13.12 RECENT VARIABILITY OF NORTHERN HEMISPHERE SNOW COVER

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1. INTRODUCTION

The impact of snow on humans and the environment is considerable. The accurate forecasting of local daily temperatures, regional climatic anomalies and the location and strength of cyclonic systems relies, in part, on knowledge of the distribution and state of regional snow cover. Model simulations of a CO2/trace-gas induced climate change show that spatial decreases in snow extent amplify global warming. Recent years have seen the availability of more accurate and complete information on the spatial extent and physical state of snow. This is leading to a better understanding of the variability of snow cover on annual to decadal scales, of cryosphere-climate interactions, and of the role snow may play in regional and global climate change.

The premier dataset used to evaluate large-scale snow extent has been the weekly visible-wavelength satellite maps of Northern Hemisphere snow cover produced by the National Oceanic and Atmospheric Administration's (NOAA) National Environmental Data and Information Service (NESDIS) (Matson et al., 1986; Robinson et al., 1993). To date, these maps constitute the longest satellite-derived environmental dataset available. NOAA/NESDIS weekly snow maps began to be produced in late 1966; however early ones (pre-1972) tended to underestimate snow extent, particularly during the fall (Kukla and Robinson, 1981). A major reason for this problem was the early inexperience of analysts in distinguishing snow cover from clouds or even from snow-free ground, compounded by the lower resolution of imagery during this era compared to the period since then. An effort to reanalyze the 1966-71 imagery and produce a new set of snow maps has recently been completed at Rutgers. In June 1999, NESDIS ceased producing the weekly maps, replacing them with a daily Interactive Multisensor Snowmap (IMS) product (Ramsay, 1998). NOAA and NASA are supporting a team of NESDIS and Rutgers researchers to propose the best means of merging the two products so as to maintain the continuity of the hemispheric time series.

This paper expands upon and updates recent AMS conference contributions (Robinson, 2000, 2002 Robinson et al., 2001), and discusses a 30-year climatology of hemispheric snow and updates and discusses time series and maps of snow anomalies.

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2. NOAA/NESDIS SNOW MAPS

Trained meteorologists produced the weekly NESDIS snow product from visual analyses of visible satellite imagery. The primary data source was visible imagery acquired from NOAA-n polar orbiting satellites and stored in hardcopy. Secondary data sources included online GOES, GMS, and METEOSAT imagery. Snow cover identification was made by the manual inspection of hardcopy imagery and graphics products, online imagery loops, and the previous week's analysis. Map quality was predicated on the availability of clear sky visible imagery and the meteorologist's experience. After all snow boundaries were identified and placed on a hardcopy, polar stereographic map, an electronic version was made through the digitization of a 89 x 89 cell acetate overlay (mid and high latitude portion of a hemispheric 128 x 128 cell (half mesh) overlay).

Snow cover between 1966 and 1971 was reanalyzed at Rutgers in a similar manner, using daily gridded composites of visible imagery for the eastern and western hemispheres of the Northern Hemisphere. Surface resolution of the imagery is approximately 25 km. The imagery was supplemented with daily reports of snow depth at several thousand stations in the U.S., Canada, China and the former Soviet Union, gridded to 1° x 1° grid cells using all reports from within a given cell. Daily surface weather charts also provided information on cloud cover, precipitation and temperature. Infrared imagery and the above ancillary information were employed in many areas to confirm interpretations made from visible data.

June 1999 saw the introduction of a daily hemispheric snow product by NOAA/NESDIS. The new Interactive Multisensor Snow and Ice Mapping System product is generated from a UNIX-based workstation application that provides the analyst the ability to visually inspect imagery and mapped data from various sources to determine the presence of snow. Daily maps are produced from a variety of visible satellite imagery, estimates of snow extent derived from microwave satellite data, and station mapped products. Maps are digitized to a 1024 x 1024 cell (sixteenth mesh) polar grid.

Before the weekly map series ended, there was a two-year period in which both maps were produced. We are currently using data from this interval to develop an accurate means of converting the daily maps to a weekly product at the lower half mesh resolution. At the moment, we have calculated preliminary areas based on a routine developed by Don Garrett at the NOAA Climate Prediction Center that considers a half mesh cell as being snow covered if 38% or more of the co-located sixteenth mesh cells are mapped as snow covered on the last day (Sunday) of the longstanding weekly chart period. We are confident that this method provides sufficiently accurate values for use in continental and hemispheric evaluations.

3. CALCULATION OF SNOW COVER AREA

Weekly areas are derived from the digitized snow files, and subsequently, monthly values are obtained by weighting the weeks according to the number of days of a map week falling in the given month (Robinson, 1993). Prior to the calculations, the digital files are standardized to a common land mask. Only those grid cells that contain more than 50% land are included.

It had long been suspected that grid cell areas for the half mesh grid provided by NOAA were somewhat incorrect. Documentation for the calculation of the cell area file (which dates back to at least the late 1970s) has never been located. Therefore, we have recalculated cell areas in the 128 x 128 half mesh grid based on the application of the general quadrilateral with spherical geometric relations in a polar stereographic projection (Smart and Green, 1977; Kidwell, 1998, Robinson et al., 2001). Overall, the revised, more accurate grid cells are somewhat larger than the older values. Revised cell areas are within about 1% of the former values, except equatorwards of 30° and polewards of 80°, where they differ by as much as 3%. It is worth noting that snow rarely covers the ground in the southern region and there is little land north of 80°.

Snow areas calculated using the new, revised cell areas are from 0.6% to 1.2% larger than those reported in earlier reports of this author. Percent differences are larger in the mid spring through mid fall, though given less snow cover during this interval, areas are larger in the winter (as much as 0.30 million sq. km.) than in summer (0.05 million sq. km.)

4. SNOW COVER CLIMATOLOGY

The mean annual Northern Hemisphere snow cover extent is 25.6 million square kilometers. This includes snow over the continents, including the Greenland ice sheet. The area covered by snow ranges from a January maximum of 46.8 million sq. km. to 3.6 million sq. km. in August (table 1). Snow covers more than 33% of lands north of the equator from November to April, reaching 49% coverage in January. In mid-winter, approximately 60% of the continental cover lies in Eurasia. Only portions of glaciers and the Greenland ice sheet remain snow covered throughout the year.

From year to year, January snow cover may vary by 8 million sq. km. October cover has varied by 13 million sq. km. and April by over 7 million sq. km. Less extensive July cover has varied by 5.5 million sq. km., however there remains some uncertainty as to whether the more extensive cover mapped in the 1970s is real or the result of mapper inexperience (subsequently minimized through training and higher-quality imagery). Summer cloudiness in the high latitudes makes it difficult to distinguish clouds from snow covered ground. Monthly standard deviations range from 1.0 million sq. km. in August and September to 2.7 million sq. km. in October. They are generally just below 2 million sq. km. in non-summer months.

	Yrs	Mean	Std. Dev	Min (yr)	Max (yr)
Jan	36	46.8	1.5	42.1 (81)	50.1 (85)
Feb	36	45.8	1.9	42.9(95,02)	51.4 (78)
Mar	36	41.0	1.9	37.3 (90)	44.5 (85)
Apr	36	31.5	1.8	28.3 (68)	35.7 (79)
May	36	20.6	1.9	16.7 (68)	24.4 (74)
Jun	35	11.1	2.1	7.4 (90)	15.8 (78)
Jul	33	5.0	1.4	3.2 (02)	8.7 (67)
Aug	34	3.6	1.0	2.3 (68)	5.8 (67,78)
Sep	34	5.7	1.0	4.0 (68,90)	8.0 (72)
Oct	35	18.3	2.7	13.1 (88)	26.3 (76)
Nov	37	34.1	2.1	28.6 (79)	38.7 (93)
Dec	37	43.4	1.9	37.8 (80)	46.3 (85)
Ann	33	25.6	1.0	23.4 (90)	27.6 (78)

Table 1. Monthly and annual climatological information on Northern Hemisphere snow extent between November 1966 and December 2002. Included are the numbers of years with data used in the calculations, means, standard deviations, and extreme maximum and minimum values and years of occurrence. Areas are in millions of sq. km. 1968, 1969,1970 have 1, 6, and 5 missing months respectively, thus are not included in the annual (Ann) calculations.

Maps depicting monthly climatologies may be viewed at the Rutgers Climate Lab snow web site (http://climate.rutgers.edu/snowcover). This site also includes individual weekly and monthly maps, and maps showing monthly anomalies from November 1966 through June 2000. Monthly areas for the hemisphere and for Eurasia and North America are also posted, along with information on how to ftp weekly areas and the weekly and monthly gridded products.

5. SNOW COVER VARIABILITY

Snow cover was more extensive in the first 20 years of the satellite record than during the past decade (figure 3). Between 1967 and 1987, annual means of snow extent fluctuated around a mean of 26.1 million square kilometers. An abrupt transition occurred in 1986 and 1988, and since 1988 the mean annual extent has been 24.6 million sq. km. Means of these two periods are significantly different (T test, $p < 0.01$). Monthly anomalies from the long-term mean are most often less than 3 million sq. km., however on occasion they range to 4 and 5 million sq. km., with October 1976 having a positive anomaly of 8.3 million sq. km. What appeared to be a gradual rebound from low extents in the late 1980s and early 1990s culminated in 1995. Since then, values have fallen back to those previously observed between 1988 and 1994.

Recent decreases in snow extent are large during the late winter to early summer, while fall and early-mid winter extents show no statistically significant change. For example, April snow cover across both continents was more extensive in the 1967 to 1987 period than from 1988 to 2002. The tendency towards less late-season cover in recent years begins in February. During 8 of the first 20 years of record, February snow extent exceeded the January value. This has occurred only once in the past 16 years.

6. 2002: A YEAR OF EXTREMES

While the annual snow extent over Northern Hemisphere lands was close to average in 2002, most individual months were anything but average. The mean annual Northern Hemisphere snow cover extent was 25.4 million square kilometers, just 0.2 million sq. km below the long-term mean. The area covered by snow in 2002 ranged from 46.9 million sq. km. in January to 2.7 million sq. km. in August. Near record low snow extents were observed in February and March 2002, and a record low was reached in July. The former two months ranked 3rd and 2nd lowest, respectively, based on 36 years of observations dating back to 1967. A completely different picture emerged late in 2002, with October, November and December each ranking among the top 5 highest over the satellite era. The October positive anomaly of 5.2 million sq. km., 28% above average, is the second largest anomaly in terms of absolute snow area on record for any month since observations began in November 1966. The widely different picture from winter to fall is illustrated in figures 1 and 2, which show anomaly maps for February and October 2002.

Anomalies of Eurasian and North American snow extents were not always in synch during 2002. January cover was extensive in Eurasia but low in North America. Both were low in February, but the January pattern was reversed in March. The fall snow season began early in Eurasia but late in North America. Both continents had extensive October and November covers, while December cover was a record maximum in Eurasia and the 6th lowest on record over North America.

7. CONCLUSIONS

The NOAA/NESDIS weekly snow map series has proven extremely valuable toward enhancing our understanding of both snow cover kinematics and synergistic relationships between snow and other climate variables. As first reported in 1990 (Robinson and Dewey, 1990), snow cover since the late 1980s continues to be less extensive than during the vast majority of the earlier satellite era. The decrease is concentrated from late winter to early summer, and is observed on both Northern Hemisphere continents. As reported in an earlier study (Robinson et al., 2001), a striking inverse relationship between annual snow and surface air temperature anomalies over continental regions of ephemeral snow cover is noted on annual and seasonal bases.

Continued kinematic and dynamic investigations should benefit greatly from what is now an over 35 year dataset of hemispheric snow extent derived from visible imagery. Those interested, may evaluate frequently-updated weekly and monthly data and analyses posted on the Rutgers Climate Lab snow web site listed previously in this paper. Hemispheric satellite microwave-derived estimates of snow extent and regional estimates of snow cover extent and depth based on station observations will soon be added to this site.

8. ACKNOWLEDGMENTS

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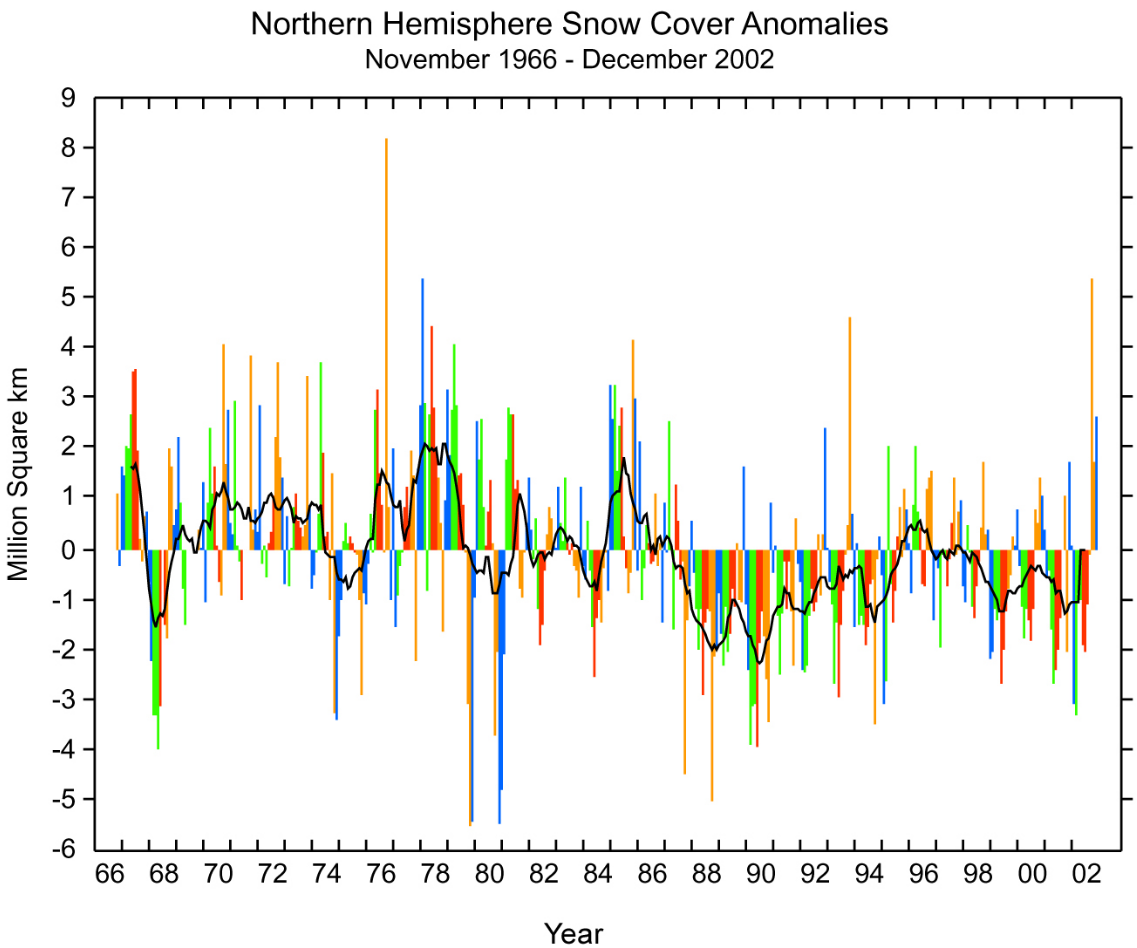

Figure 1. Anomalies of monthly snow cover extent over Northern Hemisphere lands (including Greenland) between November 1966 and December 2002. Also shown are twelve-month running anomalies of hemispheric snow extent, plotted on the seventh month of a given interval. Anomalies are calculated from NOAA/NESDIS snow maps. Mean hemispheric snow extent is 25.6 million sq. km. for the full period of record. Monthly means for the period of record are used for 9 missing months between 1968 and 1971 in order to create a continuous series of running means. Missing months fall between June and October, no winter months are missing.

February 2002 Snow Cover Departure

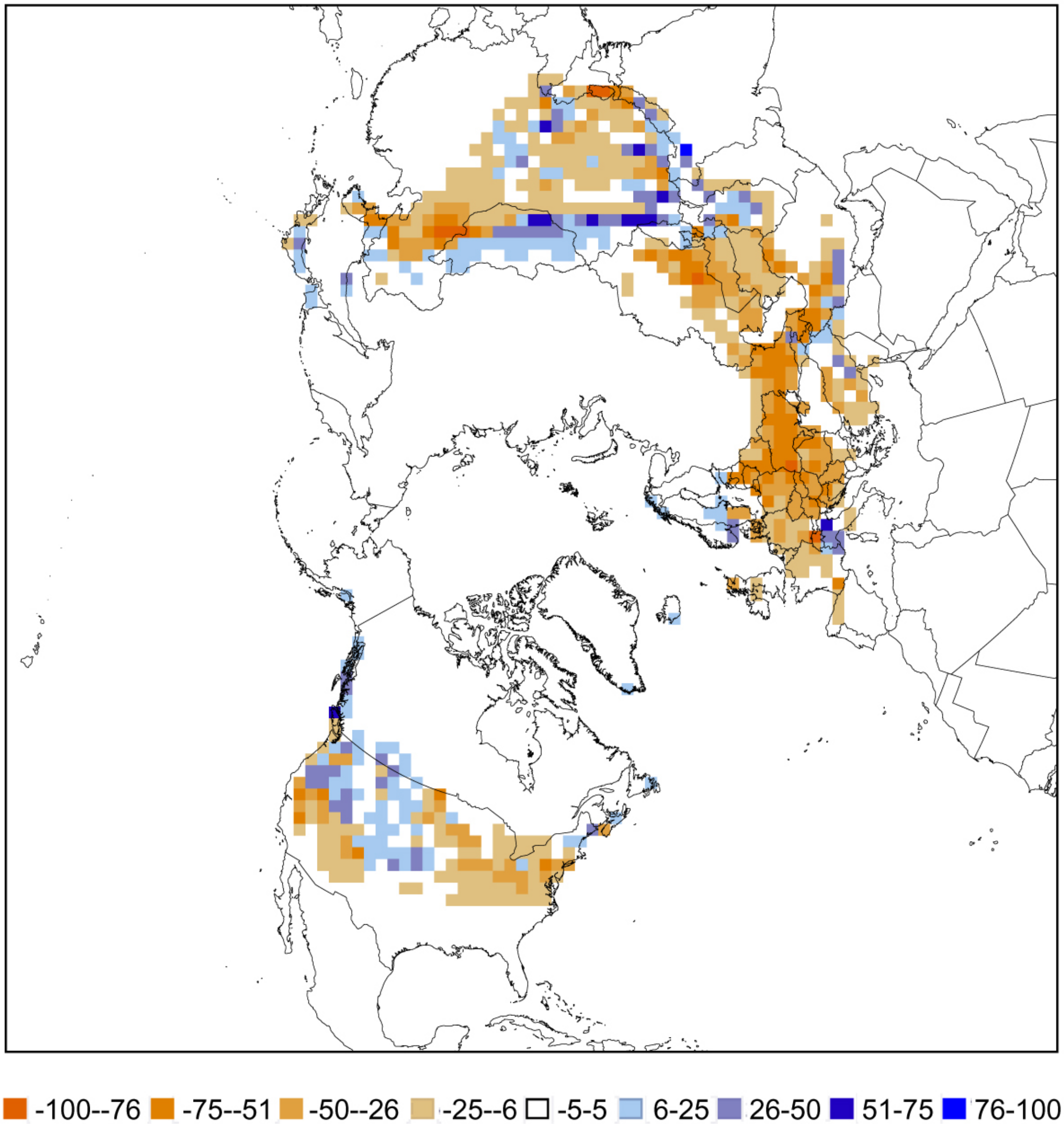

Figure 2. February 2002 monthly snow extent anomalies with respect to climatology maps covering the period November 1966 to May 1999. Departures show differences in the percent frequency of cover between 2002 and the long-term mean. February 2002 and February climatology maps may be viewed at http://climate.rutgers.edu/snowcover.

October 2002 Snow Cover Departure

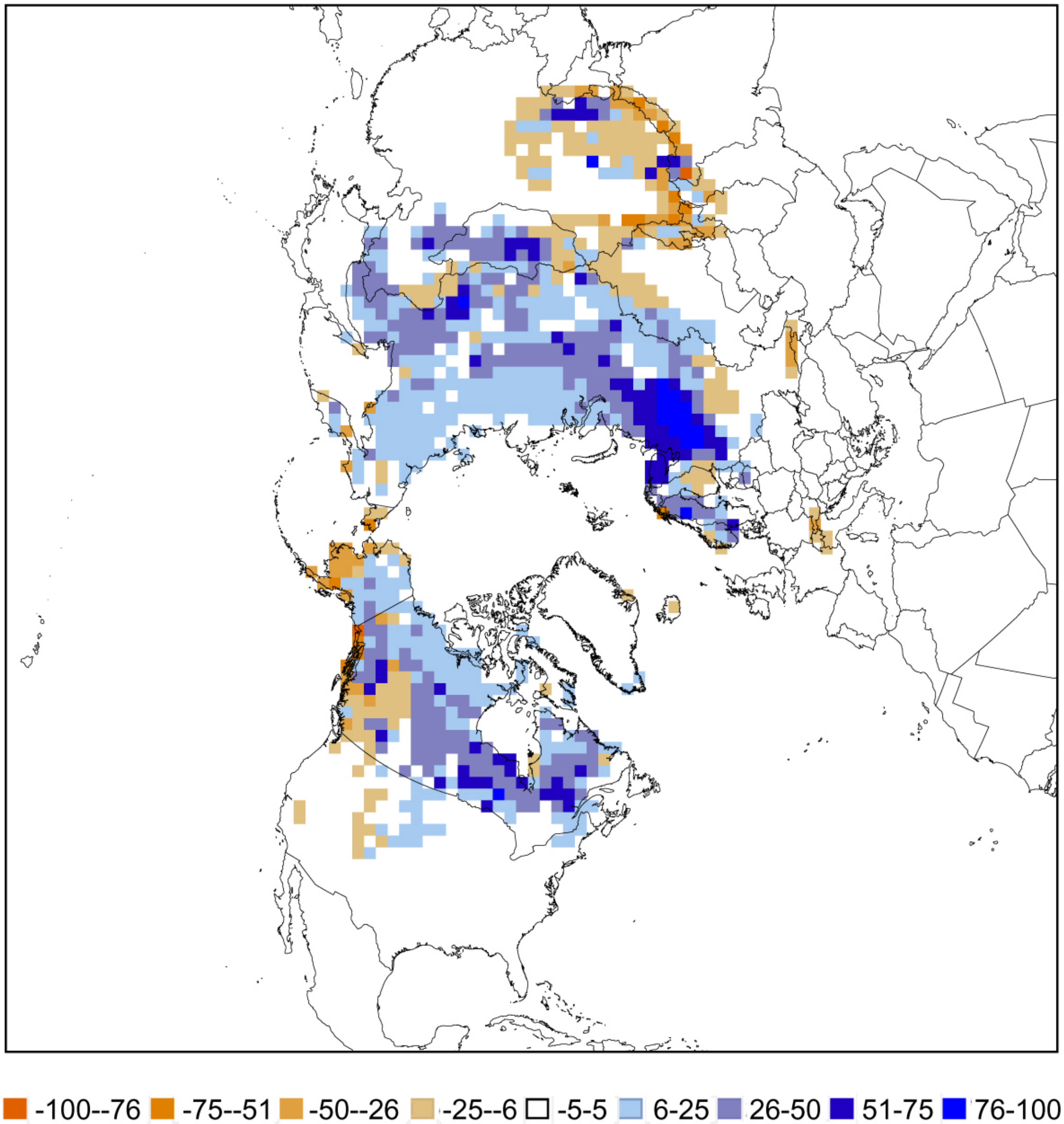

Figure 3. Same as figure 2, except for October 2002