Article

Spatial Distribution and Variation Characteristics of Permafrost Temperature in Northeast China

Wei Shan 1,2,3,*, Chengcheng Zhang 1,2,3, Ying Guo 1,2,3, Lisha Qiu 1,2,3, Zhichao Xu 1,2,3 and Yan Wang 1,2,3

1 Institute of Cold Regions Science and Engineering, Northeast Forestry University, Harbin 150040, China; chengcheng@nefu.edu.cn (C.Z.); ying-guo@nefu.edu.cn (Y.G.); lisa-qiu@nefu.edu.cn (L.Q.); xzc@nefu.edu.cn (Z.X.); 201715901@stu.ncwu.edu.cn (Y.W.)
2 Ministry of Education Observation and Research Station of Permafrost Geo-Environment System in Northeast China (MEORS-PGSNEC), Harbin 150040, China
3 Collaborative Innovation Centre for Permafrost Environment and Road Construction and Maintenance in Northeast China (CIC-PERCM), Harbin 150040, China
* Correspondence: shanwei@nefu.edu.cn

Abstract: Frozen soil is an important environmental factor in cold regions. Warming climate will increase the risk of permafrost thawing, i.e., accelerated carbon release, reduced super-frozen soil water, intensified desertification and destruction of infrastructure. Based on MOD11A2 and MYD11A2 products of MODIS Terra/Aqua, the distribution and change of surface frost number under the influence of normalized difference vegetation index and forest canopy closure in Northeast China from 2003 to 2019 were produced. From 2012 to 2015, the area of the regions where the surface frost number was higher than 0.5 continued to decrease in Northeast China. Taking 2013 as the time turning point, two periods of changes in the distribution of surface frost number in Northeast China were divided, namely, into 2003–2013 and 2014–2014. The spatial distribution of permafrost temperature is simulated by establishing the numerical relationship between the surface frost number and the annual average ground temperature of permafrost. From 2003 to 2019, the area of permafrost changed from 32.77 × 10^4 to 27.10 × 10^4 km^2. The distribution characteristics show that the area with permafrost temperature below −4 °C accounts for 0.1%, and below −3.0 °C accounts for 3.45%. The permafrost with lower temperature is mainly distributed in the Greater Khingan Mountains, from the northernmost Mohe to the Aershan in the middle of the ridge. The area where the permafrost temperature ranges from −2 to 0 °C is the largest, accounting for 73.81% of the total area. The distribution of permafrost temperatures in the Greater Khingan Mountains is mainly between −1.5 and −3 °C, while that in the Lesser Khingan Mountains is mainly between −2.0 and 0 °C. The altitude is the main factor controlling the permafrost temperature distributed at high latitudes in Northeast China. This work will provide more detailed basic data for regional research on frozen soil and the environment in Northeast China.

Keywords: Northeast China; permafrost temperature; surface frost number; normalized difference vegetation index

1. Introduction

Permafrost refers to soil or rock formations with a temperature below 0 °C and containing ice [1]. Permafrost is mainly distributed in high latitude regions, such as northern Eurasia and northern North America and high mountain plateaus in middle and low latitudes, the outer edge of the Antarctic ice sheet, and the seafloor of the polar continental shelf [2,3]. The permafrost distribution area of China accounts for about 10% of the world’s and is the third largest permafrost country in the world. The permafrost is mainly distributed in the Qinghai-Tibet Plateau, the northern northeast, and the alpine plateau areas of the central and western regions [4,5]. Due to climatic conditions and regional differences, the types of permafrost are very different. In a certain region, permafrost is not
a completely continuous distribution. Affected by special geological, structural, and local climate characteristics, the regions without permafrost become thaw zones, where seasonal permafrost generally develops. Permafrost regions includes the area with permafrost and the thaw area without permafrost. The percentage of permafrost in the permafrost area is called the continuity of permafrost. In the initial stage of permafrost mapping in China, the classification criteria for permafrost distribution types were mostly based on the continuity of the distribution area of the permafrost [6,7]. In this period, permafrost distribution mapping was manually drawn, which was mainly based on limited permafrost survey data, as well as the understanding of the temperature conditions, and topographical features that affect the formation and distribution of frozen soil.

With the development of computer technology and remote sensing technology, and the continuous improvement of the permafrost distribution model, people began to use the combination of GIS and models for permafrost mapping. Empirical models widely used in permafrost mapping include the elevation model [8], equivalent elevation model [9], frost number model [10], Stefan formula [11], TTOP (temperature at the top of permafrost) model [12], GIPL-1.0 model [13], etc. The commonly used physical models include the SiB2.5 model [14], CLM4 model [15–17], Noah model, etc. In the early days, based on the combination of ground observation data and models, Lü [18] and Zhang [19,20] explored the applicability of the frost number model in Northeast China and the variation characteristics of permafrost in the past 30 years. Cao [21] considered more variables in the model and compiled a high-resolution permafrost zoning index map for the Qinghai-Tibet Plateau, which reflects the spatial differences of permafrost well. Gruber [22] and Nan [23], who combined the models with topographic data (elevation, slope, aspect, etc.) and applied it to permafrost mapping, drew high-resolution global and Qinghai-Tibet permafrost distribution maps, respectively. Using remote sensing surface temperature as an important data source of permafrost indicator factors, applying the TTOP model, and frost number model in the simulation of permafrost distribution around the Arctic and China, the results obtained were good and contributed greatly to the accuracy of permafrost mapping [20,24–28]. In addition, geophysical exploration methods, such as resistivity bathymetry [29], ground penetrating radar [30], electromagnetic induction [31], and radiometric techniques [32], as well as emerging airborne electromagnetic methods [33], can be used in permafrost distribution mapping. Regional permafrost distributions with higher spatial resolution were obtained, but these methods have limited sampling range and cannot be used to judge the occurrence of large-scale permafrost. At present, most of the studies on the permafrost distribution in China are concentrated in the Qinghai-Tibet Plateau. This is because research on the permafrost in Northeast China started relatively late, and the ground observation data were lacking; on the other hand, the occurrence conditions of permafrost in high-latitude regions are different from on the Qinghai-Tibet Plateau, and the applicability of existing research results in Northeast China needs further research.

As an important characterization of permafrost, permafrost temperature can be used to evaluate the stable state of permafrost. On the other hand, ground temperature is an important parameter in the foundation design and construction of various engineering buildings in cold regions. Under the influence of climate warming and human activities, thawing of permafrost will affect regional ecology, hydrology, carbon cycle, landscape pattern, as well as geomorphological processes and engineering construction [34–40]. In a previous study, Wu et al. [41] established a model of the relationship between the measured annual average ground temperature, altitude, and latitude along the Qinghai-Tibet Highway. The simulation results can basically reflect the distribution of permafrost in the area along the route, but this method only roughly establishes a mapping relationship between altitude, latitude, and ground temperature. The overall trend of the ground temperature of the permafrost layer in Northeast China obeys a certain latitude zone law. The law is reflected under the comprehensive action of a series of factors, such as lithology, water content, vegetation, snow cover, surface water, groundwater, slope, and altitude. Due to the different factors in a small area, the ground temperature is also
inconsistent, and even has large changes [42]. In the past nearly 60 years, the temperature monitoring of permafrost in Northeast China has mainly come from local areas, where along roads/railways and different permafrost regions [42,43], these data and information will help us to better understand spatial characteristics of permafrost in Northeast China.

In this study, based on the surface frost number model corrected for normalized difference vegetation index and forest canopy closure, we established a regression statistical relationship with the permafrost temperature along multiple highways to simulate the large-scale spatial distribution of permafrost temperature in Northeast China. Then, the characteristics of the permafrost temperature distribution were analyzed. The large-scale distribution mapping of permafrost temperature in Northeast China with higher spatial resolution (1 km), providing basic data for research on resource development, ecological protection, climate change, and engineering construction and maintenance in permafrost regions.

2. Data and Methods

2.1. Study Area

The study selects Northeast China as the study area, which includes Heilongjiang Province, Jilin Province, and Liaoning Province, and Hulunbuir City, Hinggan League, Tongliao City, Chifeng City, and Xilingol League of the Inner Mongolia Autonomous Region, with a total area of $147 \times 10^4$ km$^2$. Northeast China has a high latitude and is affected by alternating high and low pressures and monsoons in inland and ocean areas. The annual average temperature is low and the annual range is large. The winter is cold and long, and the climate is cold and wet [44], displaying a continental monsoon climate. The terrain is dominated by plains, hills, and mountains, with the Changbai Mountain in the southeast, the Lesser Khingan Mountains in the northeast, and the Greater Khingan Mountains in the northwest. The Northeast Plain and the Inner Mongolia Plateau are distributed among the mountains. The overall distribution of landforms is a semi-circular pattern being high in northeast, southeast, and northwest, and low in south [45].

The spatial distribution of vegetation types is closely related to the terrain. The vegetation of the Greater Khingan in the north is mostly coniferous forest, and in the Lesser Khingan Mountains and Changbai Mountain is mostly coniferous broad-leaved mixed forest. Among them, broad-leaved forests are distributed in the south of the Lesser Khingan Mountains and some regions in the south of the Greater Khingan Mountains. The west slope and southwest slope of the Greater Khingan Mountains are typical grassland and meadow concentration areas, and shrubs are distributed in the ecotone with forests in the Greater Khingan Mountains. Affected by the hydrogeological conditions and the stable temperature inversion layer which is widely distributed on the underlying surface of the atmosphere, permafrost in Northeast China generally develops in mountain depressions, valley terraces, and swamp areas covered by peat layers. The surface covering with vegetation (mosses, grass, or forest) have a significant impact on the hydrothermal process and spatial distribution of permafrost [46,47].

2.2. Data Sources

Remote sensing data include the digital elevation model (DEM), land surface temperature (LST), and normalized difference vegetation index (NDVI). The DEM comes from the Shuttle Radar Topography Mission (SRTM) data of the US space shuttle Endeavour, which uses the WGS84 ellipsoid projection with a resolution of 500 m (http://www.resdc.cn/data.aspx?dataid=217, accessed on 2 March 2020). MODIS (Moderate-Resolution Imaging Spectroradiometer) land standard products (MODIS LST and MODIS NDVI) are from NASA’s Land Processes Distributed Active Archive Center (LP DAAC/NASA), time range from 2001 to 2020, the temporal resolutions are 8 days and monthly, and the spatial resolution is 1000 m (https://lpdaac.usgs.gov/, accessed on 2 April 2021).

The monitoring data of ground temperature comes from the Field scientific observation and research station of the Ministry of Education—Geological environment system of permafrost area in Northeast China (FSSE-PFNEC). The monitoring sites are located
The potential thermal interference of drilling on the temperature distribution of the permafrost can be eliminated in about one year, and the data of the second year after the start of monitoring is selected. Excluding some sections with special geological conditions, the drilling depth cannot reach or penetrate the permafrost layer. When there are multiple monitoring points in the same section, the monitoring data of natural holes that are farther away from the road and less disturbed are selected. The monitoring equipment is a series of thermistor temperature probes buried at different depths in the soil layer, the sampling frequency is 1 time per day, and the data can be transmitted wirelessly. In order to avoid the influence of seasonal changes on soil temperature, the drilling depth can reach or penetrate the permafrost layer, and the ground temperature at a depth of 12 m is used as the permafrost temperature. As in the Wallagan-Zhangling section of Beijing-Mohe Highway G111, due to complex geological conditions, the drilling depth cannot reach more than 12 m, and the ground temperature of 1 m below the floor of the permafrost active layer is used as the permafrost temperature. Figure 1 shows the location of boreholes along the highway in the Northeast permafrost region. In some areas, the burial depth of permafrost exceeds 20 m, which is less affected by the external environment. Remote sensing and ground temperature monitoring data would not measure deeper soil temperature, thus the research object mainly reflects the temperature distribution of near-surface permafrost.

**Figure 1.** Spatial distribution of DEM in the study area and road and borehole locations.

### 2.3. Methods

The daily products of MODIS LST may be missing local values due to cloud coverage, but it is very unlikely that there are clouds in the same area for 8 consecutive days. The correlation between remote sensing LST and meteorological station ground temperature on the long period time scale is obviously better than that of short period [48,49]. Therefore, 8-day synthetic products MOD11A2 and MYD11A2 of MODIS Terra/Aqua covering the study area from 2003 to 2019 were selected (band numbers: h25v03, h26v03, h25v04, h26v04, and h27v04). We utilized MODIS Reprojection Tool (MRT) tool to perform band selection, format conversion, splicing, and projection on the original data. After cutting according to the study area vector in ArcGIS software, the Cell Statistics tool under the software is used to calculate LST—the arithmetic mean of MOD11A2 and MYD11A2 of the same band number and the same time.
Satellite sensors estimate the surface temperature by detecting the thermal radiation intensity of the surface. Different types of surface coverage will lead to different thermal radiation, and the objects represented by the retrieved surface temperature are also different. In densely vegetated areas, the surface detected by the sensor mainly refers to the vegetation canopy surface, and the surface temperature basically refers to the vegetation canopy temperature. With the different degrees of canopy covering the ground, the surface temperature also represents the mixed average temperature of different degrees of vegetation canopy temperature and ground temperature under the vegetation. The relationship between MODIS LST and meteorological station ground temperature is quite different due to the influence of vegetation coverage [50]. Therefore, taking the normalized difference vegetation index and forest canopy closure as the vegetation factor—$\varepsilon_{fcc}$, which, respectively, reflects vegetation coverage and the degree of canopy covering the ground, the applicability of the MODIS surface temperature product in Northeast China was adjusted.

The average monthly changes of the NDVI of six regions in the study area from 2003 to 2019 (as shown in Figure 2a) showed that the NDVI began increasing significantly from May, and reached the maximum value from June to August. The maximum value of NDVI in Tahe was in June (NDVI = 0.905), in other regions they were in July–August (NDVI > 0.6). Then, NDVI decreased rapidly in September–October. By November, the NDVI value had decreased to the level in May. After comprehensively considering the average monthly changes of NDVI in 6 regions, the vegetation growth season in the study area was set as May–September. Therefore, the average value of NDVI in each growing season—$MANDVI_G$, was chosen to represent the overall state of inter-annual vegetation coverage. The NDVI value is between $-1$ and $1$, and the negative value indicates that the ground cover is cloud, water, snow, etc. When NDVI = 0, it means that the ground surface is rock or bare soil, etc., and the surface temperature is basically the same as the ground temperature or bare rock surface temperature. Positive values indicate vegetation cover, and increase as the coverage increases, and surface temperature refers to the mixed average value of vegetation canopy temperature and ground temperature under vegetation. Therefore, 1 is added to $MANDVI_G$ in the calculation, and vegetation factor $E_t$ is shown in Formula (1).

![Figure 2. (a) Average monthly NDVI in Northeast China from 2003 to 2019; (b) distribution of vegetation types in Northeast China.](image)

The surface vegetation factor is shown in Formula (1).

$$E_t = \varepsilon_{fcc} \times [(MANDVI_G)_t + 1]$$  \hspace{1cm} (1)

where: $E_t$ is the surface vegetation factor, $t$ is the time period ($t = 2003, 2004, \ldots, 2020$), and $\varepsilon_{fcc}$ is the forest canopy closure. According to the stand spatial structure [51,52] of the study area and the regulations of FAO, the average $\varepsilon_{fcc}$ in the study area ranges from 0.2 to 0.69,
which is moderate canopy closure. For the convenience of calculation, $\varepsilon_{fc}$ is taken as the constant value is 0.56.

$Fn$ (Formula (2)) can be used to evaluate the continuity of permafrost distribution [10], where $DDT$ is the surface melting index, which is calculated from the daily cumulative value of surface temperature greater than 0 °C from 1 January to 31 December of the current year, as shown in Formula (3); $DF$ is the surface freezing index, which is calculated from the cumulative value of daily absolute value of surface temperature less than 0 °C from July 1 of each year to June 30 of the next year, as shown in Formula (4).

$$
Fn = \frac{\sqrt{DDF}}{\sqrt{DDF} + \sqrt{DDT}}
$$

$$
DDT = \sum_{m=1}^{12} (\text{LST}_m \times N) (\text{LST}_m > 0 \degree C)
$$

$$
DDT = \sum_{m=1}^{12} \left| (\text{LST}_m) \times N \right| + \sum_{m=1}^{6} \left| (\text{LST}_m)_{m+1} \times N \right| (\text{LST}_m < 0 \degree C)
$$

We define the $Fn$ under the influence of $E_t - Fnc$, as shown in Formula (5).

$$
Fnc = E_t \times Fn
$$

where, $\text{LST}_m$ is the monthly average value of 8-day data products, $m$ is the month, $N$ is the days of the corresponding month, and $t$ is the year.

3. Results

3.1. Surface Frost Number and Permafrost Temperature

The surface frost number can reflect the surface thermal state, the possibility of permafrost existing is high [53] when the freezing index is greater than the melting index (i.e., surface frost number > 0.5). The surface frost number considering the influence of NDVI and forest canopy closure-$Fnc$ is divided into two levels: greater than 0.55 and 0.5–0.55. We can see from the area changes from 2003 to 2019 (as shown in Figure 3b) that, the area of the two levels of surface frost number areas has an obvious continuous downward trend from 2012 to 2014.

![Figure 3](image_url)

**Figure 3.** (a,b) Distribution of average surface frost numbers in Northeast China from 2014 to 2019; (c) spatial distribution trend of surface frost numbers; (d) area change curves of different surface frost number.
Taking 2013 as the time node for the phased changes of the $F_{nc}$, it is divided into two time periods: 2003–2013 and 2014–2019. The area of $F_{nc}$ greater than 0.55 from 2014 to 2019 was lower than the average of 2003–2013. The continuous decrease in the $T_p$ where:

\[ $T_p = -52.66 \times F_{nc} + 26.09$ \]

where $T_p$ is the permafrost temperature and $F_{nc}$ is the surface frost number.

![Figure 4](image)

**Figure 4.** (a) Linear relationship curves between surface frost number and permafrost temperature; (b) distribution of permafrost temperature.

### 3.2. Temperature Distribution and Characteristics of Permafrost

According to the linear relationship equation between the surface frost number and the frozen soil layer temperature in the study area (Formula (6)), the spatial distribution map of permafrost temperature in Northeast China is obtained (as shown in Figure 5). The distribution of permafrost temperature is divided at intervals of 0.5 °C, and the geographic information corresponding to the different permafrost temperature is drawn, respectively. The temperature distribution of permafrost is divided at intervals of 0.5 °C, and the corresponding geographical information of different permafrost layer temperatures is drawn,
respectively. The south boundary of permafrost in the Greater Khingan Mountains extends to Arshan, and the permafrost in other mountains, such as Huanggangliang mountains and Changbai Mountain and Yichun region of the Lesser Khingan Mountains, are also reflected. Among them, there are few areas where the permafrost temperature is lower than −4.5 °C, and the area is only $1.82 \times 10^2 \text{ km}^2$, accounting for 0.067% of the total area, mainly distributed in the north foot of the Greater Khingan Mountains and sporadically distributed in Changbai Mountain. The area below −3.0 °C is $1.84 \times 10^2 \text{ km}^2$, accounting for 6.80% of the total area. Although it is sporadically distributed in the Lesser Khingan Mountains and Changbai Mountain, it is still mainly distributed in the Greater Khingan Mountains, from Mohe at the northernmost end to Aershan in the middle of the ridge; the area below −2.0 °C is $8.61 \times 10^2 \text{ km}^2$, accounting for 31.76% of the total area; the area below −1.0 °C is $17.84 \times 10^2 \text{ km}^2$, with an area of $9.27 \times 10^2 \text{ km}^2$ at −1.0 to 0 °C, the latitude of permafrost in the Lesser Khingan Mountains is dominated by the temperature range of −2 to 0 °C, and the area of permafrost temperature in the range of −2 to 1 °C and −1.0 to 0 °C is almost the same. There is also sporadic permafrost distribution in Huanggangliang at the southernmost end of the Greater Khingan Mountains, with the temperature of −1.0 to 0 °C. The permafrost with temperature equal to or higher than −1.0 °C is defined as warm temperature permafrost [58,59]. Then, the warm temperature permafrost accounts for 34.19% of the permafrost area in Northeast China.

![Figure 5](image)

**Figure 5.** (a) Spatial distribution of permafrost temperature; (b) longitude distribution of permafrost temperature; (c) latitude distribution of permafrost temperature in Northeast China.

From 2014 to 2019, the area of permafrost with temperature lower than 0 °C was $27.10 \times 10^2 \text{ km}^2$, which is basically consistent with the total area of permafrost in Northeast China estimated based on surface land temperature and surface frost number model [20,53]. Ignoring the change of permafrost temperature under environmental and climatic conditions from 2003 to 2019, Formula (6) is used to calculate that the distribution area of permafrost in Northeast China from 2003 to 2013 was $32.77 \times 10^2 \text{ km}^2$; the distribution area and proportion of each frozen soil temperature interval are shown in Figure 6. The distribution area of permafrost temperature in the temperature range of −3 to 0 °C accounts for the most at about 86.5–94.1% of the total area. The area of permafrost temperature lower than −4 °C is very small, and the area decreases with time. The area of permafrost temperature above −2 °C increases, and the permafrost temperature in the study area increases.
The influence of aspect on the distribution of permafrost is not obvious (as shown in Figure 7b). The proportion of shady slopes and sunny slopes is 50.9 and 49.1%, respectively. The slight difference between shady slopes and sunny slopes is that shady slopes receive less solar radiation than sunny slopes. This may be due to the use of DEM with the same resolution as the remote sensing image. The slope and aspect obtained based on 1-km resolution DEM will weaken some original information of the terrain. Permafrost in different temperature ranges is distributed on the gentle slopes (slope < 5°), especially on the slopes of 0–2°. The spatial distribution of permafrost temperature in Northeast China is controlled by altitude. The Greater Khingan Mountains and Lesser Khingan Mountains are the main distribution areas of permafrost. Among them, the overall terrain trend of the Greater Khingan Mountains is northeast southwest, with a total length of more than 1200 km and a width of 200–300 km. Generally, it is 1100–1400 m above sea level. It is a mountain range composed of medium and low mountains. The terrain is high in the West and low in the East. The overall terrain of the Lesser Khingan Mountains is northwest southeast, with a total length of more than 450 km, generally 500–800 m above sea level, gentle mountains, and the whole terrain is high in the southeast and low in the northwest. The average altitude of the Greater Khingan Mountains is smaller and higher. Therefore, the minimum temperature of permafrost layer can reach −4.0 °C, the general temperature can reach −2.0 °C, and the minimum permafrost temperature in the Lesser Khingan Mountains can reach −3.0 °C, but it is generally distributed between −2.0 and 0 °C. Except that the permafrost with temperature lower than −4.0 °C is mainly distributed in the Greater Khingan Mountains, the altitude distribution curves of permafrost in other temperature ranges show two peak points, that is, both the Greater Khingan Mountains and Lesser Khingan Mountains. The permafrost temperature range is −2 to 0 °C, accounting for 68.25% of the total area. The spatial distribution of permafrost layer temperature is also affected by latitude. On the whole, the temperature of the permafrost layer is lower with the increase of latitude. For example, the terrain of the Greater Khingan Mountains gradually increases from north to south, but with the gradual increase of latitude, the temperature of the permafrost gradually decreases.
4. Discussion

4.1. Verification of Spatial Distribution of Permafrost Temperature

For the monitoring of permafrost change, it is ideal to choose the location in the undisturbed field. In the early stage, it depends on manual data collection, the data time interval is uncertain, and the maintenance cost is high. Therefore, some monitoring started after the study of permafrost in Northeast China, and there is no good continuity in time. Later, the ground temperature monitoring of permafrost section based on the project gradually increased, but the permafrost was affected by human activities, resulting in the melting of permafrost and the increase of temperature, which destroyed the original temperature field of the permafrost, and the new temperature distribution needs a certain time to reach a new balance. Therefore, the ground temperature monitoring data during the stable change of surface frost number (2014–2019) are the priority in the study. All the data in this study were used, thus the analysis data of the simulation results come from the survey reports of several recently built or under construction roads in the permafrost region. They are a: Genhe-Mangui section of Inner Mongolia provincial highway S204 (time of the survey report (TSR): May 2020), b: Wallagan-Zhangling section of Beijing-Mohe highway G111 (TSR: September 2017), c: Shiwel- LabuDalIn section of national highway G331 (TSR: July 2012), d: Kubuchun Forest Farm-Genhe section of national highway G332 (TSR: December 2020), e: Jiageda-Changqing Forest Farm section of national highway G331 (TSR: May 2020), and f: Nianzishan-Aershan section of provincial highway S308 (TSR: July 2017). The geospatial location of the route is shown in Figure 8.

Figure 7. (a) Slope distribution of permafrost temperature; (b) aspect distribution of permafrost temperature; (c) altitude distribution of permafrost temperature; (d) distribution area of permafrost temperature in Northeast China.
The comparison results show that the simulation results of the research institute are basically consistent with the frozen soil sections of the survey and drilling. The temperature range of permafrost below $-2^\circ$C is the best, which can reach 100%. There are some differences in the transition area between the permafrost and island melting area, the transition area between permafrost and non-permafrost and the distribution edge of permafrost. The temperature range of these areas is $-0.5$ to $0^\circ$C. The main reason for the difference is that the remote sensing image with 1-km resolution may ignore the local eigenvalues affecting the permafrost temperature.

4.2. Thickness of Permafrost Active Layer

The active layer in the near-surface of the lithosphere shows a seasonal variability in temperature, as a result of the climate. Thus, we judged the seasonal thaws and freezes of the layer by temperature. It can be described as the upper section of perennially frozen ground, and can be thawed to a depth over 20 m in some regions [60]. In the study, the thickness of the active layer of permafrost is determined according to the isoline of ground temperature in different locations. Since the ground temperature of boreholes at different positions of the same section is affected by different degrees of engineering disturbance, even the ground temperatures of boreholes that are closely spaced were different during the monitoring period, as shown in Figure 9. Borehole monitoring data at different locations of the Shiwei-LabuDalin section K56 + 900 of national highway G331 (as shown in Figure 9a,b) and Genhe-Mangui section K60 + 950 of the Inner Mongolia provincial highway S204 (as shown in Figure 9c,d) are shown in Figure 9. Compared with the boreholes at the slope toe and shoulder (the permafrost temperature is $-0.5^\circ$C and $-3^\circ$C, respectively), the boreholes farther away from the highway (the natural hole is more than 10 m away from the slope toe) are less disturbed and the permafrost temperature is lower ($-0.6^\circ$C and $-4^\circ$C, respectively). The lower the temperature, the greater the difference caused by the disturbance. As with the permafrost temperature, the thickness of the active layer is also disturbed. During the monitoring period, the thickness of the active layer gradually deepens, while the natural hole changes less. Of course, the existence of these differences may also be due to the fact that the permafrost is not always continuously and evenly distributed. The thickness and temperature of the permafrost layer are also different, but there are no more detailed data with which to compare the impact results caused by the differences. In addition to altitude and latitude, the thickness of permafrost is also
controlled by soil type, moisture, slope, and local special geological conditions. However, these factors are difficult to quantify and capture information for on a large scale, which is the factor restricting the development of remote sensing monitoring of permafrost in a large region. On the other hand, the data in the study are based on the natural holes along the highway. Even natural holes far away will be somewhat disturbed, which may also be a factor causing errors.

Figure 9. (a,b) Isolines of ground temperature at different positions of Genhe-Mangui section K60 + 950 of Inner Mongolia provincial highway S204; (c,d) isoline of ground temperature at different positions along the Shiwei-Labudalin section K56 + 900 of national highway G331.

4.3. Factors Affecting Permafrost Temperature

Altitude and latitude are the main factors affecting the distribution of permafrost on a large scale. The degree of influence of the two factors is discussed by analyzing the regions where the permafrost temperature is lower than $-3\,^{\circ}C$ (as shown in Figure 10). The regions with lower permafrost temperature ($<-4\,^{\circ}C$) are mainly distributed in Genhe City of the Inner Mongolia Autonomous Region, and scattered in Changbai Mountain. Mohe County in Heilongjiang Province also has lower permafrost temperature ($-3$ to $-4\,^{\circ}C$) distribution. The distribution of permafrost in Changbai Mountain is not much, but the permafrost temperature is lower than that of Mohe City, which has a higher latitude, due to the advantage of altitude.

Figure 10. (a) Slope distribution characteristics of permafrost with lower temperature; (b) elevation distribution characteristics of permafrost with lower temperature in Northeast China.
Genhe City and Mohe County, with a straight-line distance of only more than 300 km, are both located at about 52° N and belong to the same climatic zone, but the altitude difference is relatively large. The highest altitude of Mohe County is 1397 m, the lowest altitude is 200 m, and the average altitude is 600 m. The altitude is mostly between 700 and 1300 m, with an average altitude of 1000 m. The highest altitude is the Aukritui Peak of Along Mountain, reaching 1523 m, which is also the highest peak in the northern part of the Greater Khingan Mountains. The air temperature changes more obviously with altitude. Generally speaking, the air temperature in the troposphere decreases with the increase of height. In the same temperature zone, the higher the terrain, the lower the air temperature. Therefore, the lower temperature caused by the difference in altitude, is coupled with the longer duration of low temperature (the freezing period is about 210 days or more). Although, on the whole, latitude is the main factor controlling the temperature of permafrost, the Greater and Lesser Khingan Mountains with higher latitudes form a wider distribution of permafrost than Changbai Mountain. However, Changbai Mountain and Huanggangliang permafrost belong to the high-altitude permafrost in China, which is different from the natural conditions for the formation and existence of high-altitude permafrost in Northeast China. Altitude is the main factor controlling permafrost temperature in Northeast China on the 1-km scale.

5. Conclusions

The spatial distribution of surface frost values in Northeast China from 2014 to 2019 is obtained from remote sensing data. A linear regression equation is established with the borehole temperature monitoring data of permafrost temperature, and the spatial distribution of permafrost temperature in Northeast China is simulated. Based on the results, this study is summarized as follows:

1. The permafrost temperature in Northeast China is relatively high. According to the existing monitoring data and information, the lowest temperature of permafrost is −4.6 °C for the Genhe-Mangui highway, and the temperature of permafrost is generally −0.5 to −0.2 °C in the Bei’an Heihe Expressway and Shiwei labdalhin highway located in the permafrost degradation and marginal area. Of the permafrost area, 37.34% is in the state of high temperature frozen soil.

2. The spatial variation of permafrost temperature is mainly controlled by altitude. From the two main permafrost distribution areas, affected by altitude, the permafrost in the Greater Khingan Mountains is more developed than that in the Lesser Khingan Mountains, and the permafrost temperature is lower. With the increase of latitude, the temperature of the permafrost layer is lower, but this change is more obvious in the Greater Khingan Mountains and Lesser Khingan Mountains.

3. The thickness of the active layer of permafrost in Northeast China has no obvious relationship with the surface frost number and the permafrost temperature. Due to the influence of climate warming and human activities, the thickness and temperature of permafrost in different locations in the same region are also different during the process of permafrost degradation. In the study, the drilling depth (maximum 21 m) still cannot penetrate the lower limit of permafrost. In future studies, if conditions permit, deeper drilling depth should be considered.

4. The temperature of permafrost in Northeast China is generally high, which is very sensitive to climate change and human activities. The purpose of this study is to discover the distribution of permafrost, and to study its variation law in Northeast China, and provide richer basis for engineering route selection and construction treatment.

Author Contributions: Conceptualization, W.S.; data curation, C.Z. and L.Q.; formal analysis, C.Z.; funding acquisition, W.S.; methodology, L.Q.; project administration, W.S. and C.Z.; software, C.Z.; supervision, W.S.; writing—original draft, W.S., C.Z., Y.G. and Z.X.; writing—review and editing, W.S., C.Z., Y.G., L.Q. and Y.W. All authors have read and agreed to the published version of the manuscript.
Funding: We thank the National Natural Science Foundation of China (Grant No. 41641024) and Science and the Technology Project of Heilongjiang Communications Investment Group (Grant No. JT-100000-ZC-FW-2021-0182) for providing financial support and the Field scientific observation and research station of the Ministry of Education-Geological environment system of permafrost area in Northeast China (MEORS-PGSNEC).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Related data are available upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Qin, D.H.; Yao, T.; Ding, Y. Glossary of Cryosphere Science; China Meteorological Press: Beijing, China, 2014.
2. Bockheim, J.G.; Hall, K.J. Permafrost, active-layer dynamics and periglacial environments of continental Antarctica: Periglacial and permafrost research in the Southern Hemisphere. *S. Afr. J. Sci.* 2002, 98, 82–90.
3. Zhang, T.; Barry, R.G.; Knowles, K.; Heginbottom, J.A.; Brown, J. Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemisphere. *Polar Geogr.* 2008, 31, 47–68. [CrossRef]
4. Li, X.; Cheng, G.; Jin, H.; Kang, E.; Che, T.; Jin, R.; Wu, L.; Nan, Z.; Wang, J.; Shen, Y. Cryospheric change in China. *Glob. Planet. Chang.* 2008, 62, 210–218. [CrossRef]
5. Ran, Y.; Li, X.; Cheng, G.; Zhang, T.; Wu, Q.; Jin, H.; Jin, R. Distribution of permafrost in China: An overview of existing permafrost maps. *Permaf. Periglac. Process.* 2012, 23, 322–333. [CrossRef]
6. Guo, D.; Wang, S.; Lu, G.; Dan, J.; Li, E. Division of permafrost regions in Daxiao Hinggan Ling Northeast China. *J. Glaciol. Cryopedol.* 1981, 3, 1–9.
7. Shi, Y.; Mi, D. *Map of Snow, Ice and Frozen Ground in China* (1:4,000,000), 1st ed.; China Cartographic Publishing House: Beijing, China, 1988.
8. Cheng, G. Problem on zonation of high-altitude permafrost. *Acta Geogr. Sin.* 1984, 39, 185–193.
9. Lewkowicz, A.G.; Bonnave, P.P. Equivalent elevation: A new method to incorporate variable surface lapse rates into mountain permafrost modelling. *Permaf. Periglac. Process.* 2011, 22, 153–162. [CrossRef]
10. Nelson, F.E.; Outcalt, S.I. A computational method for prediction and regionalization of permafrost. *Arct. Alp. Res.* 1987, 19, 279–288. [CrossRef]
11. Jumikis, A.R. *Thermal Geotechnics*; Rutgers University Press: New Brunswick, NJ, USA, 1977.
12. Riseborough, D.W. The mean annual temperature at the top of permafrost, the TTOP model, and the effect of unfrozen water. *Permaf. Periglac. Process.* 2002, 13, 137–143. [CrossRef]
13. Sazonova, T.S.; Romanovsky, V.E. A model for regional-scale estimation of temporal and spatial variability of active layer thickness and mean annual ground temperatures. *Permaf. Periglac. Process.* 2003, 14, 125–139. [CrossRef]
14. Schaefer, K.; Zhang, T.; Slater, A.G.; Lu, L.; Etringer, A.; Baker, L. Improving simulated soil temperatures and soil freeze/thaw at high-latitude regions in the Simple Biosphere/Carnegie-Ames-Stanford Approach model. *J. Geophys. Res. Earth Surf.* 2009, 114, F02021. [CrossRef]
15. Lawrence, D.M.; Oleson, K.W.; Flanner, M.G.; Thornton, P.E.; Swenson, S.C.; Lawrence, P.J.; Zeng, X.; Yang, Z.-L.; Levis, S.; Sakaguchi, K.; et al. Parameterization improvements and functional and structural advances in version 4 of the Community Land Model. *J. Adv. Model. Earth Syst.* 2011, 3, M03001. [CrossRef]
16. Guo, D.; Wang, H.; Li, D. A projection of permafrost degradation on the Tibetan Plateau during the 21st century. *J. Geophys. Res. Atmos.* 2012, 117, D05106. [CrossRef]
17. Guo, D.; Wang, H. Simulation of permafrost and seasonally frozen ground conditions on the Tibetan Plateau, 1981–2010. *J. Geophys. Res. Atmos.* 2013, 118, 5216–5230. [CrossRef]
18. Liu, J.J.; Li, X.Z.; Hu, Y.M.; Wang, X.W.; Sun, J. Application of front number model in Northeast China pepmafrost regionalization. *Yingyong Shengtai Xuebao* 2008, 19, 2271–2276.
19. Zhang, Z.; Wu, Q.; Xun, X.; Li, Y. Spatial distribution and changes of Xing’ an permafrost in China over the past three decades. *Quat. Int.* 2019, 523, 16–24.
20. Zhang, Z.Q.; Wu, Q.; Hou, M.T.; Tai, B.-W.; An, Y.-K. Permafrost change in Northeast China in the 1950s–2010s. *Adv. Clim. Chang. Res.* 2021, 12, 18–28. [CrossRef]
21. Cao, B.; Zhang, T.; Wu, Q.; Sheng, Y.; Zhao, L.; Zou, D. Permafrost zonation index map and statistics over the Qinghai-Tibet Plateau based on field evidence. *Permaf. Periglac. Process.* 2019, 30, 178–194. [CrossRef]
22. Gruber, S. Derivation and analysis of a high-resolution estimate of global permafrost zonation. *Cryosphere* 2012, 6, 221–233. [CrossRef]
23. Nan, Z.; Li, S.; Liu, Y. Mean annual ground temperature distribution on the Tibetan Plateau: Permafrost distribution mapping and further application. *J. Glaciol. Geocryol.* 2002, 24, 142–148.
24. Jaroslav, O.; Sebastian, W.; Annett, B.; Berdnikov, N.; Christiansen, H.H.; Dashtersev, A.; Delaloye, R.; Elberling, B.; Kholodov, A.; Khomutov, A.; et al. Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km² scale. Earth-Sci. Rev. 2019, 193, 299–316.

25. Zhang, Z.; Wu, Q.; Xun, X.; Wang, B.; Wang, X. Climate change and the distribution of frozen soil in 1980–2010 in northern Northeast China. Quat. Int. 2018, 467, 230–241. [CrossRef]

26. Zhang, Z.; Wu, Q.; Xun, X.; Wang, B.; Wang, X. Climate change and the distribution of frozen soil in 1980–2010 in northern Northeast China. Quat. Int. 2018, 467, 230–241. [CrossRef]

27. Ran, Y.; Li, X.; Cheng, G.; Nan, Z.; Che, J.; Sheng, Y.; Wu, Q.; Jin, H.; Luo, D.; Tang, Z.; et al. Mapping the permafrost stability on the Tibetan Plateau for 2005–2015. Sci. China Earth Sci. 2020, 63, 62–79. [CrossRef]

28. Ran, Y.; Li, X.; Jin, R.; Guo, J. Remote sensing of the mean annual surface temperature and surface frost number for mapping permafrost in China. Acta. Antarct. Alp. Res. 2015, 47, 255–265. [CrossRef]

29. Liu, F.; Lv, Y.P.; Jiang, L.-M.; Xin, H.; Zhang, T.-B.; Lu, Q. Correlation analysis between MODIS brightness temperature and surface temperature measurements in continuous permafrost terrain. Cryosphere Discuss. 2011, 5, 51–69.

30. Lehmann, F.; Green, A.G. Topographic migration of Georadar data: Implications for acquisition and processing. Geophysics 2000, 65, 836–848. [CrossRef]

31. Christian, H.; Vonder, M.D. Detecting alpine permafrost using-electro-magnetic methods. Adv. Cold-Reg. Therm. Eng. Sci. Lect. Notes Phys. 1999, 353, 475–482.

32. Vonder, M.D.; Hauck, C.; Gubler, H.; McDonald, R.; Russill, N. New geophysical methods of investigating the nature and distribution of mountain permafrost with special reference to radiometry techniques. Permafrost. Periglac. Process. 2001, 12, 27–38.

33. Minsley, B.J.; Abraham, J.D.; Smith, B.D.; Cannia, J.C.; Voss, C.L.; Jorgenson, M.T.; Walvoord, M.A.; Wylie, B.K.; Anderson, L.; Ball, L.B.; et al. Airborne electromagnetic imaging of discontinuous permafrost. Geophys. Res. Lett. 2012, 39, L02503. [CrossRef]

34. Minsley, B.J.; Abraham, J.D.; Smith, B.D.; Cannia, J.C.; Voss, C.L.; Jorgenson, M.T.; Walvoord, M.A.; Wylie, B.K.; Anderson, L.; Ball, L.B.; et al. Airborne electromagnetic imaging of discontinuous permafrost. Geophys. Res. Lett. 2012, 39, L02503. [CrossRef]

35. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

36. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

37. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

38. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

39. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

40. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

41. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

42. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

43. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

44. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

45. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

46. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

47. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

48. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

49. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]

50. Yang, M.; Nelson, F.E.; Shiklomanov, N.I.; Guo, D.; Wan, G. Permafrost degradation and its environmental effects on the Tibetan Plateau Meteorol. 2010, 2012, 1–10. [CrossRef]
52. Wei, H.Y.; Dong, L.B.; Liu, Z.G. Spatial structure optimization simulation of main forest types in Great Xing’an Mountains. *Northeast. China Ying Yong Sheng Tai Xue Bao J. Appl. Ecol.* **2019**, *30*, 3824–3832.

53. Wei, Z.; Jin, H.J.; Zhang, J.M.; Yu, S.; Han, X.; Ji, Y.; He, R.; Chang, X. Prediction of permafrost change in northeast China under climate change. *Sci. China Earth Sci.* **2011**, *41*, 74–84.

54. Ma, J.; Li, R.; Liu, H.; Wu, T.; Xiao, Y.; Du, Y.; Yang, S.; Shi, J.; Qiao, Y. A review on the development of study on hydrothermal characteristics of active layer in permafrost areas in Qinghai-Tibet Plateau. *J. Glaciol. Geocryol.* **2020**, *41*, 195–204.

55. Yang, S.; Li, R.; Wu, T.; Hu, G.; Xiao, Y.; Du, Y.; Zhu, X.; Ni, J. The variation characteristics of different freeze-thaw status in the near surface and the relationship with temperature over the Qinghai-Tibet Plateau. *J. Glaciol. Geocryol.* **2019**, *41*, 1377–1387.

56. Yang, C.; Wu, T.; Yao, J.; Li, R.; Xie, C.; Hu, G.; Zhu, X.; Hao, J.; Ni, J.; Li, X.; et al. Temporal and Spatial Characteristics of Ground Surface Soil Heat Flux over the Qinghai-Tibet Plateau. *Plateau Meteorol.* **2020**, *39*, 706–718. [CrossRef]

57. Qin, Y.; Wu, T.; Li, R.; Wu, X.; Xie, C.; Pang, Q.; Hu, G.; Qiao, Y.; Zhao, G.; Liu, G.; et al. Thermal condition of the active layer on the Qinghai-Tibet Plateau simulated by using the Model of GIPL2. *J. Glaciol. Geocryol.* **2018**, *40*, 1153–1166.

58. Cheng, G.; Wu, T. Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau. *J. Geophys. Res. Earth Surf.* **2007**, *112*, F02S03. [CrossRef]

59. Wu, Q.; Zhang, T. Recent permafrost warming on the Qinghai-Tibet Plateau. *Geophys. Res.* **2008**, *113*, D13108. [CrossRef]

60. Dobieski, W. Permafrost active layer. *Earth-Sci. Rev.* **2020**, *208*, 103301. [CrossRef]