Dynamic Lake Ice Movement on Lake Khovsgol, Mongolia, Revealed by Time Series Displacements from Pixel Offset with Sentinel-2 Optical Images

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Abstract: As one of the most sensitive indicators of global climate change, seasonal ice-covered lakes are attracting gaining attention worldwide. As a large seasonal ice-covered lake located in Northern Mongolia, Lake Khovsgol not only provides important freshwater resources for the local population but also serves as a means of water transportation in summer and an important land-based activity for residents in winter. In this study, we used the sub-pixel offset technique with multi-temporal Sentinel-2 optical images to estimate the time-series displacement of lake ice in Lake Khovsgol from 7 December 2020 to 17 June 2021. With the processing of 112 Sentinel-2 images, we obtained 27 pairs of displacement results at intervals of 5, 10, and 15 days. These lake ice movement results covered three stages from ice-on to ice-off. The first stage was the lake ice growth period, which lasted 26 days from 7 December 2020 to 3 January 2021. Ice formation started from the south and extended northward, with a displacement of up to 10 m in 5 days. The second stage was the active phase of the ice cover, which took place from 3 January 2021 to 18 April 2021. Maximum displacement values reached 12 m in the east and 11 m in the north among all observations. The value of the lake ice movement in the north–south direction (NS) was found to be larger than in the east–west direction (EW). The third stage was the melting period, which closed on 17 June 2021. In comparison to the freezing date of November in past years, our results demonstrate the ice-on date of Lake Khovsgol has been delayed to December, suggesting a possible reason that the seasonal ice-covered lake located at the middle latitude has been affected by global warming. In addition, the lake ice movement of our results can reveal the regional climate characteristic. This study is one of the few cases to reveal the distribution characteristics and changing trends of lake ice on the Mongolia Plateau, providing a rare reference for lake ice research in this region.

Keywords: Lake Khovsgol; Sentinel-2 optical images; sub-pixel offset tracking; time series ice movement; ice ridge

1. Introduction

Seasonal ice-covered lakes, as one of the most sensitive indicators of response to greenhouse gas emissions, are closely related to regional ecological environment, production, and development in polar and high latitude regions, which have attracted increasing worldwide attention [1–5]. Lakes are important sources of atmospheric carbon dioxide and methane to the extent that they are thought to offset a majority share of the terrestrial carbon sink [6,7]. They also constitute a major component of carbon landfills in the continent [8]. Polar, temperate, and alpine lakes are completely covered with ice in winter [9]. An ice-covered lake restricts energy exchange (especially thermal energy), blocks sunlight, and eliminates wave mixing. Consequently, various physical, chemical, and biological processes proceed beneath lake ice [10]. Additionally, changes in lake ice cover are major
environmental indicators of climate change in the terrestrial cryosphere. With the strong correlation between lake ice phenology and climate change [11–14], lake ice is considered to be one of the 12 indicators of climate change in Canada (http://www.ccme.ca, accessed on 15 October 2021). Several studies on the relationship between lake ice and global warming have demonstrated that lake ice across the Northern Hemisphere is exhibiting later freezing dates, earlier break-up dates, and shorter ice cover durations due to the long-term effects of global warming [15,16]. In addition, changes in lake ice growth are influenced by numerous local and regional climatic factors, such as temperature and wind speed [3]. Therefore, the freezing and melting of lake ice is closely related to the cryosphere, atmosphere, and ecosphere [2].

Seasonal ice-covered lakes are located in boreal and temperate regions between 40° and 80° N latitude, and they are commonly subclassified into three types: (1) stable ice lakes, where ice occurs annually and ice-on and ice-off take place every year; (2) semi-stable ice lakes, where ice occurs annually but full ice coverage does not occur every year; and (3) intermittent ice lakes, where ice occasionally occurs in some years [17]. There are five basic seasonal ice-covered lake systems around the world, i.e., the Lake Baikal system, the Laurentian Great Lakes system, the European Great Lakes Ladoga and Onego system, the lake systems of Fennoscandia, and the northern Canada system. These seasonal ice lakes store most of the world’s surface freshwater and are important water resources for residents. In addition, they control the local climatic balance of precipitation and evaporation, as well as the ecosystem state. Moreover, some seasonal ice-covered lakes also serve as either water transport in summer or important land-based sites for residents in winter. However, ice-covered lakes are not completely stable in winter. Cracks and ice ridges can be observed in some ice-covered lakes [17–20], which poses certain difficulties and dangers for transportation Therefore, it is crucial to survey the detailed movements and understand the changes of seasonal ice-covered lakes in order to gain insights into local climate change and ensure the safety of local residents. Most previous studies have focused on ice-covered lakes near the Arctic Circle [5,9,21–27], but little attention has been paid to seasonal ice-covered lakes located at middle and high latitudes in Asia [2,3]. We hope that more researchers will focus on Asian lake ice and even some other cryosphere examples to fill this research gap [2,28].

Present imaging geodesy, which has large-scale coverage, high spatial-temporal resolution, and high precision, can provide valuable detailed deformation observations for investigating lake ice. Tools for imaging geodesy, include Interferometric Synthetic Aperture Radar (InSAR), Light Detection and Ranging (LiDAR), and pixel offset tracking (POT), and so on. The space-based InSAR has become a routine remote sensing technology to image the Earth because it can provide full-weather and full-time measurements with large scale coverage, high resolution, and high accuracy, resulting in its use in glacier environment [29–35]. LiDAR is another remote sensing method that uses actively dissipate LASER (Light Amplification by Stimulated Emission of Radiation) pulses to locate the positions of targets [36], which can provide a high-accuracy digital elevation model (DEM) and 3D displacement with point cloud data. More and more research is using LiDAR on the cryosphere [37,38]. InSAR can fail in some lake ice applications due to a loss of coherence, and high costs still hinder LiDAR applications. The POT method surveys displacement by calculating the pixel offset in a pair of correlated images, which can overcome the deficiencies of InSAR. In addition, both SAR and optical images (e.g., Sentinel 1/2, ALOS1/2, Landsat 8 OLI, and SPOT images) can be used with the POT method, thus increasing its applicability, and reducing its cost. Therefore, the POT method is more suitable for ice-movement monitoring than LiDAR and InSAR [39,40].

In this work, we utilized COSI-Corr software to measure the movement of Lake Khovsgol based on 112 time series of Sentinel-2 images. Lake Khovsgol is an important seasonal ice lake located in Northwestern Mongolia. The second largest lake in Asia, Khovsgol Lake contains about 70% of Mongolia’s freshwater and is used as a transport. Previous researchers have studied Lake Khovsgol’s hydrology changes and surrounding
complex soil ecology [41–43]. Kouraev et al. [44] used remote sensing images to study ice rings appearing on the surface of Lake Khovsgol. However, little research has been conducted on the movement of lake ice and its causes. Integrating a series of Sentinel-2 images and the COSI-Corr technique, the objectives of this work include three parts as follows:

1. To determine the suitability of the POT method for studying lake ice in general.
2. To explore the duration of the ice period and the variation of lake ice by POT.
3. To analyze the correlation between lake ice and climate based on the meteorological data we collected.

2. Background of Lake Khovsgol

Lake Khovsgol is located in the northwest of Mongolia, about 200 km west of the southern end of Lake Baikal near Russian Siberia (Figure 1). It is surrounded by three ridges and originated from a graben associated with surface faulting which has been developed by either remote collision from the Indian Plate’s northeastward movement or heat flow from the mantle underneath the Asian Plate [45,46]. Lake Khovsgol is 1645 m above sea level, 136 km long, and 262 m deep [44]. As the second largest lake in Asia, it holds almost 70% of Mongolia’s fresh water and 0.4% of all the fresh water in the world, as well as being the most significant drinking water reserve of Mongolia. In addition, there are two port towns close to the lake, i.e., Hargal at the southern end and Turt at the northern end (Figure 1). In winter, the average temperature of Lake Khovsgol is between −20 and −25 °C, and it does not rise above 0 °C until late spring (after mid-April), which can result in a state of complete freezing for 6–7 months. The lake ice is 1–1.5 m thick, which is strong enough to carry heavy trucks transport routes on its surface, offering shortcuts to normal roads. Residents also hold bonfire parties or other recreational activities on the lake ice. Additionally, the seasonal ice-covered lake’s high latitude and altitude influence its freezing. Its ice period is very long which can last from the beginning of November to the middle of June attested by previous studies [47].

![Figure 1](image-url) Figure 1. (a) Overview map of the Mongolian Plateau and surrounding country regions. It is superimposed on 2-arcminute SRTM Digital Elevation Model (DEM), the blue area is the location of Lake Khovsgol. (b) Map of the topography structure around Lake Khovsgol and the bathygram of the lake. It is superimposed on 3 Arc-Second Global SRTM Digital Elevation Model (DEM) with 90 m resolution. The different background colors indicate different elevations.
3. Data and Processing

3.1. Data Acquisition

Sentinel-2 optical images were used in this study to explore the lake ice displacement of Lake Khovsgol. These images are freely available to the public (https://scihub.copernicus.eu/dhus/#/home, accessed on 3 January 2021). The Sentinel-2 satellite consists of two satellites, i.e., Sentinel-2A and Sentinel-2B, which were launched in June 2015 and March 2017, respectively. The revisit periods are 10 days for a single satellite and 5 days for the satellite constellation. In high latitude regions where the image swaths from neighboring orbits have a dense overlap, the potential revisit time may be shorter than 5 days. Each Sentinel-2 optical image contains visible, near-infrared, and shortwave infrared parts with 13 bands of varied spatial resolutions, 4 bands with 10 m, 6 bands with 20 m, and 3 bands with 60 m. For details on Sentinel-2 image data, please refer to official ESA website descriptions (https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi, accessed on 28 May 2021). A commonly used Sentinel-2 image in the Level-2A format, which has been corrected for terrain distortion, can cover a size of $100 \times 100$ km$^2$ with orthorectified UTM or WGS84 projection. Their high temporal-spatial resolution, large-scale coverage, and open access data policy have made Sentinel-2 images ideal data sources to detect time series change of land [48] in comparison to other optical remote sensing images [49,50] (e.g., Landsat and SPOT satellite images).

This study collected all the Level-2A Sentinel-2 A/B optical acquisitions, spanning from 7 December 2020 to 17 June 2021. The optical images from this period are shown in Table 1. At each date, 4 acquisitions were merged into one image to cover the area of Lake Khovsgol. The percentages of cloud coverage for these images were within 0.36–60.9%. Cloud coverage is an inevitable problem of optical satellites handled with passive sensors that can directly lead to a loss of coherence between two images from different dates [51]. There is no consensus regarding which of the four 10 m resolution bands is the best band for pixel offset estimation. Given the radiometric characteristics of different bands for various surface targets, the authors of [52] thought that Sentinel-2 images of bands 4, 8, and 11 are more suitable for glacier offset tracking than other bands. In [50] the authors suggested that the pixel offset accuracy from band 8 Sentinel-2 images is slightly better than that of band 2, band 3, and band 4 Sentinel-2 images for land surface deformation monitoring. In this study, we chose band 8 as the experimental band for POT. Before pixel offset estimation, all Sentinel-2 images were preprocessed with the open-access Sentinel Application Platform (SNAP) for the image fusion and band extraction [53]. In addition, we collected local weather data from the global weather station located at 100.15° E and 50.433° N, as provided by the National Oceanic Atmospheric Administration (NOAA) (https://www.ncei.noaa.gov/maps/daily/, accessed on 15 March 2021); see Figures 2 and 3.

3.2. Pixel Offset Estimation

The Co-registration of Optically Sensed Images and Correlation (COSI-Corr) package, which was developed for co-seismic ground displacement extraction based on pixel offset analysis with optical images to derive horizontal displacement [54], was used in this study. The sub-pixel correlation algorithm performed in COSI-Corr produced a de-correlation effect between images due to rapid changes in the ice-covered lake’s surface due to snow build-up and other causes [55]. Most of the images we collected were only 5 days apart in the processing strategy, so we could ignore the difference due to the solar zenith angle. Then, we selected the frequency correlator for the correlation analysis, with a matching window of $32 \times 32$ pixels, a moving step length of 8, and a robustness iteration of 2 [50,56]. The output of the COSI-Corr package includes the horizontal ground displacement of the east–west (EW) and north–south (NS) components, as well as the relative signal-to-noise ratio (SNR) in each pair of images. A mask threshold of 0.9 based on the SNR was selected for the output EW and NS displacements. Additionally, we undertook the destriping step after correlation calculations and used a filter to remove the outlier caused by small
cloud occlusion and water reflection. The filter in the COSI-Corr package implements a Non-Local Means algorithm that can reduce the additive Gaussian white noise but retains local displacement features [54]. We chose a $7 \times 7$ pixels filter window, and the noise threshold was 1.6 times the standard deviation (The data processing flow is shown in Figure 4). All the results (following post-processing) are shown in Figures 5–7. Positive values in the EW and NS images indicate that the displacements moved in the east and north direction, respectively.

**Table 1.** The Sentinel-2 optical images used in this paper.

| Sensor        | Acquisition Dates | Sun Zenith Angle (°) | Sun Azimuth Angle (°) | Cloud Cover (%) |
|---------------|-------------------|----------------------|-----------------------|-----------------|
| S2B_MSIL2A    | 7 December 2020   | 74.086               | 170.853               | 23.0            |
| S2A_MSIL2A    | 12 December 2020  | 74.595               | 170.363               | 40.8            |
| S2B_MSIL2A    | 17 December 2020  | 74.922               | 169.821               | 42.0            |
| S2B_MSIL2A    | 27 December 2020  | 75.007               | 168.653               | 32.6            |
| S2A_MSIL2A    | 3 January 2021    | 74.976               | 165.447               | 60.9            |
| S2B_MSIL2A    | 8 January 2021    | 73.564               | 165.169               | 20.3            |
| S2A_MSIL2A    | 13 January 2021   | 72.693               | 164.282               | 32.1            |
| S2B_MSIL2A    | 18 January 2021   | 71.925               | 163.493               | 25.8            |
| S2A_MSIL2A    | 23 January 2021   | 70.527               | 162.912               | 54.6            |
| S2A_MSIL2A    | 2 February 2021   | 68.152               | 162.235               | 24.8            |
| S2B_MSIL2A    | 7 February 2021   | 67.986               | 161.583               | 46.6            |
| S2A_MSIL2A    | 12 February 2021  | 66.409               | 161.189               | 21.1            |
| S2B_MSIL2A    | 17 February 2021  | 64.723               | 160.852               | 36.2            |
| S2A_MSIL2A    | 22 February 2021  | 62.948               | 160.560               | 36.6            |
| S2B_MSIL2A    | 27 February 2021  | 61.094               | 160.330               | 53.2            |
| S2A_MSIL2A    | 4 March 2021      | 59.181               | 160.133               | 44.5            |
| S2B_MSIL2A    | 9 March 2021      | 57.220               | 159.980               | 56.2            |
| S2A_MSIL2A    | 14 March 2021     | 55.230               | 159.851               | 47.1            |
| S2B_MSIL2A    | 19 March 2021     | 53.223               | 159.748               | 50.1            |
| S2A_MSIL2A    | 24 March 2021     | 51.215               | 159.661               | 14.7            |
| S2A_MSIL2A    | 3 April 2021      | 47.258               | 159.491               | 0.68            |
| S2B_MSIL2A    | 18 April 2021     | 41.673               | 159.049               | 0.36            |
| S2A_MSIL2A    | 13 May 2021       | 34.179               | 157.250               | 91.7            |
| S2B_MSIL2A    | 18 May 2021       | 33.062               | 156.676               | 26.9            |
| S2B_MSIL2A    | 28 May 2021       | 31.291               | 155.878               | 8.3             |
| S2A_MSIL2A    | 2 June 2021       | 30.652               | 154.647               | 0.7             |
| S2B_MSIL2A    | 7 June 2021       | 30.173               | 153.938               | 0.6             |
| S2B_MSIL2A    | 17 June 2021      | 29.735               | 152.650               | 2.5             |

**Figure 2.** Weather data collected from NOAA’s stations for Lake Khovsgol from December 2020 to June 2021. (a) Air temperature data; (b) wind speed data.
The displacement accuracy of pixel offset estimation mainly depends on the pixel co-registration error. Researchers [57] previously reported that uncertainty assessment in stabilized regions may not be representative of uncertainty in all regions of an image, especially in the case of inhomogeneous masses with small moving targets. However, in the absence of in situ measurements to assess the uncertainty of moving targets, stable regions would be useful. At each stage, we randomly selected five far-field reference objects without ground deformation and calculated the standard deviation and average value to estimate the accuracy of the pixel offset [56,58–62]. Multiple stable regions were selected to reduce bias due to snow, ice, or cloud cover. We found that the uncertainty in our work was from approximately 0.7 (EW) to 2.3 m (NS) (Table 2). In the third stage, the standard deviation became larger because the freeze–thaw cycle caused a poor performance of POT. Additionally, the standard deviation overestimated the uncertainty because it did not consider reduced errors due to us averaging larger areas [63].
Table 2. The mean and standard deviation of the displacements of the stable regions in the Sentinel-2A/B image pairs. Each value is calculated by averaging the five regions.

| Reference-Image       | Secondary-Image       | EW Displacement (meters) | NS Displacement (meters) |
|-----------------------|-----------------------|--------------------------|--------------------------|
|                       |                       | Mean                     | Standard Deviation       | Mean                     | Standard Deviation       |
| 12 December 2020      | 17 December 2020      | 0.3                      | 1.4                      | 1.3                      | 1.3                      |
| 17 December 2020      | 27 February 2021      | −1.3                     | 0.8                      | −1.9                     | 1.4                      |
| 8 January 2021        | 13 January 2021       | 2.3                      | 1.0                      | −1.5                     | 1.1                      |
| 18 January 2021       | 23 January 2021       | −0.6                     | 0.7                      | −3.1                     | 1.3                      |
| 7 February 2021       | 12 February 2021      | −1.0                     | 1.2                      | −1.6                     | 1.3                      |
| 27 February 2021      | 4 March 2021          | −2.0                     | 0.7                      | 1.2                      | 1.0                      |
| 18 April 2021         | 13 May 2021           | −0.3                     | 2.3                      | −2.2                     | 2.3                      |
| 13 May 2021           | 18 May 2021           | 1.7                      | 2.1                      | 3.0                      | 2.0                      |

4. Results and Analysis

4.1. Time Series Displacement for Ice Motion

In this study, we simply divided the ice period of Lake Khovsgol into three stages based on their change characteristics. The first stage, also known as primary lake ice formation, was from 7 December 2020 to 3 January 2021 (Figure 5). It represents primary lake ice formation and climate response. Figure 5(A1–B2) shows that the displacement in the EW and NS components was $-3.8$–$0.6$ m and $-4.3$–$6.2$ m, respectively. Displacement signals were only found in the southernmost and some surrounding areas of Lake Khovsgol, occupying $\sim 1/7$ of the lake. This suggests that ice formation started from the southernmost part of Lake Khovsgol between 7 December 2020 and 17 December 2020. Between 17 and 27 December 2020, some new ice formed at the southern end of the lake, with displacement values of about $-3.8$ and $4.3$ m in the EW and NS directions, respectively (Figure 5(C1,C2)). Then, between 27 December 2020 and 3 January 2021, the ice cover size rapidly extended to the north. Figure 5(D1,D2) shows that the ice covered the entire lake by 3 January 2021, and the ice displacement was up to $12$ m in the northern area. Some areas (marked with blue lines in Figure 5(D1,D2)) lost signals because of the clouds on 3 January 2021. Our results show that the first stage started on 7 December 2020 and lasted about 26 days, after which its formation accelerated, and demonstrate that the ice formed from south to north.

The second stage, also called the ice cover active period, was from 3 January 2021 to 18 April 2021, as shown in Figure 6. From 3–8 January 2021, the lake ice showed overall movement with a northward displacement value of $9.5$ m and a westward displacement value of $7.8$ m. From 8–13 January 2021, the EW displacements ranged from $-3.1$ to $2.9$ m (Figure 6(B1)). In the NS direction (Figure 6(B2)), the displacement ranged from $-4$ to $6$ m, and two clear displacement gradients were formed in the northern part of the lake ($-51.5^\circ$ N) and near the small island ($-51.0^\circ$ N), resulting in a blocky distribution of lake ice movement. By 18 January 2021 (Figure 6(C1,C2)), the lake ice displacement in the NS direction near the island increased to $-8.1$–$2.2$ m, and the movement area expanded to the north. However, in the EW component, the displacement of the lake ice tends to be stable, and the westward displacement of the lake center area reaches $8.1$ m (the deepest area of the lake). From 18 January to 22 February 2021, the lake ice actively moved and the gradient of displacement change was obvious. Between 18 and 13 January, the lake ice moved up to $4.2$ m westward and up to $6$ m northward (Figure 6(D1,D2)). From February 22 to March 9, the trend of lake ice movement was weak, and the displacement value was around $2.4$ m.
During the second stage, most displacement values in the NS and EW components ranged from −12 to 12 m (e.g., Figure 6(B1,B2,E1,E2,F1,F2,H1,H2)), and the rest showed small-displacement magnitudes (e.g., Figure 6(J1,J2,K1,K2)). That is to say that there were strong hydrological and hydrodynamic processes most of the time, but the lake ice movement was relatively mild sometimes. Moreover, these ice changes showed an obvious block feature in some result maps, and these ice blocks along the NS direction were divided by displacement gradients, e.g., the lake ice moved had two opposite directions (approximately 51.5° N); see Figure 6(B2,E2,H2,I2). Figure 6 also shows some small areas with losses of coherence. We know from the Sentinel 2 visible band that pixels are missing in Figure 6(E1–F2) due to cloud coverage. Additionally, the lake can be seen to be covered by white snow in Figure 6(P1–Q2). We speculate that the lake surface changed too quickly in short intervals due to constant snow, thus causing the pixels to be non-tracked. Moreover, the NS displacements were much larger than the EW displacements in most of the times in Figure 6.

The third stage was the ice melt period, which began on 18 April 2021. In this stage, the movement monitoring of lake ice using POT was not satisfactory because the coherence was poor. As shown in Figure 7, we found no signals in most areas of the ice cover, and the displacement measurements of a few areas showed some abnormal values, except for the final disappearance of lake ice in June (Figure 7(F1,F2)) when we measured displacement values from about −1.2 to −1.1 m around the lakeshore. Moreover, the region’s high cloud coverage in April and May led to some data unavailability; therefore, the observation period became longer. In addition to the loss of correlation due to cloud cover, the freeze–thaw cycle was a major reason for the loss of effectiveness of POT. During the day, melting snow and water filled up internal cracks in the lake ice, which froze at night again when the temperature was negative [19]. This process led to increased surface roughness and the scattering of the lake ice, which caused difficulties and errors in the pixel offset estimation.
in short intervals due to constant snow, thus causing the pixels to be non-tracked. Moreover, the NS displacements were much larger than the EW displacements in most of the times in Figure 6.

Figure 6. (A1–Q2) represent the horizontal displacement results of the surface of Lake Khovsgol in the EW and NS directions in the second stage. It is superimposed on 3 Arc-Second Global SRTM Digital Elevation Model (DEM) with 90 m resolution. The points P1–P5 and the dashed lines AA’ and BB’ in (A1) are used for the specific displacement analysis in Section 4.2. The area marked by the dashed blue line in the figure is the missing signal due to cloud cover occlusion. The red line marked is caused by the ice and snow mixture. Displacement values are positive for the eastern and northern directions.
In order to explore the detailed temporal and spatial change of ice motion in the second stage (i.e., the lake was completely covered with ice), both time series displacements on points and along profiles were selected for analysis in this section. Five points are in Figure 3(A1)—three (P1, P2, and P3) in the northern part and two (P4 and P5) in the southern part, were selected to show accumulated displacements, as shown in Figure 8. We calculated the accumulated EW and NS components for each point, and the results are shown in Figure 8a,c,e,g,i and Figure 8b,d,f,h,j, respectively. Figure 8 shows no measurement for lack of consistency. We refer to the work of [50], who used COSI-Corr to calculate seismic deformation displacements; they excluded anomalies with Nan value and larger absolute values of deformation values from the statistics of deformation values. Therefore, we simply assume that Nan is 0 in Figure 8. Note that this assumption is not rigorous, but it does not affect our understanding of the overall the lake ice movement trend. The P1 close to the northwestern shore of the lake indicates the accumulated displacements of the EW and NS components ranging from −9.8 to 7.9 m and −0.8 to 5.8 m, respectively. It can be seen that the displacement trend of P1 started from the eastern direction and then changed to the western direction in the EW component. Meanwhile, in the NS component, it kept moving to the north and reached a maximum displacement of 5.8 m on 12 February 2021. P2 had a single direction of motion in both components and continued to move to the west and north, with cumulative displacement values of 16 and 10 m, respectively. The accumulative eastward movement of P3 reached 6 m on January 8. The displacement variation in the NS direction was smoother than in the EW direction, and the accumulated displacement from the beginning to the end of the second stage is about 0 m. In the EW direction, P4 had no significant change in January, but slowly moved eastward from 2 February 2021 until the displacement value reached 10.9 m; P5 presented a calm performance in the second stage and presented no significantly large displacement movement.
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2021. P2 had a single direction of motion in both components and continued to move to the west and north, with cumulative displacement values of 16 and 10 m, respectively. P3 had a single direction of motion in both components and moved eastward from 2 to 22 February 2021 until the displacement value reached 10.9 m; P5 presented a calm performance in the second stage and presented no significantly large displacement movement. The locations of the points are illustrated in Figure 6(A1). The displacement values in the east and north directions are positive.

Figure 8. (a–j) represent the time series of accumulated displacement monitoring results from P1–P5. The locations of the points are illustrated in Figure 6(A1). The displacement values in the east and north directions are positive.

Detailed spatial characteristics of the lake ice during the ice cover accumulation period are shown along the AA′ and BB′ profile lines in Figure 9. The profile line AA′ indicates the spatial variation of displacement along the lake length direction, and the profile line BB′ indicates the spatial variation of displacement along the lake width direction. The succession of motion values in Figure 7(A1,A2,F1,F2) is poor due to the cloud cover. Figure 9(B1,C1) shows that from 8–18 January 2021, the ice cover displacement in the EW direction changes from eastward motion to westward (from 4.2 to −4 m) and had a gentle displacement gradient, showing an overall blocky motion. In contrast, the lake ice displacement gradient in the NS direction was larger and migrated northward, always with an opposite displacement motion around the island (Figure 9(B1)). In comparison, the displacements along the AA′ profile line showed relative flatness in both components between 18 and 23 January 2021. A large lake ice movement occurred from 2 to 22 February, with an increase in the number of displacement gradients, especially at the southernmost and northernmost parts of the lake (Figure 9(G1,H1,J1)). The local movement was active, the overall displacement of the lake ice shifted from overall from north to south (Figure 9(G1–J1)), and the movement of EW direction changed from east to west. The entire ice cover was in a stable period from 22 February to 4 March, and then again showed block movement with a re-expressed displacement gradient. This suggests not only that the ice cover of Lake Khovsgol locally moves in opposite displacement patterns in the short term, but also that the movement direction of all lake ice is not fixed. Moreover, the scale of movement changes along the length of the lake proved to be larger in the NS direction than that in the EW direction. In contrast, the scale of movement changes along BB′ the profile line was flat, and the location of the displacement gradient did not significantly change.
along the length of the lake proved to be larger in the NS direction than that in the EW direction. In contrast, the scale of movement changes along BB’ the profile line was flat, and the location of the displacement gradient did not significantly change.

Figure 9. (A1–R2) represent the displacement values and changing trends on the EW and NS components along the profile AA’ and BB’. The dotted line in Figure 6(A1) indicates the position where the displacement gradient changes on the ice surface. The red dot in the figure represents the EW displacement value, and the blue dot represents the NS displacement value.
4.3. Ice Topographic Feature Extraction for Completing Lake Ice

During our time-series ice displacement surveying of Lake Khovsgol, a large number of ice ridges or ice mounds with elevated structures on the lake ice were visually observed in Sentinel-2 images, some of which were isolated and some of which were combined to form tandem images (“mountain ranges”). In a medium to large lake, ice cover becomes movable and moderate an uplift at the base of ice cover may be observed as ice thickness substantially decreases or wind speed increases. For example, in a study of the lake ice of Estonian/Russian Lake Peipsi (59° N, 27° E) on 15 and 19 March 2002, the authors of [64] observed that the southern part of the lake’s lake ice broke up under the influence of strong winds, while the northern part of the lake experienced uplift in a pattern similar to the ice mounds observed in Lake Khovsgol. Figure 10 shows the textural characteristics of the lake ice in Lake Khovsgol at different periods. Most of these large ice ridges spanned the lake and were a combination of multiple ice ridges that formed a mountain range-like structure. Most of these ice ridges across the lake were observed in the northern and central parts of the lake, though the southernmost part of the lake was found to produce a ridge along the north–south direction (Figure 10p–t). By comparing Sentinel-2 images from multiple time stages, we found that the ice ridges and ice mounds on the ice surface did not significantly change in form and position between 8 January and 4 March 2020. However, new fractures were created or old fractures were deepened and became visible around the ice ridges over time (Figure 10c,e,h,m,r; illustrated with red line), especially after February 7. These cracks on the ice cover usually extended for tens to hundreds of meters or more, forming a complex network that made navigation on the ice more difficult. The width of the cracks was generally 0.5–2 m, ranging from 1–2 cm to over 4 m and experiencing changes during the day [19]. During the day, melting snow and water filled up internal cracks in the lake ice, which froze at night when the temperature was negative [19].

Figure 10. (a–t) represent the ice ridges and crevasses on the ice surface as observed through band 8 of Sentinel-2 optical remote sensing images. Red lines represent emerging or deepening crevasses.
5. Discussion

In this study, we found that sub-pixel offset measurements extracted from Sentinel-2 optical images performed well for monitoring lake ice. The Sentinel-2 optical images used in this study have a higher spatial resolution (10 m) and shorter revisit period (5 days) than other optical images (e.g., Landsat 8), which allowed us to improve the accuracy and time resolution of our POT measurements. Our results showed that the monitoring of spatial and temporal variations of ice sheet displacements can be accomplished with uninterrupted high-density data gain (112 Sentinel-2 optical images), continuous acquisition times (most were 5 days, and a few were 10 or 15 days), and high-resolution matching (10 m) when constructing horizontal displacement measurements of seasonal ice sheet movements from −12 to 12 m (with an uncertainty of 0.7–2.3 m). In previous studies, the displacement accuracies for the Pleiades (0.7 m), Worldview (0.5 m), SPOT6-7 (1.6 m), and Landsat (15 m) satellites were found to be 0.13, 0.3–0.56, 0.5, and 0.47–0.60 m, respectively [61,65–67], suggesting that the COSI-Corr can reach an accuracy of 1/10 pixel [55,56,68–70]. We can also achieve an accuracy of 1/10 pixel in the second stage of lake ice. The InSAR technique was the first space-geodesy technique used in previous studies to detect ice displacement changes, such as in Prudhoe Bay and Barrow, Alaska [71–73]. However, InSAR has had limited applications in deriving lake ice displacement due to the need to penetrate microwaves into thick snow-covered ice, the highest achievable sensitivity for thin ice being a few tens of centimeters and probability of coherence loss [74]. For Lake Khovsgol, some studies have shown that InSAR measurements completely lack coherence and can only be used on land [74–76]. However, POT has shown strong potential to track ice changes, even during the growth seen in our study [77], so it also has strong potential for studies of the cryosphere (e.g., ice flow, river ice movement, and glacier ablation).

Our results revealed dynamic lake ice movements on Lake Khovsgol from ice-on to ice-off lasting nearly 6 months from 7 December 2020 to 17 June 2021. In a previous study by Kouraev et al. [47], in situ field survey records for several consecutive years showed that Lake Khovsgol started to freeze in November each year and started to melt in May or June of the following year. However, our results showed that in 2020, the lake freezing date was postponed to December, which proves that global warming is already having an impact on the icing trends of seasonal lake ice. We collected annual mean temperature data from NOAA for Lake Khovsgol from 1980 to 2020 (Figure 3). The data showed that the annual average temperature in the region had increased from −5 to −2.5 °C over the last 40 years, showing a generally linear increase. Appropriately, strong correlations between lake ice duration and global warming have long been demonstrated [11–13,15,16,78–80]. Magnuson et al. [16] showed that in lakes across the Northern Hemisphere from 1846 to 1995, the temperature increased by about 0.12 °C/decade, the freezing dates were delayed by 0.58 d/decade on average, and the thawing dates were advanced by 0.65 d/decade on average. In addition, Choiński et al. [9] collected lake ice observations from 18 lakes in Poland for the last 50 years (1961–2010), and they showed that lake ice had been appearing later and disappearing earlier and that the duration and thickness of ice cover had decreased. Thus, variations in lake ice are good indicators of climate change response.

Additionally, lake ice has obvious regional characteristics, and its formation is closely related to local climatic factors [2]. Figure 2a shows that the local temperature started to sharply drop after 17 December 2020, when the ice of Lake Khovsgol happened to be rapidly growing. The temperature started to rise gradually after 3 January 2021, but remained below 0 °C. From 18 April 2021, the temperature reached 0 °C and started to gradually rise. The lake ice movement then entered the third stage, where the snow melted during the day due to rising temperatures and then froze again at night when the temperature dropped. The freeze–thaw cycle continued during this stage. Similar freeze–thaw cycles have been observed in Lake Baikal in Russia and Nam Co Lake on the Tibetan Plateau [3,19]. The results of our time series monitoring of lake ice indicated that each stage of lake ice—freezing, accumulation, and melting—showed a strong correlation with the local temperature. In a study of river ice, Li et al. [2] indicated that river ice
accumulation periods are longer than melting periods, but periods of rising temperatures are longer than periods of falling temperatures. Our lake ice monitoring results were similar; we found that Lake Khovsgol’s ice accumulation period lasted for about 4 months from January to late April and its ice melting period lasted for about 2 months from late April to early May. However, local temperatures always increased, except for a drop from December 12 to early January.

Wind speed is another factor that affects the movement of ice in Lake Khovsgol [3]. According to the wind speed data that we collected (Figure 2b), the wind speed increased from 8 January to 2 February 2021, and the lake ice was actively moving during this period. In contrast, from 22 February to 4 March, the wind speed variation was smaller and the lake ice movement was milder. In addition, according to the research from Gou et al. [3] on the ice of Nam Co Lake, higher wind speeds in December correspond to earlier freeze-up and larger wind speed values, which lead to thicker lake ice.

The freezing and melting of lake ice is related to many factors, such as lake depth and runoff [17,72]. Korhonen et al. [79] underlined that the mean depth determines the amount of heat accumulated in a lake and is thus responsible for the delayed appearance of ice [81]. Our results showed that Lake Khovsgol started to freeze from the shallowest water on the southern shore (the area located in the northern part of the lake is the deepest and has the most heat storage). After the date at which the temperature dropped below freezing, we observed a time delay in ice-cover freezing that was roughly linear with the lake depth, with each additional meter of lake depth corresponding to an additional day of delay [17,72]. Thus, the icing trend of Lake Khovsgol is from south to north. The opposite is true for melting ice, and although POT results for the third stage are not available, the visible band of Sentinel-2 optical images showed that the lake ice breaks up from the north (Figure 11e), which is exactly where groundwater flows into Lake Khovsgol. The study shows that many permanent rivers flow into Lake Khovsgol [82], and the runoff direction of the lake is from north to south. In conclusion, the mechanism of ice formation and the factors influencing its motion are too complicated for us to provide more than quantitative analysis and reasonable hypotheses based on our own observations and the conclusions of others’ studies.

Figure 11. True color images of Lake Khovsgol at different times (B4, B3, B2). (a) shows that the lake started to freeze from the south, while the north remained water. (b) shows that the ice cover has completely covered the whole lake and the ice ridges/mounds are clearly visible. The red area is the selected stable area. (c) shows the intense solar radiation on the lake surface in April, which formed bubbles and air channels on the ice surface, giving the ice a white, snow-like appearance. (d) shows an example of the third phase obscured by clouds. (e) shows the lake ice breaking up from the north.
6. Conclusions

We used Sentinel-2 optical remote sensing images with the sub-pixel offset technique to derive the time series displacement of lake ice from 7 December 2020 to 17 June 2021, in order to characterize the spatial–temporal distribution and movement of ice in Lake Khovsgol, Mongolia. Sentinel 2 was found to perform well in the near-infrared band (B8), which could achieve an accuracy of approximately 1/10 pixel for the horizontal displacement of lake ice movement. In our study, the ice cover dynamics in Lake Khovsgol were found to be similar to those observed in other locations. We observed that lake ice has been appearing later due to the long-term effects of global warming. We additionally observed that the amount of annual lake ice is influenced by regional climatic factors, such as local temperature and wind speed. The monitoring results showed that the first stage of lake ice formation lasted 26 days, the second stage lasted nearly 4 months, and the third stage lasted 2 months. During the second stage, the lake ice movement was obvious, with horizontal displacement values of up to 12 m. In addition, the displacements in the NS direction were larger than those in the EW direction. During the third stage, POT performed poorly, as measurements were negatively affected by the physical properties of the ice-covered lake’s surface. It is worth noting that ice ridges and ice fractures occur during the accumulation period, during which the ice-covered Lake Khovsgol is not a safe and stable land transport route—especially after late spring when the lake ice is accompanied by freeze–thaw cycles. The authors of this study were the first to monitor lake ice on the Mongolia Plateau. Thus, we have provided not only a warning for residents to perform a series of activities on the ice during the freezing season but also some reference measurements for future studies of lake ice in this region.

Author Contributions: J.Z. and P.H conceived and designed the experiments; J.Z. and P.H. performed the experiments; J.Z. and P.H. analyzed the experiment data. X.H. and Z.L. gave suggestions for the discussion; J.Z. wrote the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the National Natural Science Foundation of China (42174004, 41704005).

Data Availability Statement: Not applicable.

Acknowledgments: The Sentinel-2 optical (https://scihub.copernicus.eu/, accessed on 3 January 2021) data were provided by the ESA through their open data policy. Most figures were plotted using Generic Mapping Tools (GMT).

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

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