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Monitoring Northern Hemisphere Snow Cover

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Abstract

Accurate information on snow cover is essential for understanding details of climate dynamics and climate change. It is critical that snow observations be as lengthy and geographically extensive as possible. Data on snow extent and the physical characteristics of continental snowpacks are gathered from ground sites and aircraft or satellite platforms. Here, these means of observing snow cover are reviewed, recent endeavors to improve or enhance data collection are discussed, and some results of short and long-term monitoring efforts are presented. Included are monthly continental and hemispheric snow areas derived from shortwave satellite data using a new consistent methodology, and a discussion of recent deficits in spring snow cover. Also, a comparison of these hemispheric snow areas with estimates of less extensive cover derived from satellite microwave data is presented, and progress in developing regional algorithms to extract more accurate snow information from satellite microwave returns is discussed. Continental snow cover is emphasized, however a discussion of snow on top of arctic sea ice is included. The latter focuses on a new ten-year time series of spring and summer snow conditions in the Arctic Basin. Finally, recommendations are made for ongoing monitoring efforts for the remainder of this decade and beyond, and for retrospective studies covering all or a portion of the past century.

Introduction

Across the middle and high latitudes of the Northern Hemisphere, the impact of snow on humans and the environment is considerable. Falling snow or snow lying on the ground or on ice influence hydrologic, biologic, chemical and geologic processes at and near the surface of the Earth. Snow exerts an impact on activities as diverse as engineering, agriculture, travel, recreation, commerce, and safety. Empirical and modelling studies also show snow cover to have an influential role within the global heat budget, chiefly through its effect of increasing surface albedo (Berry, 1981; Walsh et al., 1985; Robinson & Kukla, 1985; Kukla et al., 1986; Barnett et al., 1989). Global models of anthropogenically-induced climate change suggest enhanced warming in regions where snow cover is currently ephemeral (Manabe & Wetherald, 1980; Hansen et al., 1984; Dickinson et al., 1987). For this reason, snow cover has been suggested as a useful index for detecting and monitoring such change (Barry, 1985; Schlesinger, 1986).

Accurate information on snow cover is essential for understanding details of climate dynamics and climate change. It is also critical that snow observations be as lengthy and geographically extensive as possible. Snow data are gathered from ground sites and aircraft or satellite platforms. There are advantages and liabilities to each of these sources that are related to their accuracy and coverage. Here, these means of observing snow cover are reviewed, recent endeavors to improve or enhance data collection are discussed, and some results of short and long-term monitoring efforts are presented. Emphasis is on continental snow cover, however a discussion of snow on top of arctic sea ice is also included. Finally, recommendations are made for ongoing monitoring efforts for the remainder of this decade and beyond, and for retrospective studies covering the past century.

Continental Snow Cover

Surface-Based Observations

Surface-based snow cover data are mainly gathered from observing stations on a once per day basis. The general practice is to record the average depth of snow lying on level open ground having a natural surface cover. At primary stations, the water equivalent of the snowpack may also be measured. In some regions, snow courses have been established, where snow depth, water equivalent and perhaps other pack properties are measured along prescribed transects across the landscape. Observations are often limited to once per month and the number of courses is extremely limited in North America. More frequent and abundant course data are gathered in the Commonwealth of Independent States, although to date these data are not digitized and are generally unavailable in any form (A. Krenke, per. commun.). The remainder of this discussion deals with station (point) observations.

Current station observations of snow cover are of a sufficient density for climatological study in the lower elevations of the middle latitudes. Elsewhere, data are spotty at best. There is no hemispheric snow cover product based entirely on station reports. The U.S. Air Force global snow depth product relies heavily on surface-based observations as input into a numerical model that creates daily charts with global coverage (Hall, 1986). Disadvantages include having to rely on extrapolations and climatology in data-sparse regions (McGuffie & Robinson, 1988). Recently, an improved interpolation scheme incorporating horizontal and vertical components has been added to the model (Armstrong & Hardman, 1991). A method to determine depth using microwave data in data sparse regions has also been added to reduce the reliance on climatology.

There have been a number of regional snow cover products over the years that are based on station data. Of greatest longevity are the WWCB charts that have been produced since 1935. These, and daily U.S. National Oceanic and Atmospheric Administration (NOAA) charts, are produced for the conterminous United States solely from first order station observations, thus neither has a particularly high resolution. Since December 1983, the position of the snow line has not been plotted on the WWCB charts. Only point data for those stations reporting snow cover has been presented. This is a major limitation, as the charts give no indication as to where the snow-free stations are located.

Observations from the primary stations used in the preparation of WWCB and other regional charts are among the most complete and accurate over the long term. However, the consistency of first order station observations suffers from the numerous station relocations from cities to airports in the middle part of this century (particularly in the U.S.). Potential influences of urbanization on the depth and duration of snow on the ground also must be considered. To date, no comprehensive study has been done on either of these subjects.

In a number of countries, there are numerous stations with relatively complete records of snow extending back fifty years or more. Until recently, most data have remained unverified and disorganized (Robinson, 1989). As a result, few studies have dealt with long-term trends or low-frequency fluctuations of snow over even small regions (Arakawa, 1957; Manley, 1969; Jackson, 1978; Pfister, 1985). Through the cooperative efforts of a number of scientists and data centers, this situation has begun to be rectified. Examples include the exchange of data through the US/USSR Bi-Lateral Environmental Data Exchange Agreement and between the Lanzhou Institute of Glaciology and Geocryology and Rutgers University. These and other data are in the process of being quality controlled, and routines to fill in gaps in snow cover records are being developed (Robinson, 1988; Hughes & Robinson, 1992).

These data have begun to be analyzed for several regions. For example, marked year-to-year variability in snow cover duration is recognized over the course of this century in the U.S. Great Plains (fig. 1). A broader analysis of this region and areas further east, using data from 146 stations, shows notable decadal variations in snow extent. These stations, all with records back to at least 1910, are grouped into 1° latitude x 4° longitude divisions to account for the inhomogeneous spacing of the stations and occasional data gaps in the network. Division values are an average of all available reports, which range from one to eight depending on the day and the region. Of the past nine decades, the January snowline was at its southernmost position in the 1970s and was at its northernmost location, roughly three or four degrees of latitude poleward of the 1970s line, in the 1900s (fig. 2). A division is considered to be snow covered in a given decade when more than half of the days have a cover of ≥2.5 cm for at least five Januarys. A decade-by-decade count of the number of divisions meeting this criterion shows the first five decades of this century to have less January snow cover than the most recent four (fig. 3). This is particularly notable in the central Great Plains.

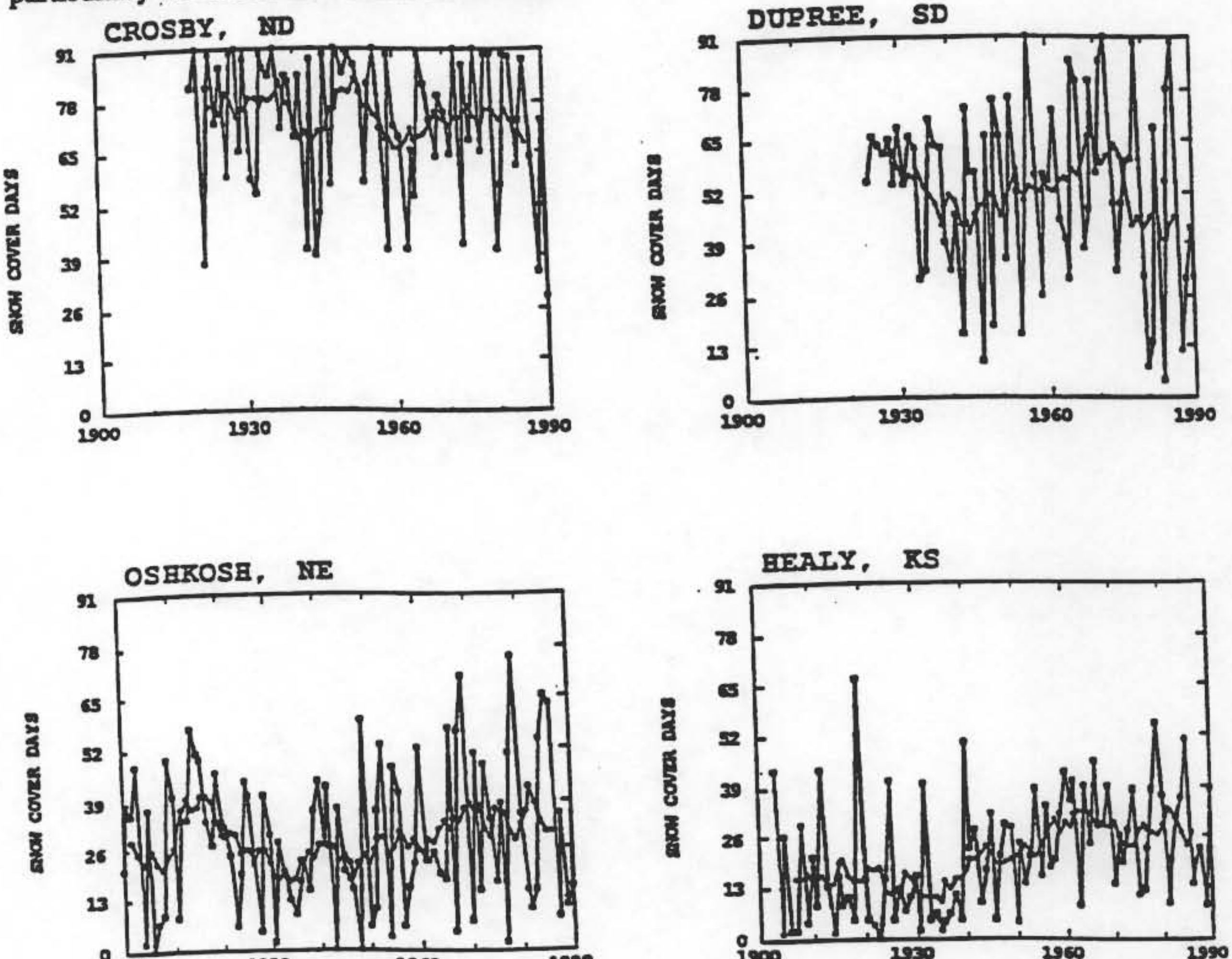


Figure 1. Time series of winter days with ≥2.5 cm of snow cover at several stations on the U.S. Great Plains. Also shown smoothed with a nine-point binomial filter, with only those points plotted where nine years are available for filtering (e.g., plotted year ±4 yr).

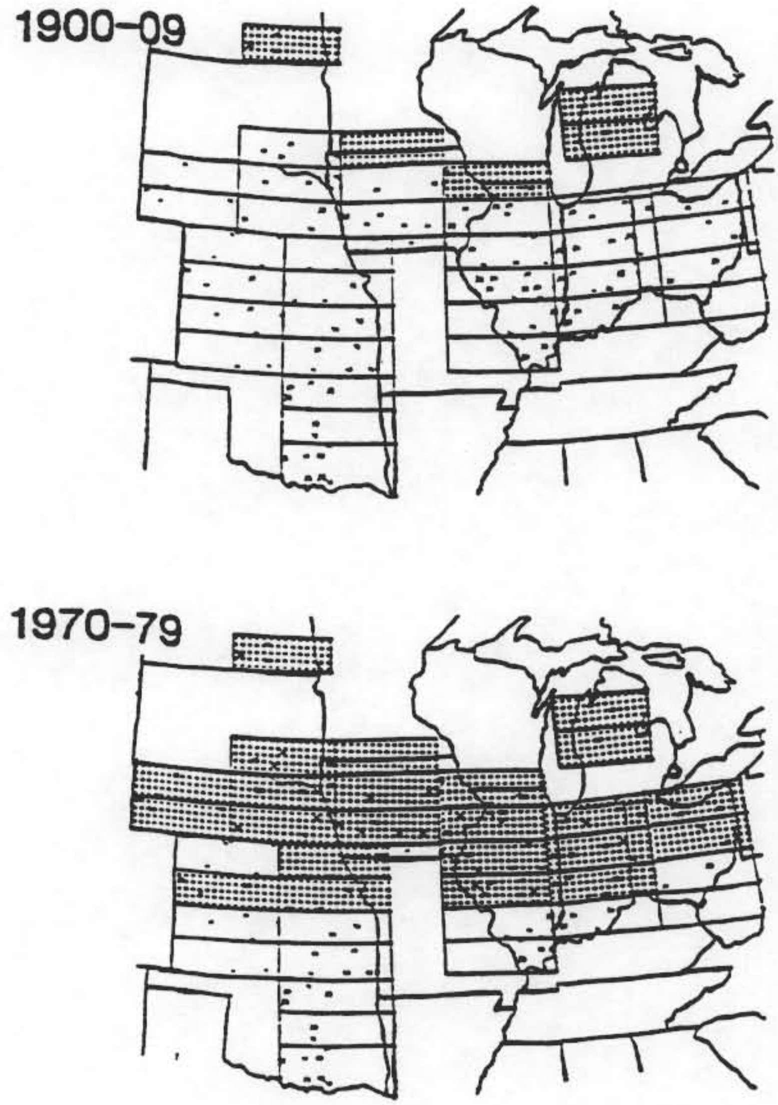


Figure 2. January snow cover over the central U.S. from 1900-09 and 1970-79. Study divisions with five or more years with more than half of the days in the month with a snow cover of ≥2.5 cm are stippled. Study stations are marked with Xs.

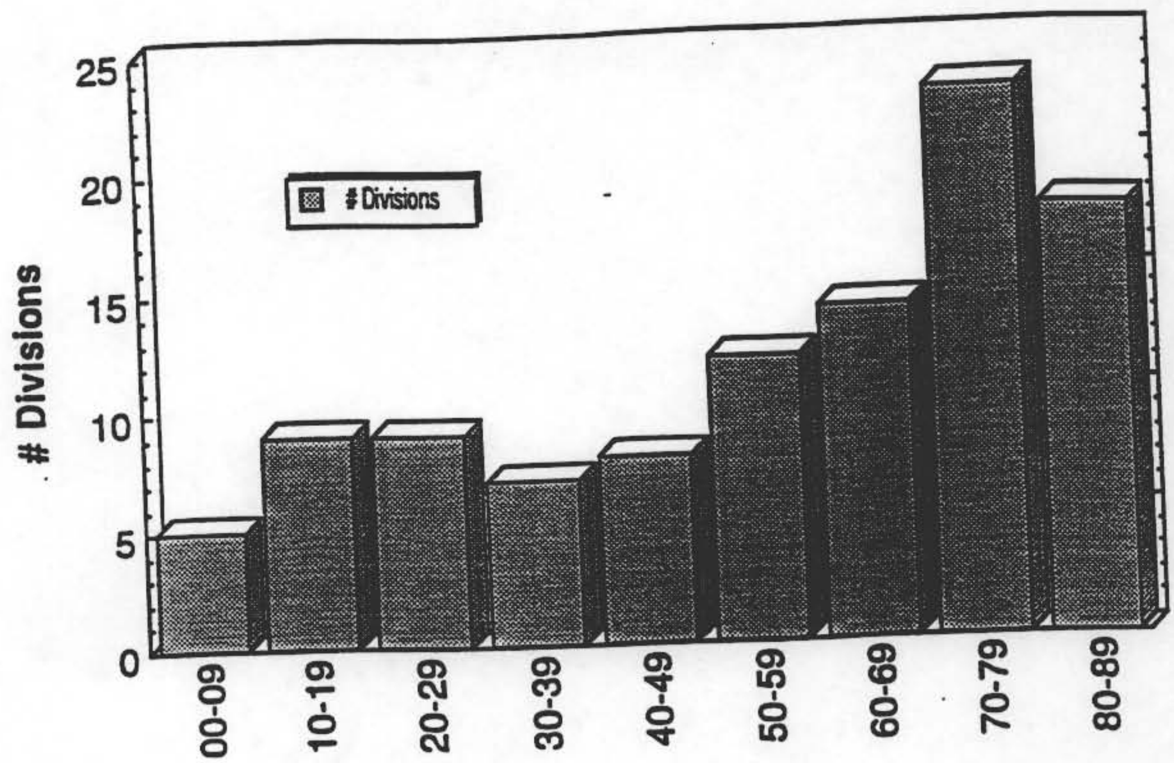


Figure 3. Decadal summary of study divisions in the central U.S. (cf. fig. 2) with more than half of the days in January having a snow cover of ≥2.5 cm in at least five years. Pre-1980 data from the station network, 1980-89 data from NOAA weekly snow charts.

Aircraft-Based Observations

Observations of snow cover from aircraft are limited in both space and time, and when made tend to be for specific investigations. One ongoing program that provides useful information for water supply and flood forecasts over portions of the U.S. and Canada is conducted by the Office of Hydrology of the U.S. National Weather Service. Sensors on board low flying aircraft measure natural terrestrial gamma radiation, from which the extent and mean areal water equivalent of a snowpack is inferred. Knowing the background (snowfree) radiation along a flight line permits subsequent estimates of snow water equivalent by calculating the attenuation of the radiation signal. Flight lines are typically 16 km long and 300 m wide, covering an area of approximately 5 km^2. A network of 1400 lines covering portions of 25 states and 7 Canadian provinces is currently being flown under this program. The principal sources of error using this methodology are incomplete or inaccurate information on mean soil moisture and characteristics of the air mass along the flight line, and radiation counting limitations (Carroll & Schaake, 1983). Underestimates occur if substantial amounts of forest biomass exist in the region or if the snow cover along the line is uneven (Carroll & Carroll, 1989 a & b).

Space-Based Observations

Regional and hemispheric snow extent is monitored using data recorded in shortwave (visible and near-infrared) and microwave wavelengths by sensors on board geostationary and polar orbiting satellites. Several snow cover products are produced using these data.

Shortwave Charting

Shortwave data provide continental coverage of snow extent at a relatively high spatial resolution. Snow is identified by recognizing characteristic textured surface features and brightnesses. Information on surface albedo and percent snow coverage (patchiness) is also gleaned from the data. Shortcomings include,-1) the inability to detect snow cover when solar illumination is low or when skies are cloudy, 2) the underestimation of cover where dense forests mask the underlying snow, 3) difficulties in discriminating snow from clouds in mountainous regions and in uniform lightly-vegetated areas that have a high surface brightness when snow covered, and 4) the lack of all but the most general information on snow depth (Kukla & Robinson, 1981; Dewey & Heim, 1982).

NOAA Snow Charts

In 1966, NOAA began to map the snow and ice areas in the Northern Hemisphere on a weekly basis (Matson et al., 1986). That effort continues today, and remains the only such hemispheric product. NOAA charts are based on a visual interpretation of photographic copies of shortwave imagery by trained meteorologists. Up to 1972, the subpoint resolution of the meteorological satellites commonly used was around 4 km. Beginning in October 1972, the Very High Resolution Radiometer (VHRR) provided imagery with a spatial resolution of 1.0 km, which in November 1978, with the launching of the Advanced VHRR (AVHRR), was reduced slightly to 1.1 km. Charts show boundaries on the last day that the surface in a given region is seen (fig. 4). Since May 1982, dates when a region was last observed have been placed on the charts. An examination of these dates shows the charts to be most representative of the fifth day of the week.

It is recognized that in early years the snow extent was underestimated on the NOAA charts, especially during Fall. Charting improved considerably in 1972 with the deployment of the VHRR sensor, and since then charting accuracy is such that this product is considered suitable for continental-scale climate studies (Kukla & Robinson, 1981).

Despite the shortwave limitations mentioned earlier, the NOAA charts are quite reliable at many times and in many regions. These include regions where, 1) skies are frequently clear, commonly in Spring near the snow line, 2) solar zenith angles are relatively low and illumination is high, 3) the snow cover is reasonably stable or changes slowly, and 4) pronounced local and regional signatures are present owing to the distribution of vegetation, lakes and rivers. Under these conditions, the satellite-derived product will be superior to charts of snow extent gleaned from station data, particularly in mountainous and sparsely inhabited regions. Another advantage of the NOAA snow charts is their portrayal of regionally-representative snow extent, whereas charts based on ground station reports may be biased due to the preferred position of weather stations in valleys and in places affected by urban heat islands, such as airports.

The NOAA charts are digitized on a weekly basis using the National Meteorological Center Limited-Area Fine Mesh grid. This is an 89 x 89 cell northern hemisphere grid, with cell resolution ranging from 16,000 km^2 to 42,000 km^2. If a cell is interpreted to be at least fifty percent snow covered it is considered to be completely covered, otherwise it is considered to be snow free.

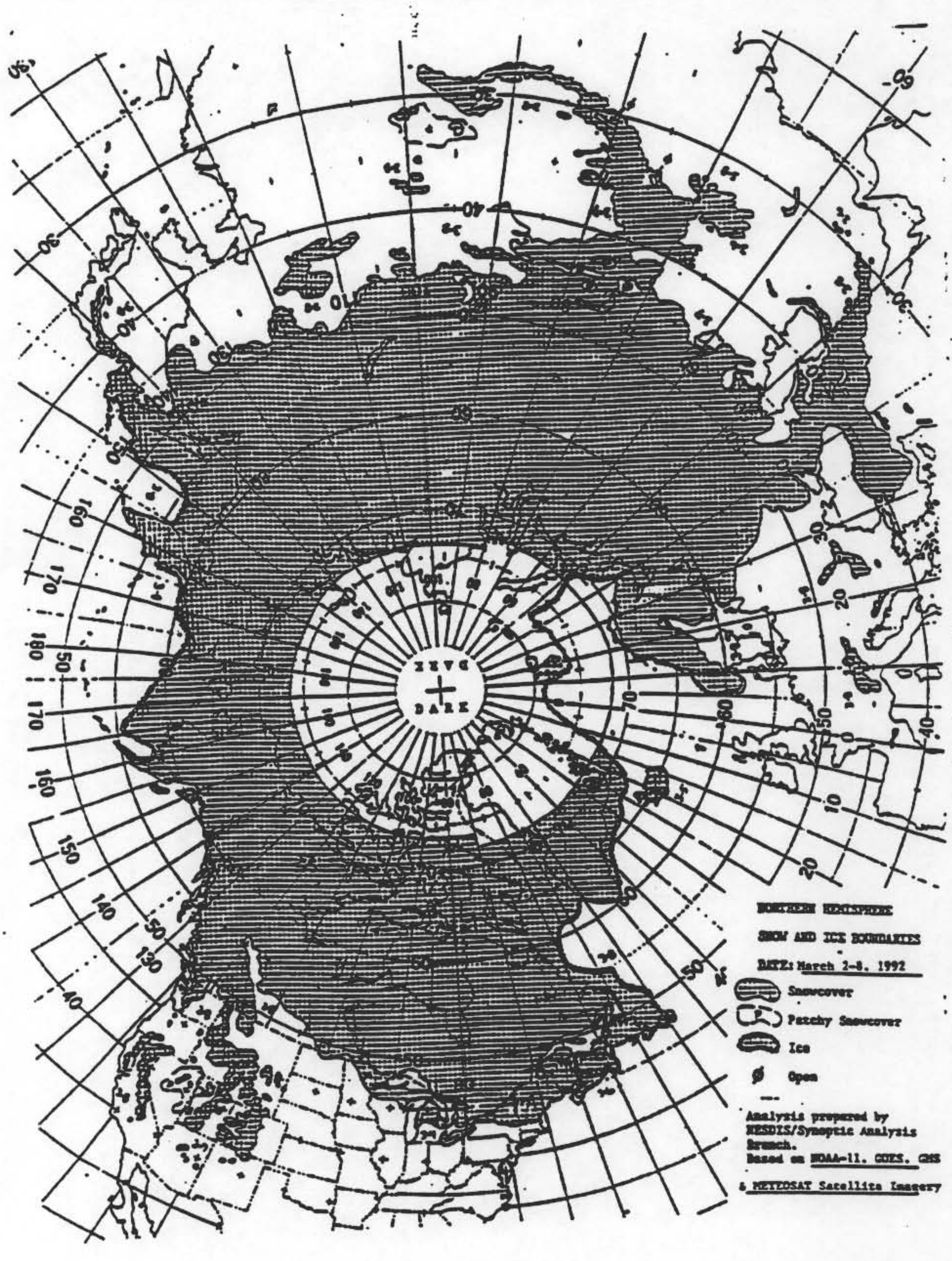


Figure 4. NOAA snow chart for March 2-8, 1992.

Figure 5 shows the mean position of the North American snow line for four months of the year. Snowlines are derived from NOAA digital data by calculating the percentage of the time each digitized cell is recognized as snow covered. To acquire accurate information on the area of land covered with snow for a particular time in a specific year requires a more sophisticated approach. A new routine to calculate monthly snow areas from NOAA data is presented here. The development of this routine follows the discovery of a major inconsistency in the manner in which NOAA has calculated monthly snow cover areas (Robinson et al., 1991). Prior to 1981, NOAA calculated continental areas from monthly summary charts, which consider a cell to be snow covered if snow is present on two or more weeks during a given month (Dewey & Heim, 1982). Since 1981, NOAA has produced monthly areas by averaging areas calculated from weekly charts. A comparison of these two methodologies shows areas computed using the monthly approach to be from several hundred thousand to over three million square kilometers greater than those calculated using weekly areas. The offsets are not consistent. Also contributing to the problem are 53 cells (covering 1.8×10^6 km^2) not considered consistently in the area calculations throughout the period of record. In 1981, NOAA changed their land mask, in the process eliminating 26 cells from consideration of being snow covered (categorizing them as water), while 27 others began to be examined. As discussed below, neither of the NOAA masks is accurate; both fail to accurately identify all cells, and only those cells, at least half covered by land.

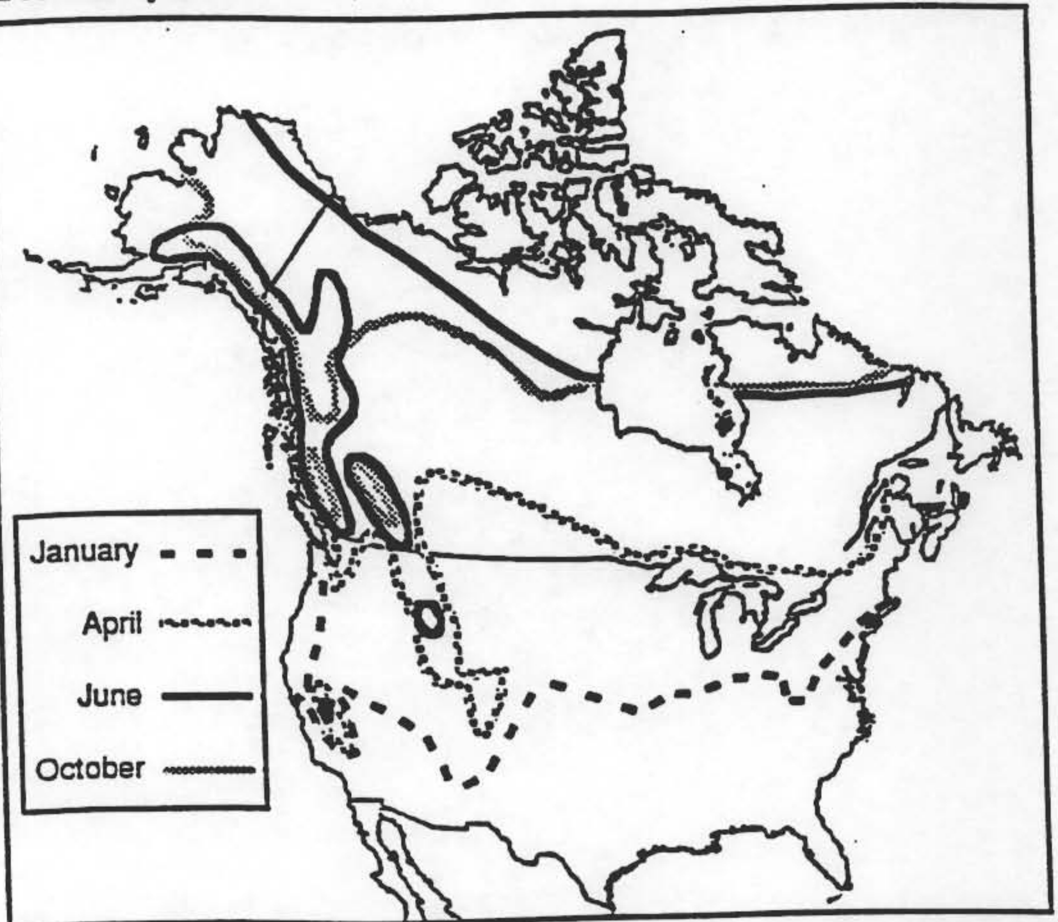


Figure 5. Mean North American snowlines for October, January, April and June. Lines are derived from NOAA weekly snow charts covering the interval from January 1971 through June 1990. The mean snowline is defined as the isoline denoting a fifty percent frequency of snow cover.

Our new, consistent methodology (Rutgers Routine) calculates weekly areas from the digitized snow files and weights them according to the number of days of a given week that fall in the given month. A chart week is considered to center on the fifth day of the published chart week (cf. above). No weighting has been employed in either of the NOAA routines.

In addition, a definitive land mask has been developed using digital map files analyzed on a geographic information system (GIS). The percentage of land in each of the 7921 NMC grid cells is calculated using the National Geophysical Data Center's five minute resolution ETOPO5 file as the primary data source. As this file does not include large interior lakes, the Navy Fleet Numerical Oceanography Center's 10 minute resolution Primary Terrain Cover Types file is used to properly account for these water bodies. Some 48 cells polewards of approximately 30°N which had been considered land in the pre 1981 NOAA and/or the 1981 to present NOAA mask are actually predominantly water covered (< 50% land). Conversely, 54 land cells are found to have been considered water on one or both NOAA masks. Those cells falling under the latter require a first-time analysis to determine whether they might be snow covered. This is accomplished by selecting nearest representative land cells (cells which NOAA has continuously charted as land) and assigning their snow status to the "new" land cells. Spot checks of a number of hard copy weekly charts prove this to be an adequate approach.

Continental Snow Cover From NOAA Charts: 1972-1991

According to values generated using the Rutgers Routine, the extent of snow cover over northern hemisphere lands is greatest in January. On average, some 46.5 million km^2 of Eurasia and North America are snow covered in this month, with February a close second with an average of 46.0 million km^2 (table 1, fig. 6). August has the least cover, averaging 3.9 million km^2, most of this being snow on top of the Greenland ice sheet. The past two decades of monthly data are close to normally distributed, and monthly standard deviations range from 0.9 million km^2 in August to 2.9 million km^2 in October. The annual mean cover is 25.5 million km^2 with a standard deviation of 1.1 million km^2. The snowiest year was 1978 with a mean of 27.4 million km^2, with 1990 the least snowy at 23.2 million km^2.

Table 1. Monthly and annual snow cover (million km^2) over northern hemisphere lands during the period January 1972 through May 1992. Areas are calculated using the Rutgers Routine.

	Maximum (yr)	Minimum (yr)	Mean	Median	Std. Dev.
Jan	49.8 (1985)	41.7 (1981)	46.5	46.1	1.8
Feb	51.0 (1978)	43.2 (1990,92)	46.0	45.6	2.0
Mar	44.1 (1985)	37.0 (1990)	41.0	40.8	1.9
Apr	35.3 (1979)	28.2 (1990)	31.3	31.4	1.8
May	24.1 (1974)	17.4 (1990)	20.8	20.6	1.9
Jun	15.6 (1978)	7.3 (1990)	11.6	11.4	2.1
Jul	8.0 (1978)	3.4 (1990)	5.3	5.5	1.2
Aug	5.7 (1978)	2.6 (1988,89,90)	3.9	3.8	0.9
Sep	7.9 (1972)	3.9 (1990)	5.6	5.6	1.1
Oct	26.1 (1976)	13.0 (1988)	17.6	17.5	2.9
Nov	37.9 (1985)	28.3 (1979)	33.0	32.8	2.3
Dec	46.0 (1985)	37.5 (1980)	42.5	42.7	2.3
Annual	27.4 (1978)	23.2 (1990)	25.5	25.4	1.1

Twelve-month running means of continental snow extent best illustrate the periods of above normal cover that occurred in the late 1970s and mid 1980s (fig. 7). Intervals with lower snow extents include the mid 1970s and early 1980s, however neither approach the deficit of snow cover observed in recent years. Of the 58 months between August 1987 and May 1992, only five had above normal snow cover (Jan 88, Sep 89, Dec 89, Dec 90, Nov 91). The lowest year on record was 1990, when monthly minima occurred in eight months (table 1). Spring cover has shown pronounced deficits over the past five years in Eurasia and six years in North America; areas in these Springs have been at or below lows established prior to this period (fig. 8). During the same interval, both continents have had low seasonal cover in the Fall and Summer, although frequently neither continent has been at or approached record low levels. Winter cover has been close to average over the past six years.

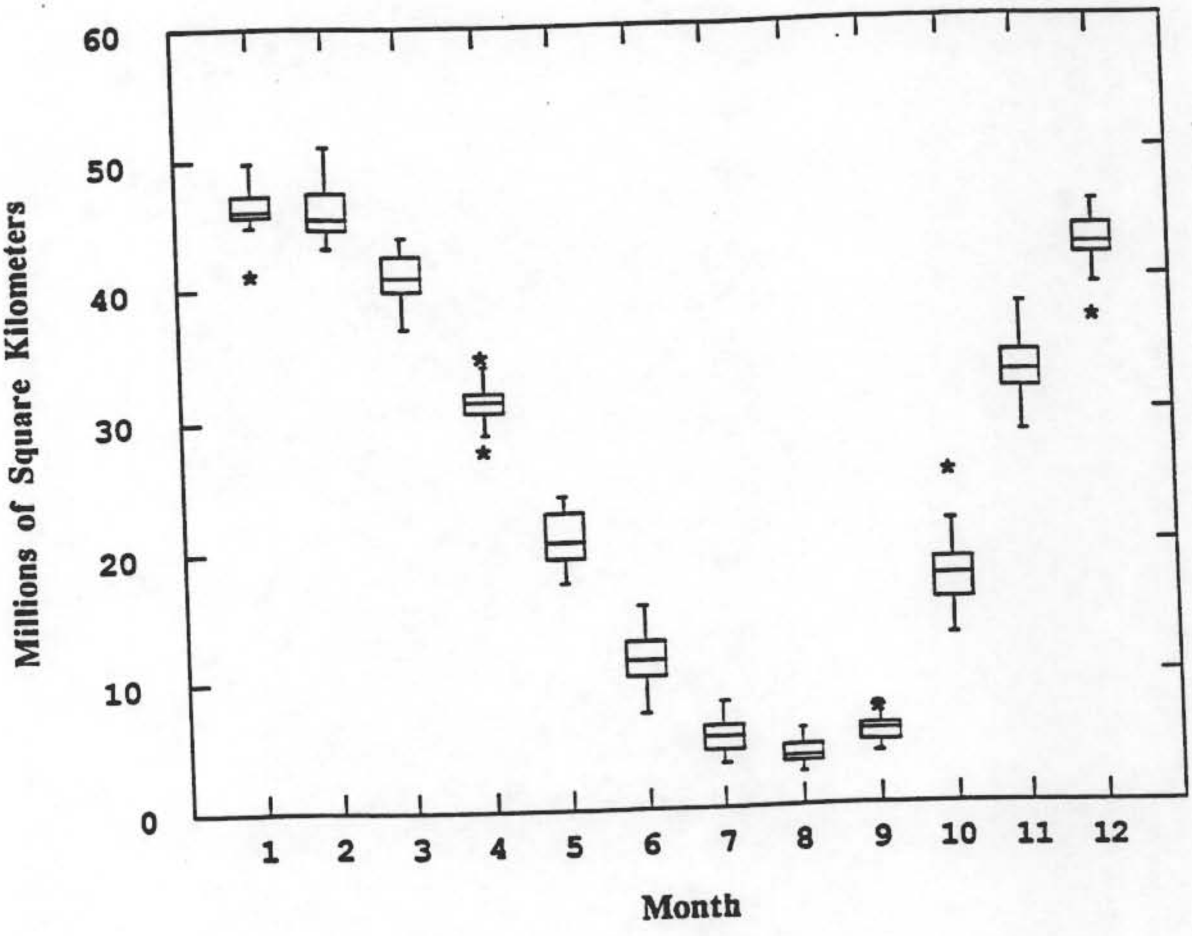


Figure 6. Monthly snow cover over northern hemisphere lands (including Greenland) between January 1972 and May 1992. The median area of cover is the horizontal line within the twelve monthly boxes, and the interquartile range (ICR) is between the top and bottom of the box. Whiskers show the extreme values between ±1 and ±1.5 * ICR, and asterisks show values outside this range. Values are calculated from NOAA weekly snow charts using the Rutgers Routine.

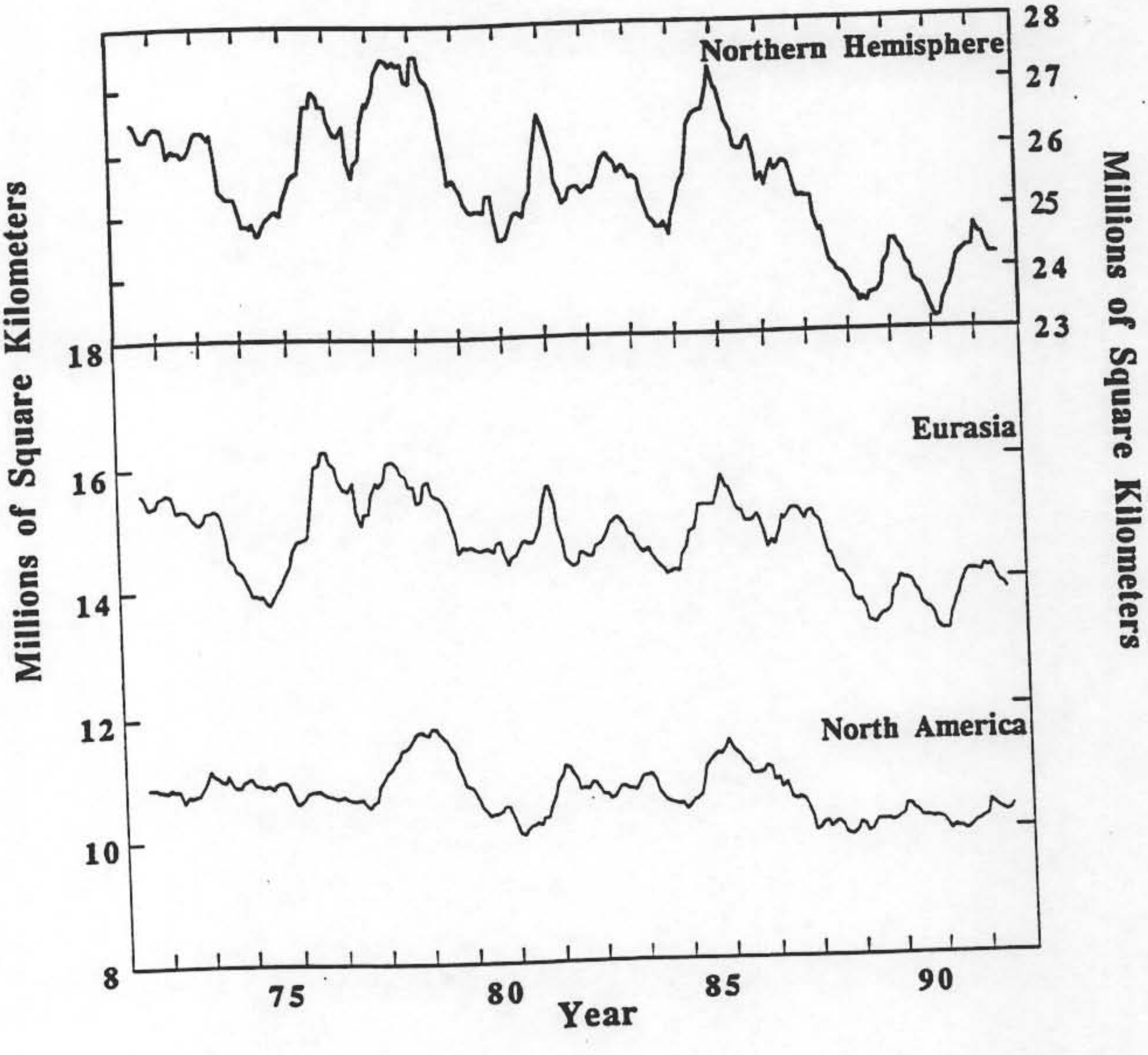


Figure 7. Twelve-month running means of snow cover over northern hemisphere lands (including Greenland) for the period January 1972 through May 1992. Running means are also shown for Eurasia and North America (including Greenland). Values are plotted on the 7th month of the 12 month interval, and are calculated from NOAA weekly snow charts using the Rutgers Routine.

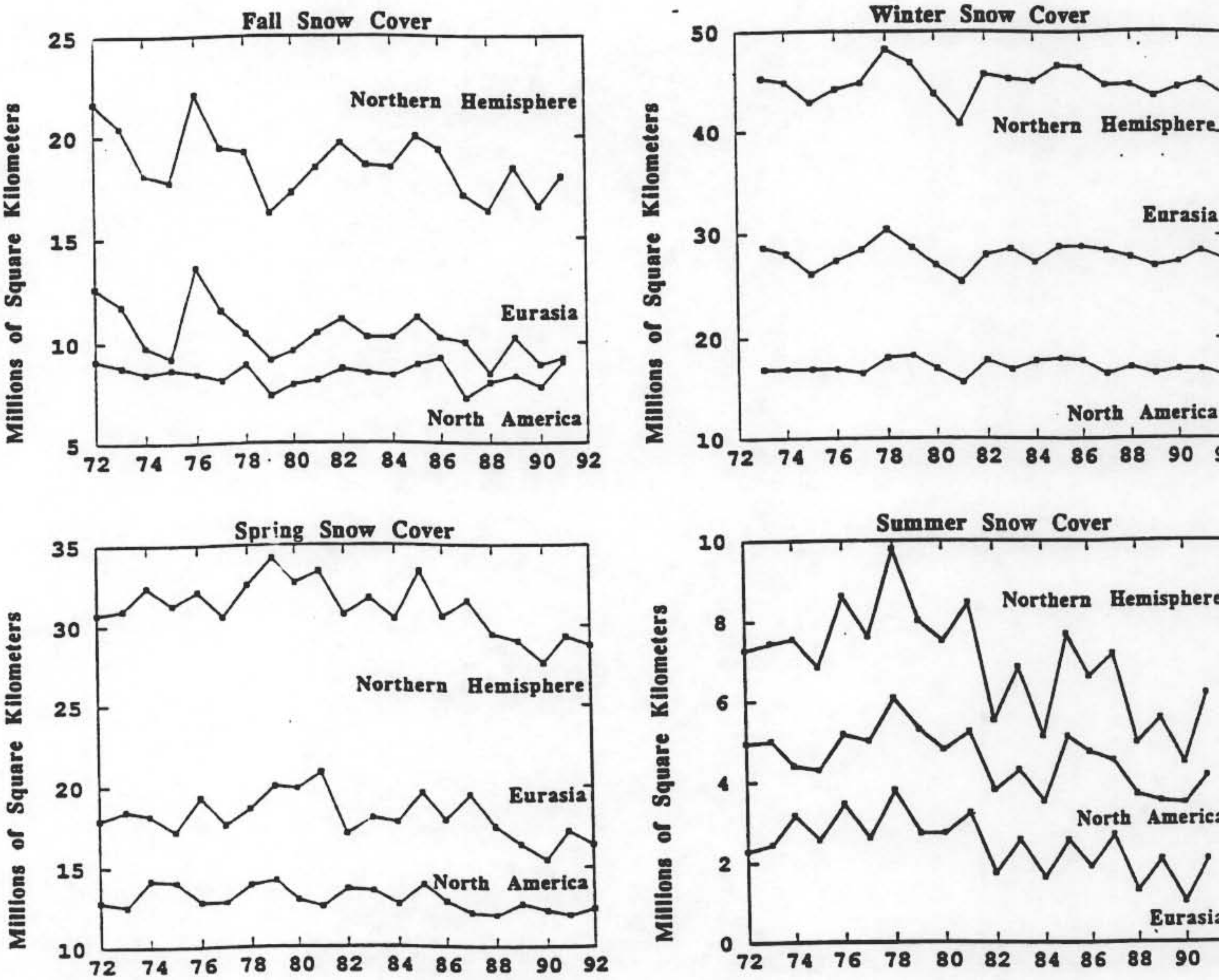


Figure 8. Seasonal time series of snow cover over Eurasia and North America (Greenland is excluded). Values are calculated from NOAA weekly snow charts using the Rutgers Routine.

Microwave Charting

Microwave radiation emitted by the earth's surface penetrates winter clouds, permitting an unobstructed signal from the earth's surface to reach a satellite. The discrimination of snow cover from microwave data is possible mainly because of differences in emissivity between snow-covered and snow-free surfaces. Estimates of the spatial extent as well as the depth or water equivalent of the snowpack are gleaned from equations employing radiation sensed by multiple channels in the microwave portion of the spectrum (e.g., Kunzi et al., 1982; McFarland et al., 1987). Snow estimates from satellite-borne microwave sensor data have been available since the launch of the Scanning Multichannel Microwave Radiometer (SMMR) in late 1978. The spatial resolution of the data is on the order of several tens of kilometers. Since 1987, close to the time of SMMR failure, the Special Sensor Microwave Imager (SSM/I) has provided information for the determination of snow extent and volume. The lack of sufficient ground truth data on snow depth or volume makes an adequate assessment of the reliability of such microwave estimates uncertain. Therefore the remainder of this discussion focuses on the microwave monitoring of snow extent.

As with shortwave products, the microwave charting of snow extent is not without its limitations. The resolution of the data makes the detailed recognition of snow cover difficult, particularly where snow is patchy, and it is difficult to identify shallow or wet snow using microwaves. It is also apparent that because of region-specific differences in land cover and snowpack properties, no single algorithm can adequately estimate snow cover across northern hemisphere lands.

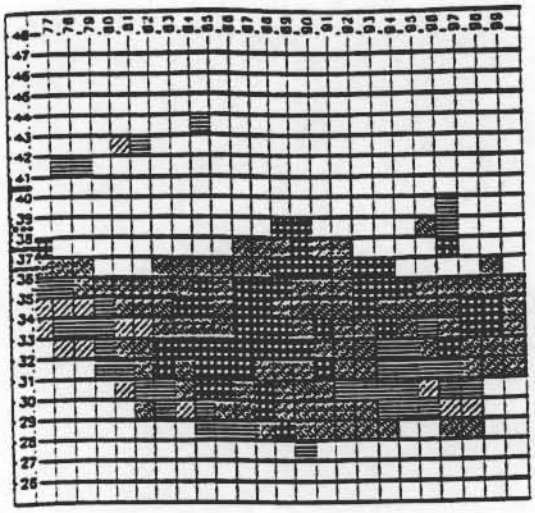
Regional Investigations

Efforts are underway to better understand regional microwave signatures, and in some cases to develop region-specific algorithms. Landscapes of interest include mountains (Chang et al., 1991; R. Armstrong, per. commun.), forest (Hall et al., 1982; Hallikainen & Jolma, 1986), tundra (Hall et al., 1986) and prairie (Goodison, 1989). Also, over the Tibetan Plateau and adjacent high mountains of south central Asia, snow cover tends to be overestimated when a single hemispheric (generic) algorithm is employed (Robinson et al., 1984). In a recent investigation, the generic algorithm of Chang et al. (1987) (hereafter, NASA) is adjusted using shortwave-derived charts and GIS techniques to better represent snow conditions in this region (Robinson et al., 1990).

The theoretical NASA algorithm uses the difference in brightness temperatures of 18 and 37 GHz SMMR data to derive a snow depth/brightness temperature relationship for a uniform snow field. A snow density of 0.3 g/cm^3 and a snow crystal radius of 0.3 mm are assumed, and by fitting the differences to the linear portion of the 18 and 37 GHz responses a constant is derived that is applied to the measured differences. This algorithm can be used for snow up to one meter deep. The shortwave charts are constructed expressly for this study, and for the purpose of this study are considered accurate. Microwave and shortwave data are reduced to $1^\circ \times 1^\circ$ cells for this analysis.

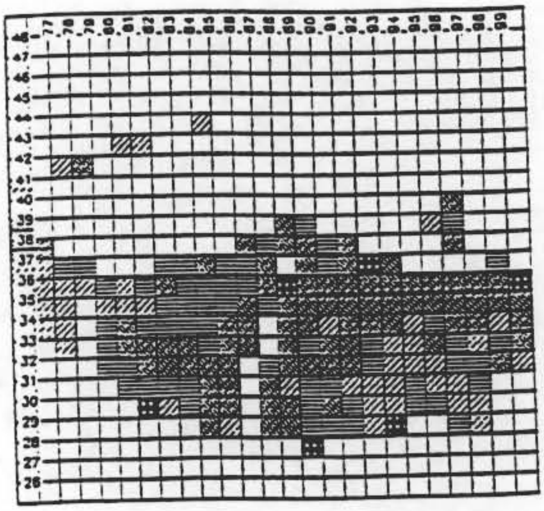
Given the linear nature of the NASA algorithm, snow cover is subtracted from all cells in one centimeter increments until the extent of snow cover in the microwave chart is in close spatial agreement with the shortwave product. In 15 Plateau cases, between 4 and 16 cm of snow have to be subtracted (offset) from original cell totals to reach closest agreement with the shortwave chart. The mean microwave offset for the Plateau is 8 cm, while for the adjacent high mountains the mean is 6 cm, with cases ranging from 0 to 16 cm. Figure 9 shows the shortwave, generic microwave and adjusted (to the mean offset) microwave charts for the two regions for January 1987. The 8 and 6 cm offsets compare to mean offsets of 0 to 4 cm in the lower elevation basins and lower mountains elsewhere in western China.

A



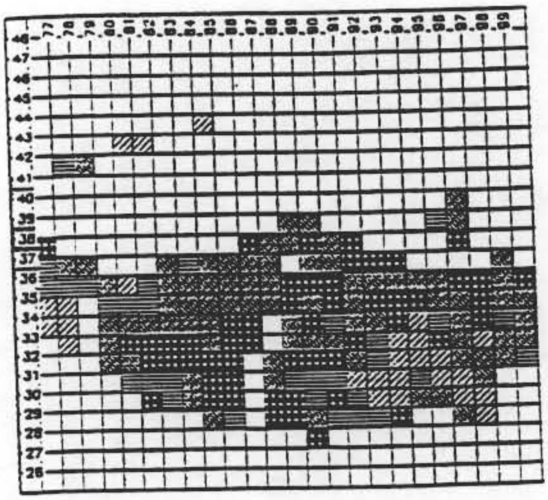
A) The shortwave chart is constructed using Defense Meteorological Satellite Program imagery and shows 1° x 1° cells with, 1) (cf. legend) patchy (10-30% cover), 2) partial (30-80%) and 3) full (80-100%) snow cover, along with 4) areas of snow-free ground (<10% snow cover). Empty cells are outside the study region.

B



B) The generic microwave chart is constructed using the algorithm of Chang et al. (1987) and shows cells with snow depths ranging from, 1) 3-10 cm, 2) 11-20 cm and 3) >20 cm, along with 253) snow-free (<3 cm snow) ground. Empty cells are outside the study region or where data within the region is missing.

C



C) The adjusted microwave chart shows the cells considered to be snow covered once 8 cm of snow is subtracted from the generic reports over the Plateau and 6 cm subtracted over the high mountains. Cover categories are the same as for the generic chart.

Figure 9. The shortwave, generic microwave and adjusted (to the mean offset) microwave charts for the Tibetan Plateau and surrounding high mountains for mid-January 1987.

The overestimation of snow cover when employing the generic NASA algorithm over this high elevation area may be associated with the patchiness and general shallow depth of the snow cover in the area, or to particular characteristics of the snowfree surfaces in the region. However, it appears that the major cause of the overestimation has to do with the thin atmosphere at these elevations. The generic algorithm was developed and tested for low elevation sites, and by removing the atmosphere from the theoretical algorithm, the match between the microwave and shortwave products is much improved (A. Chang, per. commun.). However, this comes at the expense of adjacent lower elevation regions, where the revised microwave snow area estimates are low.

Continental snow cover from microwave charts: 1978-1987

The difficulties in monitoring snow extent over Tibet using the generic NASA algorithm are rather unique in that they show an overestimation of snow. Most of the errors in microwave sensing are in the opposite direction. This is apparent when comparing microwave estimates of monthly continental snow extent with NOAA shortwave values (Chang et al., 1990). This is the only such time series available to date, and covers the interval from November 1978 through August 1987. NASA mean monthly snow cover for northern hemisphere lands (exclusive of Greenland) runs from less than one to as much as thirteen million square kilometers below NOAA areas for the nine years of coincidental estimates (fig. 10). These absolute differences are greatest in the late Fall and early Winter.

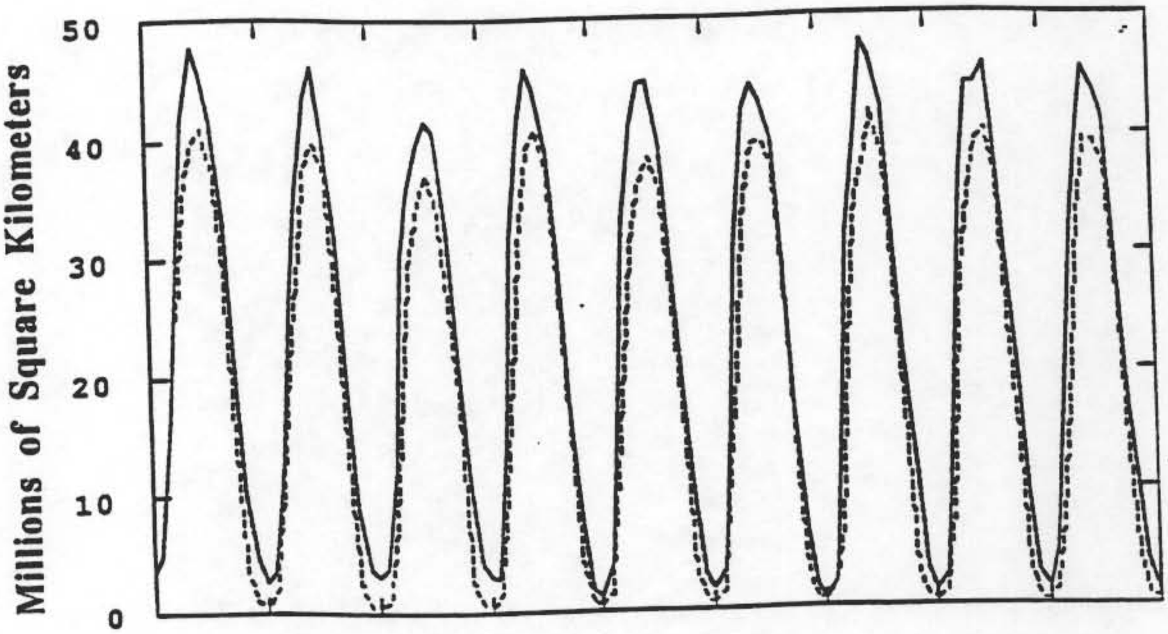


Figure 10. Extent of snow cover over northern hemisphere lands (excluding Greenland) computed from NOAA shortwave charts using the Rutgers Routine (solid line: Sep 78-Aug 87) and from NASA microwave charts (dashed: Nov 78-Aug 87).

In a relative sense, microwave areas are between 80 and 90% of shortwave values in Winter and Spring, 20 to 40% of the shortwave estimates in Summer, and 40 to 70% of shortwave areas in Fall (fig. 11). A possible explanation for the great disparities in the latter two seasons may be the wet and shallow nature of the snowpack interfering with accurate microwave recognition of snow. Depth may be the most important of the two variables, given the better agreement in Spring, although it has been suggested that unfrozen soil beneath the pack is a major contributor to the underestimates during Fall (B. Goodison, per. commun.)

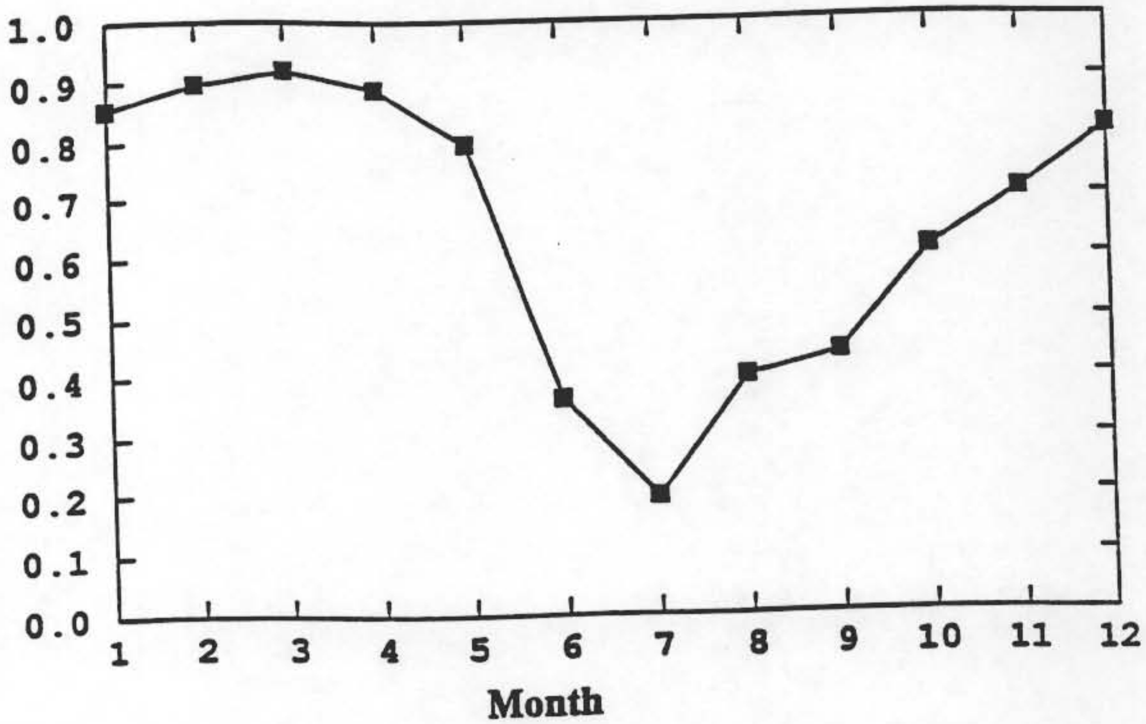


Figure 11. Fractional difference between monthly snow cover area derived from NOAA shortwave and NASA microwave charts for northern hemisphere lands (excluding Greenland). NOAA values, derived using the Rutgers Routine, exceed NASA estimates for each month within the November 1978 through August 1987 study period.

While the preceding discussion has dealt with SMMR data, snow monitoring employing SSM/I data shows the same strengths and liabilities as the former (Goodison, 1989; Hall et al., 1991). The SSM/I has 19 and 37 GHz channels, thus SMMR algorithms perform much the same as they do with the 18 and 37 GHz channels. In addition, the 85 GHz channel on the SSM/I has shown promise in improving the monitoring of shallow (<5 cm) snow cover (Nagler & Rott, 1991).

Snow Cover Over Arctic Sea Ice

Most studies of snow on top of arctic sea ice have been of limited spatial and temporal scope. They have primarily been concerned with the snow melt season and the resultant impact of snow melt on the surface albedo of the pack ice. Studies have been based largely on observations at drifting stations, on fast ice, and during aircraft missions (e.g., Kuznetsov & Timerev, 1973; Pautzke & Hornof, 1978; Hanson, 1980). Others have used these measurements (e.g., Marshunova & Chernigovskiy, 1966; Hummel & Reck, 1979; Kukla & Robinson, 1980) and satellite passive microwave data (Carsey, 1985) to estimate regional summer albedos. These albedos, to a large extent, are dictated by the condition and distribution of the snow cover on top of the ice, particularly in the Spring and early Summer.

Only one time series of snow conditions on top of arctic sea ice has been produced to date (Robinson et al., 1992). This effort employs shortwave satellite imagery to map manually surface brightness changes over sea ice throughout the Arctic Basin from May to mid-August over a ten year period. Due to gaps in available imagery, the ten years are not continuous, falling between 1975 and 1988. Only melt is mapped, as cloudiness and low solar illumination preclude charting of the onset of fall snow cover across the basin.

The year 1986 typifies the pattern of snow melt found in most years (fig. 12). Snow melt is observed to begin in May in the marginal seas, progress northward with time, and finally begins near the Pole in late June. In most years, snow melt is completed in the central arctic by late July. Large year-to-year differences occur in the timing of snow melt, exceeding one month in some regions. The onset of melt, defined by the date when at least 50% of all non-water cells in a given portion of the basin are class 2 or greater (cf. fig. 12 caption for class descriptions), is observed to vary from mid May in the Kara and Barents seas to late June in the central Arctic (table 2, fig. 13). Melt onset was particularly early in 1977 and 1984 and late in 1975 and 1979. The onset of advanced melt (>50% of a region class 3 or greater) starts about one month after melt onset in all but the central arctic, where it is three weeks later, and in the East Siberian/Laptev area, where it is reached within one week of melt onset. Within a region, the year-to-year variation in the onset of advanced melt is from approximately two to four weeks, somewhat less than variations in melt onset. For most of the basin, advanced melt was earliest in 1987, followed closely by 1977, and latest in 1978.

Table 2. Dates of the onset of spring snow melt on top of sea ice in five regions of the Arctic Basin (cf. fig. 13). Mean dates and the range in dates (days) between extreme years are also given. Dashes denote those years where cloudiness precludes an accurate estimate of onset.

	Central Arctic	Beaufort Chukchi	Laptev E. Siberian	Kara Barents	NW North Atlantic
1975	7/8	6/14	6/29	5/12	6/8
1977	6/5	5/21	5/21	5/12	5/12
1978	6/23	5/24	6/8	5/18	5/24
1979	6/29	6/20	6/17	5/30	6/2
1980	7/2	6/11	6/23	5/15	6/23
1984	6/14	5/9	6/11	5/3	5/6
1985	6/20	6/8	6/14	5/27	5/27
1986	7/5	6/11	6/14	5/6	-
1987	6/11	5/30	6/5	5/12	5/18
1988	6/14	5/9	6/17	-	-
Mean	6/23	5/30	6/14	5/15	5/27
Range	27 d	42 d	39 d	24 d	48 d

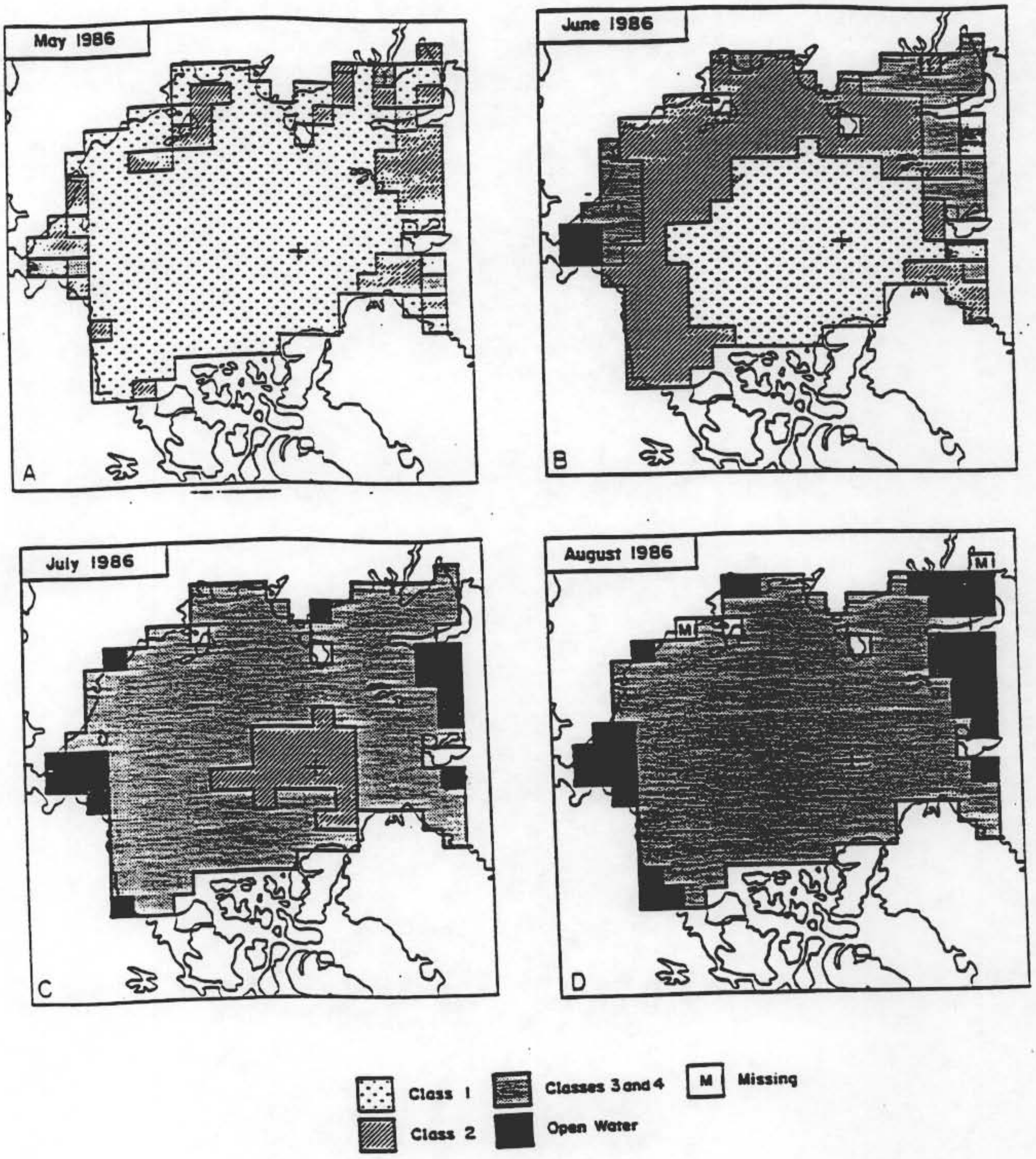


Figure 12. Progress of arctic snow melt during 1986 as shown by the mean brightness classes for study grid cells in the basin for, A) May, B) June, C) July, and D) 1-16 August. Class 1 corresponds to fresh snow cover over 95% of the ice and class 2 is found when snow covers between 50-95% of the surface, with the remainder being bare or ponded ice. Class 3 represents the advanced to final stage of snow melt, with numerous meltponds and between 10-50% of the ice surface snow covered, or, following pond drainage, predominantly bare ice. Heavily-ponded or flooded ice is represented by class 4, and is generally limited to regions of fast ice near outlets of major rivers along the Siberian coast.

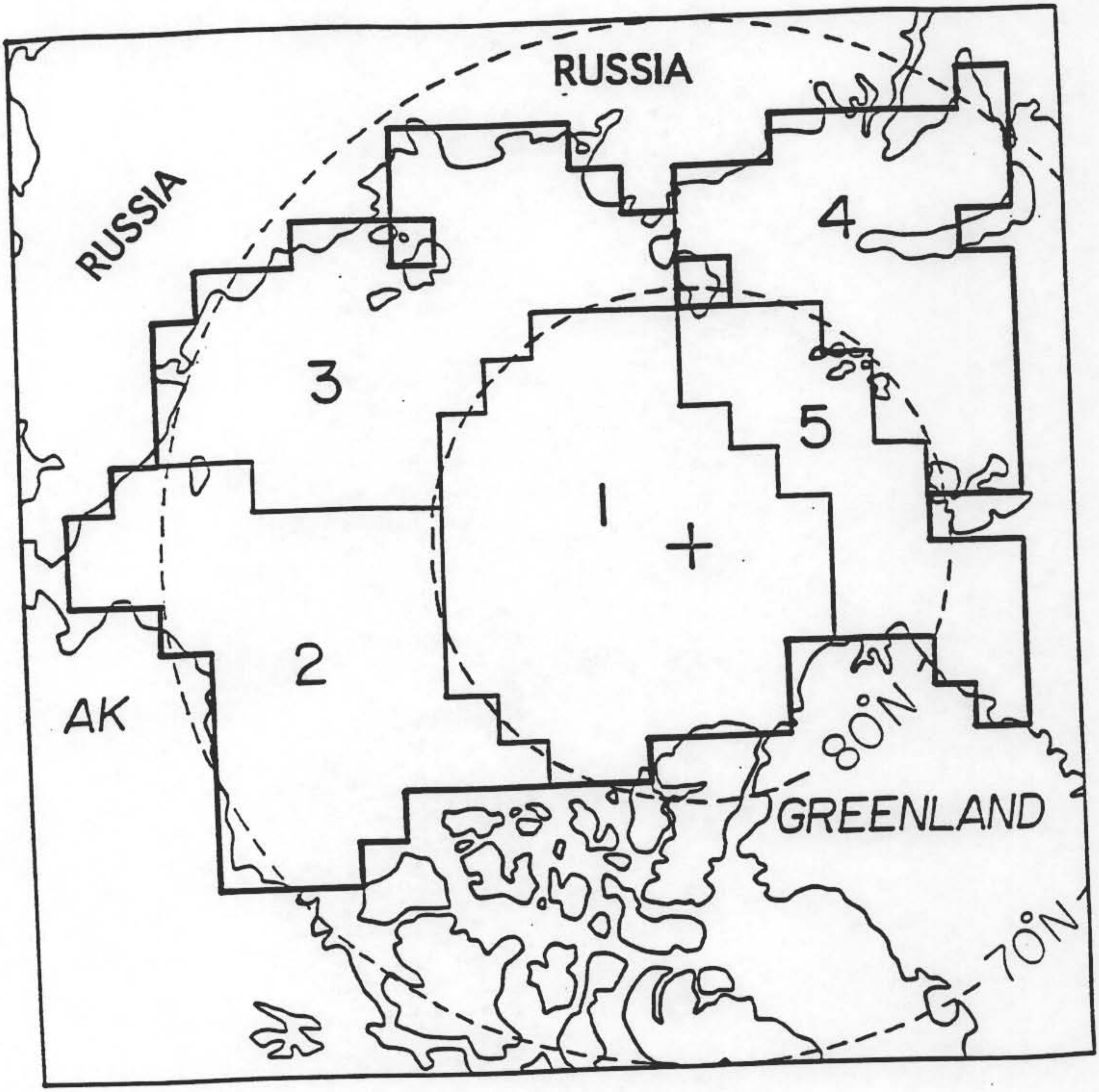


Figure 13. Arctic Basin study area, including, 1) Central Arctic, 2) Beaufort/Chukchi seas, 3) East Siberian/Laptev seas, 4) Kara/Barents seas, and 5) NW North Atlantic subregions.

Microwave remote sensing over arctic sea ice has shown promise in identifying what may be the initial appearance of liquid water within the snow pack or at the snow/ice interface (Anderson & Robinson, 1985; Cavalieri et al., 1990). This signal is recognized approximately three weeks prior to the onset of melt as observed using shortwave imagery. Further study is needed to better understand this signal and to integrate this information with shortwave data.

Snow Monitoring In The 1990s

Much remains to be accomplished in the 1990s to assure that accurate information on the extent and other characteristics of snow cover is available on regional and hemispheric levels. This includes ongoing efforts to monitor surface conditions during the decade and beyond, as well as retrospective efforts to improve estimates of past snow covers. The following discussion is not meant to be exhaustive, rather it highlights some of the more important work across a broad spectrum of needs.

Ongoing Monitoring

1) Maintain the NOAA shortwave satellite charting effort in its present form. To abruptly or, perhaps more seriously, subtly alter the manner in which these charts are produced would severely weaken what is presently the longest and most consistent satellite-derived data set of any surface or atmospheric variable. Any alteration would require "restarting the clock" and losing precious years when employing snow cover as a means of identifying and monitoring climate change.

2) Produce all-weather, all-surface snow charts using shortwave and microwave satellite data and station observations. The maintenance of the shortwave effort need not exclude the development of new and no doubt more accurate means of monitoring snow extent. For instance, geographic information systems techniques should be developed to produce a new series of operational hemispheric snow charts on at least a weekly basis. These charts would provide the most detailed information possible on snow extent, water equivalent and depth, and surface albedo over land surfaces, and, at the least, snow extent and albedo over sea ice and the Greenland ice sheet.

To begin with, these charts need not employ a consistent methodology. Rather they should be designed to accommodate improvements in all the realms of snow monitoring, be they increased station coverage, operational satellite monitoring of the surface at 1.6 µm, new regional microwave algorithms, or improved GIS techniques. The current NOAA product can handle the time series duties over the continents for the time being, and time series of snow over sea ice should be continued using proven techniques.

Retrospective Monitoring

1) Continue the assembly, digitization and quality control of historic to recent station data from throughout middle and high latitude lands. Data from snow courses and remote snow measurement networks (i.e., mountain observations) should also undergo the same scrutiny.

2) Construct regional snow charts from ground data. Interpolative techniques, which account for horizontal and vertical variations, should be used to estimate snow extent and depth for regions with sufficient data. This charting should extend back as far as possible and continue into the microwave satellite era. Charts within the satellite era

would permit cross checks of extent and depth estimates with shortwave and microwave products.

3) Utilizing data from urban and rural locations, study the impact of urbanization on snow cover depth and duration.

4) Rechart continental snow cover for the 1966 to 1971 interval. Recharting is also recommended for the Tibetan Plateau and adjacent mountains through the middle 1970s and for high-latitude lands during the Summer. These endeavors, along with spot checks across the continents in subsequent years, would expand and improve the NOAA time series and would permit the establishment of quantitative error ranges to these charts.

5) Produce a time series of surface albedo over northern hemisphere lands. Using GIS techniques, NOAA weekly snow chart data should be merged with available information on the surface albedo of snow covered and snowfree landscapes.

6) Once greater confidence in regional microwave algorithms is attained, a reassessment of hemispheric snow cover using SMMR and SSM/I data should be undertaken. This should include estimates of snow extent and depth and/or water equivalent.

7) Expand the ten-year data set of snow extent over arctic sea ice to include as many years as possible between the early 1970s and present.

Conclusions

The critical role that snow cover plays in the global heat budget and the expected role of snow feedbacks in anthropogenically-induced climate change support the continued diligent monitoring of snow cover over continents and sea ice. With the availability and better understanding of data from a variety of satellite and ground sources, and the ability to integrate and examine these data using geographic information techniques, more accurate and extensive knowledge of snow cover across the Northern Hemisphere is within reach. This information, along with expanded retrospective analysis efforts, will solidify the position of snow as one of the key indicators of future change in the climate system.

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