UTILIZING MULTIPLE DATASETS FOR SNOW COVER MAPPING

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Statement of Significance

Global snow cover has a significant impact on the Earth's energy balance. Three methods are currently used to estimate snow cover on a large scale: interpolation of climate station data, mapping from satellite-attained optical data, and mapping from satellite-attained passive microwave (PM) data. Salomonson *et al.* (1995) conclude that both optical and PM data should be used in synergy to provide optimum results in snow cover mapping. Likewise, Barry *et al.* (1995) remark that no single sensor or methodology alone can provide all the information required. In this study, NOAA snow charts (NSCs), Special Sensor Microwave Imager (SSM/I) derived snow cover, and climate station snow depth data are combined with additional climatic and surface elevation data to produce an optimum snow-cover product for North America. Many of the problems associated with the optical and PM methods, when used alone, have been diminished although the boreal forest remains a problem area. In addition, the Multiple Dataset Snow-Cover Product (MDSCP) provides more information on the state of the snow cover with four snow-cover classes (fully covered, high elevation snow, patchy snow, and no snow) rather than two (snow and no snow.)

Relationship to MPTE Science Plan

This study presents a snow cover product that combines several sources of remotely-sensed and ground-based data. It addresses MPTE concerns regarding (1) algorithm development and (2) monitoring land-cover change.

Popular Summary

Integrating data from several sources to map global snow cover has several advantages, as is shown in this study. First, snow is mapped irrespective of cloud cover due the inclusion of PM and station data. Second, the combination of the NSC and station data reduces the PM errors of omission in the spring caused by melting snow. Third, the MDSCP is a spatially complete snow-cover map for the end of the week, whereas the NSCs are composites over one to seven days while the PM-derived maps have sizeable swath gaps. Fourth, the MDSCP has four classes of snow cover (fully covered, thin or patchy, high elevation, or no snow cover) compared with the normal two (snow and no snow), which provides more information about the state of the snow cover. Fifth, the percent snow-covered area has been calculated for each class based on an analysis of the climate station data. These values are used to calculate the North American snow-covered area with greater accuracy than in the past. Last, the MDSCP can be used operationally without station data, although some spatial information is lost.

The primary disadvantage with the MDSCP is poor resolution. Compared with the NSCs (cell size between 16,000 and 42,000km^2), the EASE-grid SSM/I and MDSCP cell resolution (628km^2) is significantly better. However, for the purposes of mapping snow it is advantageous to have a resolution of less than 1km. This would reduce the problem of not mapping snow in the boreal forest during the late fall / early winter, as only the very densely forested stands would obscure the underlying snow. MODIS-derived daily global snow-cover maps, with a resolution of 500m, will be available for the 1999 / 2000 snow season. With this resolution, it is foreseeable that these optical data will be used as the primary source of snow-cover information, rather than the passive microwave data, except over areas with thick cloud cover. In the year 2000, EOS PM-1 AMSR-derived snow-cover maps will also be available, at a resolution of 12.5km.

Barry, R.G., Fallot, J-M., and Armstrong, R.L. (1995), Twentieth-century variability in snowcover conditions and approaches to detecting and monitoring changes: status and prospects. *Progress in Physical Geography*, 19(4):520-532.

Salomonson, V.V., Hall, D.K., and Chien, J.Y.L. (1995), Use of passive microwave and optical data for large-scale snow cover mapping. *Proceedings of the 2nd Topical Symposium on Combined Optical-Microwave Earth and Atmosphere Sensing,* Atlanta, GA, April 3-6, 1995, 35-37.

Utilizing Multiple Datasets for Snow Cover Mapping

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ABSTRACT

Snow-cover maps generated from surface data are based on direct measurements, however they are prone to interpolation errors where climate stations are sparsely distributed. Snow cover is clearly discernable using satellite-attained optical data because of the high albedo of snow, yet the surface is often obscured by cloud cover. Passive microwave (PM) data is unaffected by clouds, however the snow-cover signature is significantly affected by melting snow and the microwaves may be transparent to thin snow (< 3cm). Both optical and microwave sensors have problems discerning snow beneath forest canopies.

This paper describes a method that combines ground and satellite data to produce a Multiple-Dataset Snow-Cover Product (MDSCP). Comparisons with current snow-cover products show that the MDSCP draws together the advantages of each of its component products while minimizing their potential errors. Improved estimates of the snow-covered area are derived through the addition of two snow-cover classes ("thin or patchy" and "high elevation" snow cover) and from the analysis of the climate station data within each class. The compatibility of this method for use with Moderate Resolution Imaging Spectroradiometer (MODIS) data, which will be available in 1999, and with Advanced Microwave Scanning Radiometer (AMSR) data, available in 2000, is also discussed. With the assimilation of these data, the resolution of the MDSCP would be improved both spatially and temporally and the analysis would become completely automated.

1. INTRODUCTION

When snow covers the ground the exchange of energy at the surface is altered radically. Snow has a very high albedo (0.40 to 0.95) compared with soil

(0.05 to 0.40) and vegetation (0.05 to 0.26). Due also to its high thermal emissivity and low thermal conductivity, snow cover strongly influences the overlying atmosphere (Chang *et al.*, 1985). It has been suggested that anomalies of the snow cover may induce complex feedback mechanisms leading to local and global climate fluctuations (Hahn and Shukla, 1976; Walsh and Ross, 1988). In addition, snow cover is an essential component of the global hydrological cycle.

Because of the influence of snow on weather and climate, and the need to know where and how much snow exists, some investigators have used interpolation techniques to project snow-cover information obtained at climate stations to a larger area. Brown and Braaten (1998) used daily snow-depth measurements from approximately 3000 sites to estimate the snow cover over Canada. Even with this many stations, though, large areas in the Northwest Territories were considerably undersampled. Knowledge of the global snow-covered area from surface-based measurements is similarly limited due to large gaps in the recording networks in both space and time. It is therefore important to develop alternative techniques to remotely observe the global distribution of snow cover.

NOAA has produced satellite-derived end-of-the-week snow-cover maps for the whole of the Northern Hemisphere since 1966 (Matson *et al.*, 1986; Robinson *et al.*, 1993). These maps are important for monitoring the snow cover at the continental to global scale. Consequently, they are vital for improving large-scale hydrological models, refining medium- and long-range weather forecasts, and for fine tuning general circulation models (Rango, 1985). In addition, long-term changes in snow cover may indicate responses to climate change (Barry, 1985).

The NSCs are derived from satellite-attained reflected visible radiation data in the wavelength range 0.55 to 0.75 microns. The satellites used for the identification of snow are the Geostationary Operational Environmental Satellites (GOES), the Meteosat, the Geostationary Meteorological Satellite (GMS) and the NOAA polar-orbiting satellites. Snow is discriminated from cloud by observing cloud movement and by identifying surface features such as mountain ridges and river valleys. If a region is completely obscured by cloud then the analyst goes back to the last day that the surface can be seen (Robinson *et al.*, 1993). Last, the hand-drawn maps are digitized on to an 89 by 89 cell Northern Hemisphere grid with cell sizes ranging from 16,000 to 42,000km^2.

The NOAA National Environmental Satellite, Data, and Information Service (NESDIS) updated the snow cover mapping procedure in 1997 with the interactive multi-sensor snow and ice mapping system (IMS). The new maps take less time to prepare, are fully digital and are produced daily (Ramsay, 1998). In this study however, only the end-of-the-week NOAA snow-cover maps are used.

Satellite-attained PM data are used to estimate the snow-covered area when the snowpack is dry, as there is sufficient contrast in the brightness temperature range between snow and bare ground due to a lower dielectric constant and the effect of scattering in snow (Chang *et al.*, 1976; Rango *et al.*, 1979). The onset of melt, however, transforms a snowpack from one that scatters microwave radiation to one that absorbs and re-emits it (Ulaby and Stiles, 1980). This dramatically increases the brightness temperature (T_B) to that approaching the physical temperature of the medium and makes snowfield monitoring more difficult. For this and other reasons, it has been suggested by several authors that PM data should be used in conjunction with visible and near-infrared data for the determination of snow-covered area (Foster *et al.*, 1984; Robinson *et al.*, 1993).

Grody and Basist (1996) developed a decision tree method for identifying snow cover using PM data from the Special Sensor Microwave/Imager (SSM/I). Their approach uses filters derived from microwave scattering theory (Chang *et al.*, 1976; Ulaby *et al.*, 1982; Stogryn, 1986) and field experiments (Hall *et al.*, 1984; Mätzler and Huppi, 1989; Neale *et al.*, 1990; Grody, 1991) to separate the scattering signature of snow from the scattering signatures of precipitation, cold deserts, and frozen ground. A comparison between the NSCs and SSM/I-derived snow maps averaged over the current and adjacent weeks showed that the PM method maps slightly less snow, but the difference was no more than 3%. This was attributed to different temporal sampling (the NSC map is an end-of-the-week product, while their SSM/I map was averaged over the whole week), and the SSM/I's reduced sensitivity to shallow dry snow and melting snow (Basist *et al.*, 1996).

Three methods have been described above that are currently used to estimate snow cover on a large scale: interpolation of climate station data, mapping from satellite-attained optical data (the NSCs), and mapping from satellite-attained PM data. Each method has problems, however, and these and their effects are summarized in Table 1. Salomonson *et al.* (1995) conclude that both optical and PM data should be used in synergy to provide optimum results in snow cover mapping. Likewise, Barry *et al.* (1995) remark that no single sensor or methodology alone can provide all the information required.

In this study, the above data are combined with additional climatic and surface elevation data to produce an optimum snow-cover product for North America. This paper describes in detail the datasets and the methodology used to fulfill this objective. The new maps are compared with NSC and PM-derived snow-cover maps as well as with several NOHRSC snow-cover maps. Estimates of the North American snow-covered area are also produced. Last, we consider whether this approach can be used with Earth Observing System (EOS) MODIS and AMSR data, and whether the maps can be produced operationally. MODIS is scheduled to be launched in 1999 aboard EOS Terra and AMSR is scheduled to be launched in 2000 aboard EOS PM-1.

2. DATA

The following datasets, projected to the National Snow and Ice Data Center (NSIDC) 25-km Equal Area Scalable Earth (EASE) Northern Hemisphere grid (with the exception of cloud cover), were used in this analysis. Only data for North America were used as only those climate station data were obtained.

- NOAA digitized snow-cover charts (NSCs) derived from Advanced Very High Resolution Radiometer (AVHRR) and GOES data (distributed on CD by NSDIC);
- The Grody and Basist (1996) PM snow-cover product (which uses a decision tree method employing SSM/I data);
- Climate station snow-depth data from the USA and Canada;
- Navy maximum and minimum surface elevation data;
- Surface mean daily air temperature data obtained from the NOAA Climatic Diagnostics Center (CDC); and
- Cloud cover inferred from the NSCs (the dates written on the maps establish the day when the area was last cloud-free).

Figure 1 shows the location of the climate stations used in this study. The Canadian data were obtained from the Atmospheric Environment Service (*ca.* 3000 stations) and data from over 8000 stations within the United States were obtained from the National Climatic Data Center. A station location is defined as snow covered when the recorded snow depth is greater than or equal to 1cm.

It was deemed necessary to segregate terrain based on geomorphic complexity. This is because snow cover over complex terrain is less contiguous than over flat regions. Using the Navy maximum and minimum elevation data, the surface was divided into complex and non-complex terrain (Figure 2). Each EASE-grid pixel (25 by 25km) was classed as "complex" if the difference between the maximum and minimum elevation within the pixel is greater than 500 meters. This cutoff was chosen to best concur with known regions of mountainous terrain.

The period of analysis for this study, August 1987 through July 1995, was determined by the availability of the digitized NSCs in EASE-grid format (obtained from the Weekly Snow Cover and Sea Ice Extent CDs). The period of this analysis will be extended through May 31, 1999 when the CDs are updated. After this date, the weekly NSCs will be discontinued and only the daily product will be produced. The EASE-grid SSM/I brightness temperature data were also obtained from NSIDC. Due to instrument problems however, there are periods when either no PM data are available, a specific channel is out, or the data coverage is severely limited. Table 2 shows the days corresponding to the end-of-week NSCs between August 1987 and July 1995 when the SSM/I data is limited.

3. METHODS

This study uses a series of decisions that determines where and when snow should be mapped. In addition to mapping pixels as "snow covered" or "snow free," two other snow classes are produced. These are "thin or patchy" and "high elevation" snow cover. In general, the snow cover is considered "thin or patchy" when the satellite maps and station data disagree in areas of non-complex terrain. Thus, parts of the pixel may be snow covered while parts are snow free, or the snow cover may be thin (< 3cm). "High elevation" snow cover is similarly classified for areas of complex terrain, but it implies that the pixel is snow free at lower elevations and snow covered at high elevations. The input data for the analysis are the Grody and Basist (1996) PM snow-cover maps, the NSCs, surface air temperature, surface complexity and cloud cover.

Figure 3 is a decision tree diagram that describes the snow-cover classification procedure. To simplify the decision tree, sky conditions are assumed cloudy. A final, manual step (not shown in Figure 3) modifies the snow-cover product in areas of no or little cloud. The PM map is used as a starting point for the analysis. This is because the Grody and Basist (1996) algorithm filters out much of the scattering signatures caused by precipitation, cold deserts, and frozen ground. The main problems that remain are caused by wet snow, dense forests, and thin dry snow. All of these sources of error are errors of omission and lead to a potential underestimation of snow cover. It is reasonable, therefore, to use the PM-derived snow-cover map as the probable minimum snow-covered area at this resolution. Thus, an EASE-Grid pixel mapped as snow covered by the PM method is likely to have snow on the ground, which makes this a good starting point for the analysis. Comparisons of the PM data with climate station, NSC, air temperature, and surface roughness data determine the snow-cover class of each pixel: "fully snow covered", "thin or patchy" snow cover, or "high elevation" snow cover.

In PM swath gaps the NSC data are used as the primary source of snow-cover information and are modified, if necessary, by the ground data. In areas within the SSM/I swaths, where the NSC map shows a more extensive snow cover than the PM map and the air temperature is greater than 273K, the NSC snow cover not mapped by the PM method may be melting. In this situation, the NSC map is probably more accurate than the PM map, and is used as the primary data source. When the NSC map shows a more extensive snow cover than the PM map and the air temperature is less than 273K, the NSC snow cover may be thin, or if there are clouds present, it may have been misidentified. In this case, the PM snow cover is given priority.

If both satellite-derived maps show "no snow" and the nearby climate stations unanimously show "snow" (there must be at least two nearby stations), the snow cover may be dirty and wet or tall vegetation may be obscuring the snow cover from the view of the satellites. In this situation, snow cover is mapped based on the ground data alone.

Last, cloud cover information is manually gleaned from the hand-drawn NSCs. If an area is obscured by cloud on the last day of the week, the analyst uses data for that region from a previous day. The date corresponding to the cloud-free scene used to map the snow is marked on the map. Thus, if the date corresponds to the last day of the week, then the area was cloud free for at least some of that day. Under these conditions, the NOAA snow cover map is considered more accurate than if it were cloudy and a previous day's data were used. Given this assumption, two modifications (not shown in Figure 3) are made to the snow-cover product for areas of no or little cloud.

First, if the cloud-free area is non-complex and the PM map shows "snow" while the NSC shows "no snow," then any "fully snow-covered" pixels are reclassified as "thin or patchy." Second, if there is a PM swath gap and the NSC shows "snow" while nearby climate stations unanimously report "no snow," then any pixels classified as "no snow" are reclassified as "thin or patchy" snow cover. Both changes depict an increase in the confidence of the satellite-attained optical data. These are the only changes from the decision tree that need to be made given cloud-free conditions.

4. RESULTS

Figure 4 shows the NSC for the week April 2-9, 1995, and the PM-derived snow-cover map, the surface air temperature freezing line and the MDSCP for April 9, 1995. The main difference between the MDSCP and the NSC and PM maps is the inclusion of the "thin or patchy" and "high elevation" snow-cover classes. As these classes are determined principally by climate station data, their occurrence in areas of sparse ground data coverage is rare. Hence, care should be taken when interpreting the spatial pattern of the snow-cover classes. Despite this, the inclusion of these classes significantly enhances the interpretation of snow cover in the dense climate station areas and is therefore highly beneficial for snow cover analyses.

From the example in Figure 4, two other differences between the MDSCP and the input satellite-derived products that highlight the improvements in the new product can be seen. First, the NSC shows snow from the Great Lakes northwest through Minnesota, North Dakota and Saskatchewan while the PM map shows this as snow free. Since the surface air temperature is below 273K for this area, and since climate stations unanimously show no snow, the MDSCP maps it as snow free. It is likely therefore, that the NSC is overestimating the snow cover here, probably due to the presence of extensive cloud cover. Second, the PM map shows no snow east of Lake Erie while the NSC maps snow. The air temperature freezing line runs through this area. Where the temperature is above 273K the snow may be wet, which can cause the PM method to underestimate snow. The MDSCP maps this area as "thin or patchy" snow because there are mixed reports of snow and no snow from the climate stations in the area. Where the temperature is less than 273K, the MDSCP maps no snow in accordance with the PM and station data. Here, as in the mid-west, cloud cover may have led to an overestimation of the NSC snow cover.

Figure 4 shows, therefore, that the MDSCP is a weighted composite of the input satellite and ground-based data. Moreover, the weights are based on the relative degrees of confidence in these data. A problematic area is the North American boreal forest. Here, confidence in both satellite-derived datasets is relatively low (Table 1) while station data are sparse. Consequently, confidence in the MDSCP in this region is also low. Upon inspection of the eight years of data, both the NSCs and the PM snow-cover maps, and hence the MDSCP, may be underestimating the snow cover in the boreal forest, particularly in the late fall to early winter.

For example, in 1987 half of the climate stations in the boreal forest of Ontario, Manitoba and Saskatchewan (14 of 30) reported snow on October 25. Both the NSC and the PM snow map show continuous snow cover north of the taiga/tundra border, though both map no snow within the forest. The situation is the same on November 1 (15 of 30 stations). By November 8, both satellite methods are mapping some snow in the forest, although the station data suggest that the snow cover is more extensive (23 of 30 stations report snow). On 22 November the NSC completely fills in the forest as fully snow covered while the PM-based method still shows patchy snow. The NSC "jump" in snow-covered area is probably in response to snow south of the forest, as the NOAA analysts commonly "fill in" the area north of the snowline as snow covered.

The pattern described above recurs every October. In 1991 in fact, the NOAA analyst has written "Estimated Boundary" through the North American boreal forest on October 27. This confirms that it is very difficult to map snow cover from space in this region, particularly when the snowline is proceeding south in the early winter. Currently the MDSCP does not improve on the NSC or PM snow-cover maps for this region and season as all the input datasets have problems. However, the errors associated with this problem should be reduced when higher resolution MODIS (500 m resolution) and AMSR (12.5 km resolution) products become available. The assimilation of these data is discussed later.

Validation of the MDSCP is difficult, since the input datasets are those that the product would be compared with (NSCs, PM snow-cover maps and climate station data). In addition, withholding ground data from the analysis for the purposes of validation is undesirable, as the more station data in the analysis, the more accurate the product. One product that is not used as input however, which can be used for comparison purposes, is the NOHRSC snow-cover product. NOHRSC has developed and implemented a snow classification algorithm that is used to classify both GOES and AVHRR imagery (Carroll, 1995). The non-automated algorithm is a multi-spectral, physically based classifier that isolates snow from cloud and from all other surfaces. Several weekly snow-cover composites, produced for the contiguous United States, were compared with the MDSCP. Results showed that the maps are similar, despite the different resolution (1km versus 25km), integration period (weekly versus daily) and projection (Lambert Equal Area versus EASE-grid).

An example of a NOHRSC / MDSCP comparison is shown as Figure 5. The NOHRSC map is a composite over the period January 14-18 while the MDSCP represents the snow cover on January 15, 1995. Aside from a difference in the snow cover in the Nebraska panhandle – eastern Wyoming region (NOHRSC maps snow while the MDSCP does not), the two maps agree very well. Upon inspection of the ground data from western Nebraska and eastern Wyoming, it was found that few climate stations reported snow (4 of 96 stations) throughout the period January 14-16, 1995. On January 17 and 18, 1995 however, many more stations in this region reported snow (65 of 96 stations). Hence for January 15, the MDSCP represents the snow cover more accurately than does the NOHRSC 5-day composite.

With the inclusion of the "thin or patchy" and "high elevation" snow-cover classes, the MDSCP provides more information about the state of the snow cover than any of the current satellite-derived products. It is necessary to quantify these classes with respect to their typical percent snow cover so that the continental snow-covered area may be calculated. This is accomplished by calculating the mean percent of climate stations within each snow-cover class that is reporting snow. The analysis was performed for the winter months (December through February – to ensure adequate snow coverage) over the entire 8-year period, 1987-1995, and was repeated for "thin or patchy snow," "high elevation snow" and "fully snow-covered" areas. The results are presented in Table 3.

The mean number of stations per wintertime snow-cover map in each class is sufficiently high to use the mean percent of stations with snow cover as a proxy for the mean percent snow cover within each class. From Table 3 therefore, the mean percent snow cover for "thin or patchy" snow pixels is 34.3%. This value makes sense, as with around 34% of the pixel covered with snow the satellites may detect enough snow to map the pixel as snow covered while the station data may disagree.

The mean percent of stations reporting snow in areas of "high elevation" snow cover is 24.6%. However, this does not represent the mean percent snow cover. When a station reports no snow in an area of complex terrain where the MDSCP shows "high elevation" snow cover, then it is assumed that while the valleys may be snow free there is snow at higher elevations. To derive a mean percent snow cover for the "high elevation" class, it is assumed that a pixel has 100% snow cover when a station reports snow and 50% snow cover when a station reports no snow. These values have not been validated, although an investigation comparing 30m Landsat TM data to the MDSCP is planned. The percent snow cover in a "high elevation" snow-cover pixel is calculated as follows:

$$\%SC_{HE} = 24.6 + (100 - 24.6)*0.5$$
$$= 62.3\%$$

The climate station analysis was also performed for areas classified as "fully snow covered." It is unrealistic to assume that any 625 square kilometer area is 100% snow covered, with the exception of Greenland and the Antarctic. Local topographic (in general, slopes greater than 50° cannot retain snow) and vegetative variability, in combination with the re-distribution of snow by wind, result in areas of snow-free land even in regions that have snow cover for over half of the year. Recent work by Hall *et al.* (submitted) for four different areas in North America show that SSM/I pixels classified as 100% snow covered are actually 70 to 72% snow covered when mapped using 30m resolution Landsat TM data. The mean percent snow cover of the MDSCP "fully snow-covered" pixels from the analysis of climate station data is 75.4 (Table 3). This agrees well with the Landsat TM analysis results.

As the majority of climate stations are located south of around 55°N (Figure 1), the percent snow cover estimates may be biased. It is conceivable that the percent of snow cover in "fully snow covered" pixels in high latitudes is much higher than 75%, for example. To test this hypothesis, data from Alaska and the Canadian Northwest Territories were isolated and analyzed. The mean percent of stations reporting snow in "fully snow covered" pixels for the period 1987 through 1995 was 68.8%, with a mean number of stations of 171, and a mean standard deviation of 6.18. The percent snow cover is lower than when all the data are used, however the standard deviation is higher (the result of a lower sample size). Overall, it can be said that there is no evidence to suggest a change in the percent snow cover with latitude.

The percent snow cover for the three snow classes are estimates based on a limited number of climate station data. A study incorporating many Landsat TM scenes, or other data of relatively high resolution such as from MODIS, for each snow-cover class is required to validate these percent snow cover values. Nevertheless, it is considered at present that the use of these percent snow cover values is more realistic than assigning each snow-covered pixel a value of 100%.

A time series plot of North American snow-covered area (including Greenland) derived from the NSCs and the MDSCP is shown as Figure 6. The mean percent snow cover for each of the MDSCP classes has been used in the calculation of the MDSCP snow-covered area, with the exception of Greenland where the pixels are considered to be 100% snow covered. The difference between the two datasets is up to 5.3 million square kilometers in winter. This is due to the NSCs mapping snow-covered pixels as 100% while the MDSCP maps these pixels as either 75%, 62%, 34% or 0% snow covered, contingent upon the snow-cover class. Because the number of snow-covered pixels is greatest in winter, and as the winter snowline is in an area of high climate station density (hence more pixels are classed as "thin or patchy" or "high elevation" snow cover), this is the season of greatest difference in the estimated North American snow-covered area.

The difference between the NSC- and MDSCP-derived snow-covered area is relatively consistent from year to year. The mean difference, along with the standard deviation, is shown in Figure 7. The variability is greatest in late fall, as this is the period of rapid transition of the snow-covered area. On average over the year, though, the variability is quite low at around half a million square kilometers or less. It is suggested, therefore, that the long time series of NSC-derived snow-covered area (1966 onwards) could be amended using the mean difference curve shown in Figure 7, yielding a 30-year time series of data for North America based on the results of this analysis.

Over the period 1987-1995 the availability and condition of the SSM/I brightness temperature data varies (Table 2). Between February 1, 1989 and December 31, 1991 there were no data from the 85GHz channel due to degradation of the instrument by solar illumination (Wentz, 1992). The PM-derived snow-cover maps included in the MDSCP analysis were produced without 85GHz data during this period. To test the sensitivity of no 85GHz data, SSM/I and MDSCP maps were produced with and without the 85GHz channel for the period September 27, 1992 through May 9, 1993. This snow season was chosen because there is only one day when the PM data are missing and only two days when the coverage is poor (Table 2). Figure 8 shows that the North American snow-covered area derived from SSM/I data without the 85GHz data is up to 2 million square kilometers less than that with the 85GHz channel in late fall. The difference decreases through the winter as the snowline stabilizes and the area covered by thin snow (< 3cm) is reduced (the 85GHz channel is sensitive to thin snow.) In spring, the difference further decreases as the PM data is adversely affected equally at all frequencies by the presence of liquid water.

The snow-covered area for the 1992/1993 period derived from the MDSCP with all the input data, without the SSM/I 85GHz channel, without any SSM/I data, and without any climate station data is shown as Figure 9. The effect of no 85GHz data in the MDSCP analysis is around 800,000km^2 in the late fall. Thus, the MDSCP maps are less sensitive by a factor of two to the loss of the 85GHz channel, compared with the PM-derived snow-cover maps. The "no 85GHz" curve from Figure 9 was smoothed with a 4-week moving average and used to correct the North American snow-covered area time series during the period February 1989 through December, 1991. The uncorrected and corrected time series are shown in Figure 10.

A sensitivity test was also performed to observe the effect of no PM data on the MDSCP. From Figure 9 it can be seen that the effect is largest when the snowline is in transition in the fall and spring. During these seasons, however, there is no pattern to the difference between using and omitting the PM data, hence no correction to the data has been made. Last, a test was performed to interpret the influence of omitting all the climate station data from the analysis (Figure 9). If the MDSCP is to be used operationally, it may not be possible to assimilate the station data in a timely fashion. The effect on the snow-covered area increases steadily over the fall to a constant difference of around 800,000 km^2 throughout the winter, and then falls off steadily during the spring. This is because while the location of snow-covered pixels is generally unchanged, many fewer pixels are classified as "thin or patchy" and no pixels are classified as "high elevation" snow cover when climate station data are not used. The effect is more noticeable in the winter because the number of pixels classified as "thin or patchy" or "high elevation" snow cover is greater when the snowline is at lower latitudes.

Despite a loss of information about the state of the snowpack, an adjustment to the total snow-covered area can be performed, as the pattern caused by omitting the climate station data is highly regular (Figure 9). Thus, the MDSCP can be used operationally for the purposes of calculating the snow-covered area, particularly if a satellite-derived surface air temperature dataset is used. Also, if the snow cover is mapped with a binary discriminator, i.e. snow covered or snow free, then the inclusion or omission of climate station data makes only a negligible difference.

5. DISCUSSION

Grody and Basist (1996) conclude that the majority of the errors associated with the PM-derived snow-cover map appear on the "conservative" side. Therefore, given problematic conditions such as melting or thin dry snow, dense forest cover, or precipitation events, the PM snow-cover map may show less snow than is present. The main error of commission is the misclassification of frozen ground as snow cover, however this is mostly accounted for in their filtering scheme. Hence, in all likelihood, if an EASE-Grid pixel is mapped as snow by the PM method there is snow on the ground.

This acknowledgement yields a conservative map of the snow cover at this scale, and hence, a starting point for a multiple-dataset analysis. Using the elevation data and information from nearby climate stations, the snow-cover class can be identified. Next, the NSC data are analyzed, in conjunction with air temperature, elevation, and climate station data, to determine whether any additional pixels should be classed as snow covered.

This method has several advantages. First, snow is mapped irrespective of cloud cover due the inclusion of PM and station data. Second, the combination of the NSC and station data reduces the PM errors of omission in the spring caused by melting snow. Third, the MDSCP is a spatially complete snow-cover map for the end of the week, whereas the NSCs are composites over one to seven days while the PM-derived maps have sizeable swath gaps. Fourth, the MDSCP has four classes of snow cover (fully covered, thin or patchy, high elevation, or no snow cover) compared with the normal two (snow and no snow), which provides more information about the state of the snow cover. Fifth, the percent snow-covered area has been calculated for each class based on an analysis of the climate station data. These values are used to calculate the North American snow-covered area with greater accuracy than in the past. Last, the MDSCP can be used operationally without station data, although some spatial information is lost.

The primary disadvantage with the MDSCP is poor resolution. Compared with the NSCs (cell size between 16,000 and 42,000km^2), the EASE-grid SSM/I and MDSCP cell resolution (628km^2) is significantly better. However, for the purposes of mapping snow it is advantageous to have a resolution of less than 1km. This would reduce the problem of not mapping snow in the boreal forest during the late fall / early winter, as only the very densely forested stands would obscure the underlying snow. MODIS-derived daily global snow-cover maps, with a resolution of 500m, will be available for the 1999 / 2000 snow season. With this resolution, it is foreseeable that these optical data will be used as the primary source of snow-cover information, rather than the passive microwave data, except over areas with thick cloud cover. In the year 2000, EOS PM-1 AMSR-derived snow-cover maps will also be available, at a resolution of 12.5km.

These EOS datasets will significantly enhance the MDSCP. First, the MODIS snow-cover product (SNOWMAP) will be a daily product (Hall *et al.*, 1998); hence, the temporal resolution will be enhanced by a factor of seven. Second, SNOWMAP is fully automated and has a Normalized Difference Vegetation Index (NDVI) component to map snow cover more accurately, even in dense forests (Klein *et al.*, 1998). Third, SNOWMAP, surface temperature data and the MODIS cloud cover algorithm will be generated at the same time using data from the same instrument. This will eliminate the manual identification of cloud cover from the NSCs in the current analysis. Last, both the MODIS and AMSR data will have higher spatial resolutions than the datasets currently used in the MDSCP analysis. This will improve the accuracy of the respective snow-cover maps, and hence the accuracy of the combined product.

6. CONCLUSIONS

This analysis utilizes the three main snow-cover mapping techniques (mapping from ground data, satellite-attained optical data, and satellite-attained passive microwave data) in conjunction with terrain information, air temperature and cloudiness to produce an improved snow-cover product. Many of the problems associated with the optical and passive microwave methods, when used alone, have been diminished although the boreal forest remains a problem area. The MDSCP maps have been shown to agree well with the NOHRSC snow-cover maps. In addition, the MDSCP provides more information on the state of the snow cover with four snow-cover classes rather than two. The percent snow-cover estimate for each class has also been calculated, providing a more realistic estimate of the North American snow-covered area than previously available. These enhancements would directly benefit hydrological and climate modeling, particularly in the EOS era with the availability of MODIS and AMSR data.

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REFERENCES

Barry, R.G. (1985), The cryosphere and climate change. In *Detecting the Climatic Effects of Increasing Carbon Dioxide*, US Department of Energy, DOE/ER 0235:109-148.

Barry, R.G., Fallot, J-M., and Armstrong, R.L. (1995), Twentieth-century variability in snowcover conditions and approaches to detecting and monitoring changes: status and prospects. *Progress in Physical Geography*, 19(4):520-532.

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

Brown, R.D., and Braaten, R.O. (1998), Spatial and temporal variability of Canadian monthly snow depths, 1946-1995. *Atmosphere-Ocean*, 36(1):37-54.

Carroll, T.R. (1995), Operational remote sensing of snow: United States. Presented at the *International Union of Geodesy and Geophysics*, XXI General Assembly, Boulder, Colorado, July 2-14, 1995.

Chang, A.T.C., Gloersen, P., Schmugge, T.J., Wilheit, T., and Zwally, J. (1976), Microwave emission from snow and glacier ice. *Journal of Glaciology*, 16(74):23-39.

Chang, A.T.C., Foster, J.L., Owe, M., Hall, D.K., and Rango, A. (1985), Passive and active microwave studies of wet snowpack properties. *Nordic Hydrology*, 16:57-66.

Chang, A.T.C., Foster, J.L., Hall, D.K., Goodison, B.E., Walker, A.E., Metcalfe, J.R., and Harby, A. (1997), Snow parameters derived from microwave measurements during the BOREAS winter field campaign. *Journal of Geophysical Research*, 102(D24):29,663-29,671.

Foster, J.L., Hall, D.K., Chang, A.T.C., and Rango, A. (1984), An overview of passive microwave snow research and results. *Reviews of Geophysics and Space Physics*, 22(2):195-208.

Grody, N.C. (1991), Classification of snowcover and precipitation using the special sensor microwave imager. *Journal of Geophysical Research*, 96:7423-7435.

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

Hahn, D.G., and Shukla, J. (1976), An apparent relationship between Eurasian snow cover and Indian monsoon rainfall. *Journal of Applied Sciences,* 33(12):2461-2462.

Hall, D.K., Foster, J.L., and Chang, A.T.C. (1984), Nimbus-7 SMMR polarization responses to snow depth in the mid-western U.S. *Nordic Hydrology*, 15:1-8.

Hall, D.K., Tait, A.B., Riggs, G.A., and Solomonson, V.V. (1998), *Algorithm Theoretical Basis Document (ATBD) for the MODIS Snow-, Lake Ice- and Sea Ice-Mapping Algorithms*, Version 4.0. Available from the MODIS web site: http://ltpwww.gsfc.nasa.gov/MODIS/MODIS.html, 50p.

Hall, D.K., Tait, A.B., Foster, J.L., Chang, A.T.C., and Allen, M. (submitted), Intercomparison of satellite-derived snow-cover maps. *Annals of Glaciology*.

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

Matson, M., Ropelewski, C.F., and Varnadore, M.S. (1986), *An Atlas of Satellite-Derived Northern Hemispheric Snow Cover Frequency.* U.S. Department of Commerce, Washington, DC, 75p.

Mätzler, C.H., and Huppi, R. (1989), Review of signature studies for microwave remote sensing of snowpacks. *Advances in Space Research*, 9:253-265.

Neale, M.U., McFarland, M.J., and Chang, K. (1990), Land-surface classification using microwave brightness temperatures from the special sensor microwave imager. *IEEE Transactions on Geoscience and Remote Sensing*, 28:307-311.

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

Rango, A., Chang, A.T.C., and Foster, J.L. (1979), The utilization of space-borne microwave radiometers for monitoring snowpack properties. *Nordic Hydrology*, 10:25-40.

Rango, A. (1985), An international perspective on large-scale snow studies. *Hydrological Sciences Journal*, 30:225-238.

Robinson, D.A., Dewey, K.F., and Heim Jr., R.R. (1993), Global snow cover monitoring : An update. *Bulletin of the American Meteorological Society*, 74(9):1689-1696.

Salomonson, V.V., Hall, D.K., and Chien, J.Y.L. (1995), Use of passive microwave and optical data for large-scale snow cover mapping. *Proceedings of the 2nd Topical Symposium on Combined Optical-Microwave Earth and Atmosphere Sensing,* Atlanta, GA, April 3-6, 1995, 35-37.

Stogryn, A. (1986), A study of the microwave brightness temperature of snow from the point of view of strong fluctuation theory. *IEEE Transactions on Geoscience and Remote Sensing*, GRS-2:220-231.

Ulaby, F.T., and Stiles, W.H. (1980), Microwave radiometric observations of snowpacks, NASA CP-2153. In *NASA Workshop on the Microwave Remote Sensing of Snowpack Properties*, Ft. Collins, CO, 20-22 May 1980, 187-201.

Ulaby, F.T., Moore, R.K., and Fung, A.K. (1982), *Microwave Remote Sensing: Active and Passive*, Volume 2. Addison-Wesley, Reading, MA, 2162p.

Walsh, J.E., and Ross, B. (1988), Sensitivity of 30-day forecasts to continental snow cover. *Journal of Climatology*, 1:739-754.

Wentz, F.J. (1992), Final report, production of SSM/I datasets. *Remote Sensing Systems Technical Report 090192*, Santa Rosa, CA, 9p.

FIGURE CAPTIONS

Figure 1: North American climate station locations.

Figure 2: Surface roughness index. The gray-colored pixels have a maximum and minimum elevation difference of greater than 500 meters.

Figure 3: Decision tree diagram describing the derivation of the MDSCP snow-cover classes, performed on each EASE-Grid pixel for North America.

Figure 4: Snow cover comparison for April 9, 1995. The four maps represent: a) the NSIDC Snow and Ice map, which depicts the digitized NOAA snow chart (green) and passive microwave-derived sea ice (purple); b) the Grody and Basist (1996) passive microwave-derived snow-cover product (green); c) the surface mean daily air temperature, showing areas less than 273K (blue) and greater than or equal to 273K (red); and d) the multiple-dataset snow-cover product, which shows pixels that are fully snow covered (green), have a thin or patchy snow cover (yellow), have a high elevation snow cover (cyan), or represent sea ice (purple).

Figure 5: Comparison of the NOHRSC January 14-18, 1995 snow-cover composite (top map) with the MDSCP January 15, 1995 snow-cover map (bottom map).

Figure 6: North American (including Greenland) snow-covered area comparison. The solid line is the estimate from the NOAA snow charts and the dashed line is the MDSCP estimate, using the mean percent snow-cover values from the text.

Figure 7: The mean (solid line) and standard deviation (dashed line) of the difference between the NSC- and MDSCP-derived snow-covered area for North America for the period 1987 through 1995.

Figure 8: The difference between the PM-derived North American snow-covered area calculated with the inclusion (solid line) and omission (dashed line) of the 85GHz channel data for the period September 27, 1992 through May 9, 1993.

Figure 9: The difference between the MDSCP-derived North American snow-covered area calculated with the inclusion of all the available data (solid line), and with the omission of the 85GHz channel data (short and long dashes), all PM data (short dashes), and all the station data (long dashes). The period is September 27, 1992 through May 9, 1993.

Figure 10: North American (including Greenland) snow-covered area calculated from the MDSCP with (solid line) and without (dashed line) the correction for no 85GHz channel data.

Table 1: Summary of the known problems associated with current large-scale snow cover mapping techniques.

Snow Mapping Method	Problems	Effects
Climate station interpolation.	Large gaps in spatial coverage of stations. Potential temporal discontinuities.	Interpolation between distant stations leads to large uncertainties. Projection of point data over large areas may be problematic.
NOAA weekly snow charts compiled from optical data.	Clouds obscure ground. Dense forests may obscure underlying snow cover. Maps are only produced once a week. No data during nighttime. Resolution of digitized data is very poor.	If cloudy, the analyst goes back to last clear day. The snowline may have changed markedly in this time, particularly in the spring and fall seasons. Snow cover may be underestimated in areas of dense forest. Poor temporal and spatial resolution causes loss of detail.
Passive microwave-derived maps using Grody and Basist (1996) decision tree technique.	Melting snow signature looks like bare soil. Emitted radiation from forests may mask snow. Thin snow may be transparent. Snow on the ground may be misclassified as precipitation at high microwave frequencies.	Maps underestimate snow cover when snow is wet, particularly in the spring. Snow in areas of dense forests, thin snow cover, or misclassified snow may also be underestimated.

Table 2: SSM/I data record 1987-1995.

Days with no PM data	Days with no 85GHz channel	Days when PM data coverage is poor
1987: 340, 347, 354, 361		
1988: 3, 10, 129, 360		1988: 150, 276, 290, 318, 332
1989: 15, 204, 295	1989: 36 – 365	1989: 78
1990: 238, 294, 301, 315, 357	1990: 7 – 364	1990: 49, 322, 336, 364
1991: 69	1991: 6 – 335	1991: 6, 62, 139, 342
1992: 159		1992: 33, 348
		1993: 122
1994: 170, 310, 324		1994: 37 – 121, 317, 359
		1995: 148

Table 3: Percent of climate stations reporting snow within each MDSCP snow-cover class. The data are the mean values for the winter months (DJF) for the period 1987 through 1995.

MDSCP snow-cover class	Mean number of stations in class	Mean percent snow cover	Mean standard deviation
Thin or patchy snow	1177	34.3	5.85
High elevation snow	302	24.6	6.37
Fully snow covered	1549	75.4	3.73

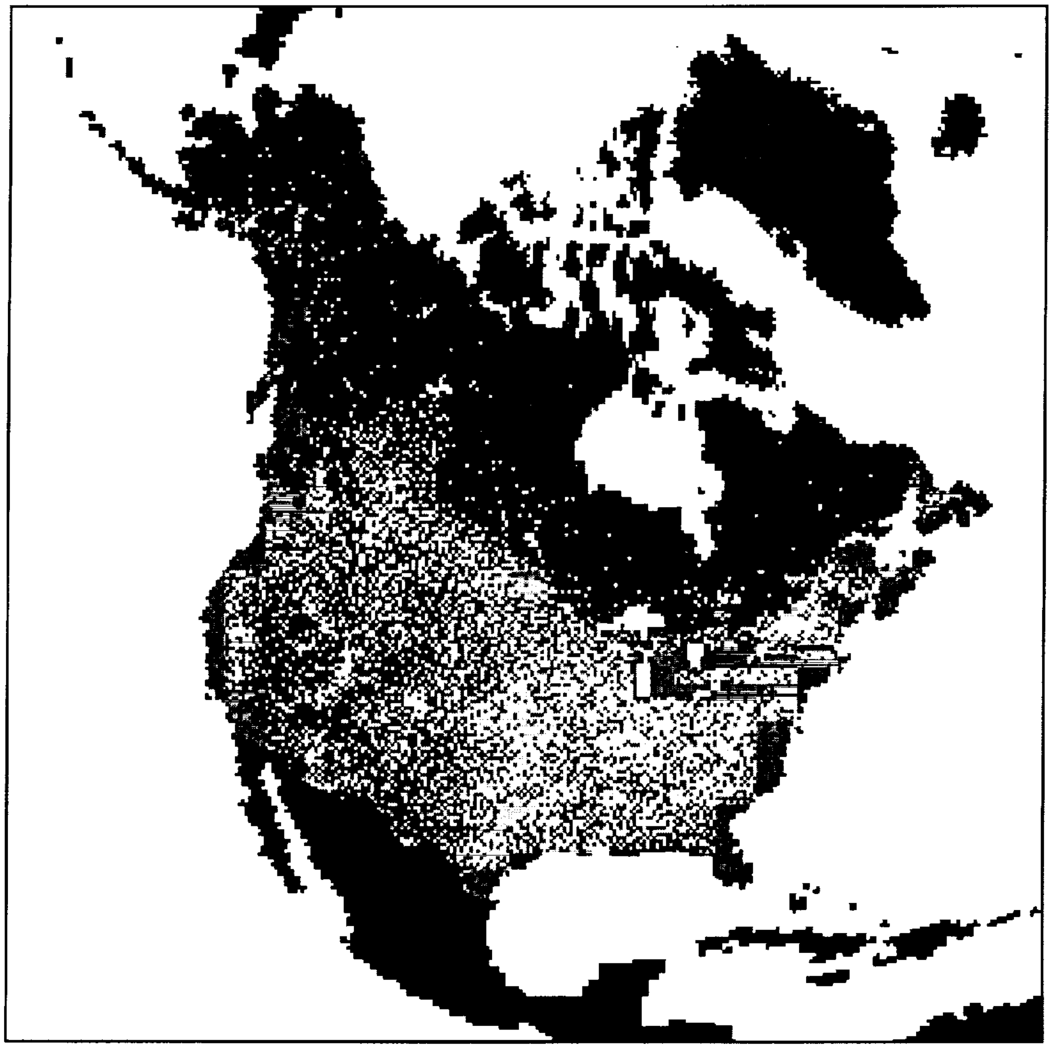


Figure 1

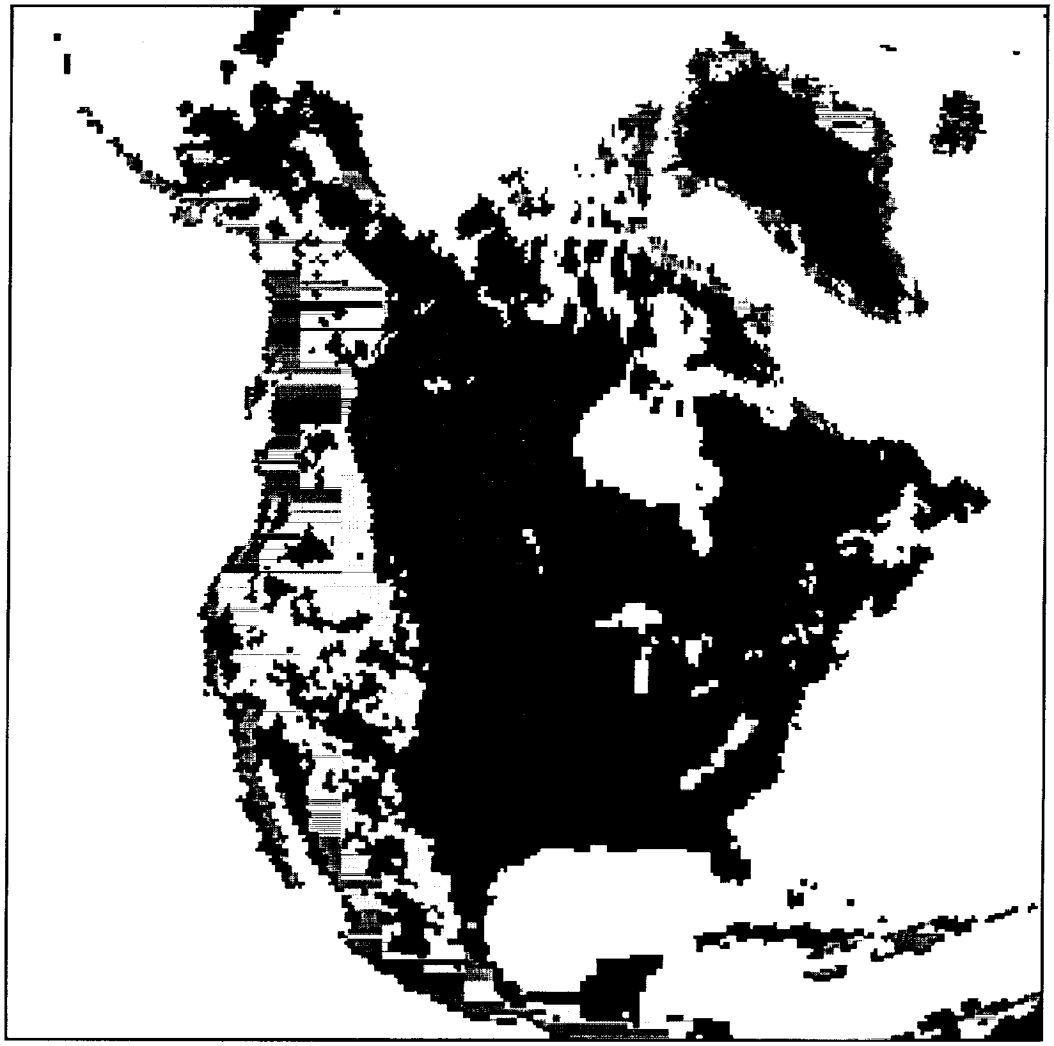


Figure 2

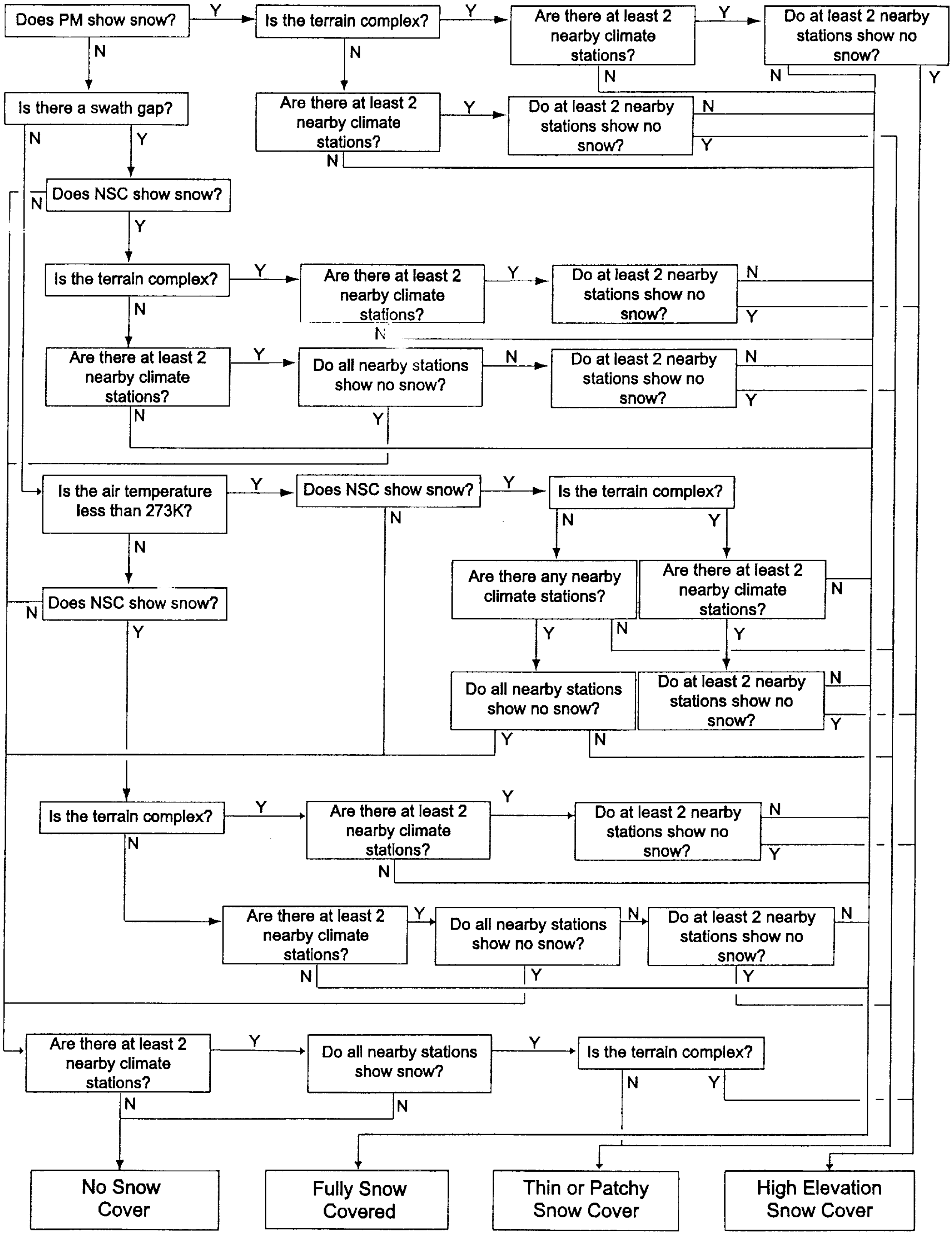

Does PM show snow?
Is the terrain complex?
Are there at least 2 nearby climate stations?
Do at least 2 nearby stations show no snow?
Is there a swath gap?
Are there at least 2 nearby climate stations?
Do at least 2 nearby stations show no snow?
Does NSC show snow?
Is the terrain complex?
Are there at least 2 nearby climate stations?
Do at least 2 nearby stations show no snow?
Are there at least 2 nearby climate stations?
Do all nearby stations show no snow?
Do at least 2 nearby stations show no snow?
Is the air temperature less than 273K?
Does NSC show snow?
Is the terrain complex?
Are there any nearby climate stations?
Are there at least 2 nearby climate stations?
Do all nearby stations show no snow?
Do at least 2 nearby stations show no snow?
Does NSC show snow?
Is the terrain complex?
Are there at least 2 nearby climate stations?
Do at least 2 nearby stations show no snow?
Are there at least 2 nearby climate stations?
Do all nearby stations show no snow?
Do at least 2 nearby stations show no snow?
Are there at least 2 nearby climate stations?
Do all nearby stations show snow?
Is the terrain complex?
No Snow Cover
Fully Snow Covered
Thin or Patchy Snow Cover
High Elevation Snow Cover

Figure 3.

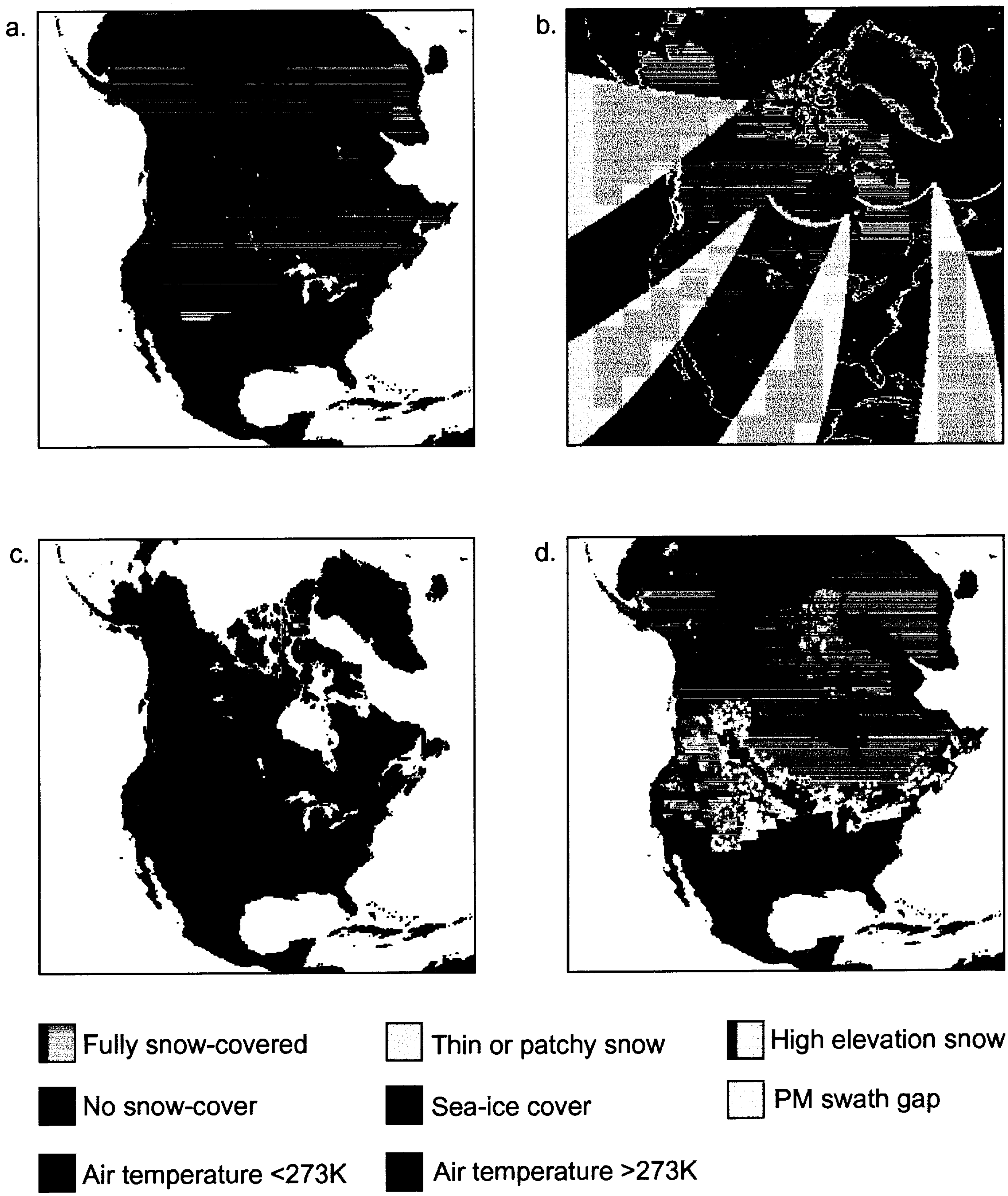
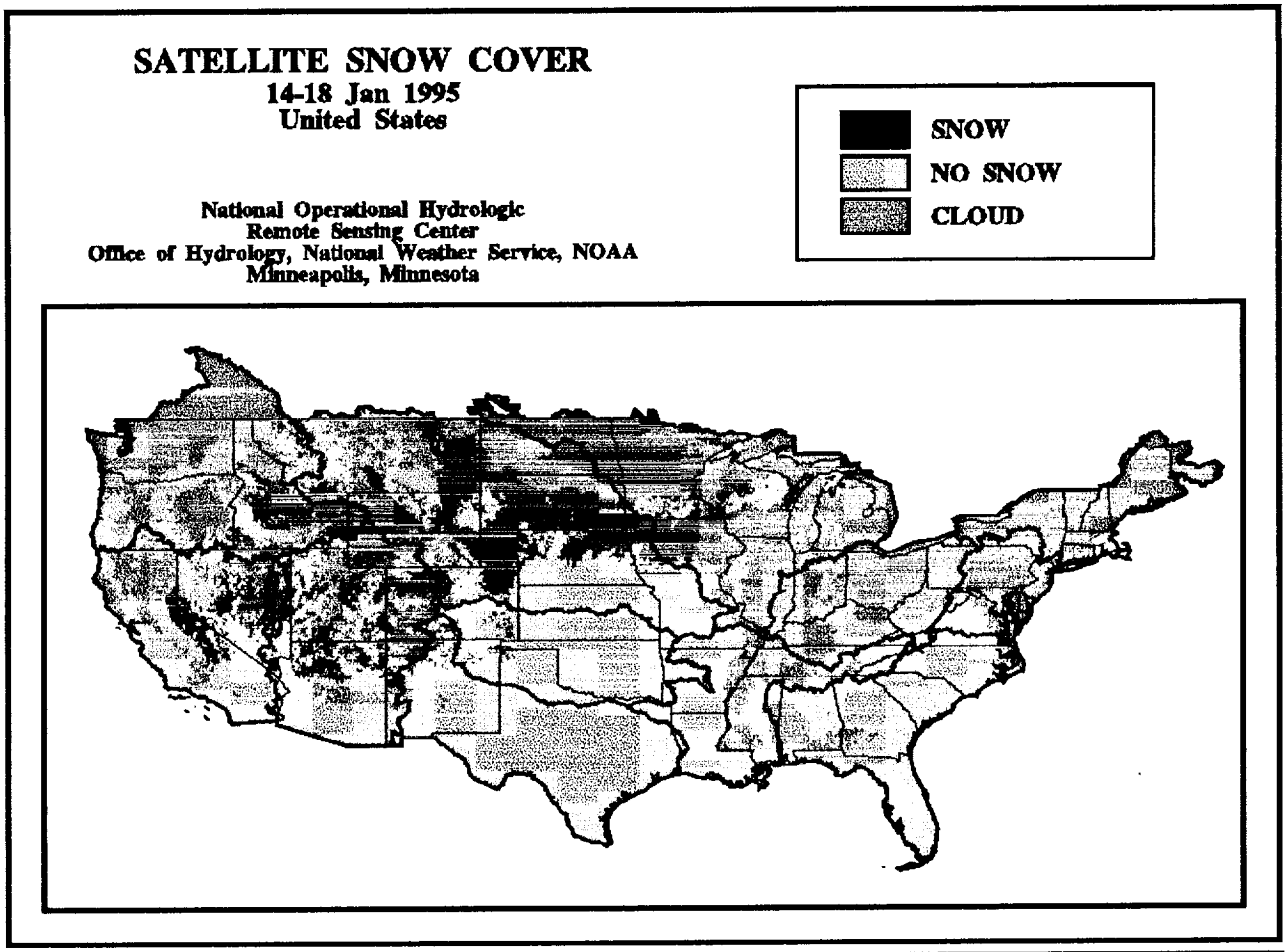

a.
b.
c.
d.
Fully snow-covered
Thin or patchy snow
High elevation snow
No snow-cover
Sea-ice cover
PM swath gap
Air temperature <273K
Air temperature >273K

Figure 4


SATELLITE SNOW COVER
14-18 Jan 1995
United States
National Operational Hydrologic
Remote Sensing Center
Office of Hydrology, National Weather Service, NOAA
Minneapolis, Minnesota
SNOW
NO SNOW
CLOUD

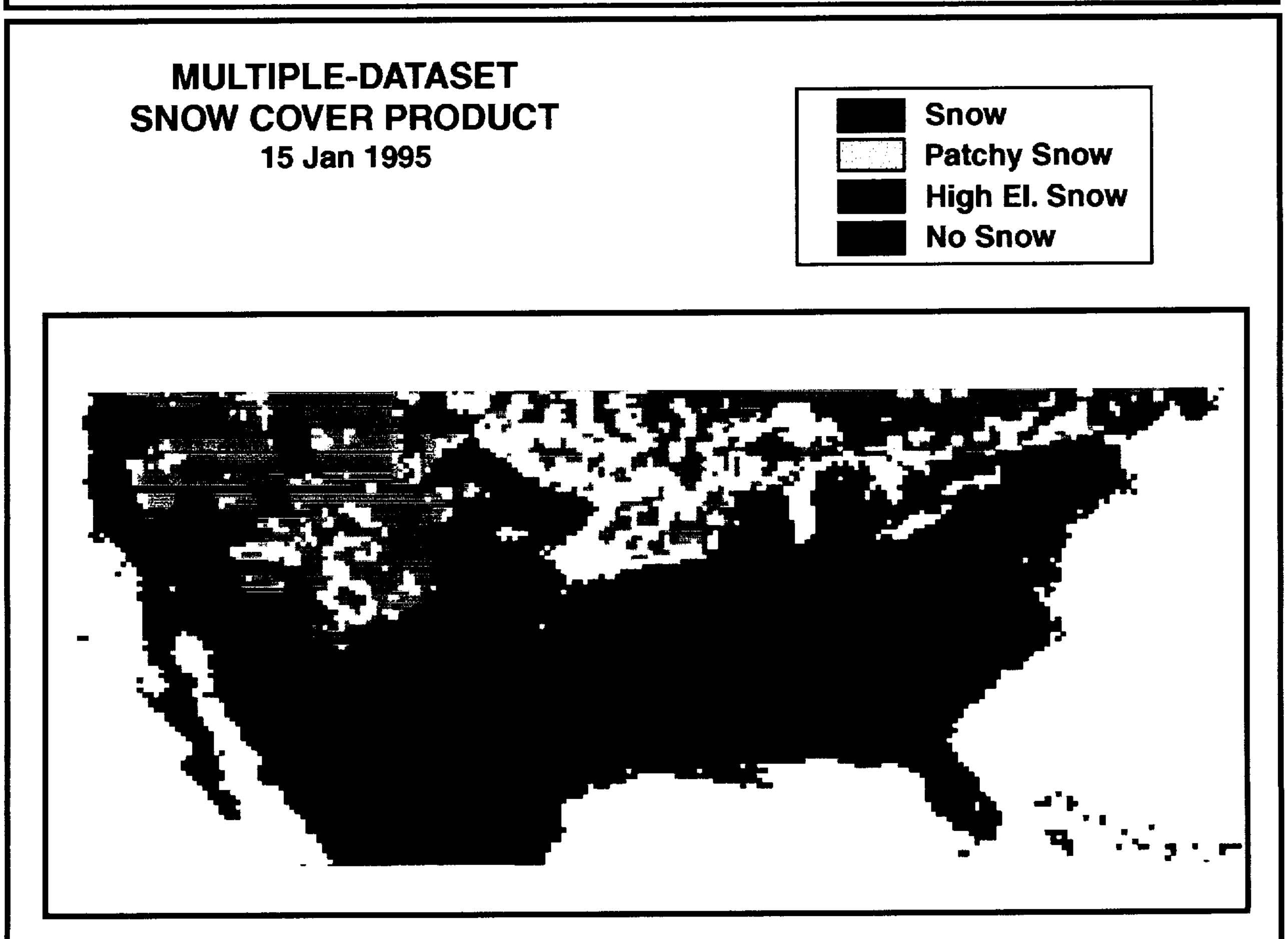

MULTIPLE-DATASET
SNOW COVER PRODUCT
15 Jan 1995
Snow
Patchy Snow
High El. Snow
No Snow

Figure 5

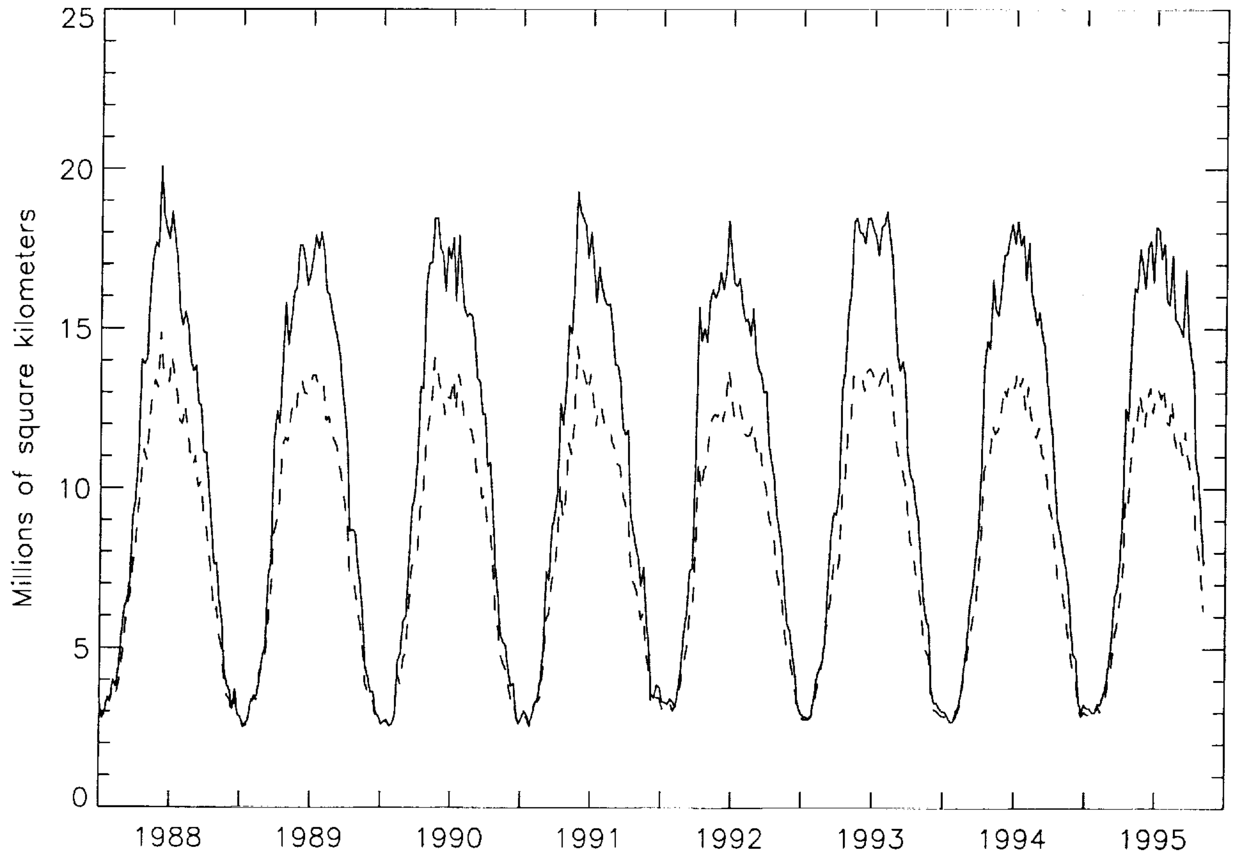

25
20
15
10
5
0
Millions of square kilometers
1988
1989
1990
1991
1992
1993
1994
1995

Figure 6

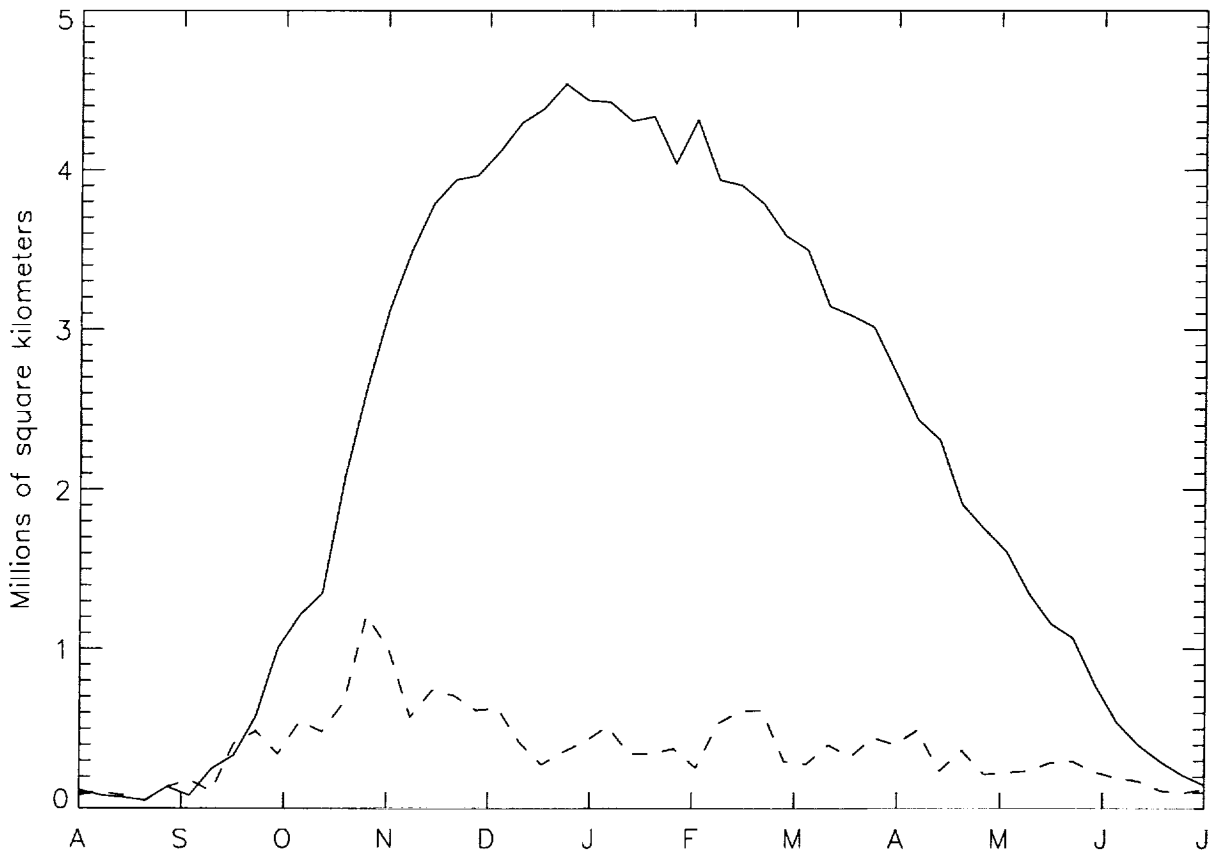
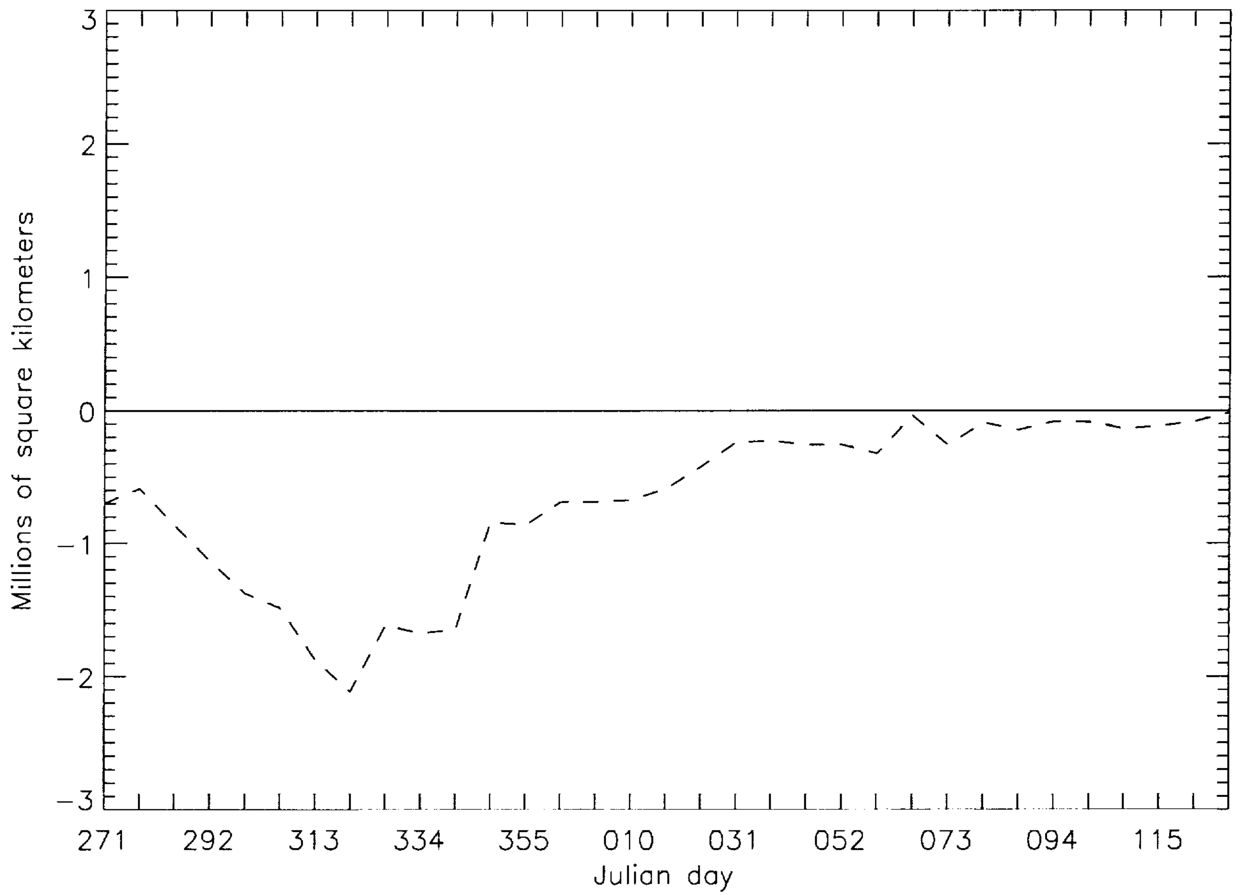


Figure 7


3
2
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Millions of square kilometers
271
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355
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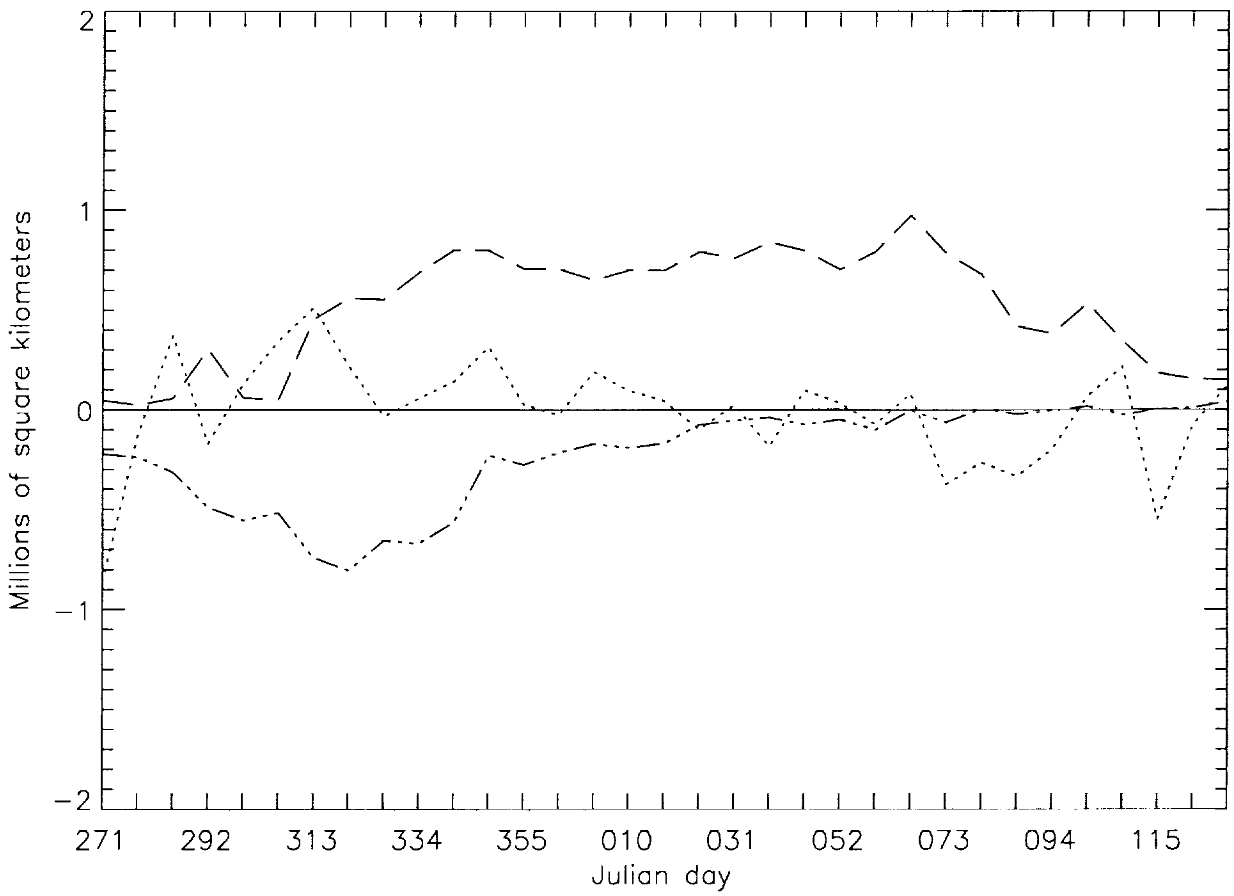
073
094
115
Julian day

Figure 8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Millions of square kilometers
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Figure 9

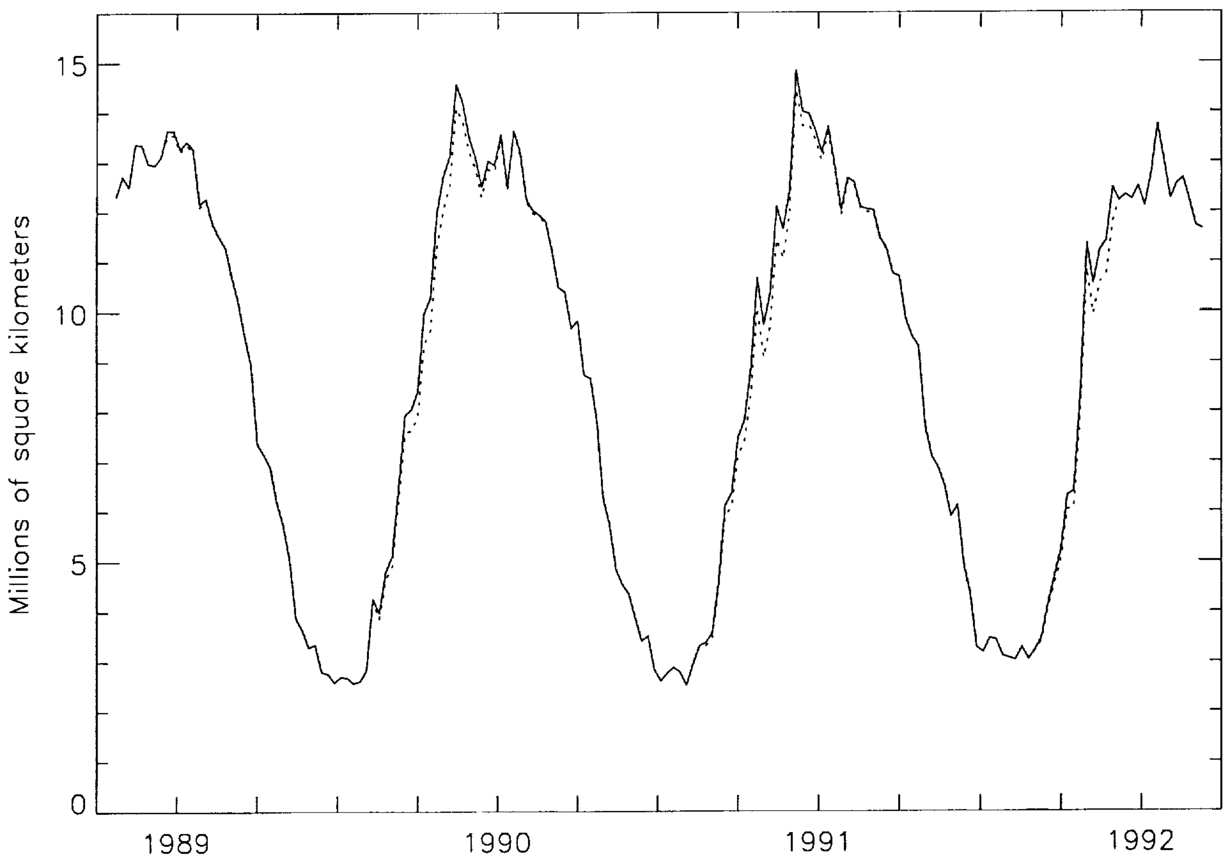

Figure 10