

Distribution of seasonally and perennially frozen ground in the Northern Hemisphere

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ABSTRACT: This report provides an overall estimate of the extent of perennially, seasonally, and intermittently frozen ground of the exposed land surface in the Northern Hemisphere. Permafrost regions occupy about $24.91 \times 10^6 \text{ km}^2$, 25.6% (including glaciers and ice sheet) or $22.79 \times 10^6 \text{ km}^2$, 23.9% (excluding glaciers and ice sheet) of the land surface in the Northern Hemisphere. Using the 0 and 5°C isotherms of mean monthly air temperature, the extent of seasonally and intermittently frozen ground, respectively, can roughly be estimated over the land areas. The long-term average maximum extent of seasonally frozen ground is about $48.12 \times 10^6 \text{ km}^2$ or 50.5% of the exposed lands in the Northern Hemisphere. Intermittently frozen ground accounts for additional $6.27 \times 10^6 \text{ km}^2$ or 6.6% of the exposed lands in the coldest month of the year.

1 INTRODUCTION

The World Climate Research Programme (WCRP) Climate and Cryospheric (CliC) Project recently recognized that better understanding of the interactions and feedback of the land/cryosphere system and their adequate parameterization within climate and hydrological models are needed (Allison et al. 2000). Freeze/thaw cycles influence the thermal and hydraulic properties of the soil, which in turn have a significant impact on the surface energy and moisture balance, hence on weather and climate. Land surface characteristics such as surface radiation balance, and latent heat exchange will depend on whether water in the soil is liquid or frozen. Freezing of soil moisture reduces the hydraulic conductivity leading to either more runoff due to decreased infiltration or higher soil moisture content due to restricted drainage. The existence of a thin frozen layer near the surface essentially shuts off soil moisture exchange between the atmosphere and the deeper soils. Knowing whether the soil is frozen or not is important in predicting surface runoff and spring soil moisture reserve (Willis et al. 1961; Cary et al. 1978). Freezing and thawing processes have a considerable impact on ecosystem diversity and productivity. Greenhouse gas exchange between the atmosphere and the land surface may be minimal when the soil is frozen, but is accentuated in the early spring following thaw. Indeed, Skogland et al. (1988) noted this release as a “respiratory burst” (also see Sommerfeld et al., 1993). Vegetation growing seasons are determined primarily by the thaw period in permafrost and seasonally frozen ground regions. In turn, the timing of spring thaw and the duration of the growing season are strongly linked to the carbon balance (Oechel et al. 2000). Frolking et al. (1996) found that earlier spring thaws lead to significant increases in simulated net carbon uptake. The influence of seasonally and perennially

frozen ground extends to engineering in cold regions, trafficability for humans and other animals, and a variety of natural hazards and costs associated with living in cold regions.

It is clear that understanding the distribution and characteristics of permafrost and seasonal freezing and thawing processes, their seasonal and interannual variations in timing, duration, area extent and thickness, and potential response to climatic change are prerequisite for predicting the future changes in climate and in global environment. However, our knowledge of the distribution of frozen ground, especially seasonally and intermittently frozen ground, is very limited. The objective of this article is to investigate the distribution and characteristics of intermittently, seasonally, and perennially frozen ground in the Northern Hemisphere.

2 DATA SOURCES AND METHODOLOGY

Data used in this study include the following: (1) the digital version of the International Permafrost Association (IPA) circum-arctic map of permafrost and ground-ice conditions (Brown et al. 1998, Zhang et al. 1999), (2) NOAA weekly snow charts, provided by the EOS Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center, University of Colorado, Boulder, CO. (Armstrong 2001); and (3) mean monthly air temperature (Willmott & Matsuura 2000) and soil temperature.

2.1 *Permafrost – digital version of the IPA circum arctic map*

The International Permafrost Association (IPA) recently published a Circum-Arctic Map of Permafrost and Ground Ice Conditions (IPA map thereafter)

(Brown et al. 1997). The digital version of the IPA Map in ARC-INFO format was published on a CD for the 7th International Conference on Permafrost held in June, 1998, at Yellowknife, Canada (Brown et al. 1998). It is available on the Circumpolar Active Layer Permafrost System (CAPS) CD-ROM (IPA 1998). The digital version of the IPA map in ARC-INFO format was converted into a $0.5^\circ \times 0.5^\circ$ grid as well as NSIDC Equal Area Scalable Earth (EASE) Grid format at resolutions of 12.5 km and 25 km (Zhang et al. 1999). Information in the IPA map comprises permafrost extent and continuity, as well as the estimated excess ground ice content, the northern limit of trees, the northern limit of subsea permafrost, and the extent of permanent sea ice cover. Permafrost thickness and temperature at the base of the layer of annual temperature fluctuation are also included for selected areas and sites. In this study, we make use of areal extent of the permafrost region in the Northern hemisphere based on the NSIDC EASE-Grid version at 25 km resolution. Data are available via ftp at: ftp://ftp.ngdc.noaa.gov/Snow_Ice/Permafrost/.

2.2 Mean monthly air and soil temperatures

Data of mean monthly air temperature (MMAT) and number of days of near-surface soil freeze are available from some of the former Soviet Union standard meteorological stations. Soil temperature at these stations was measured routinely for many years every six hours at depths of 0, 5, 10, 15, 20, and up to 320 cm. Frozen ground is defined when daily mean soil temperature is below the freezing point. Detailed data collection procedures are described by Gilichinsky et al. (1998) and Zhang et al. (2001).

The data set of MMAT in the Northern Hemisphere was obtained from the Center for Climatic Research, University of Delaware, at "<http://climate.geog.udel.edu/~climate/>" and made available by Willmott and Matsuura (2000). Original data sources used for this gridded climatology of MMAT include both Global Historical Climatology Network (GHCN version 2) and Legates and Willmott's (1990) station records of monthly and annual mean air temperature. Station averages of air temperature were interpolated to a 0.5° by 0.5° latitude/longitude grid, where the grid nodes are centered on 0.25° . In this study, the data set of MMAT was used to map the extent of seasonally and intermittently frozen ground in the Northern Hemisphere.

2.3 Seasonal snow cover – NOAA snow chart

The NSIDC has developed the Northern Hemisphere EASE-Grid Weekly Snow Cover and Sea Ice Extent data set for the period from 1972 to 1997 (Armstrong & Brodzik 2002). Snow cover extent is based on the

digital NOAA National Environmental Satellite, Data, and Information Service (NESDIS) Weekly Northern Hemisphere Snow Charts, revised by Robinson et al. (1993) and regrided to the NSIDC EASE-Grid at 25 km resolution (Armstrong & Brodzik 1995). The original NOAA-NESDIS weekly snow charts are based on a manual interpretation of visible imagery. According to Robinson et al. (1993), the extent of snow cover over the Northern Hemisphere land surface is greatest in January. In this study, the extent of average monthly snow cover in January for the period from 1972 through 1997 was used for assessing the distribution of seasonally frozen ground in the Northern Hemisphere.

3 RESULTS

3.1 Perennially frozen ground or permafrost

Mapping permafrost distribution at local-, regional-, and global-scale has been conducted and summarized by many investigators during the past few decades (see Zhang et al. for a detailed review 2000). However, the earlier studies were based upon very limited field data regarding the actual occurrence of permafrost. Classifications of permafrost categories were qualitative, based upon climatic (air temperature) data, when available, and with location of zonal boundaries guided in part by topography. Recently, a single comprehensive and authoritative permafrost map for the Northern Hemisphere was published by the International Permafrost Association (Brown et al. 1997).

Figure 1 shows permafrost regions in the Northern Hemisphere obtained from the IPA and reformatted in the NSIDC EASE-Grid (Zhang et al. 1999). Overall, permafrost exists at high latitudes and high altitudes. The circumpolar region is dominated by continuous permafrost (>90% of area underlain by permafrost) and in general permafrost becomes discontinuous (50%–90%), sporadic (10% to 50%), and isolated (<10%) as one moves southwards and at lower elevation. More discussions on permafrost distribution with latitudes, longitudes, and elevation in the Northern Hemisphere are provided by Zhang et al. (1999).

Estimates of the total area of permafrost regions have long been a challenge (see Zhang et al. 2000). One technical problem is whether to include or exclude glaciers and ice sheets as permafrost. Washburn (1979) and Brown and Haggerty (1998) included glaciers and ice sheets as permafrost in their statistics. Zhang et al. (1999) argued that glaciers and ice sheets should be excluded from permafrost according to the definition of permafrost (ground, either soil or rock, that remains at or below 0°C for at least two years regardless as to whether or not it contains ice, see Associate Committee on Geotechnical Research,

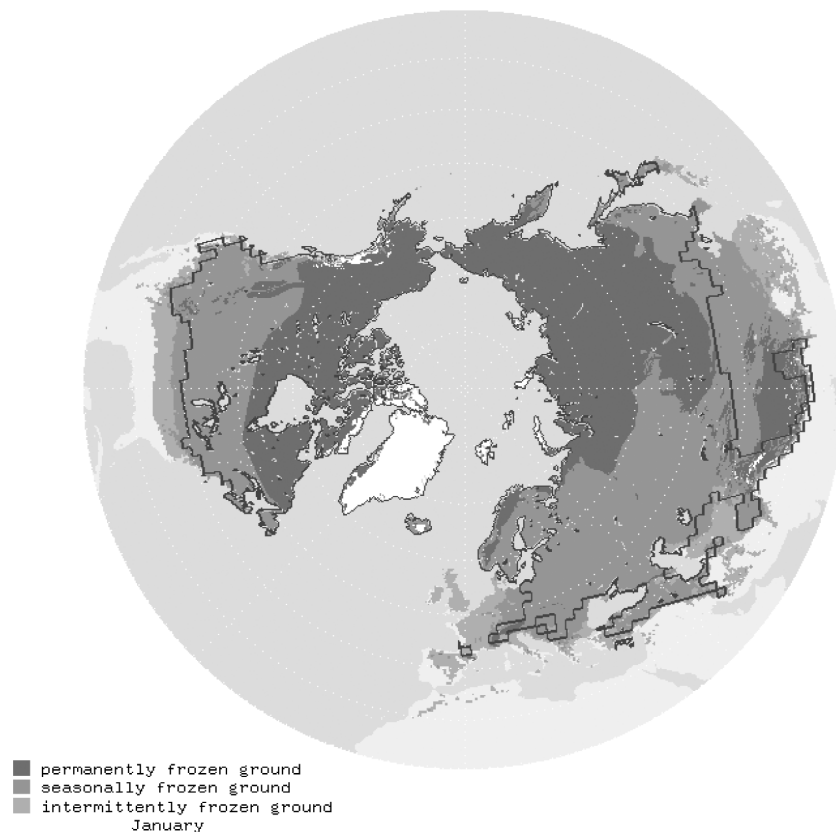


Figure 1. Distribution of permafrost, average maximum extent of seasonally and intermittently frozen ground (1950–1996), and average maximum snow extent (Solid line 1972–1995) in the Northern Hemisphere.

Table 1. Statistics of permafrost areas in the Northern Hemisphere.

Total land area (10^6 km^2)	Permafrost area			Values reported by
	Area (10^6 km^2)	Fraction* (%)		
Including glaciers, and ice sheets	100.30	24.67	24.6	Washburn (1979)
	100.407	25.49	24.4	Brown and Haggerty (1998)
	97.46	24.91	25.6	This study
Excluding glacier, and icesheets	98.18	22.55	23.0	Washburn (1979), Modified in this study**
	98.287	23.37	23.8	Brown and Haggerty (1998), modified in this study**
	95.34	22.79	23.9	Zhang et al. (1999)

* Total area in the permafrost regions divided by the total land area in the Northern Hemisphere.

** Areas of glaciers and ice sheets (about $2.12 \times 10^6 \text{ km}^2$) are excluded from their earlier estimates for both total land area and permafrost area in the Northern Hemisphere.

1988). Here, we summarize the statistics for both approaches (Table 1). For the case including glaciers and ice sheet, permafrost regions occupy about $24.91 \times 10^6 \text{ km}^2$ or 25.6% of the land surface in the Northern Hemisphere. These results are within three percent of the estimates by Washburn (1979) and Brown and Haggerty (1998). If the total area of glaciers and ice sheets (about $2.12 \times 10^6 \text{ km}^2$) in the Northern Hemisphere is excluded from the statistics of Washburn (1979) and Brown and Haggerty (1998), their results are also very close to those by Zhang et al. (1999). The fraction of permafrost regions in this study is about one percent higher than those by

Washburn (1979) and Brown and Haggerty (1998). The major difference is that the total land area for the Northern Hemisphere used in this study is about three percent lower than the values by Washburn (1979) and Brown and Haggerty (1998). The value used in this study is based upon the most recent available data from a 1 km resolution global land cover characteristics data base (USGS 1999), supported by the Advanced Very High Resolution Radiometer (AVHRR) images. We also exclude the large inland water bodies, such as large lakes and rivers, from the total land area. The term “exposed land” as used here, excludes glaciers, ice sheets, and large inland water bodies.

Another noteworthy issue is to distinguish between the concepts of “permafrost regions” and “areas underlain by permafrost”. Outside of the continuous permafrost region, actual permafrost underlies less than 90% of the ground surface, and this proportion decreases to 0% at the southern limit of the permafrost. This issue has been discussed in considerable detail by Zhang et al. (2000) and the results indicate that the actual area underlain by permafrost is estimated to be about 12.21 to $16.98 \times 10^6 \text{ km}^2$, or 12.8% to 17.8% of the exposed land area in the Northern Hemisphere.

3.2 Seasonally and intermittently frozen ground

The extent of seasonally and intermittently frozen ground is mapped using mean monthly air temperature. To do so, a relationship between the near-surface soil freeze/thaw status and MMAT needs to be established. Ground-based measurements at selected stations and sites indicate that soils at 5 cm depth experience freezing for at least two to three weeks when the mean monthly air temperature is at or near 0°C (Fig. 2). Soils at 5 cm depth may experience freeze/thaw cycles even though mean monthly air temperature is as high as -10°C (Fig. 2). In this study, seasonally frozen ground is defined as the near-surface soil that experiences more than 15 days of freeze per year, while intermittently frozen ground is defined as the near-surface soil that experiences from 1 to 15 days of freeze per year. Using these definitions, the extent of seasonally frozen ground is recognized as region north of the 0°C isotherm of MMAT obtained from surface air temperature climatology (Willmott & Matsuura 2000). The extent of the intermittently frozen ground is determined as the zone between 0 and 5°C isotherms of MMAT. The active layer over permafrost is included as seasonally frozen ground.

Compared to the distribution of permafrost, seasonally and intermittently frozen ground extends to lower latitudes and altitudes (Fig. 1). According to values generated using the method described above (Fig. 2), the extent of seasonally frozen ground over the Northern Hemisphere lands is greatest in January. On average (1950–1996), approximately $48.12 \times 10^6 \text{ km}^2$ or 50.5% of the exposed land in the Northern Hemisphere experiences seasonal freezing and thawing in January. It should be noted that the active layer over permafrost is considered as part of seasonally frozen ground in this study. Intermittently frozen ground accounts for additional $6.27 \times 10^6 \text{ km}^2$ or 6.6% of the exposed land in January.

Geographically, the average southern boundary of the maximum extent of seasonally frozen ground is approximately along 37°N latitude in North America except in the Rocky Mountains area where the southern boundary extend to about 30°N latitude due to the

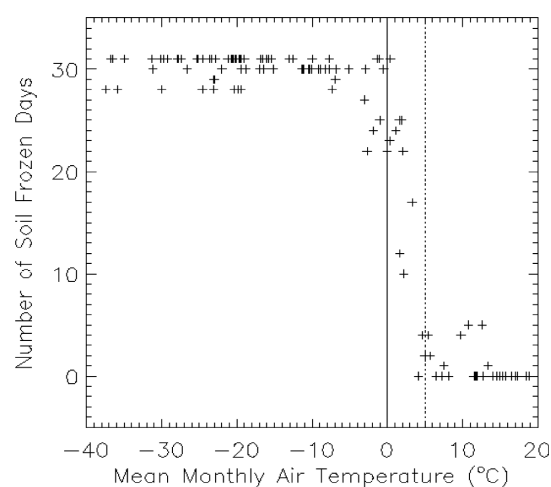


Figure 2. Relationship between mean monthly air temperature and monthly total number of days of soil freezing at 5 cm depth at several Russia hydrometeorological stations from 1966 to 1990.

effect of higher elevation (Fig. 1). In Europe, the southern boundary is roughly along the 40°N latitude. Over central Asia, the southern boundary moves to the south of 30°N latitude, again, due to the elevation effect. The boundary moves northwards to about 35°N latitude in eastern Asia as elevation decreases. The southern boundary in Asia is in good agreement with the boundary drawn by Zhou et al. (2000). Intermittently frozen ground generally occurs south of the southern boundary of seasonally frozen ground, especially in North America and Asia.

Seasonal snow cover has a great impact on distribution of permafrost and seasonally frozen ground due to its role on surface energy balance. The maximum extent of seasonal snow cover, on average over the period from 1972 through 1997, is approximately $42.78 \times 10^6 \text{ km}^2$, about 11% less than the extent of seasonally frozen ground. In North America, the boundary of maximum snow cover extent is roughly along the 40°N latitude for regions east of the Rocky Mountains, slightly north of the southern boundary of the seasonally frozen ground (Fig. 1). In the western United States and much of the Europe, mean snow line approximately coincides with the southern boundary of seasonally frozen ground. In Asia, except the Kashmir Plateau and the Himalaya Range, mean snow line is well north of the southern boundary of the seasonally frozen ground. The major part of the Qinghai-Xizang (Tibetan) Plateau is permafrost region without consistent snow cover. Snow-free conditions on the Qinghai-Xizang Plateau and much of northern China are very favorable for development of permafrost and seasonally frozen ground, respectively.

Figure 3 illustrates monthly variations of frozen ground and snow cover extent in the Northern Hemisphere. Overall, the extent of frozen ground is

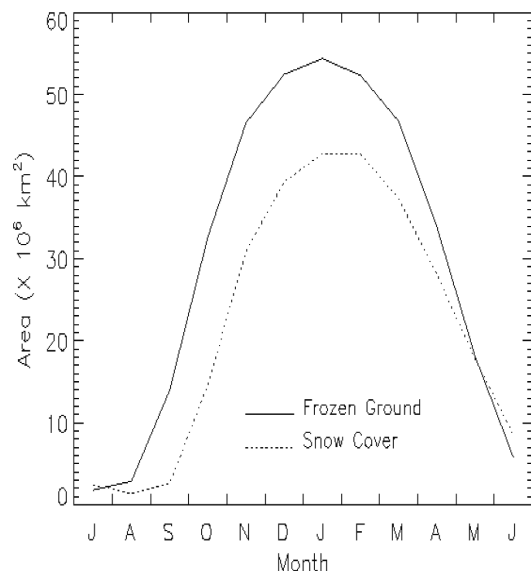


Figure 3. Monthly variations of the average extent of frozen ground (from 1950 to 1996 for both seasonally and intermittently frozen ground) and snow cover (from 1972 to 1995) in the Northern Hemisphere.

larger than the extent of snow cover. This generally indicates that soils freeze before snow covers the land surface. Using passive microwave remote sensing data, Zhang and Armstrong (2001) demonstrate that the near-surface soil freezes, on average, approximately four days before snow covers the land surface over the contiguous United States. In spring, frozen ground over snow-free land appears to retreat rapidly due to the increase in air temperature, while soil freeze/thaw status under snow cover is still an unanswered question from this study. The extent of frozen ground reaches minimum in July.

It has to be recognized that the estimate of the extent of seasonally frozen ground using 0°C mean monthly air temperature is a rough, preliminary approximation. There are many other factors such as snow cover, vegetation, soil type, soil moisture, and geological structure. Accurate estimation of the extent of seasonally frozen ground needs further investigation.

4 SUMMARY

This study provides an overall estimate of the extent of perennially, seasonally, and intermittently frozen ground of the exposed land surface in the Northern Hemisphere. The results can be summarized as follows:

- 1) Permafrost regions occupy about $24.91 \times 10^6 \text{ km}^2$ or 25.6% of the land surface in the Northern Hemisphere¹ (including glaciers and Ice Sheets), which is very close to the estimates by Washburn (1979) and Brown and Haggerty (1998). For comparison by excluding glaciers and ice sheets,

permafrost regions occupy approximately $22.79 \times 10^6 \text{ km}^2$ or 23.9% of the exposed land surface (Zhang et al. 1999). Since permafrost does not exist everywhere in permafrost regions, permafrost actually underlies approximately from 12.21 to $16.98 \times 10^6 \text{ km}^2$ or from 12.8% to 17.8% of the exposed land area (Zhang et al. 2002).

- 2) On average, the maximum extent of seasonally frozen ground is approximately $48.12 \times 10^6 \text{ km}^2$ or 50.5% of the exposed lands in the Northern Hemisphere. Intermittently frozen ground accounts for additional $6.27 \times 10^6 \text{ km}^2$ or 6.6% of the exposed lands in the coldest month of the year.
- 3) Geographically, the average southern boundary of the maximum extent of seasonally frozen ground is within 35°N to 40°N latitudes except high mountain areas where the boundary moves to south of 30°N latitude due to the impact of high elevation.
- 4) Maximum extent of seasonal snow cover is, on average from 1972 through 1995, approximately $42.78 \times 10^6 \text{ km}^2$, about 11% less than the maximum extent of seasonally frozen ground. Compared to the average southern boundary of seasonally frozen ground, the mean snow line is far north (up to 15° in latitude) in Asia, and roughly coinciding or slightly north (2° to 3° in latitude) in Europe and North America.

This study indicates that using the 0°C and 5°C isotherms of mean monthly air temperature, the extent of seasonally and intermittently frozen ground, respectively, can roughly be estimated over the Northern Hemisphere. This method may be further calibrated and validated as data sets become available. Due to the complex influence of snow cover on the ground thermal regime, it is possible that soils may or may not be frozen under thick snow cover. Certainly, soil freeze/thaw status under snow cover cannot be determined from this method alone although we have found that soil generally freezes before snow cover is established. Depth of seasonally freezing and thawing ground is one of the important parameters needed for other studies and applications such as surface energy and water balance, surface and subsurface hydrology, plant growth, carbon cycle, and related engineering concerns. Seasonal freezing and thawing processes have received relatively great attention in permafrost regions but very little in seasonally frozen ground regions. Finally, the response of seasonally and intermittently frozen ground to changes in air temperature and seasonal snow cover needs further investigation.

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