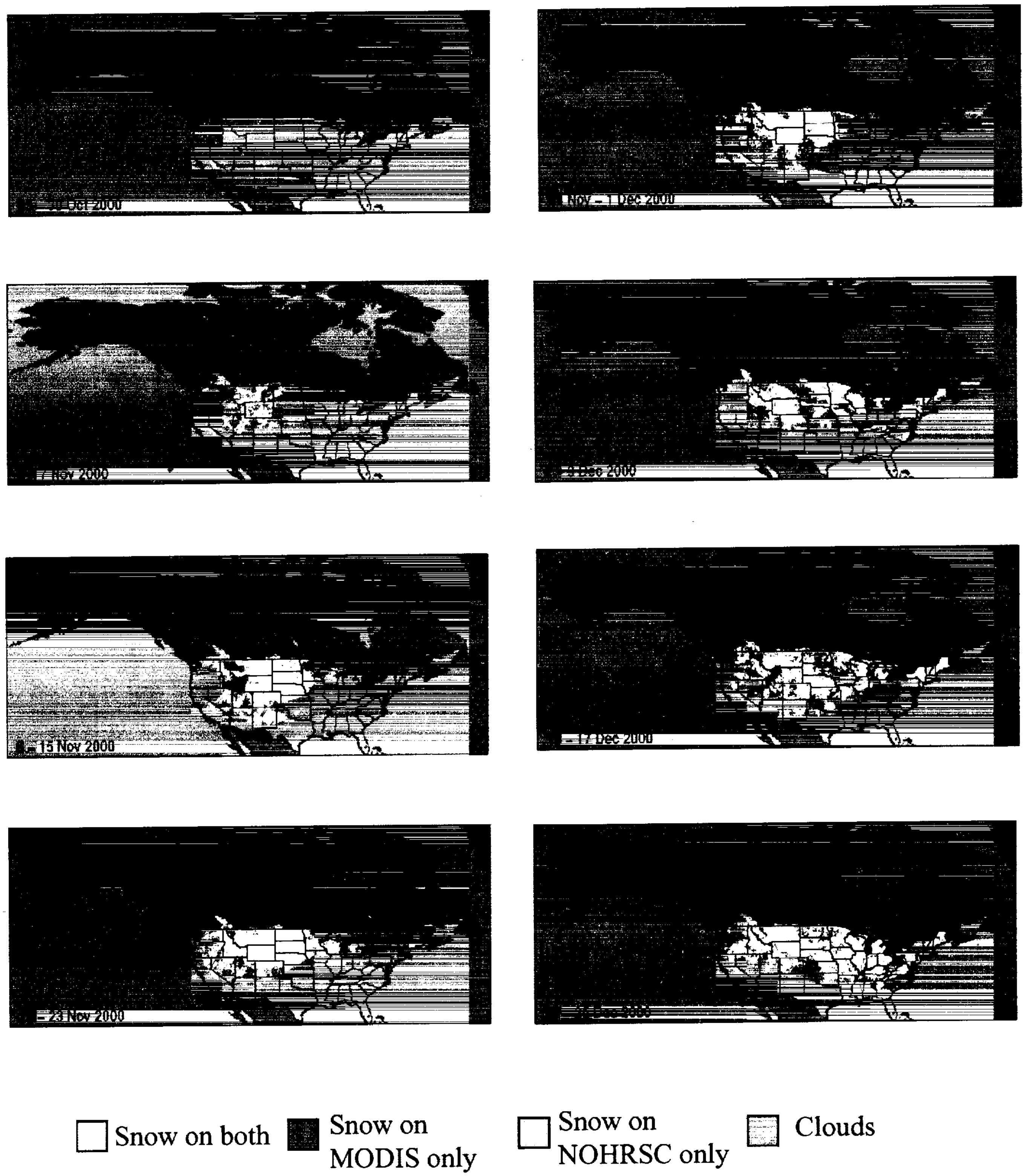
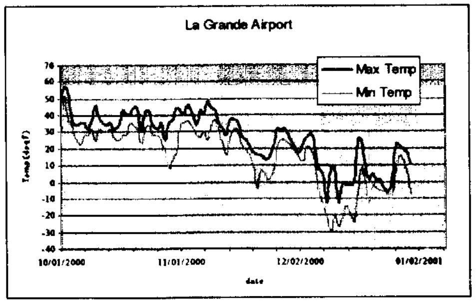
7 Nov 2000
15 Nov 2000
23 Nov 2000
10 - 17 Dec 2000
Snow on both
Snow on MODIS only
Snow on SSM/I only
Clouds


15 Nov 2000
23 Nov 2000
Snow on both
Snow on MODIS only
Snow on NOHRSC only
Clouds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Max Temp
Min Temp
Temp (deg F)
10/01/2000
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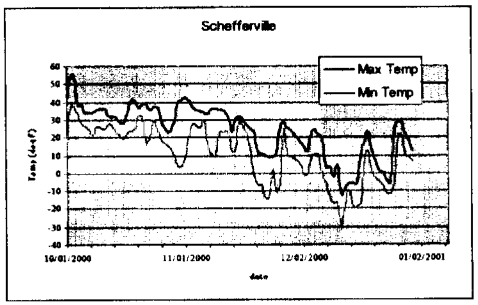
date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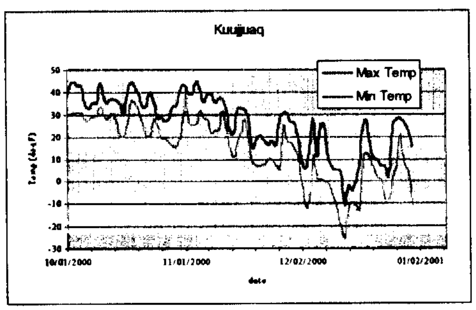
Kuujjuaq
Max Temp
Min Temp
Temp (deg F)
10/01/2000
11/01/2000
12/02/2000
01/02/2001
date