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An Approach to Assessing Changes in Snow Cover
An Example for the Former Soviet Union

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ABSTRACT

The question of what are the most suitable indices of temporal change in snow cover conditions, and the most appropriate means for their detection is important in monitoring climate system changes. The extent and variability of seasonal snow cover is recognized to be an important climatic and hydrologic parameter. Trends in snow cover are also expected to serve as an indicator of any global climatic changes.

Passive microwave data afford the possibility of all-weather mapping of daily snow extent, and potentially water equivalent, with a spatial resolution ≈25-50km well suited for regional and global climate modelling. Newly-released snow depth data for stations in the former Soviet Union are described and for a ten-day average are compared with passive microwave-derived estimates. Possible sources of differences are discussed including problems related to wet snow, mountainous terrain and vegetation, as well as errors caused by the interpolation of station data used for validation.

INTRODUCTION

More than a century ago the Russian climatologist A.I Voeikov stressed the impact of snow cover on global and regional climate. Recent studies provide information to quantify this impact. According to Robinson *et al.* (1991) snow cover was 4 x 10^6 km^2 more extensive in the 1970s than in the 1980s. Year-to-year variations are even more pronounced.

A critical question for global change detection can be stated as follows: what measures are suitable for assessing change in key environmental variables and how can change(s) be determined? Seasonal snow cover is a major climatic and hydrologic variable as well as being quite unstable and readily modified by conditions in the overlying atmosphere. Snow is the most spatially extensive component of the cryosphere covering between about 41 x 10^6 and 50 x 10^6km^2 of the Northern Hemisphere continents at maximum extent in January or February (Robinson *et al.*, 1991). Taking into account the Southern Hemisphere and sea ice, Kotlyakov and Krenke (1982) estimated that 6% of the Earth is under a permanent snow cover and another 15% (not simultaneously) is under seasonal snow cover; this totals 105 x 10^6 km^2. The annual average value is about 57 x 10^6 km^2.

Snow melt provides a large fraction of the water for irrigation, hydroelectric power generation and public consumption in many northern hemisphere midlatitude and subtropical river basins. Steppuhn (1981) estimates that snow melt is the source of one-third of global irrigation water. Snow cover also provides the basis for winter recreational activities that are a major source of revenue in many mountainous regions. Conversely, major costs are associated with snow clearance or control on highways and in urban centers (Colbeck *et al.*, 1979).

For climatological and hydrological purposes, four characteristics of snow cover are important: extent, depth, and water equivalent of the snow pack, and surface albedo or reflectivity. Monitoring by satellite of northern hemisphere snow extent has a 20-year history (Wiesnet *et al.*, 1987; Lucas and Harrison, 1990) but there are longer and more detailed data sets of surface observations of various types that provide additional information. Station records include observations of snowfall amount at synoptic weather stations and depth of snow on the ground (possibly including data on snow water equivalent) at synoptic and climate stations. Numerous such daily records exist in national data bases (Barry, 1986; Barry and Armstrong, 1987) but there are no comprehensive archives and many of the necessary station histories are poorly documented or unavailable, necessitatingintensive quality control work (Robinson, 1989). Other ground survey records are also available and these are examined below. At present, only mean albedo information is available for land areas; there are no products on a monthly or more frequent basis

(Robinson and Kukla, 1985).

This paper discusses the problems of using various types of satellite remotely sensed and surface data, individually and in combination, to address questions of change detection relating to snow cover. The data concerned are for areas in the former Soviet Union (FSU), where several new sources of data are now becoming available. We consider first the definition of suitable parameters for change detection using various types of observation. The data types and their spatio-temporal characteristics are then discussed. Examples are given for several of the major types of data, of the accuracies potentially available and of inherent uncertainties. Finally, the relationships between changes in snow cover and climatic variables are discussed.

INDICATORS OF CHANGE IN SNOW COVER

Up to now, changes in snow cover have been identified only in terms of hemispheric or continental extent as mapped by visible and infrared satellite sensing (Robinson *et al.*, 1991). However, there are many possible change indicators. Figure 1 presents a schematic view of a seasonal snow cover and identifies a number of parameters that can be analyzed from surface and/or remote sensing observations. The primary ones refer to a change in the date of the beginning or end of continuous snow cover, assuming some appropriate operational definition of temporal continuity at a site, or over a small area. Over a more extensive region, poleward or altitudinal shifts of snow line on a specified date, or in mountain areas changes in the 'climatic snowline' (Green, 1975) can be mapped (Pfister 1985; Maisch, 1987, Krenke, *et al.* 1991, for example). The duration of snow cover combines the start and end dates, but changes in duration might obscure the seasonal emphasis of a temperature and energy budget change. Temporal outliers (first snow cover, early summer snow events) from the main snow season might also be pertinent in some climatic regimes. The timing of peak accumulation and the snow water equivalent at that date provide different climatic indicators, representing primarily winter precipitation conditions, the total accumulation in the case where temperatures average below freezing.

Snow cover extent changes are readily identifiable from frequent surface or satellite observations whereas information on peak accumulation requires frequent snow pack depth and snow water equivalent (SWE) measurements. Surface observations of SWE are necessary for accurate data although airborne gamma radiation measurements of SWE are made operationally in central Asia (Getker and Shentsis, 1983) and the United States and Canada (Carroll and Carroll, 1989). Infrared sensors can provide information on the melting state of the snow surface (Rott, 1987). Together, this gives the possibility of establishing the date of the maximum SWE and the extent of melting snow which is of primary importance for the hydrological models. Passive microwave remote sensing is capable of giving useful estimates of the large-scale (ca. 50km) spatio-temporal variability of SWE in dry snow conditions. More subtle change indicators might include the frequency of winter melt events or the timing of initial spring melt. Such events are readily detectable from passive microwave data (Anderson, 1987; Walker and Goodison, 1993) whereas site records give only localized information that may not reflect conditions over a wide area. This problem concerns all aspects of site data and it is discussed further below in the context of data interpolation/extrapolation.

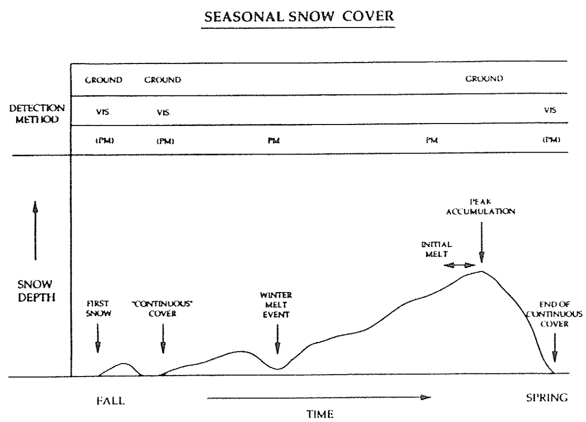

Figure 1. Schematic illustration of seasonal snow cover showing parameters that can be analyzed from surface and/or remote sensing observations.

Consideration of the possible types of change in a seasonal snow cover, as described above, illustrates the great variety of information potentially available and the potential difficulties created in using a single index.

DATA TYPES

Satellite remote sensing

1. NOAA-NESDIS Weekly Northern Hemisphere Snow Cover Charts

Since 1966 visible images from NOAA polar orbiting satellites have been used to map Northern Hemisphere snow cover on a weekly basis (Matson, 1985). Analysis of these charts suggests that they best depict the extent of snow cover on about day 5 of each week (Robinson, 1993). Transient snow covers may be undetected and mapping is less reliable in autumn and heavily forested areas (Wiesnet *et al.*, 1987). Subsequently, these charts have been digitized as to presence/absence of snow for the National Meteorological Center (NMC) grid with cell sizes of 16,000 to 42,000 km^2 (Matson, 1985; Matson *et al.*, 1986). Recent examination of the updated record of snow extent by Robinson *et al.* (1991) has uncovered discrepancies introduced by changes in the cell coverage (land mask) used in the area calculations and a change in the procedure used to determine average monthly extent since 1981. However, these changes do not affect the areas in the FSU currently being discussed.

2. Passive microwave data

Microwave energy emitted from the surface of the earth has been measured continuously since June 1987 by the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) which provides data at four separate frequencies (19.4, 22.2, 37.0 and 85.5 GHz) each for horizontal and vertical polarization except 22 GHz which has only a vertical polarization channel (Weaver *et al.*, 1987). (From 1978 to 1987 similar data, but for different frequencies, were collected by the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR). SSM/I coverage is global and frequent, at least daily for locations above 43 degrees latitude, and once every two to three days for those areas where snow might be expected at latitudes below 43 degrees.

When snow covers the ground, some of the microwave energy emitted by the underlying soil is scattered by the snow grains. When moving from snow-free to snow-covered land surfaces, a sharp decrease in emissivity is often a clear indicator of the presence of snow. The amount of scattering is related to both the amount of snow (number of grains) and the specific measurement wavelength of the sensor. The microwave scattering response continues until a saturation depth which is a function of wavelength. Thus, the maximum depth that can be sensed using current techniques is approximately 1.0 to 1.5 m. Algorithms have been developed which indicate the presence of snow and compute snow water equivalent, or snow depth given an assumed density (Chang *et al.* 1981; Chang *et al.* 1987a and 1987b; Kunzi *et al.* 1982; Hallikainen and Jolma, 1986; MacFarland *et al.* 1987; Goodison, 1989; Aschbacher, 1989; Josberger *et al.* 1989; Rott *et al.* 1991; Grody, 1991).

Passive microwave remote sensing offers several advantages over visible-band data. It allows data collection in nearly all weather conditions and during darkness, and also provides the potential to compute snow water equivalent and to detect melt (Kunzi *et al.* 1982; Foster *et al.* 1984; Rott, 1987). These additional variables comprise important input to energy budget, hydrologic, and global circulation models.

There are also disadvantages to the passive microwave data. The resolution is coarse when compared to that typically available from visible-band sensors (Rott, 1987). Resolution depends on the channel frequency and is approximately 25-30 km for those channels used in the snow cover algorithms. In addition, the mapping application of passive microwave has been limited to dry snow conditions. Once liquid water is present on the ice grains, the snow surface becomes a strong emitter with a signal similar to bare ground. However, recent work (Walker and Goodison, 1993) describes a method to discriminate areas of wet snow from areas of snow-free land in open non-forested regions. If the snow refreezes, it again become "visible" to the microwave sensor.

Another problem results from the fact there may be objects which are primarily emitters which extend above the snow cover, such as dense coniferous forests. The emission from such surface features will tend to reduce the scattering component contributed to the total signal by the snow on the ground, thus indicating a lesser amount of snow cover than is actually present. Finally, there are complications which result from the snow structure itself. The amount of microwave scattering is not only dependent on the number of grains, but is also proportional to the size of the grains. However, for regional scale studies, it appears that only the mean grain size may be required and not the detailed layer by layer structure of the snow cover (Armstrong, *et al.*, 1993).

Few snow products are currently available from passive microwave data. Monthly charts of Northern Hemisphere continental snow extent have been produced from SSMR data by a team of NASA scientists (Chang *et al.*, 1990). This is the only such time series available to date, and covers the interval from November 1978 through August 1987. A single algorithm is used to estimate snow depth on a 0.5° x 0.5° grid. Monthly values are averages of depths reported for a given grid in the five or six pentad charts centered in a given month (SMMR data are gathered every other day and three of these passes are used for each pentad chart; there is a one day gap between each pentad). If the average is ≥2.5 cm the cell is considered snow covered all month. Robinson

(1993) notes that the 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 corresponding areas on the NOAA weekly charts for the nine years of coincidental estimates. Test products are being developed at NSIDC using SSM/I data and the application of the Goodison (1989), Rott *et al.* (1991), and modified Chang et al. (1987b) algorithms.

Surface observations for the former Soviet Union

1. First-order weather station data

Snow data are contained within the daily meteorological observations made at first order weather stations. Snowfall is collected in precipitation gauges of the Tretyakov design with a wind shield (Groisman *et al.* 1991); the catch is melted and registered as liquid water equivalent. Depth of snow on the ground is also measured by permanent stakes; if snow covers at least half of the ground visible from the station, an average depth is determined for the stakes. A meteorological data set including records of daily snow depth at 284 stations in the FSU for various periods up to 1984 is available from the National Climatic Data Center, Asheville, NC (Figure 2). They are currently in station order (one data record is one station through the period of measurement). These data will be valuable for change detection using time series analysis by station or region. More than 150 sites have record lengths of 50-60 years with some sites being continuous since the 1870s. There are also similar measurements at some 2,000 stations that are not yet in a form suitable for international exchange. This data set has the potential for validation and integration with satellite remote sensing data. However, the data must first be reformatted to synoptic order (all stations for one time). In addition for use with SSM/I data, which began in 1987, this data set must be updated from 1984 to the present.

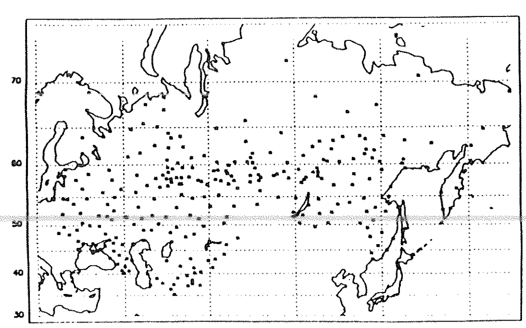

Figure 2. Map of first-order stations in the FSU for which daily snowdepth records are available through 1984.

2. Hydrometeorological station data

First-order hydrometeorological stations and secondary posts (numbering approximately 2,000) measure snow depth at permanent stake locations. The data provide 10-day mean depths, the number of days in the month with snow cover and a characterization of the site (open, closed, mixed). In addition snow surveys are conducted along transects 1-2 km in length with an average frequency of every 10 days. There may be one to six transects in the vicinity of the hydrometeorological stations. The snow cover reports are published in "Meteorologicheskiy Ezhemesyachnik" (Meteorological Monthly) for 38 regions of the FSU.

3. Local field studies

The data sets described above represent the entire former Soviet Union. Additional snow measurements are made at specific field study locations. For example, data for 1986-1990 from the north Caucasus (43°N, 42°E; 89 stations) and the Valdai region (57°N 33°E; 39 stations, 1986-1990) have been provided for the present collaborative project between the Institute of Geography, Moscow and the University of Colorado at Boulder. These data sets typically cover only limited geographic areas, as small as 25-50km^2 in the case of Valdai. With respect to SSM/I data, their primary application would be to analyze within-pixel variation of measured values. These data are intended primarily for hydrologic purposes and are in station order with irregular observation dates. Because of this they are of limited use for remote sensing validation. For example, although during the 1988-1989 winter measurements were made at the 39 stations in the Valdai on 33 individual dates, the maximum number of stations reporting on any one day was 12, and typically there are only 3 or 4 reports per station calendar day.

COMPARISON OF PASSIVE MICROWAVE AND STATION DATA

An important application of station data is in the analysis and validation of remotely sensed data. The general problem of intercomparing satellite and station data is illustrated in Figure 3. The passive microwave data products are gridded to a cell size of 40 km x 40 km. The available station records are irregularly distributed with respect to the grid array although interpolated values, weighted according to distance and elevation can be derived from them (Hardman and Armstrong, 1993). Transect measurements provide spatial sampling over a short distance (≈ 1-2 km in length) and are typically available for both open and forested terrain in the same general area. If the percentage of forest-covered area can be determined for each passive microwave grid cell, it will at least be possible to determine an appropriately-weighted average SWE value for each cell containing such transect observations.

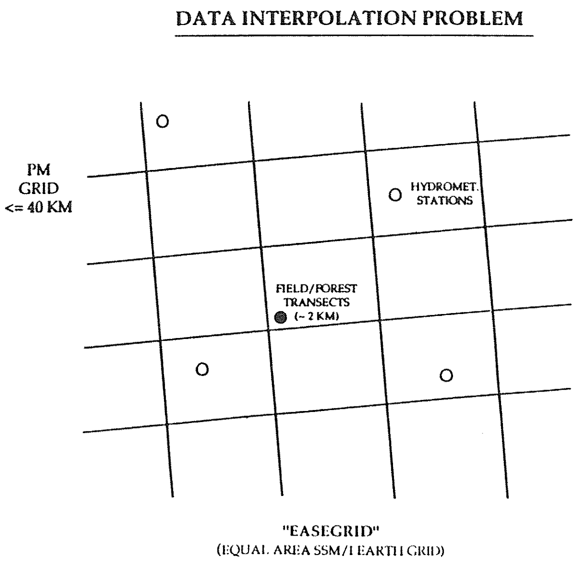

Figure 3. Schematic illustration of SSM/I pixels, stations and snow transects.

In the example presented here, average snow depth for the period February 1-10, 1989 is derived from DMSP SSM/I passive microwave data using a prototype algorithm currently being tested at NSIDC (based on the 19GHz and 37GHz horizontal SSM/I channels). The SSM/I grid resolution is 40 km in an azimuthal equal-area projection and based on the Equal Area SSM/I Earth Grid (EASE-GRID) under development at NSIDC. These data are compared to point measurements which have been interpolated to the SSM/I grid using inverse distance weighting.

The ability of point (station) data to depict the snow extent boundary is limited at best, and is particularly poor in locations where station data are sparse. The maximum snow extent will be some spatial response to the distance parameters used in the interpolation scheme. However, for comparison with algorithm-derived snow depth and water equivalent, station data play an essential role. Figures 4 (station data) and 5 (SSM/I data) show an example of this comparison for the complete area of coverage. (Note: Original figures are produced in color but are reproduced here in black and white to reduce cost.) For the period 1-10 February, 1989 the actual snow cover extends beyond the southern (political) boundary of the FSU data set. The SSM/I data indicate snow cover extending below 30°N in some locations (and show good agreement with the NOAA/NESDIS Northern Hemisphere Snow Boundary Map which is based on visible satellite data for that period). Analysis of data for February 1989 indicates that in some locations the depths represented by the two methods are not in good agreement. For example, deeper snow is consistently indicated by the station data (Figure 4) centered in the region of 60°E between 60 and 75°N (Ural Mountains) while the SSM/I image (Figure 5) indicates a distinct region of shallow snow. Further investigation will seek to determine whether this response can be related to the influence of the local topography or vegetation cover. In contrast, the SSM/I-derived snow cover indicates significantly greater snow depths in the northwest quadrant of the FSU compared to station data. However, station data are very sparse in this region and therefore may not be considered a valid source of data for comparison with the SSM/I. This is the region of the Siberian Plateau and the Verkhoyansk and Cherskiy Mountain Ranges which are 500 to 1500m higher in elevation than the Siberian Plain to the west, and as such is a logical location for increased snow amounts.

For optimal results, quantitative comparisons between station and SSM/I data should focus on areas of maximum station density, where the spatial frequency of the reporting stations at least approximates the spatial resolution of the SSM/I grid. In the example shown in Figure 6 (43-60°N and 30-63°E) the density of point data generally meets this requirement. Figure 6 compares the algorithm output with the interpolated point data through the use of digital image subtraction and depth/frequency histograms. The SSM/I histogram indicates mean depths (x axis) of approximately 20 cm and a maximum of 60 cm while the surface data show a much greater range, with maximums of 80 to 100 cm. The difference histogram shows the general bias towards an undermeasurement by the SSM/I algorithm. In the northwest portion of the subtracted image the algorithm shows significant undermeasure while it shows a slight overmeasure north and west of the Caspian and Black seas. The region represented here is one of relatively uniform terrain and vegetation. Additional analysis will be required to determine the reasons for these differences in snow amounts.

CONCLUDING REMARKS

The question of what are suitable snow cover indices has only been briefly explored. At the present

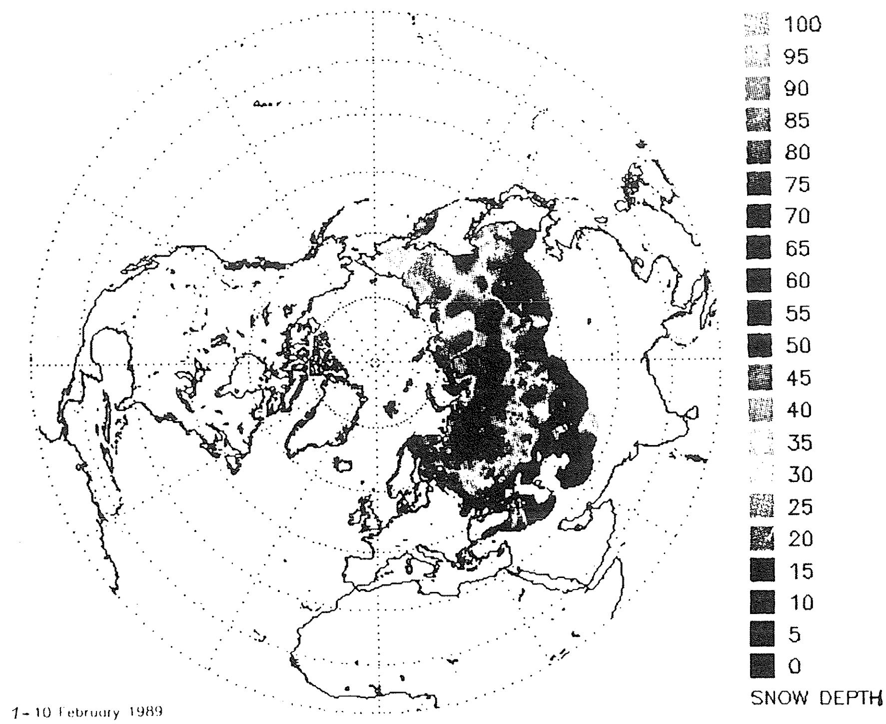

Figure 4. Snow depth (cm) for 1-10 February 1989 interpolated (with inverse distance-squared weighting) from station data for the FSU.

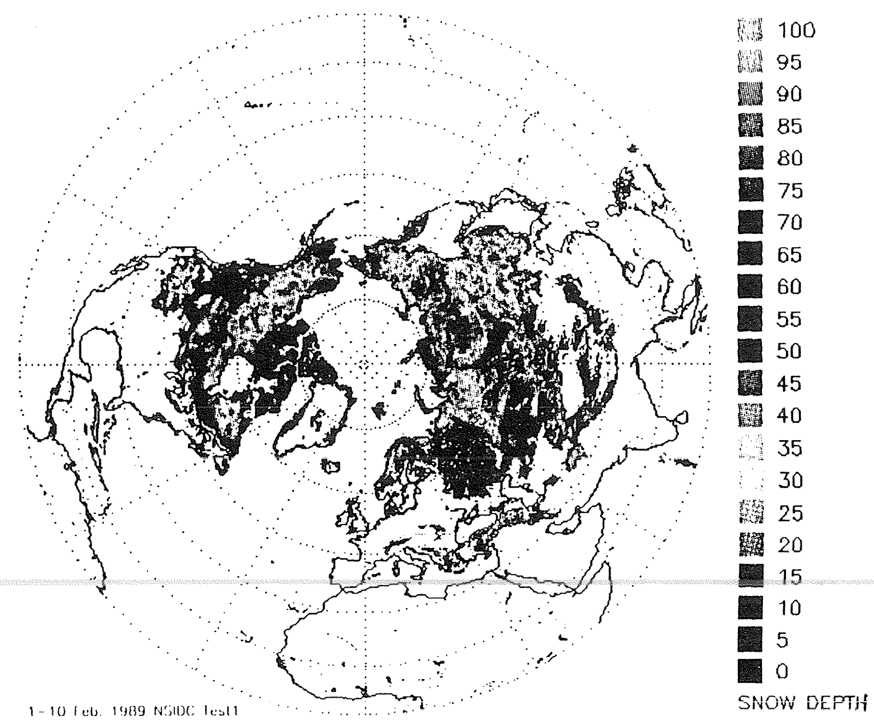

Figure 5. As figure 4, mapped from SSM/I passive microwave data.

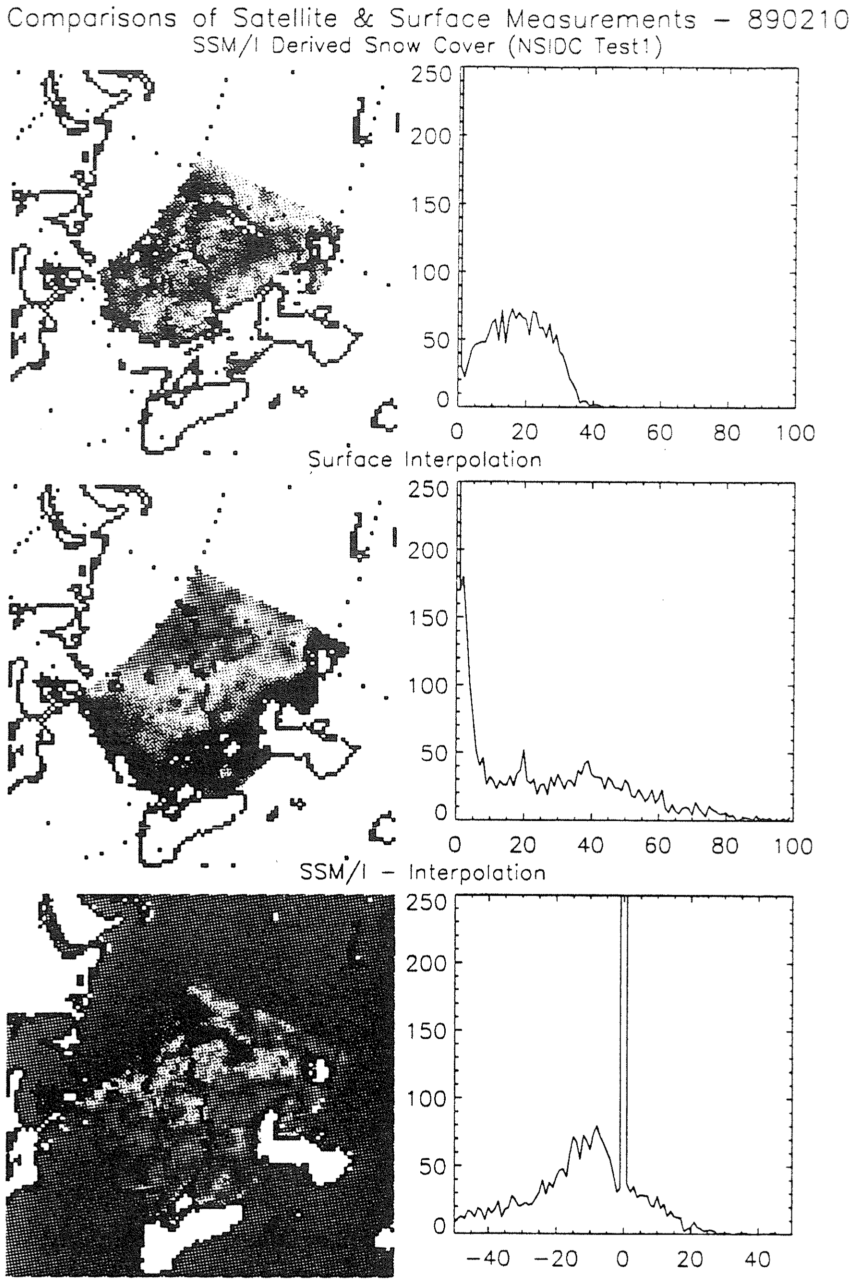

Figure 6. Snow depth (cm) for part of the FSU with a high-density station network and histograms of depth frequencies for (a) SSM/I-derived (b) interpolated station data and (c) difference data for (a)-(b).

time, data availability is a determining factor. Most continental- to hemishere-wide data refer only to spatial extent.

The currently available hemispheric data on snow cover provide only weekly estimates of extent and the digitized version is based on presence/absence values over a coarse resolution (1.0-2.0°) northern hemisphere grid. Passive microwave-derived estimates of global snow extent and depth are now becoming available on a daily basis. The key to their full utilization, however, is their comprehensive evaluation against station data including the development of appropriately weighted interpolation routines, and adjustments for topography and vegetation cover. The data from the FSU provide a valuable test set to address these issues. The expanded use of snow data to explore other indices of change in snowfall and snowcover conditions remains a challenge for the future.

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