A Seasonal Snow Cover Classification System for Local to Global Applications

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ABSTRACT

A new classification system for seasonal snow covers is proposed. It has six classes (*tundra, taiga, alpine, maritime, prairie,* and *ephemeral*), each class defined by a unique ensemble of textural and stratigraphic characteristics including the sequence of snow layers, their thickness, density, and the crystal morphology and grain characteristics within each layer. The classes can also be derived using a binary system of three climate variables: wind, precipitation, and air temperature. Using this classification system, the Northern Hemisphere distribution of the snow cover classes is mapped on a 0.5° lat × 0.5° long grid. These maps are compared to maps prepared from snow cover data collected in the former Soviet Union and Alaska. For these areas where both climatologically based and texturally based snow cover maps are available, there is 62% and 90% agreement, respectively. Five of the six snow classes are found in Alaska. From 1989 through 1992, hourly measurements, consisting of 40 thermal and physical parameters, including snow depth, the temperature distribution in the snow, and basal heat flow, were made on four of these classes. In addition, snow stratigraphy and texture were measured every six weeks. Factor analysis indicates that the snow classes can be readily discriminated using four or more winter average thermal or physical parameters. Further, analysis of hourly time series indicates that 84% of the time, spot measurements of the parameters are sufficient to correctly differentiate the snow cover class. Using the new snow classification system, 1) classes can readily be distinguished using observations of simple thermal parameters, 2) physical and thermal attributes of the snow can be inferred, and 3) classes can be mapped from climate data for use in regional and global climate modeling.

1. Introduction

Classification systems are common in many areas of science and engineering, and snow is no exception. It is standard to classify falling snow flakes using the system of Magono and Lee (1966), which is based on work by Nakaya (1954). Snow on the ground can be classified using systems presented by Sommerfeld (1969), UNESCO (1970), or the International Classification System of Snow on the Ground (Colbeck et al. 1992) or its predecessor, the Commission on Snow and Ice (CSI 1954). These classification systems are useful when describing snow at scales ranging from millimeters (snow grains) to centimeters (hand specimens), or slightly larger.

Classification systems are useful in two ways: first, they allow a complex description of character or form to be compressed into brief code (i.e., an ordinary dendritic crystal developed in one plane: P1e), and second, they allow the user to infer or extrapolate more information about the material than is actually measured. For example, once a snow flake is classified as form P1e, a Nakaya diagram (Nakaya 1954; Magono and Lee 1966) can be consulted to determine under what temperature and vapor saturation conditions the snow crystal formed.

Despite a considerable literature on the subject, there has been little comparable use of *snow cover* classification systems (*snow cover* is the blanket of snow that covers an area and may include both depth and extent). Table 1 contains 14 existing snow cover classification systems. For each system, the number of classes and the basis for the classification system are indicated. The number of classes ranges from 3 to 11; the basis ranges from geography and vegetation to snowshoe design. Publication dates in Table 1 conceal the fact that some of the systems are more than 70 years old; Formozov (1946) and Rikhter (1954) developed their systems in the 1920s and 1930s, but their work was not translated for many years. Their systems are the earliest systems of which we are aware, and it is not surprising they come from the Ukraine, Russia, and Siberia, where the seasonal snow cover has such a profound impact on daily life.

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TABLE 1. Historical seasonal snow classification systems.

Author(s)	Date	Basis	Classes	Equivalents
Formozov	1946	vegetation and ecological zones	tundra	tundra
			forest	taiga
			steppes and desert	prairie and ephemeral
			mountain	mountain
Roch	1949	mountain climate	maritime	mountain/maritime
			intermountain	mountain/alpine
			continental	mountain/alpine
Rikhter	1954	depth and duration	>70 cm	maritime and alpine
			50–70 cm	taiga and prairie
			30–50 cm	taiga
			10–30 cm	maritime, taiga, and prairie
			<10 cm	ephemeral
			10–50 cm, long duration	tundra
			mountain	mountain
Espenshade Jr. and Schytt	1956	depth and duration	Pacific coast	maritime and ephemeral
			Great Plains	prairie
			MacKenzie	taiga
			upper Ontario	maritime and ? [a]
			northern Great Lakes–St. Lawrence	maritime
			Labrador	deep taiga
			northern Arctic	tundra
			Ungava–Baffinland	tundra
			mountain	mountain
Gold and Williams	1957	depth	Arctic	tundra
		duration	prairie	prairie
		density	northern tree line	taiga
		hardness	freeze-thaw	maritime or ephemeral
		temperature	western and coastal mountains	mountain/maritime or alpine
Bilello	1957	density	interior Alaska and western U.S.	taiga, prairie, and mountain
	1969	change in density	Arctic	tundra
	1984		coastal	maritime and mountain
			miscellaneous	?
Benson	1959	temperature	dry snow facies	
(perennial snow)	1962	liquid water	percolation facies	
			wet snow facies	
			ice facies	
Benson	1967	climatic zones	Arctic	tundra
	1969		interior	taiga
	1982		maritime	maritime
			transitional	transitional
Potter	1965	depth	Arctic archipelago	tundra
		duration	MacKenzie and Keewatin	taiga and tundra
		political unit	British Columbia	maritime and taiga(?)
			prairie provinces	prairie
			N. Ontario, Quebec, Labrador	?
			S. Ontario, St. Lawrence, Atlantic provinces	maritime and ephemeral
Pruitt Jr.	1970	duration	tundra	tundra
	1984	depth	steppes	prairie
		density	taiga	taiga
		hardness	maritime	maritime
			mountain	mountain
Pruitt Jr.	1970	snowshoe design	Naskapi	?
			Bearpaw	maritime or ephemeral
			Athapaskan hex. weave	taiga
			Athapaskan square weave	extreme taiga
			3 cross pieces	?
McKay and Findlay	1971	vegetation zones	boreal forest	taiga
McKay	1972	time-density curves	subalpine forest	taiga/maritime
			Columbia forest	Alpine
			mountain forest	Alpine
			coastal forest	maritime
			taiga	taiga
			tundra	tundra
			aspen grove	Alpine

Table 1. (*Continued*)

Author(s)	Date	Basis	Classes	Equivalents
			prairie	prairie
			Acadian forest	maritime
			Great Lakes forest	maritime
Irwin	1979	trafficability	Arctic snow	?
		grain and crystal	woodland snow	taiga
		size and shape	late spring snow	maritime?
			crusted spring snow	maritime and ephemeral
			tundra snow	tundra
			temperate snow	maritime
McKay and Gray	1981	vegetation zones	tundra	tundra
			taiga and boreal forest	taiga
			grasslands and steppes	prairie
			mixed forest	?
			mountain	mountain

[a] ? indicates that the equivalent class in the new system is uncertain.

Existing seasonal snow cover systems (Table 1) see little use, perhaps because they are not sufficiently generic. Of these systems, the most widely recognized in the United States is that proposed by Roch (1949a,b) for avalanche prediction. He divided the mountainous areas of the western United States into maritime, intermountain, and continental for the purpose of characterizing the prevalence and type of avalanches that occur in each region. It is a geographically based system and primarily qualitative. Only recently have some of the snow characteristics in each class been quantitatively established (Armstrong and Armstrong 1987). But even with this improvement, Roch's system is of little practical use in dealing with general snow covers.

Most of the classification systems in Table 1 were proposed prior to the 1970s. In the early 1970s remote sensing from satellites became recognized as a powerful tool for delineating the areal distribution of vegetation and land cover, including snow. Older geographic methods of classification, identification, and mapping have been discarded in favor of this newer tool. Unfortunately, remote sensing of snow cover attributes has proved difficult. A recent review by Dozier (1992) indicates that other than extent, most snow cover attributes, such as water equivalent, grain size, depth, and strength, are difficult to measure remotely, and require using local algorithms. A need for old-style classification and mapping still exists, at least at a sufficient level to identify the correct local algorithm for a particular region. In addition, the existence of an applicable classification system allows properties that cannot be sensed remotely (like strength or stratigraphy) to be inferred.

In this paper, we propose a physically based classification system for seasonal snow covers. Each snow class is defined in terms of typical sequences of snow layers, the thickness and density of these layers, and the crystal morphology and grain characteristics within the layers. Lateral variability and, in some cases, the rate at which the attributes of the snow cover change with time, are also considered when determining the class. The system is based on observations we have made on snow covers in Alaska, but has been augmented with observations from other locations as well. Nomenclature and parts of older classification systems were adopted where appropriate, so it is really a composite rather than an entirely "new" system.

We believe our new system is more general and more globally applicable than the older systems. We think it also reflects basic natural groupings of snow cover characteristics. It is based on physical characteristics because these are of primary interest (and accessible for measurement) when someone digs a snow pit or uses remote sensing over a snow-covered area. Being based on observable properties as opposed to geographic location or local vegetation, our system can be used like snow grain and snow specimen classification systems to both describe and infer attributes of the snow cover.

One of the main attributes that can be inferred is the climatic regime that produced the snow cover. We recognize that the characteristics of snow layers and the sequence of layers comprising a specific snow cover arise from the winter climate of that location. We relate our snow classes to climate in a simple manner that allows use of standard weather or climate station data to infer the snow cover class, without the need for making snow pit observations. Maps of the distribution of our snow classes in the Northern Hemisphere, based on observed meteorological climatologies and vegetation, are presented. Since each snow class has representative densities, grain sizes, thermal characteristics, etc., the hemispheric snow maps can be used to describe the spatial distribution of snow properties relevant to many regional and global applications.

We see at least three general uses for these maps. First, they can be used in regional and global climate models (e.g., general circulation models; see Gates 1992) to improve the parameterization of snow cover. For example, winter heat loss from the ground and depth of freezing is controlled to a large extent by the snow cover. Using snow cover maps, and values of the bulk thermal conductivity for each class of snow cover, more realistic winter land–surface heat fluxes can be computed.

Second, the maps can be used to choose the correct local algorithm for deriving snow water equivalent (SWE) from satellite microwave brightness temperatures (T_B) (e.g., Chang et al. 1987). Efforts are under way to determine the annual distribution of SWE over the entire Northern Hemisphere using *Nimbus*-7 SMMR microwave data (Foster and Chang 1993). It is increasingly clear that T_B is affected by the stratigraphy and the texture of the snow as well as its SWE (Mätzler 1986; Hall et al. 1986; Sturm et al. 1993), and it is now recognized that considerable improvement in accuracy can be achieved if a local algorithm is used. The snow maps could be used to identify the appropriate algorithm. As an example, SWE of the *prairie* snow in the Ukraine may be more accurately determined using a *prairie* snow algorithm from Canada rather than relying on a general algorithm.

Third, the maps can be used to infer a whole range of information about the snow cover that cannot be remotely sensed and may be too detailed or time consuming to measure. For example, descriptions and measurements of physical parameters (thermal conductivity, air permeability, grain size distribution, strength) of *taiga* snow that we have made in Alaska (Sturm and Johnson 1991, 1992; Sturm and Holmgren 1993) can be extrapolated to other regions where *taiga* snow cover is found, such as Siberia.

During the process of mapping and attempting to validate the maps, we discovered that the widely distributed set of stratigraphic and physical measurements needed to check the mapping algorithm does not exist. As a step toward remedying this problem, simple methods of discriminating one snow cover class from another (generally requiring little or no expertise) are explored and shown to be practical.

2. A new classification system

The seasonal snow cover, the blanket of snow that covers an area during one or more periods of the winter but melts away in the spring (as compared with perennial snow, which does not completely melt), has characteristics of both depth and extent. It is completely analogous with the concept of "formation" used in sedimentary geology. Snow cover properties derive not only from the nature, size, and bonding of the individual grains in each layer of snow [which would fall under a classification system like that of Colbeck et al. (1992)], but also from the sequence of layers, their interaction, and the way they vary laterally. Layer and grain characteristics are time dependent and change in a particular way in a particular snow cover, depending on the weather. Of course, it is the climate that ultimately determines the physical character of the snow cover through the temperature during and after deposition, the precipitation or condensation rate and character, and the wind history.

Based on the above definition, a seasonal snow cover classification system is the subdivision of all possible combinations of textures, layers, and lateral variability into groups with properties that have close affinity or are found to be recurrent in nature. We divide seasonal snow covers into six classes: *tundra*, *taiga*, *alpine*, *prairie*, *maritime*, and *ephemeral* (Fig. 1). A typical stratigraphic column is shown for each class (Fig. 2) and class characteristics are described (Table 2). Lateral variability of the snow cover and the rate at which the attributes of the snow cover change with time are also considered in the system, particularly for the *ephemeral* class.

We have chosen class names that we feel will be helpful in connoting the physical nature of the snow cover. For consistency, some of the names have been retained from older classification systems (*tundra*, *taiga*), but no longer require an association with a particular vegetation. For example, a *tundra* snow cover can exist even where there is no tundra, as long as the snow is thin, has few or no features due to melting, and is composed of layers of wind slab and depth hoar. Similarly, geographic names (*prairie*, *maritime*, *alpine*)

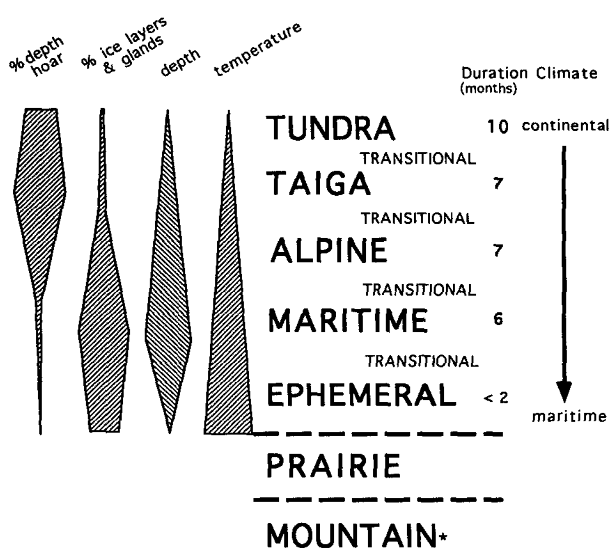

FIG. 1. Seasonal snow cover classes in the new system. Note that mountain (*) snow is a special designation for regions where the snow cover is highly variable.

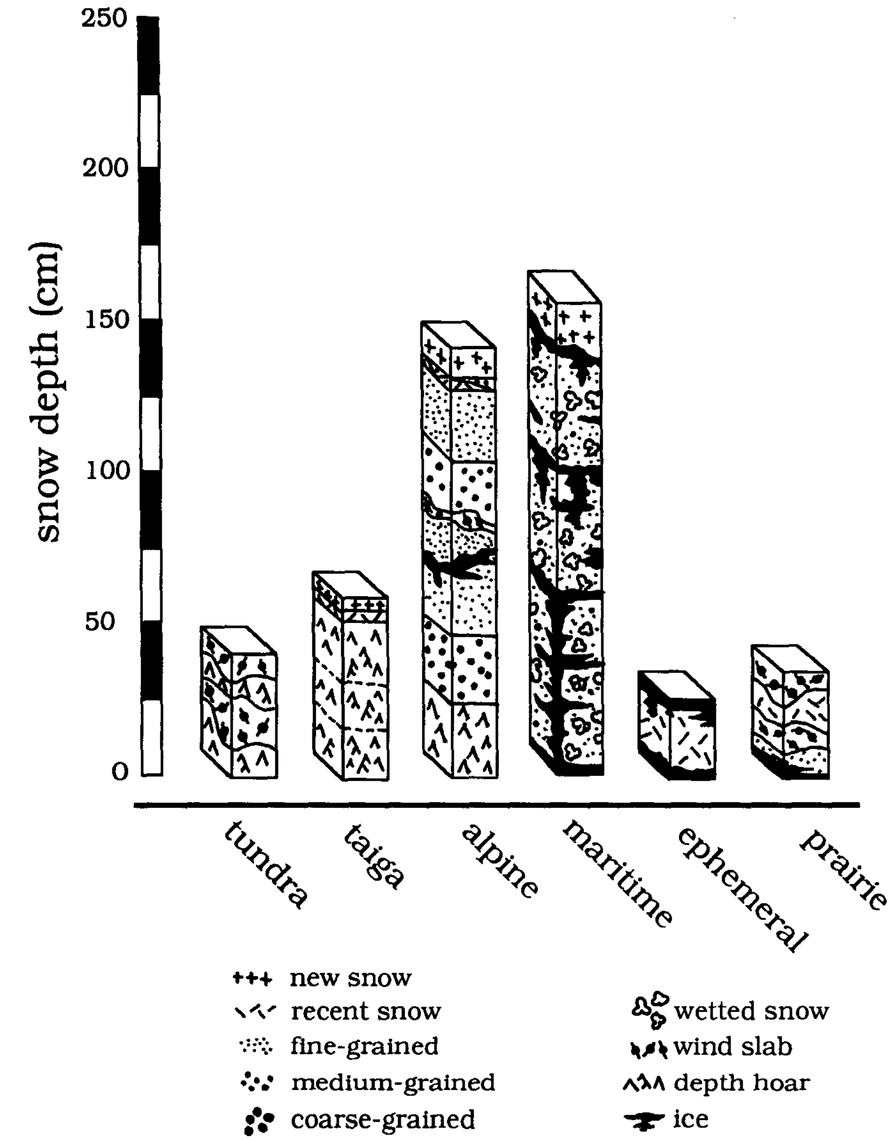

FIG. 2. The basic stratigraphic and textural attributes of each class of snow cover as they would appear in middle to late winter. Symbols follow Colbeck et al. 1992.

refer only to the physical characteristics of the snow cover, not where it is located. We recognize that the classes are gradational; therefore, snow covers with characteristics that are transitional between classes are possible, though in our experience the main classes are more common. Where possible, we have correlated our classes with those of the older systems (Table 1).

In common with many of the older systems, we have found it difficult to classify the snow cover of mountainous regions. Mountain snow covers have as their chief attribute a high degree of lateral or spatial variability. Wind turbulence over steep, complicated terrain and highly variable solar radiation distribution are the chief causes of this variability. As an example, in the mountains it is not unusual to find significantly different snow conditions on opposite sides of a ridge. In such cases it would be possible to classify the snow on each side of the ridge into one of the six snow classes, given sufficiently detailed snow information. But since these data are rarely available, we instead recognize a *mountain* snow class or label that can be used to flag regions of high snow variability.

a. Data collection

We made a series of stratigraphic, textural, and thermal snow cover measurements for two purposes: first, to develop a dataset on which we could test various

TABLE 2. Snow class descriptions.

Snow cover class	Description	Depth range (cm)	Bulk density (g cm^{-3})	Number of layers
tundra	A thin, cold, wind-blown snow. Max. depth approx. 75 cm. Usually found above or north of tree line. Consists of a basal layer of depth hoar overlain by multiple wind slabs. Surface sastrugi common. Melt features rare.	10–75	0.38	0–6
taiga	A thin to moderately deep low-density cold snow cover. Max. depth: 120 cm. Found in cold climates in forests where wind, initial snow density, and average winter air temperatures are all low. By late winter consists of 50% to 80% depth hoar covered by low-density new snow.	30–120	0.26	>15
Alpine	An intermediate to cold deep snow cover. Max. depth approx. 250 cm. Often alternate thick and thin layers, some wind affected. Basal depth hoar common, as well as occasional wind crusts. Most new snowfalls are low density. Melt features occur but are generally insignificant.	75–250	no data	>15
maritime	A warm deep snow cover. Max depth can be in excess of 300 cm. Melt features (ice layers, percolation columns) very common. Coarse-grained snow due to wetting ubiquitous. Basal melting common.	75–500	0.35	>15
ephemeral	A thin, extremely warm snow cover. Ranges from 0 to 50 cm. Shortly after it is deposited, it begins melting, with basal melting common. Melt features common. Often consists of a single snowfall, which melts away, then a new snow cover reforms at the next snowfall.	0–50	no data	1–3
prairie	A thin (except in drifts) moderately cold snow cover with substantial wind drifting. Max. depth approx. 1 m. Wind slabs and drifts common.	0–50	no data	<5
[a]mountain	A highly variable snow cover, depending on solar radiation effects and local wind patterns. Usually deeper than associated type of snow cover from the adjacent low-lands.		no data	variable

[a] Special class.

ways of discriminating one snow class from another and second, to develop a tabulation of thermal, physical, optical, and radiometric properties for each class of snow. A few preliminary property values are listed in Table 2, and we are in the process of collecting measurements for all the snow classes; these results will appear in another paper.

The data were collected between 1989 and 1992 along a 1300-km transect from Prudhoe Bay to Valdez, Alaska (Fig. 3) (Sturm and Holmgren 1993, 1994; Sturm et al. 1993; Benson and Sturm 1993). Three major mountain ranges, the Coast Range, Alaska Range, and Brooks Range, run east-to-west across the transect, dividing it into distinct climatic zones (Searby and Branton 1973). In these regions *tundra*, *taiga*, *alpine*, *maritime*, *prairie*, and *mountain* snow covers develop in relatively close proximity to one another. Eight instrumented sites (Fig. 3) were established with one site in *alpine* snow, two sites each in *tundra* and *taiga* snow, two sites in *maritime* snow, and one in *mountain/maritime* snow (Table 3). The snow class was initially identified from field observations made in 1987 (Hall et al. 1991), and in consultation with C. S. Benson and G. Clagett, who have extensive experience with the Alaskan snow cover.

Hourly measurements at each site included: the temperature in the snow at 20 locations, the temperature at the snow–ground interface at 10 locations, heat flow at the snow–ground interface, solar radiation, snow depth, and the local meteorology. Snow temperature measurements were made with thermistors suspended above the ground in the autumn (Fig. 4) and buried by natural snowfall. This technique minimized the thermal disturbance and is described by Sturm (1991) and Sturm and Johnson (1991).

The data consist of 40 measured time series (4000 to 6000 data points per series) per winter per site. An additional five time series of calculated parameters (bulk vertical temperature gradient, temperature gradient at the base of the snow, vapor pressure gradient in the snow, temperature profile curvature, and spatial average of the snow–ground interface temperature) were generated from the observed data. From these, average winter values were calculated. To calculate averages comparable between sites where the snow cover formed and melted at different dates, a "standard win-

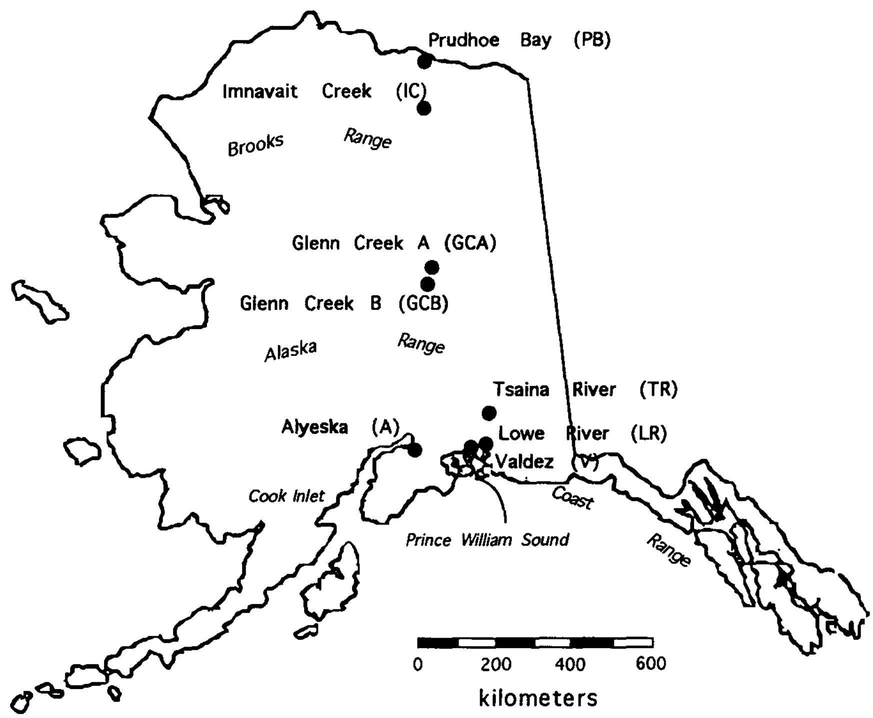

FIG. 3. Data logger and snow pit site locations in Alaska.

ter period" was defined. It covered approximately 180 days, extending from the first sticking snow until just before the onset of spring melt. The result was 45 winter average values for each site. Since the sites ran three winters and there were eight sites, there were 24 cases for analysis.

Snow depth, density, stratigraphy, and grain size were measured each time the sites were visited, approximately every six weeks. Measurements were made in trenches 5-m long in order to survey the lateral variability of each layer and to make multiple measurements of density and stratigraphy. Grain size was estimated from disaggregated samples using a stereo-microscope and gridded card. Snow grain and crystal forms were observed at the same time. During the course of the project 110 trenches were surveyed and measured. Thermal conductivity and air permeability measurements were made in selected trenches.

b. *Discriminating classes using index parameters*

Previous snow cover classification and mapping have suffered from the lack of available data. Classification requires traditional snow pit observations that are time consuming to make and require special expertise. Here we present a simpler method of identifying the snow

TABLE 3. Site locations, snow cover types, and thermistor configurations.

Site	Latitude	Longitude	Snow type	Vegetation	Thermistor Horizontal spacing	Thermistor Vertical spacing
Prudhoe Bay	70°18′N	148°33′W	tundra	wet sedge meadow	10 thermistors at 15 cm	10 at 5 cm
Imnavait Creek	68°37′N	149°12′W	tundra	dry sedge tussocks	10 thermistors at 15 cm	10 at 5 cm
Glenn Creek A	64°57′N	147°35′W	taiga	black spruce	10 thermistors at 15 cm	10 at 7.5 cm
Glenn Creek B	64°57′N	147°35′W	taiga	birch and white spruce	10 thermistors at 15 cm	10 at 7.5 cm
Tsaina River	61°12′N	145°30′W	alpine	white spruce	10 thermistors at 15 cm	10 at 25 cm
Lowe River	61°07′N	145°49′W	maritime	spruce/cottonwood	10 thermistors at 15 cm	10 at 25 cm
Valdez	61°06′N	146°13′W	maritime	cottonwood	none	10 at 25 cm
Alyeska	60°58′N	149°05′W	mtn/maritime	spruce/hemlock	12 thermocouples at 15 cm	12 at 25 cm

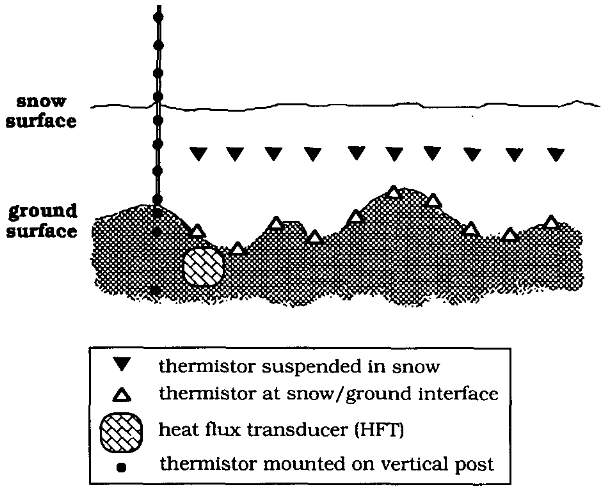

FIG. 4. A typical thermistor and heat flow meter array. The 10 thermistors installed at the snow–ground interface spanned 1.35 m, and allowed calculation of the standard deviation (sd) of the interface temperature as well as the mean. Thermistors on the vertical post allowed calculation of vertical temperature gradients.

class. We believe that by using this method it would be possible to develop a comprehensive worldwide dataset of snow classes, and perhaps even use existing databases to extend its coverage. The method consists of finding an "index" or "indices" by which the snow cover class can be identified without the need to dig a snow pit and make stratigraphic and textural observations. In developing this method, our working hypothesis was that the physical attributes of a snow cover and the relationship of the snow cover to the local climate would combine to produce a unique thermal regime (e.g., temperature gradients, heat flow, and temperature as a function of position) within each snow cover type. We, therefore, have focused on thermal parameters as the most likely candidates for "indices," but we have also tested physical parameters like depth and density.

1) Discriminating classes using winter average values

Twelve of the most pertinent average winter values measured at the Alaskan sites are listed in Table 4. Five of these have been plotted to discern how well a single value can discriminate between classes (Fig. 5). Class fields were drawn using simple rules: vertical lines between classes were placed equidistant between class names along the abscissa; horizontal lines were placed half-way between the data points of each class. The fields have been overlain by different patterns for accentuation. A particular parameter is a good discriminator between two classes if the data are well separated. It is a poor discriminator if the data lay close together or overlap. The plots indicate that for the four snow cover classes for which we have detailed observations (*tundra*, *taiga*, *alpine*, and *maritime*), discrimination using a single variable is possible in a limited way. However, in most cases there is some overlap between the classes, particularly for *alpine* and *maritime* snow. As illustrated in the bottom right panel in Fig. 5, the boundary between classes in some cases coincides with values known to have physical significance. For example, studies (Akitaya 1974; Marbouty 1980; Colbeck 1983) have shown that a snow layer must be subjected to vertical temperature gradient in excess of 10°–25°C m^{-1} in order for depth hoar to form. This critical vertical temperature gradient coincides with the boundary between *taiga* and *maritime* snow (*alpine* snow falls on the boundary). *Taiga* snow consists of 60% or more depth hoar, *maritime* snow rarely contains any depth hoar, while *alpine* snow often has a thin layer of depth hoar at its base.

We used R-mode principal component factor analysis (Klovan 1975; Davis 1986; Wilkinson et al. 1992) to determine whether the snow cover classes could be discriminated better using multiple rather than a single winter average value. Using all 12 variables listed in Table 4, 87% of the variance could be explained by the first two factors or eigenvectors. A varimax rotation was then used to maximize and minimize the component loadings along these eigenvectors and the results were plotted (Fig. 6). Factor 1 was found to be primarily a combination of temperature variables with the snow depth also factored in, while factor 2 was a combination of density and temperature gradient variables, suggesting a thermal resistance factor. Thus, a two-factor plot based on 12 variables (Fig. 6) can be viewed as separating the classes by their climate temperature (air temperature, snow–ground interface temperature, etc.) along the abscissa, and by their thermal attributes (thermal conductivity and diffusivity, which are primarily determined by density) along the ordinate. The characteristic "V" shape of the symbols in the factor plot arises because, in general, taiga snow has the lowest thermal conductivity and diffusivity of the snow classes. The resulting plot shows the classes to be well separated, indicating good discrimination.

Twelve variables are too many on which to base a practical discrimination method; too much effort, equipment, and time is required to collect the data. In addition, a high degree of correlation (Table 5) exists between many of the variables listed in Table 4, further suggesting reducing the number of variables. We have tried several different combinations of 3- and 4-variable discriminations and found that these can result in as good a discrimination as using 12 variables. While several different groups of variables adequately discriminate the classes, we have chosen to use a group of variables we know to be easy to measure, and that includes variables already routinely measured at automated snow courses and weather stations. The variables are

TABLE 4. Winter average values from Alaskan sites. Values are averages computed from hourly time series, except for depth, bulk density, and load, which are computed from monthly snow pit studies.

			Variables											
Location	Year	Type	snow depth (cm)	air temp. (°C)	interface (°C)	sd inter (°C)	temp drop (°C)	temp grad (°C cm^{-1})	basal grad (°C cm^{-1})	hflux (W m^{-2})	sd hflux (W m^{-2})	bulk density (g cm^{-3})	load (g cm^{-2})	bulk vap grad (g cm^{-3}/cm)
Prudhoe Bay	1991/92	1	20.0	−27.42	−19.01	7.92	−8.41	−0.47	−0.55	11.59	7.96	0.32	9.10	−6.56E-05
Imnavait Creek	1991/92	1	30.0	−19.84	−8.45	3.38	−11.39	−0.40	−0.36	11.25	6.32	0.27	11.24	−5.68E-05
Glenn Creek A	1991/92	2	45.5	−16.32	−3.26	1.33	−13.06	−0.31	−0.20	5.16	3.42	0.21	13.69	−6.07E-05
Glenn Creek B	1991/92	2	37.9	−13.86	−4.14	1.37	−9.72	−0.34	−0.23	4.99	3.21	0.21	12.40	−7.37E-05
Tsaina River	1991/92	3	100.1	−10.19	−0.49	0.43	−9.70	−0.18	−0.11	3.79	4.52	0.28	45.56	−5.73E-05
Lowe River	1991/92	4	99.1	−6.58	−0.19	0.19	−6.39	−0.13	−0.05	2.02	2.30	0.26	30.47	−4.60E-05
Valdez	1991/92	4	105.0	−4.53	0.16	0.14	−4.69	−0.07	−0.07	2.41	1.87	0.29	40.53	−2.89E-05
Alyeska	1991/92	9	255.1	−6.47	−1.95	0.49	−4.52	−0.02	−0.02			0.33	82.14	−5.69E-06
Prudhoe Bay	1990/91	1	16.4	−26.50	−18.63	6.21	−7.85	−0.56	−0.69	11.30	9.54	0.32	7.78	−3.68E-05
Imnavait Creek	1990/91	1	21.2	−23.21	−12.45	4.52	−10.76	−0.53	−0.57	10.90	8.26	0.25	5.48	−4.79E-05
Glenn Creek A	1990/91	2	61.2	−17.78	−2.37	0.67	−15.42	−0.38	−0.14	4.74	3.01	0.22	17.89	−7.97E-05
Glenn Creek B	1990/91	2	60.5	−15.04	−2.60	0.73	−12.44	−0.31	−0.21	4.81	2.69	0.22	18.55	−7.26E-05
Tsaina River	1990/91	3	64.7	−12.49	−1.28	0.61	−11.20	−0.22	−0.01	3.97	3.23	0.24	22.87	−5.70E-05
Lowe River	1990/91	4	80.7	−8.49	−0.34	0.34	−8.15	−0.18	−0.13	2.72	2.91	0.27	41.04	−5.46E-05
Valdez	1990/91	4	86.5	−5.36	−0.32	0.41	−5.05	−0.07		1.40	1.24	0.27	35.25	−2.32E-05
Alyeska	1990/91	9	146.9	−5.39	−0.80	0.18	−4.59	−0.03	−0.03			0.28	48.46	−1.04E-05
Prudhoe Bay	1989/90	1	10.0	−27.52	−22.00	7.87	−5.54	−0.59		20.33	15.73	0.32	3.24	−5.88E-05
Imnavait Creek	1989/90	1	16.2	−21.10	−15.25	5.44	−5.77	−0.39	−0.67	18.25	6.58	0.27	4.54	−3.58E-05
Glenn Creek A	1989/90	2	51.5	−19.92	−5.37	1.55	−14.54	−0.29	−0.14	4.67	2.21	0.20	14.29	−4.47E-05
Glenn Creek B	1989/90	2	41.5	−16.84	−6.60	2.57	−10.24	−0.28	−0.21	4.08	1.95	0.20	12.79	−4.32E-05
Tsaina River	1989/90	3	124.9	−12.63	−1.07	1.24	−11.59	−0.12	−0.03	1.60	1.44	0.28	47.66	−2.81E-05
Lowe River	1989/90	4	147.2	−8.55	−0.16	0.07	−8.39	−0.07	−0.05	1.07	1.05	0.30	58.17	−2.38E-05
Valdez	1989/90	4	158.8	−9.62	−0.01	0.13	−9.40	−0.08	−0.04	0.78	0.93	0.33	71.25	−2.80E-05
Alyeska	1989/90	9	196.0	−7.89	−0.66	0.05	−7.24	−0.04	−0.02			0.31	65.41	−1.16E-05

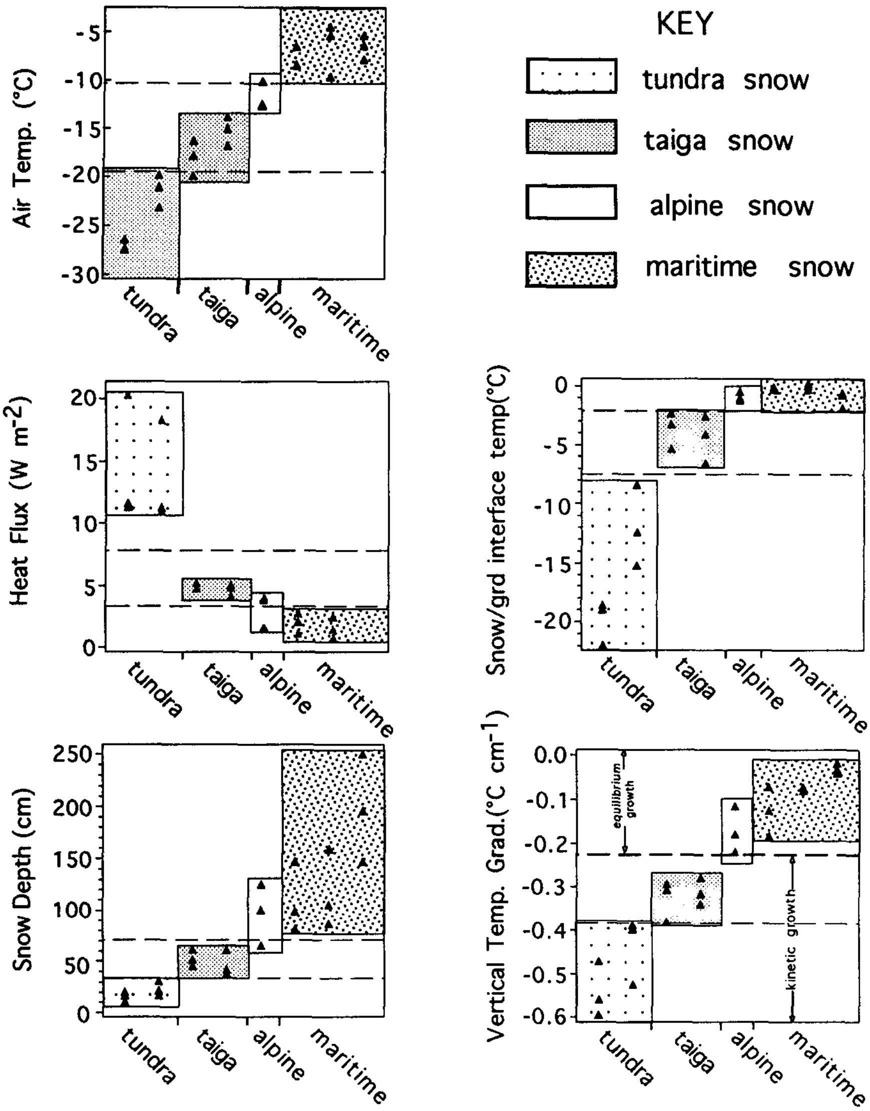

FIG. 5. Five representative single-value discrimination plots. The snow class is indicated along the abscissa, and the value of the parameter along the ordinate. The boundaries are set equidistant between the data points. Note that one boundary for vertical temperature gradients corresponds to the critical gradient necessary for depth hoar growth according to Akitaya (1974), Marbouty (1980), and Colbeck (1983).

snow depth, air temperature, snow–ground interface temperature, and *bulk density*. The resulting two-factor plot (Fig. 6 bottom) differs little from the plot based on 12 variables (Fig. 6, top) and, in fact, has better separation between classes and explains more of the variance (94%). Each snow class plots in a distinctive group, well separated from neighboring groups, with only a little overlap between *alpine* and *maritime* snow. Component loadings suggest that again, factor 1 on the abscissa accounts mostly for temperature (air and interface), while factor 2 on the ordinate accounts for density and depth, which can be interpreted as a measure of the thermal attributes.

Using multivariate analysis and the same four variables, we have derived a discriminant function that can be used to classify the type of snow at a new location based on the data collected at our 24 "training" sites. The matrix equation is

$$\begin{bmatrix} a_{11} & a_{12} & & a_{1n} \\ a_{21} & a_{22} & & a_{2n} \\ & & \ddots & \\ a_{n+1\,1} & a_{n+1\,2} & & a_{n+1\,n} \end{bmatrix} \begin{bmatrix} v_1 \\ \vdots \\ v_n \\ 1 \end{bmatrix} = \begin{bmatrix} s_1 \\ \vdots \\ s_n \end{bmatrix}, \quad (1)$$

where n is the number of variables used (four in this case); the coefficients a_{ij} are given in Table 6, the v_i are

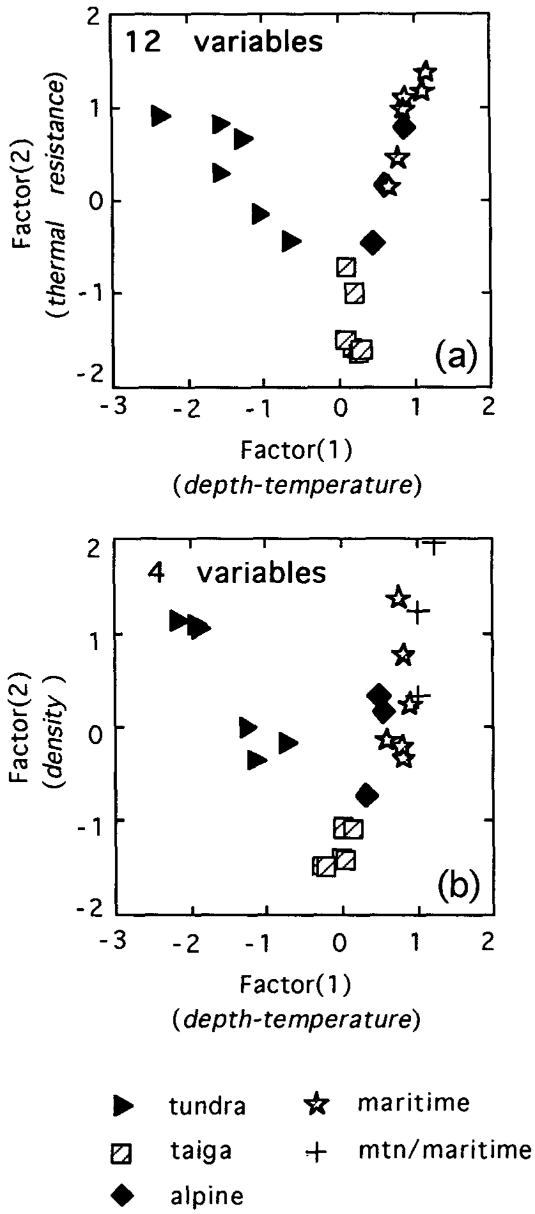

FIG. 6. (a) R-mode principal component two-factor plot based on the 12 variables in Table 4; 87% of the variance is explained using these two factors. (b) R-mode principal component two-factor plot based on four variables: snow depth, air temperature, snow-ground interface temperature, and bulk density. Ninety-four percent of the variance is explained using these two factors.

the average snow depth, air temperature, snow–ground interface temperature, and bulk density in that order; and the s_i are the discriminate scores: s_1 corresponds with tundra snow, s_2 with taiga snow, s_3 with alpine snow, s_4 with maritime snow, and s_5 with mountain/maritime snow. The highest s value determines the class. Table 6 illustrates how the discriminant function can be used. The f test for this function at a 5% level of significance requires f (0.95; degrees of freedom: 20,54) be greater than 1.8; its calculated value is 64.9, indicating that the between-group variance is significantly greater than the within group variance.

Two caveats should be noted regarding the discriminant function. 1) The "training" set on which the function is based does not include *prairie* or *ephemeral* snow classes. Therefore, the function will incorrectly assign snow conditions appropriate to these classes to one of the 4 classes that were in the training set. 2) The "training" set was extremely limited, with only 24 cases; thus, the function must be considered provisional at this time. As we discuss below, a program is under way to collect a more extensive dataset.

2) DISCRIMINATING CLASSES USING TIME SERIES

Winter average values do not reflect the time history of the snow cover, and our experience suggests that different classes of snow covers form and evolve quite differently. To take advantage of these time-dependent differences in discriminating the snow covers, we have examined time series of the different thermal parameters. These showed distinct differences between classes that are best illustrated by the snow–ground interface temperature (Fig. 7). For simplicity, we look chiefly at *tundra*, *taiga*, and *maritime* snow. As anticipated from the winter average values, the snow–ground interface beneath *tundra* snow was significantly lower than the interface beneath *taiga* snow, which was lower than beneath *maritime* snow. Not only were the mean temperatures different, but so also were the amplitudes of the fluctuations. In the relatively thin, wind-blown *tundra* snow, with its small thermal inertia, the snow–ground interface fluctuated as much as 30°C. Fluctuations beneath the *taiga* snow cover were more subdued (5°C), but still present. Beneath the *maritime* snow covers, with snow temperatures near 0°C and liquid water often present, the snow–ground interface generally was within a few tenths of a degree of freezing. The standard deviation of the interface temperature about the mean is a useful, though imperfect, measure of this time-dependent behavior and that is why it appears in Tables 4 and 5. Heat flow at the snow–ground interface, the magnitude of the vertical temperature gradient, and spatial variability of the snow–ground interface all showed similar distinctive differences in the time series between snow cover classes.

The time series data can be used to check how often during a winter a spot measurement of a single thermal parameter would correctly discriminate the snow cover class. Clearly, making a spot measurement is simpler than making continuous measurements for the purpose of identifying a snow class based on an index parameter. We illustrate this by using the snow–ground interface temperature. The approximate interface temperature boundary value between *tundra* and *taiga* snow covers

TABLE 5. Alaskan site winter averages, correlation coefficient matrix.

	snow depth	air temp.	interface temp.	sd. interface temp.	temp. drop	temp. grad	basal grad.	heat flux	sd heat flux	bulk density	load	bulk vapor grad
snow depth	1											
air temp.	0.807	1										
interface temp.	0.762	0.908	1									
sd interface temp.	−0.721	−0.885	−0.987	1								
temp. drop	0.094	0.194	−0.235	0.258	1							
temp. grad.	0.903	0.924	0.848	−0.800	0.160	1						
basal grad.	0.770	0.836	0.953	−0.920	−0.293	0.861	1					
heat flux	−0.790	−0.786	−0.879	0.856	0.235	−0.796	−0.925	1				
sd heat flux	−0.743	−0.801	−0.885	0.869	0.212	−0.862	−0.913	0.853	1			
bulk density	0.396	0.062	−0.197	0.251	0.610	0.162	−0.173	0.078	0.253	1		
load	0.979	0.787	0.697	−0.651	0.199	0.871	0.697	−0.733	−0.649	0.510	1	
bulk vapor grad.	0.489	0.258	0.037	−0.028	0.516	0.442	0.059	−0.118	−0.178	0.518	0.497	1

is −7.5°C (Fig. 5). The boundary value between *taiga* and *alpine/maritime* snow covers is −2.5°C (Fig. 5). If these values are superimposed on the time series (heavy horizontal lines, Fig. 7), the probability that a spot measurement will correctly discriminate the snow cover class will be equal to the fraction of time the value falls between the boundaries. In the case illustrated in Fig. 7, spot measurements would have discriminated the snow correctly in excess of 84% of the time. Similar tests with spot values of heat flow at the snow–ground interface, temperature gradient, and spatial variability of the snow–ground interface temperature give comparable success rates.

In summary, each of the snow covers we have studied in Alaska has unique thermal characteristics, which allow it to be distinguished from the other classes. Four parameters, three of which are routinely measured at many locations worldwide (snow depth, air temperature, and bulk density), are sufficient to discriminate the classes from one another. The additional measurement of the snow–ground interface temperature is easily made and is a good index measure of the thermal attributes of the snow cover.

3. Snow cover classes and climate

a. *Binary climate classification system*

The new seasonal snow cover classification system can also be derived directly from a consideration of the possible range of winter atmospheric conditions instead of the physical properties of the snow. The relationship between the snow cover classes and climate can be illustrated by using a simplified binary system, with air temperature, precipitation, and wind as the important climate variables. For the binary system, we ask whether the snow cover exists in windy or relatively calm conditions, whether there is a lot or a little snow on the ground, and whether the air temperature is typically high (near 0°C) or low? The answers to these questions give eight possible classes of snow covers. However, in one case, (*maritime* snow) the physical attributes of a snow cover are tied only to two of the three climate variables, and in two other cases, the combinations are rare (Fig. 8). Thus the number of classes is reduced to 5. However, we add a sixth class—the *ephemeral* class—as a special case defined by temperature only. This class exists only where the mean winter temperature is "very high" (i.e., near or above freezing), and the snow cover does not last more than a week or two. As such, the *ephemeral* class is not dependent upon precipitation amount or wind speed. (A second type of *ephemeral* snow cover can exist but is more difficult to identify from climate parameters. It is the thin prairie snow that melts or sublimates away due to Chinook-type winds.)

The resulting classification scheme can be depicted as a flow chart (Fig. 8) or graphically as a cube divided into eight smaller cubes (plus *ephemeral* snow) (Fig. 9). To implement the classification based on these climatic variables, the boundaries between high and low

TABLE 6. Discriminant function determined from Alaskan data. Highest score: 125, snow class: taiga.

Coefficient matrix a_{ij}						Variable matrix v_i		Discriminate score s_i	
−0.624	−0.460	−0.521	−0.516	−0.256		85 [snow depth (cm)]		114	(tundra)
−3.987	−3.890	−2.118	−0.386	0.520	×	−23 [air temp (°C)]	=	125	(taiga)
4.541	5.074	5.544	4.964	3.271		−3 [interface temp (°C)]		112	(alpine)
913.814	699.335	949.738	1032.718	852.433		0.25 [bulk density (g/cm3)]		88	(maritime)
−139.179	−84.503	−112.909	−120.278	−102.515		1		67	(mtn/maritime)

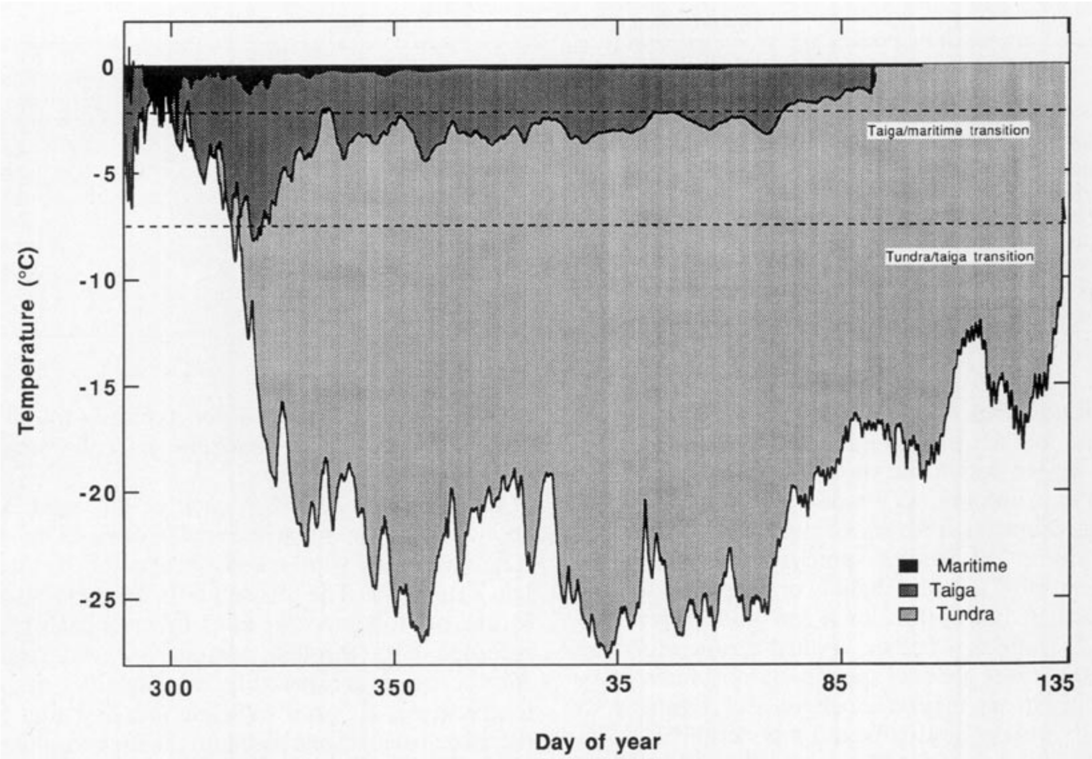

FIG. 7. Hourly snow–ground interface temperature from *tundra, taiga,* and *maritime* snow covers. Not only is the average temperature different among the three classes, but the character of the signals differs as well. Dashed lines indicate the boundaries between classes as determined from single variable discrimination plots (Fig. 5).

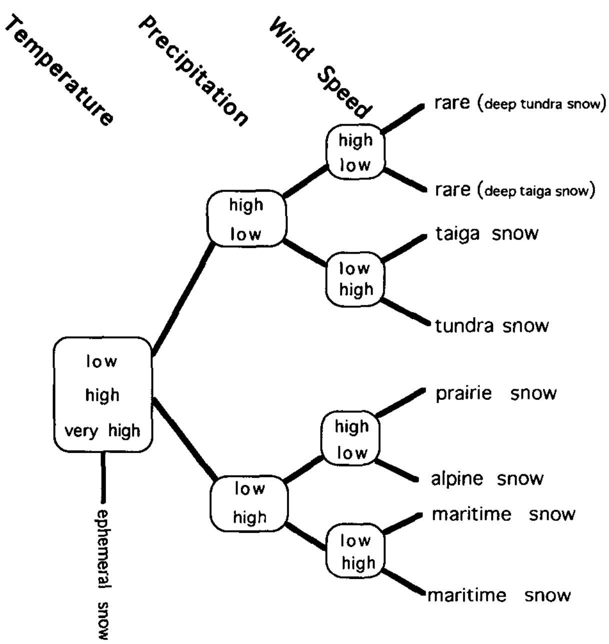

FIG. 8. A dichotomous key for snow class identification.

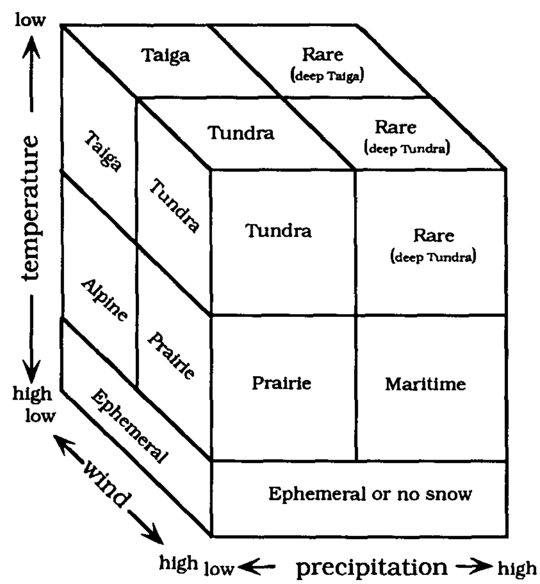

FIG. 9. A graphical representation of the relationship between the snow classes and the three major climate variables. The hidden cube in the lower right rear corner would be *maritime* snow.

TABLE 7. Climate parameters from Alaskan sites.

Site	Class	CDM (°C)	Precipitation rate (mm day^{-1})	Wind (m s^{-1})
Prudhoe Bay (PB)	tundra	227.4	0.4	4.5
Imnavait Creek (IC)	tundra	183.3	0.4	2.4
Glenn Creek A (GCA)	taiga	156.4	1.0	0.1
Glenn Creek B (GCB)	taiga	142.6	0.9	0.1
Tsaina River (TR)	alpine	122.4	2.6	0.1
Lowe River (LR)	maritime	99.9	3.0	0.4
Valdez (V)	maritime	91.5	3.9	
Alyeska (A)	mountain/maritime	56.4	7.5	

precipitation, high and low wind speed, and very high, high, and low temperature must be defined.

The way in which the three key climatic variables (preciptation amount, air temperature, and wind speed) affect the character of the snow cover is well established. The amount of winter precipitation determines whether a snow cover is shallow or deep, and whether it consists of many thin, or a few thick layers. The depth also affects whether vertical temperature gradients, the prime agent of snow metamorphism, are of sufficiently strong to produce depth hoar. Deeper snow results in weaker gradients and less depth hoar. The air temperature also affects temperature gradients, with lower temperatures more favorable to the production of strong gradients, particularly since these lower temperatures are usually found in locations that have thinner snow covers. Air temperature also controls whether any melting will occur, and, therefore, the production of melt features in the snow. Wind affects the grain size and density of the snow cover. High winds produce pulverized grains that pack together easily and result in high density snow. These tiny grains have high radii of curvature and readily sinter into cohesive slabs with great strength.

b. Boundary values from Alaskan sites

We have used the data collected at our eight Alaskan sites to define the winter temperature, precipitation, and wind speed boundary values required for snow classification using climatic variables. To generate an index of the combined influence of winter temperature and duration, we use the cooling degree month (CDM), defined as

$$\mathrm{CDM} = \begin{cases} \sum\limits_{m} (T_c - T_a), & \text{if} \quad T_a < T_c \\ 0, & \text{if} \quad T_a \geq T_c, \end{cases} \qquad (2)$$

where m is the month of the year (1–12), T_a is the monthly mean air temperature, and T_c is a critical or threshold temperature. In this application $T_c = 10°\mathrm{C}$ was chosen to allow for snow covers that exist in locations where the monthly mean temperature might be above freezing, a condition typically found where there are wet, warm *maritime* or *ephemeral* snow covers.

From data collected at each of the eight Alaskan snow study sites, we have calculated the CDM, precipitation rate, and wind speed averages for the three winters (Table 7). The instruments at these sites were turned on in September or October of each year, and recorded data through March. In most regions of Alaska the air temperature is lower than the critical temperature, T_c, prior to September and after March; therefore calculations based on the measurements necessarily underestimate the CDM. Calculations using meteorological data from nearby National Weather Service observing stations suggest that our site CDM data are low by up to 15%. In addition, because the precipitation value is calculated from snow cover depth and bulk density (and does not correct for losses by sublimation), the computed precipitation values are also an underestimate, and can be considered a lower bound on the precipitation.

To assign a boundary value to each decision branch in our dichotomous key (Fig. 8), we seek to answer questions like What precipitation rate produces a deep versus a shallow snow cover? and What range of winter air temperature (actually CDM) separates a snow cover with high temperature and wetted characteristics, from one with no wetting and low temperature characteristics? Our Alaska snow classifications and associated meteorological observations (Table 7) suggest that the differences between *tundra* and *taiga* climatologies can be used to distinguish the wind speed threshold, and that the differences between the *tundra/taiga* and *maritime* climatologies can be used to distinguish the CDM and precipitation thresholds.

Using the data from Table 7, we conclude that the CDM value that differentiates relatively high from low temperature snow covers is between 100° and 150°C CDM. We have no data for *ephemeral* snow covers, but we know they are found only where the climate is even warmer than that of the relatively high temperature snow covers. That implies a CDM value considerably lower than 100°; we estimate approximately 50°.

The average winter precipitation rate that separates deeper from shallower snow covers falls between 1 and 3 mm day^{-1}. The average winter wind speed separating the windy and relatively calm snow classes lies between 0.5 and 2 m s^{-1}.

4. Mapping the distribution of snow cover classes

a. Considerations for mapping

Three methods exist for mapping the distribution of snow cover classes: 1) using stratigraphic and textural measurements from snow pits, 2) using index measurements of some parameter related to the stratigraphy and texture, and 3) using climate data.

Snow pit observations are labor intensive and a body of worldwide pit observations from which snow classes could be inferred for mapmaking does not exist. Several large databases, which may provide index parameters, do exist. These databases include information on snow depth, water equivalent, and load (depth–density product). Snow depth is determined daily at thousands of meteorological stations worldwide, and data from these stations have been used to construct snow depth and snow cover duration maps (Boughner and Potter 1953; ACFEL 1954; Potter 1965; McKay and Gray 1981). Snow water equivalent (SWE) is determined daily or monthly at approximately 600 sites distributed throughout the western United States (USDA Soil Conservation Service-Basin Outlook Reports), and similar measurements are made in other countries (Bilello 1984). Snow depth data, used with algorithms developed at the limited number of meteorological stations where snow load information is collected, have been used to map regional snow loads in the United States (Thom 1966; ASCE 1990) and Canada (Boyd 1965). Similarly, mean winter snow pack density has been mapped from these and other specialized data for North America (Bilello 1957, 1969) and the former USSR (Bilello 1984).

Unfortunately, the snow data in the existing databases suffer from several shortcomings when trying to develop snow class maps. First, many data have been collected at weather stations, which tend to be at airports or in urban areas, leaving large regions with little or no coverage. For example, there is a single snow course for the entire barren grounds region of Canada (Goodison 1994, personal communication). Second, these urban weather stations are often affected by enhanced wind scour or melting and, therefore, are not typical of the general snow cover. Similarly, most measurements of SWE [like those generated by the Soil Conservation Service (SCS)] come from mountain basins that are hydrologically important but may be atypical of the general snow cover. Third, and the chief restriction on the use of the existing snow depth and water equivalent data, is that not enough parameters are collected at each site to use the four-variable index method presented above to discriminate the snow type. At SCS snow sites, they collect load (depth times density) but not depth; at NWS sites they generally collect depth but not density, and the snow–ground interface temperature is collected at very few sites.

Climate data (precipitation, air temperature, and wind), on the other hand, are sufficiently widely distributed for continuous snow classification mapping over most of the earth. We have mapped snow cover classes for the Northern Hemisphere using the three climate variables depicted in Figs. 8 and 9. Sixty-year global climatologies of observed monthly mean precipitation and surface air temperature on a 0.5° latitude by 0.5° longitude grid (Legates and Willmott 1990) were used to calculate grid cell values of the winter CDMs and precipitation. The CDM computations used a T_c value of 10°C, and winter precipitation was defined as the months where $T_a < T_c$.

Wind was more difficult because the resolution of available data was low, and the data seemed inappropriate to our task. Gridded global fields of monthly mean surface and upper-level wind speeds were available from the National Meteorological Center (NMC) in the United States and the European Centre for Medium-Range Weather Forecasts (ECMWF). These fields had 2.5° by 2.5° resolution, but we found they could not resolve the wind speed gradients across Alaska, and so they were of little use.

These global wind datasets also seemed inadequate for determining snow cover characteristics because they were not representative of conditions at the snow surface. As far as the evolution of the snow cover is concerned, surface wind speed (or surface wind shear stress) is of primary importance. The surface wind determines whether the snow blows or not and, therefore, whether it becomes dense and forms slabs. Large roughness lengths associated with dense, tall vegetation like forests can significantly reduce surface wind speeds, regardless of the winds aloft. For forested regions, global wind fields, generally derived from meteorological stations in clearings, are inappropriate when considering the evolution of the snow cover, even if they are of sufficient resolution.

We chose to use a vegetation classification as a proxy for the wind. We reasoned that the primary control, as far as the snow cover was concerned, was whether there were trees (low wind) or no trees (high wind). This assumption was suggested by our Alaska snow site station observations (Tables 3 and 7), where there was a dramatic wind speed difference between the *tundra* (tundra tussocks, 2–5 m s^{-1} wind speed) and *taiga* (boreal forest, less than 0.2 m s^{-1} wind speed) snow classes. The decision was also supported by published literature, where observations (Oliver 1971; Businger 1975) and modeling studies (Gross 1987; Schilling 1991) have well documented that wind speeds within and below the forest canopy are generally low.

The converse, that regions with short vegetation experience high winds frequently enough to produce *tundra* and *prairie* snow covers, was not so obvious. Global atmospheric circulation patterns are primarily the result of differences in radiative heating between the equator and the poles, and the earth's rotation. The strongest atmospheric motions occur in middle and high latitudes, roughly between 40° and 70°. Cyclones and anticyclones are common and strong thermal gradients with vigorous westerly winds lead to a continuous production of eddies near the surface of the earth. The eddies interact with the earth's surface through the atmospheric boundary layer and are strongly influenced by the height of surface roughness elements. This sensitivity is illustrated by the general circulation model simulations of Sud et al. (1988), which predicts a twofold increase in boundary layer wind speed in response to reducing the global land roughness length from 45 to 0.02 cm. Given the strong atmospheric motions found in the middle and high latitudes, we assume that where the surface roughness is relatively small, there are sufficient wind speeds to produce the "high wind" snow classes. Note that these winds do not have to occur on a daily or even weekly basis; a "high" wind event may only have to occur once every month or two to develop wind-related snow characteristics. Different atmospheric dynamics occur in lower latitudes, so our arguments are expected to break down in those regions. Fortunately, these are also regions where there is little or no snow.

Using a 0.5° by 0.5° gridded global earth-surface classification of Olson et al. (1985), which has 54 ecosystem, water, and ice classes, we created four superclasses: tall vegetation (trees), and short vegetation (grassland, tundra, shrubland, low crops, etc.), water, and ice. CDM and winter precipitation data were coregistered to the vegetation data, then a computer algorithm that followed the dichotomous key shown in Fig. 8 was used to determine the seasonal snow class for each grid cell. For the mapping algorithm, we chose boundary values, consistent with our Alaskan data, of 125°C CDM, and 2 mm day^{-1} precipitation, and the wind was assumed to be low if the vegetation was tall, high if the vegetation was short. For the "very high" CDM threshold distinguishing the *ephemeral* snow class (Figs. 8 and 9), we had no information. Therefore, we tuned this parameter empirically by adjusting it downward from our original estimate of 50° CDM until we correctly established *ephemeral* snow in several test areas like Washington, D.C., and Seattle, Washington. This coincided with a threshold value of 30° CDM.

The resulting distributions of snow cover classes in Eurasia and North America are shown in Figs. 10a and 10b. The resolution of these maps is 0.5° (~50 km), and variations in snow cover class due to orographic or local effects appear only where those influences have been captured by the 0.5° by 0.5° gridded atmospheric and vegetation data sets. *Ephemeral* snow has not been differentiated from areas where snow is never found (i.e., Saudi Arabia), because if it snowed in these regions, the snow would likely be quite short lived. Mountainous regions, in particular, suffer from the relatively coarse resolution of the climate and vegetation data. While the general character of the mountain influence has been captured, as seen, for example, in the coastal mountains of the western United States and Canada, differences in snow class from the valleys to the mountain tops is not shown at this resolution. Only in cases where the climatology of Legates and Willmott (1990) included stations located in the mountains, can the presence of the mountains be observed as small areas (one or two cells) of locally deeper and/or colder snow.

b. *Snow class map validation*

Opportunities for snow class map validation are limited due to the scarcity of data. Here, we check our climate-derived snow class maps against indirect data from the former USSR based on the work of Rikhter (1954), and direct data from a swath across Alaska based on snow pit measurements.

For the former USSR, Rikhter mapped six snow zones and 22 snow districts using the duration of snow cover and the maximum 10-day depth. These have been translated into our six snow classes (Table 8). His map, redrawn using our snow classes (Fig. 11a), has been compared with snow class distributions derived using climate variables (Fig. 11b). The climate algorithm generally indicates *tundra* and *taiga* snow cover in the same areas as Rikhter. Climate-derived *prairie* snow overlies his *prairie* snow in the vicinity of the Aral Sea, but is more extensive north of the Black Sea. This greater extension is at the expense of Rikhter's *ephemeral* snow in the Ukraine, Latvia, and Estonia. Near Moscow, the climate-derived map shows a checkerboard of *maritime* and *alpine* snow, but Rikhter indicates two large areas of the same classes, not intermixed. In the Kola Peninsula and adjacent area, the climate parameters suggest that there is mixed *tundra* and *taiga* snow covers, but Rikhter's map indicates a deeper snow that we translate as being *alpine*.

Algorithm validation by comparison to Rikhter's maps is less than definitive. First, translation of Rikhter's district descriptions into our six classes is open to some interpretation (Table 8), and some of his districts contain two or more classes of snow. Where this is the case, we have had to make an arbitrary assumption of the boundary between the classes. Second, the method and data used by Rikhter to prepare his maps are not given. While Rikhter had considerable personal knowledge of the snow of the former Soviet Union, it is likely that his data were sparse, particularly in remote areas of Siberia and

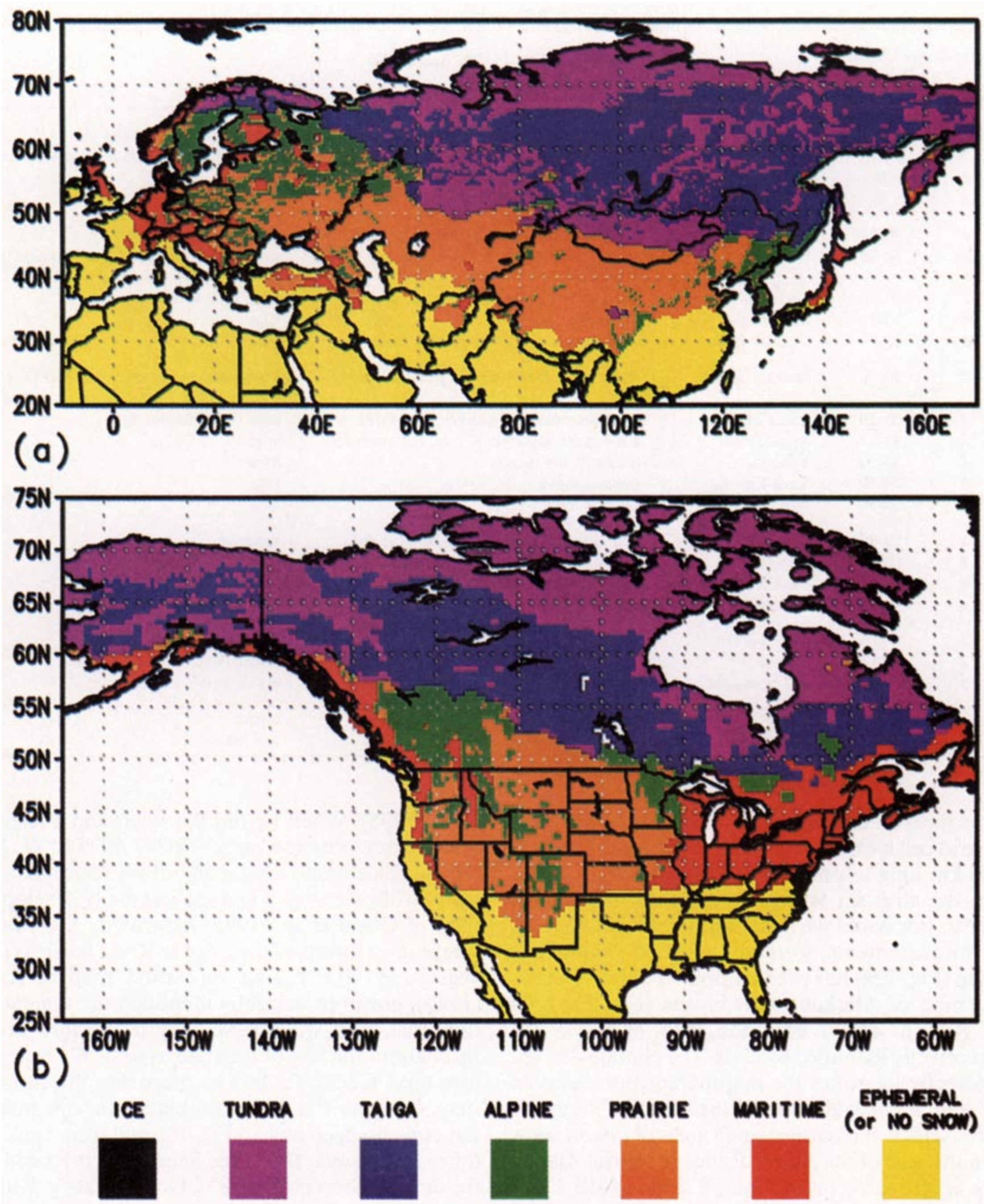

FIG. 10. Snow class distribution based on climate variables in (a) Eurasia and (b) North America.

Central Asia. It is also likely that he ignored local detail or snow class variance when defining and mapping his 22 districts. Thus, the accuracy of his map is not clear. His map and our climate-derived map coincide over an area of 1.75×10^7 km^2; of this, we have snow class agreement over 62%, or 1.08×10^7 km^2, of the area.

In Alaska, we have mapped the snow cover along a north–south transect centered on the Trans-Alaska Pipeline. Our map is based on extensive formal (Liston 1986; Hall et al. 1991; Sturm 1991, 1992a,b; Sturm and Holmgren 1993, 1994; Benson and Sturm 1993; see also the measurements described above) and informal stratigraphic and textural measurements. Based

TABLE 8. Rikhter's snow districts translated into our six snow classes.

Rikhter's (1954) snow classes

Zone	District	Snow depth	Location	Notes	Class
I	1	>70 cm	west Urals	low density, no thaws, tundra in N., forests in S.	windy Alpine (N) to taiga (S)
I	2	>70	Ob'-Yenisey	low density, wind rare, long no-snow periods	taiga (W) to Alpine on w. slope Siberian Plateau
I	3	>70	Kamchatka-Chukchi	wind, thaws, depths >2 m	Alpine
I	4	>70	Pacific marine	strong gale winds, freq. thaws, high density	maritime
II	1	50–70	Northwest	warm Gulf stream, many blizzards, freq. thaws	Alpine to maritime
II	2	50–70	North European	colder, lower density E., more blowing, some thaws	maritime (W) to taiga (E) to w/prairie (SE)
II	3	50–70	Ob'Irtysh	blizzards and tundra N., less so to south	tundra (N) to taiga (S)
II	4	50–70	Mid-Siberian	thaws rare, little wind	taiga
II	5	50–70	Okhotsk Coast	windblown and uneven; possible thaws	prairie
III	1	30–50	central European	warm spells, thaws: steppes and drifts in SE	Thin maritime, ephemeral or FRED (W) to prairie (SE)
III	2	30–50	Tobol'Irtysh	no thaws, colder than above: some drifts in S.	taiga (W) to tundra (S)
III	3	30–50	Angara River	a few melts, mostly thin, cold, not much drift	taiga
III	4	30–50	Yakutsk	cold, still, low density	taiga
III	5	30–50	Yana-Kolyma	same as above	taiga
III	6	30–50	Bureya-Amur	same as above	taiga
IV	1	10–30	western	freq. thaws (W) eliminate snow, little drifting	ephemeral
IV	2	10–30	Kazakhstan	colder and more drift than above	prairie
IV	3	10–30	Biysk and Minusinsk	thaws and drift rare: long duration	taiga
IV	4	10–30	Transbaikal	continental climate	taiga?
V	1	<10	Southwestern	high instability, thaws frequent	ephemeral
V	2	<10	Caspian	colder w/more mobility than above	prairie (N) to emphemeral (S)
V	3	<10	S. Transbaikal	very thin, but cold; thaws rare: some wind	prairie to thin taiga
VI	—	10–50	Arctic	much wind	tundra
—	—	—	mountain	high variability	mountain

on these measurements, we have assigned each 0.5° × 0.5° grid cell along a strip that is about 200 km wide by 1400 km long to one of the six snow cover classes. Cells in the strip for which we have no direct measurements, nor could we confidently extrapolate from nearby measurements, were not assigned values. The strip map (Fig. 12a) has been compared to the climate-derived map of Alaskan snow covers (Fig. 12b). Of 2.52×10^5 km^2 area in common, 90%, or 2.26×10^5 km^2, is correctly identified by class. The climate-derived map correctly identifies the major transition between *tundra* and *taiga* snow along the Brooks Range in northern Alaska. It identifies small areas of *tundra* snow on the north side of the Alaska Range in central Alaska, and the *alpine* snow on the inland slope of the Coast Mountains NE of Prince William Sound. Similarly, it correctly identifies a mixed area of *alpine* and *prairie* snow near the head of Cook Inlet, and the transition to *maritime* snow south toward the Kenai Peninsula and Prince William Sound. The overall match between maps is particularly surprising when one considers that the climatology of Legates and Willmott (1990), on which the climate-derived map is based, uses data from only about 40 Alaskan meteorological stations.

We originally prepared our climate-derived snow class map of Alaska using the vegetation data of Olson et al. (1985). When we did this we found a large areal discrepancy centered on 62°30′N, 146°00°W. In this region, the climate-driven algorithm identified *tundra* snow, while we knew *taiga* snow actually develops. The map of Olson et al. (1985) incorrectly identified the sparse taiga forests of the Copper River Basin as tundra vegetation. The Alaska vegetation map of Küchler (1970), however, correctly identified the vegetation in this area, and we believe that it is more accurate throughout the rest of the state as well. We have therefore used Küchler's data in preparing the snow class map shown in Fig. 12b. Comparison of this map with the same mapped area in Fig. 10b will show some slight differences, since the latter figure was prepared using the data of Olson et al. (1985). Unfortunately, Küchler's data are limited to Alaska only.

5. Discussion

Is the new snow classification system valid? Does it reflect real and discrete variations in seasonal snow covers, or in nature is there a continuous spectrum of depths, stratigraphies, and textures? A large range of snow cover characteristics can be found in nature, and even in one location the snow cover evolves through many states during the winter. Our experience suggests

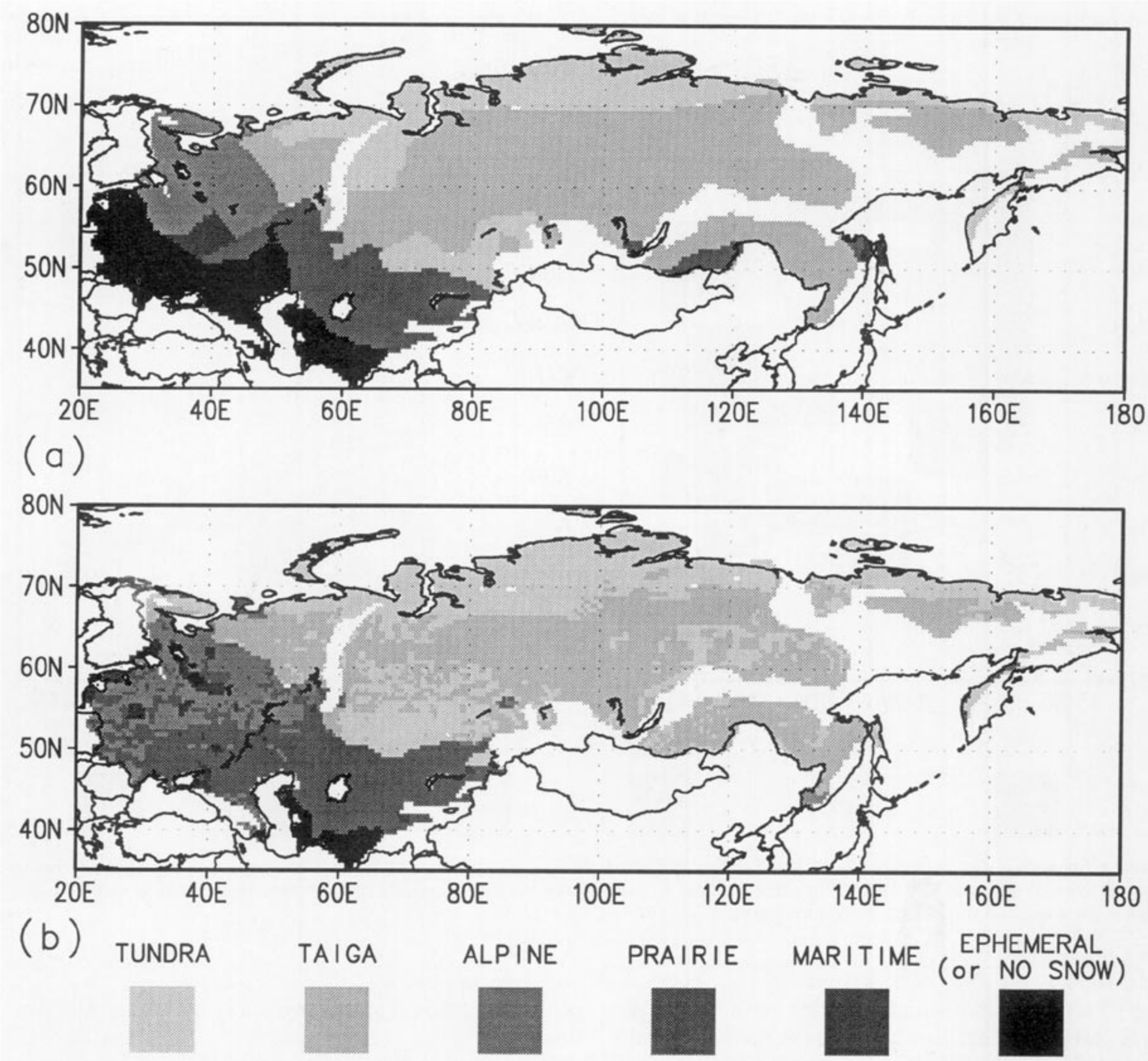

FIG. 11. Snow class distribution in the former USSR based on (a) Rikhter's (1954) map (cast in terms of our classes) and (b) climate variables. There is 62% agreement between the two maps. The white areas are mountain ranges where the snow was classified by Rikhter as mountain snow.

that most often the snow cover will exhibit characteristics that fit into a single class.

The case for discrete snow cover classes is strengthened by work that indicates there are distinct classes of climate. Köppen introduced a numerically based climate classification scheme in 1918 (see Chang 1959; Wilcock 1968; Trewartha 1968) in which he used monthly and annual temperature and precipitation to calculate a continuous index. He set class boundaries based on observed patterns of vegetation and reasoned that changes in vegetation reflected changes in the climate. Thornthwaite (1931, 1948) also defined a numerical climate classification scheme, based on the potential evapotranspiration of plants as calculated from mean monthly temperature and precipitation. Again, he set his class boundaries based on vegetation and soil types. In both systems, which are widely accepted, the authors argue for discrete climate classes, and their class maps are similar in many ways to our snow cover maps.

Our own observations also support the discrete nature of the snow cover. We have observed that within a climatic zone, the range of weather conditions is sufficiently limited to give rise to the same class of snow cover year after year. For example, during the 3 years that we collected data near Fairbanks, all time record snow depth was recorded: 250% of normal, based on a 90-year record. Yet even with this extraordinary amount of snow, texturally and stratigraphically, the

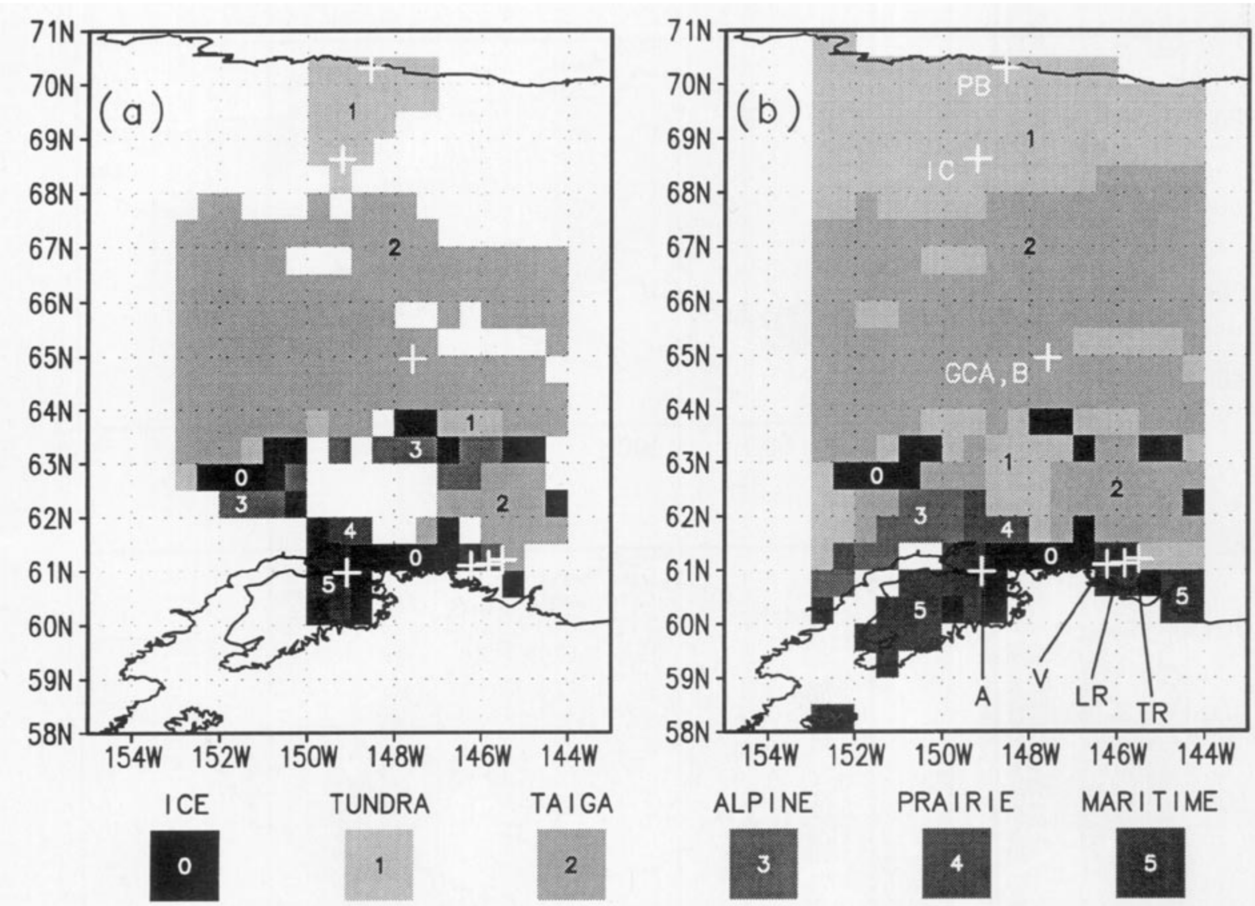

FIG. 12. Snow class distribution in Alaska based on (a) field observations and (b) climate variables. Data logger site locations referred to in the text are also indicated (see Table 7 for abbreviations). Comparison of the two maps indicates that the climate-derived map correctly identifies the snow class for 90% of the common area.

snow cover was still distinctly a *taiga* snow cover. We also found that differences between classes were always greater than the year-to-year difference within a class. This "fixed" nature of the snow cover is manifest in the fact that similar classes of snow cover have shown up time after time in historical classification systems (Table 1).

The *alpine* snow cover class illustrates one reason why discrete snow covers tend to form. Texturally, it includes features of both cold and warm snow covers (depth hoar, ice lenses, and percolation columns), and in some ways it can be thought of as a "transitional" snow cover, not cold and shallow enough to be a *taiga* snow cover, but not warm and deep enough to be a *maritime* snow cover either. But rather than reflecting a "transitional" climate, this type of snow cover results from weather patterns that actually alternate between two climate types. Thus, a warm, wet storm may deposit considerable snow, followed by a period of colder, more continental weather. This alternation results in interstratification of dissimilar layers and produces a snow cover that is stratigraphically and texturally distinctive.

It is important to stress again that the new snow cover classes are based on physical characteristics and not on associations with vegetation or specific geographic areas. While the close relationship between snow and vegetation is well established (Kuz'min 1963; McKay and Findlay 1971; Adams 1976), it is actually part of a three-way relationship between climate, vegetation, and snow that can be quite complicated. We felt it was preferable to define the snow classes based simply on their physical characteristics, then to relate these classes to the climate, the vegetation, or a geographic location. We have intentionally employed vegetation or geographic names because they suggest the character of the snow cover better than any new names we considered. Also, several of the names have had long use and are strongly associated with a particular type of snow cover.

The accuracy of our snow cover classification maps is dependent upon the completeness and accuracy of the 0.5° by 0.5° gridded atmospheric and vegetation datasets used in the mapping. Some errors in the snow maps can be traced to incorrectly identified vegetation, as was the case where tall but sparsely distributed vegetation (i.e., thin forest) was classified as tundra. Where this happened, our algorithm incorrectly indicated a snow cover affected by wind (*tundra* or *prairie* snow). Another example of this sensitivity to the vegetation data can be seen in Fig. 10b, where there is a distinct change in the snow cover class along the Alaskan–Yukon border. We are aware of no real change in the snow in this location, and we assume it is because the sources for the vegetation maps changed at the border.

Other errors in the snow maps can arise from sparse meteorological station density. Legates and Willmott (1990) used averaging techniques to assign climate data to regularly spaced grid cells based on nearby meteorological stations. Where the station density was low, these interpolated values can be in considerable error. Such inaccuracies are particularly acute in the mountains where temperature and precipitation gradients are large and frequently not captured by the generally low-elevation meteorological datasets.

Despite these problems, our maps are probably accurate enough for most regional- and global-scale climate applications. Comparisons with direct data indicate correct classification of between 62% and 90% of the area. Better vegetation maps would increase this accuracy, as would improved climatological data. Better identification of the boundary values between classes might also increase the accuracy of the maps, but this would require collecting data from places representing the full range of snow cover types (and not just the four classes we looked at in Alaska) over a period of several years.

Our future efforts include trying to check the snow cover maps against better and more extensive snow datasets, and then optimizing the mapping algorithm so that the area of correctly classified snow is maximized. The extensive snow datasets needed to do this do not currently exist, but we have begun a project that will provide some data toward this end. In collaboration with the USDA-Soil Conservation Service, we have installed thermistors at the snow–ground interface at 40 sites in the western United States where air temperature and SWE are already recorded daily. Data from these sites will allow classification of the sites using air temperature, temperature drop across the snow, snow–ground interface temperature, and load. As shown above, these parameters have adequately discriminated the Alaskan snow covers. In combination with observations of snow stratigraphy and texture in the western United States, we will ascertain if index discrimination works outside of Alaska. If so, it may then provide a way of generating extensive snow class determinations from which ground-based snow cover class maps can be derived.

Data describing considerably more of the physical parameters for each snow class also needs to be collected. This includes bulk density, stratigraphic descriptions, thermal conductivity, and strength. Some of these data are available from the literature, if the type of snow cover can be identified. We have sufficient data on *tundra*, *taiga*, and *maritime* snow covers to make a reasonably comprehensive listing for those classes. However, for other types of snow covers, these data will have to be measured and a "dictionary" of properties for each class established.

6. Conclusions

A new classification system for seasonal snow covers is proposed. It has six classes: *tundra*, *taiga*, *alpine*, *prairie*, *maritime*, and *ephemeral*. Each class is defined by a unique ensemble of textural and stratigraphic characteristics including the sequence of snow layers, their thickness, density, and character and the crystal morphology and grain characteristics within each layer. The classes can also be derived using a binary system of three climate variables: winter wind, precipitation, and air temperature. The new system retains nomenclature found in older systems. Northern Hemisphere distributions of the snow cover classes were mapped using climatological data on a longitude 0.5° by latitude 0.5° grid. These maps were compared to maps prepared from snow cover data collected in Alaska and the former Soviet Union. For areas where both climatologically based and texturally based snow cover maps are available, there is 90% to 62% agreement.

Five of the six snow classes are found in Alaska. Between 1989 and 1992, hourly measurements consisting of 40 thermal and physical parameters including snow depth, temperature distribution in the snow, and basal heat flow were made on four of these classes. Snow stratigraphy and texture were measured every 40 days. Winter average values were computed from hourly measurements and used in a principal component factor analysis. Snow cover classes could be readily discriminated using these winter average values. Discrimination using the four most easily measured parameters (air temperature, snow depth, snow–ground interface temperature, and density) produced reliable results. Analysis of the hourly time series data indicated that a spot measurement of one or more thermal values (like the snow–ground interface temperature) could correctly identify the snow cover class better than 84% of the time. We conclude that under the new snow classification system 1) classes can readily be distinguished using simple thermal parameters, thus making it possible to classify a snow cover without having to dig a snow pit and make textural measurement, and 2) classes can be mapped with reasonable accuracy from basic climatic data (monthly mean temperature, precipitation, and wind speed) and the resulting snow class distributions can be used for regional and global climate modeling applications. We stress that an accurate widely distributed set of snow physical parameters is needed in order to conduct a more rigorous test of our snow class mapping algorithm, but we think that identifying the snow class using index values, such as the snow–ground interface temperature, is the key to developing this set.

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