~~The Capability~~Fusion of ~~high spatial-temporal remote sensing imagery~~Landsat 8 OLI and COCI for hourly monitoring surface morphology of lake ice with high resolution in Chagan Lake of Northeast China

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Abstract. The surface morphology of lake ice ~~undergoes remarkable~~remarkably changes under the combined influence of thermal and mechanical forces~~, which has been rarely observed by remote sensing~~. However, research on the surface morphology of lake ice and its interaction with climate is scarce. A large-scale linear structure has repeatedly appeared on satellite images of Chagan Lake in recent years. ~~We proposed a method to extract linear structure on the lake ice surface. We applied it to high spatial-temporal images merged by~~The Geostationary Ocean Color Imager (GOCI) with a 1-hour revisit and Landsat 8 Operational Land Imager (OLI) with a spatial resolution of 30 m provide the possibility to study the hourly changes in the large-scale linear structure. We merged the Landsat and GOCI images using an enhanced spatial and temporal adaptive reflectance fusion model (ESTARFM~~).~~), and extracted the lengths and angles of the linear structure. We monitored the hourly changes in the surface morphology ~~in Chagan Lake~~during the cold season from ~~November~~ 2018 to ~~March~~ 2019~~, which were further verified as ice ridges during the field investigation.~~. The average length of the ~~ice ridges during~~linear structure in the completely frozen period was 21141.57 ± 68.36 m. The average azimuth angle was 335.48° ± 0.23°, nearly perpendicular to the ~~wind~~ domain~~. Besides~~ wind in winter. Through two field investigations during the two recent cold seasons, we ~~discovered spherical~~verified the linear structure as ice ~~balls along the southwestern coast.~~ridges. The ~~deformation~~evolution of surface morphology is closely ~~related to wind direction, snowfall, and~~ associated with air temperature~~.~~, wind, and shoreline geometry.

Keywords: remote sensing, lake ice, GOCI, surface morphology, wind, ESTARFM

1 Introduction

Lake ice is one of the essential climate variables in the cryosphere (Bojinski et al., 2014) and is closely associated with lake environments, ecological regulation, public transportation, and the safety of human activities (Hampton et al., 2017; Magnuson et al., 2000; Leppäranta, 2015; Brown and Duguay, 2010; Arp et al., 2020). The shortening of ice cover duration and thinning of ice thickness have been common trends throughout the world (IPCC, 2021; IPCC SROCC, 2019; Murfitt and Duguay,
45 2021). Recent work using remote sensing mainly focused on lake ice phenology (Weber et al., 2016; Zhang et al., 2021; Xie et al., 2020; Murfitt and Duguay, 2020; Du et al., 2017), lake ice classification (Tom et al., 2020; Hoekstra et al., 2020), ice thickness (Murfitt et al., 2018b; Kang et al., 2014; Gogineni and Yan, 2015) and ice albedo (Li et al., 2018; Lang et al., 2018). However, previous work on the surface morphology of lake ice is scarce. The surface morphology, i.e., ice ridges and fractures, is controlled by the dynamic processes of lake ice, which have attracted widespread concern in academia and the public. In
50 this study, we monitored the surface morphology of Chagan Lake in Northeast China by combining high spatial-temporal remote sensing data and the results of field investigations and explored the potential influences of climate factors.

Satellite remote sensing is macroscopic, multi-source, and wide-range and has been successfully applied in the global remote sensing monitoring of lake ice (Murfitt and Duguay, 2021; Doernhoefer and Oppelt, 2016; Du et al., 2019).(Murfitt and Duguay, 2021; Doernhoefer and Oppelt, 2016; Du et al., 2019). Visible light and multispectral data were first used forto monitor lake
55 ice monitoring based on the spectraspectral difference between ice and water, but; however, the best period for monitoring to monitor lake ice changes is easilyprone to be missed due to the influenceinfluences of clouds, fog, and light (Howell et al., 2009; Cai et al., 2019; Yang et al., 2019; Qi et al., 2020).(Howell et al., 2009; Cai et al., 2019; Yang et al., 2019; Qi et al., 2020). Active microwave data are used to identify the presence of ice through the differences in the backscatter of water and ice, while passive microwave data are through the differences in bright temperature (Cai et al., 2017).(Cai et al., 2017).
60 Microwave remote sensing can penetrate the dry snow on the surface of lake ice surface to, and observe the internal structure and stratification of lake ice (Jones et al., 2013),) from the early stage of qualitative differentiation between ground ice and

floating ice to the quantitative inversion of ~~lake ice~~the phenology and thickness ~~(Ke et al., 2013; Jeffries et al., 2013; Howell et al., 2009; Kang et al., 2014).~~of lake ice (Ke et al., 2013; Jeffries et al., 2013; Howell et al., 2009; Kang et al., 2014). Although the temporal resolution of ~~the~~ active microwave remote sensing data has been improved from 30 days (ERS) to daily return

65 visits (Radasat-2), ~~the~~ ~~cost~~optimized technique is too ~~expensive~~costly and more suitable for case studies ~~for~~of small or medium lakes ~~(Murfitt et al., 2018a; Geldsetzer et al., 2010).~~(Murfitt et al., 2018; Geldsetzer et al., 2010). With high temporal resolution and ~~time series~~temporal coverage, passive remote sensing data can detect ice ~~cover~~covers under all weather conditions and ~~is~~are limited by their low spatial resolution and significant mixed image effects. Thus, passive remote sensing is more suitable for monitoring large-scale lake ice ~~monitoring (Du et al., 2017; Qiu et al., 2018). In summary,~~(Du et al., 2017; Qiu et al., 2018).

70 Although multi-~~sensor, multi-temporal and multi-spatial resolution~~source remote sensing ~~image data have been successfully applied~~is available to ~~monitoring the~~monitor lake ice~~. Still~~ processes, single-sensor remote sensing data cannot simultaneously ~~balance clear and~~achieve accurate remote sensing monitoring ~~with~~and high frequency.
~~Lake ice's growth and decay process change very fast, requiring high temporal resolution to capture surface morphology. The satellite sensor with moderate spatial resolution, such as VIIRS and MODIS, can monitor the temporal changes of lake ice~~

75 ~~daily but fail to reflect spatial details of surface morphology. The satellite sensors with medium spatial resolution, such as Landsat and Sentinel, could provide fine texture, but frequent images are not available to capture the fast changes. The fusion methods consist of unmixing, weight function, and dictionary-pair learning methods (Sisheber et al., 2022; Zhu et al., 2016). The most common weight function method includes the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM) (Feng et al., 2006), spatial and temporal adaptive algorithm (STAARCH) (Hilker et al., 2009), enhanced version Enhanced~~

80 ~~Spatial and Temporal Adaptive Reflectance Fusion Model (ESTARFM) (Zhu et al., 2010), flexible spatiotemporal data fusion (FSDAF) model (Zhu et al., 2016), and so on. Previous studies have proved that these spatial-temporal fusion methods could improve the monitoring abilities of remote sensing for specific applications but fail to monitor the abrupt changes in landscapes and spectral differences. All these models are derived by pairs of coarse and fine resolution, e.g., one pair for STARFM, and two pairs for ESTARFM. ESTRAM performs better than STRAFM model in heterogeneous landscapes (Zhu et al., 2010;~~

85 ~~Knauer et al., 2016; Wang et al., 2021b; Jarihani et al., 2014). STAARCH could require two pairs of bases strictly when monitoring the spatial changes, one before and one after the changes. FSDAF is more robust than the other three methods but has limited detection for the tiny changes (Zhu et al., 2016), which make it difficult to monitor the surface mopholgoy changes. Therefore, we generated fusion images with high spatial-temporal resoluiton based on ESTARFM model for further exploration.~~

90 The growth and decay processes of lake ice change very fast, requiring high temporal resolution to capture surface morphology. Satellite sensors with moderate spatial resolution, such as visible infrared imaging radiometer (VIIRS) and moderate resolution imaging spectroradiometer (MODIS), can monitor the temporal changes in lake ice daily but fail to reflect the spatial details of surface morphology. Satellite sensors with medium spatial resolution, such as Landsat and Sentinel, can provide fine texture but have no frequent images to capture fast changes. Fusion methods include the unmixing method, weight function method,

95 and dictionary-pair learning method (Sisheber et al., 2022; Zhu et al., 2016). The most common weight function method

includes the spatial and temporal adaptive reflectance fusion model (STARFM) (Feng et al., 2006), spatial and temporal adaptive algorithm (STAARCH) (Hilker et al., 2009), enhanced spatial and temporal adaptive reflectance fusion model (ESTARFM) (Zhu et al., 2010), and flexible spatiotemporal data fusion (FSDAF) (Zhu et al., 2016). Previous studies have proved that these spatial-temporal fusion methods can improve the monitoring abilities of remote sensing for specific

100 applications but fail to monitor the abrupt changes in landscapes and spectral differences. All these models are derived by pairs of coarse and fine resolution, e.g., one pair for the STARFM and two pairs for the ESTARFM. The ESTRAFM performs better than the STRAFM in heterogeneous landscapes (Zhu et al., 2010; Knauer et al., 2016; Wang et al., 2021b; Jarihani et al., 2014). When monitoring spatial changes, the STAARCH strictly requires two pairs of bases, including one before and one after the changes, which limits its wide application. The FSDAF is more robust than the other three methods but has limitations in

105 detecting tiny changes (Zhu et al., 2016), making it difficult to monitor the changes in surface morphology. Therefore, we generated fusion images with the high spatial-temporal resolution based on the ESTARFM for further exploration.

The evolution of a lake ice season is ~~primarily~~mainly a thermodynamic process ~~under the influence of wind forcing, water level variations, and~~ influenced by thermal and mechanical forces. ~~The thermal~~Thermal forces enable the surface to melt and freeze ~~when~~at the turn of the day and night ~~alternate,~~ and the mechanical strength of ~~wind~~winds and ~~flow make~~currents makes

110 the ice bulk move and collide, ~~and then~~causing water ~~course~~courses, ice ridges, and ice fractures to appear, develop and disappear. Therefore, the surface morphology of lake ice exhibits a periodical spatial-temporal difference ~~periodically~~, which differs significantly from the flat and smooth surface of lake ice. The ~~horizon~~horizontal and linear ~~structure~~structures of lake ice ~~was~~are monitored by optical satellites for large lakes in Europe, ~~which were~~ and have been explained by ice displacement ~~(Leppäranta, 2015). The high~~(Leppäranta, 2015). High-resolution satellite-airborne ~~Synthetic Aperture Radar~~synthetic

115 aperture radar (SAR) images have been used to monitor ~~sea ice~~the surface deformation of sea ice, such as ice ridges ~~(Dierking, 2010).~~(Dierking, 2010). Moreover, airborne aerial platforms, such as unmanned aerial vehicles (UAVs) (Li et al., 2020), airborne radar (Jeffries et al., 2013), and ground-penetrating radar (Gusmeroli and Grosse, 2012), have effectively complemented remote sensing data sources ~~for monitoring~~to monitor the changes in ~~lake ice morphology, such as Unmanned Aerial Vehicle (UAV) (Li et al., 2020), airborne radar (Jeffries et al., 2013), and ground-penetrating radar (Gusmeroli and~~

120 ~~Grosse, 2012).~~ the morphology of lake ice. The spatial distribution of ~~lake ice~~the surface morphology ~~presents~~of lake ice is complex, variable and discontinuous ~~characteristics,~~, which is characterized by highlighting linear features ~~in~~on remote sensing images. ~~At present,~~Currently, there are few studies ~~study~~on the changes in the surface morphology of lake ice and the ~~impact~~influence factors, ~~so it~~. It is meaningful to develop a quantitative method to describe the ~~lake ice~~surface morphology and explore the potential influences.

125 This study ~~proposed~~proved the ~~workflow based on ESTARM fusion~~capability of high spatial-temporal remote sensing images ~~to monitor surface morphology in a highly dynamic process. The objectives of our work are to (1) propose a reliable method to extract~~for monitoring the surface morphology of lake ice~~; (2) monitor the changes in surface morphology for~~ in Chagan Lake ~~using~~, Northeast China. Our work aimed to (1) generate high spatial-temporal satellite ~~imagery~~images using Landsat and Geostationary Ocean Color Imager (GOCI); (2) monitor the hourly spatial changes in the surface morphology, including

130 length and angle, of Chagan Lake; (3) ~~explore~~discuss the beneficial climate conditions during the formation ~~mechanism~~ of the surface morphology ~~observed from satellite and field investigation.~~ of lake ice.

2 Materials

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2.1 Study area

~~The~~ As one of the ten largest lakes in China, Chagan Lake ~~basin~~ (124°03′~~'~~–124°34′E, 45°09′~~'~~–45°30′N) (Figure 1~~), one of the ten largest lakes in China,~~) plays an essential role in fisheries, agricultural irrigation, and winter recreation in the surrounding areas ~~(Wen et al., 2020).~~ (Wen et al., 2020). The average and maximum water depths are 2.5 and 4.5 ~~meters (Duan et al., 2007; Song et al., 2011).~~ m, respectively (Duan et al., 2007; Song et al., 2011). The lake has a water area of ~~252.86~~329.72 km^2 and a ~~length~~perimeter of ~~107.28~~201.03 km ~~from~~according to Landsat 8 OLI ~~8~~ on January 10, 2019. The salinity of lake ~~area~~water ranges from 0.31‰ to 0.78‰ (Liu et al., 2020). The catchment of Chagan Lake is characterized by semi-arid and sub-humid continental monsoons with air temperature, precipitation, and evaporation of 5.5 ℃, 430 mm, and 1496 mm ~~(Song et al., 2011; Duan et al., 2007).~~, respectively (Song et al., 2011). The ~~salinity ranges from 0.31 to 0.78 ‰ (Liu et al., 2020). The~~ recharge sources mainly ~~consist of~~comprise precipitation, groundwater, and adjacent irrigation discharge ~~(Liu et al., 2019). The bottom of Chagan Lake is relatively flat, the~~ (Liu et al., 2019). Salinized soil ~~is primarily powdery-sandy with the type of white calcium alkaline, and salinized soil farmlands~~farmland and grassland pastures are widely distributed in the catchment area. ~~The~~ Chagan Lake is a typical lake with seasonal ~~frozen lake, and the existence of~~ ice cover ~~lasts~~, and the ice covers exist from November to April each cold season, with the maximum ice thickness ranging from 0.8 to 1.1 ~~meters (Liu et al., 2020; Hao et al., 2021).~~m (Liu et al., 2020; Hao et al., 2021). We conducted two field investigations ~~from~~on December 30 ~~to~~ 31, 2020, and January 2 ~~to~~ 4, 2022. ~~The goal was~~ to verify the ~~linear structure observed~~results from remote sensing ~~images~~. We measured the ice ~~thickness by~~thicknesses using an electronic digital calliper with a resolution of 0.01 mm. ~~Besides~~Moreover,
150 we ~~also~~ measured the water ~~depth by~~depths using a hand-held sonar detector (SpeedTech SM-5) with a resolution of 0.1 ~~meters~~m and compared the ~~difference between autumn~~depths of fall (September 17, 2021) and winter (January 2 ~~to~~ 4, 2022).

[Figure 1 is added here]

2.2 Materials

2.2.1 GOCI

155 The ~~Geostationary Ocean Color Imager (~~GOCI~~) was~~ is the first satellite for detecting ocean ~~colour~~color from a geostationary orbit~~, which~~ and has been widely applied in deriving ~~the~~ optical, biological, and biogeochemical properties ~~(Ryu et al., 2012; Ryu and Ishizaka, 2012). GOCI~~ (Ryu et al., 2012; Ryu and Ishizaka, 2012). The GOCI data have been available since April 2004, covering about 2500 km × 2500 ~~km²~~km around the Korean Peninsula. ~~Its~~It has six visible bands ~~range from 412 to 443 and 540 to 555, 660 to 680 nm~~ and two near-infrared bands ~~range from 745 to 865 nm.~~, and Table 1 provides the detail of band information. The GOCI provides eight hourly observations from ~~local times from~~ 8:~~00~~30 to 15:~~00~~30 local time, with a spatial

resolution of 500 m. The ~~best~~COCI has the most significant advantage of ~~COCI is the frequent~~high temporal resolution with eight images daily ~~and could~~, which can offer ~~the~~ details ~~for~~of freeze-up and break-up processes. A total of 96 GOCI images during the cold season ~~of~~from 2018~~-~~ to 2019 were used in this ~~paper.~~study (Table 2). The atmospheric correction ~~has been carried out~~was performed by GOCI data processing software (GDPS).

165 **[Table 1 is added here]**

[Table 2 is added here]

2.2.2 Landsat

The Landsat 8 satellite was launched on February 11, 2013~~, carrying~~. It carries the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS), which have been widely used ~~for~~to monitor lake and river ice ~~monitoring (Wang et al., 2021a;~~
170 ~~Yang et al., 2020), with the~~ (Wang et al., 2021; Yang et al., 2020). The OLI ~~having~~has nine bands~~. It has~~, with a spatial resolution of 30 m for Bands 1~~—~~7 and Band 9 and a spatial resolution of 15 m for Band 8. It has a temporal resolution of 16 ~~days. Four~~d. Six Landsat images during the cold season ~~of~~from 2018~~-~~ to 2019 were prepared for data fusion with ~~the~~ GOCI. The capture ~~date is~~dates were November 6, 2018, November 22, 2018, December ~~08, January 25~~8, 2018, February 26, ~~and~~2019, March 14, ~~respectively.~~ 2019, and April 15, 2019. The path and row are 119 and 29~~,~~ respectively. We downloaded the Landsat
175 calibrated surface reflectance Tier 1 collection for Landsat 8 OLI ('LANDSAT/LC08/C01/T1_SR') from ~~the~~ Google Earth Engine (GEE) for further work. ~~More details of~~Table 1 compares the band information ~~of~~on Landsat and GOCI ~~can be. From it, we~~ found that the band range of Band 3 of the GOCI (480–500 nm) overlapped with that of Band 2 of the Landsat 8 OLI (450–515 nm). The water body had relatively strong reflectance in ~~Figure S1~~the blue band (400–480 nm), and the blue band images clearly displayed the linear structure. Therefore, we merged Band 3 of the GOCI and Band 2 of the Landsat 8 OLI and
180 generated the 96 hourly fusion images for further work.

2.2.3 Auxiliary data

~~The cold season is defined from October of the current year to April of next year according to the local climate. The surface temperature of the lake was extracted from MOD11A1 products for each cold season from 2000 to 2021, following the~~
185 ~~processing procedure of our previous work (Song et al., 2016; Hao et al., 2021). Daily air temperature, precipitation, wind direction, and wind speed of Qian'an station (ID: 50948) were utilized to explain the influence of climate on lake ice from 2010 to 2021. The longitude and latitude of Qian'an are 124.011° E and 44.998° N, with an elevation of 146.3 meters. The climate records are used to explain the lake ice development. A 16-degree angle with an interval of 22.5° was used to indicate the direction of the wind.~~
190 The lake ice phenology of the cold season from 2018 to 2019 was extracted from the combined time series of the surface temperature of lake water provided by MOD11A1 and MYD11A1 products (Song et al., 2016; Hao et al., 2021). The freeze-up date is defined as the first day when the surface temperature of lake water is below 0℃ in winter; the break-up date is

defined as the first day when the surface temperature of lake water is above 0°C in spring. We utilized the daily air temperatures, precipitation, wind directions, and wind speeds of Qian'an station (ID: 50948) to explain the influence of climate on lake ice from 2010 to 2021. Qian'an has a longitude and latitude of 124.011° E and 44.998° N, respectively, with an elevation of 146.3 m. Sixteen directions with an interval of 22.5° were used to describe the wind directions, including north (N), north-northeast (NNE), northeast (NE), east-northeast (ENE), east (E), east-southeast (ESE), southeast (SE), south-southeast (SSE), south (S), south-southwest (SSW), southwest (SW), west-southwest (WSW), west (W), west-northwest (WNW), northwest (NW), and north-northwest (NNW). The climate records were used to explain the relationship between lake ice and climate.

3 Methods

3.1 The framework of methodology

Figure 2 presents the flow chart of our work herein. We pre-processed the Landsat 8 OLI and GOCI and prepared the reflectance images of Band 2 of the Landsat band 28 OLI and Band 3 of the GOCI band 3. Then, we merged the GOCI and Landsat 8 OLI using the ESTARFM model and generated new fusion data with a spatial and temporal resolution of 30 metersm and 1 hour., respectively. After that, we identified the geographic location of the linear structure on the surface of lake ice surface was identified, and extracted the morphological parameters were extracted, including lengthlengths and angle. angles.

[Figure 2 is added here]

3.2 The ESTARFM fusion

The enhanced spatial and temporal adaptive reflectance fusion model (ESTARFM) was proposed by Zhu et al. (2010) based on the STARFM model., in which used two pairs of Landsat and GOCI images were used to generate the spatial-temporal fusion data., was proposed by Zhu et al. (2010) based on the STARFM. Firstly, the coarse GOCI data waswere projected and resampled to a fine Landsat image at two known times $T_m t_m$ and $T_n t_n$. Secondly, similar neighbourhoodneighborhood pixels were searched bywith a moving window by setting spectral differences. Thirdly, we calculated the normalized weight of each similar pixel was calculatedby considering the spatial, spectral, and temporal differences. Then, the coarse GOCI values were transferred to fine Landsat data using the pixel-based conversion coefficients fromin the linear regression. Finally, the coarse GOCI data at the same time were used to calculate the fine fusion data at the predicted time (T_p,) are calculated by the coarse GOCI data at the same time, which aret_p), expressed as follows (Liu et al., 2021; Bai et al., 2017; Zhu et al., 2010):(Liu et al., 2021; Bai et al., 2017; Zhu et al., 2010):

$$L_b(x_{w/2}, y_{w/2}, T_p) = L_b(x_{w/2}, y_{w/2}, T_k) +$$
$$\sum_{i=1}^{n} W_i \times v_i \times (G_b(x_i, y_i, T_p) - G_b(x_i, y_i, T_k)) \ (k = m, n)$$

$$L_b\left(x_{w/2}, y_{w/2}, t_p\right) = T_m \times L_{bm}\left(x_{w/2}, y_{w/2}, t_p\right) + T_n \times L_{bn}\left(x_{w/2}, y_{w/2}, t_p\right) \tag{1}$$

Wherewhere L_b and G_b represent the $(x_{w/2}, y_{w/2}, t_p)$ is the final predicted fine-resolution reflectance of MODIS and GOCI images in band b, w stands forat the prediction time t_p; w represents the size of the moving window size and the corresponding center is $(x_{w/2}, y_{w/2})$. W_i is the $x_{w/2}, y_{w/2})$; $L_{bk}(x_{w/2}, y_{w/2}, t_p)$ is the fine-resolution reflectance at t_k (k = m or n) at the base date; T_k is the time weight of a, calculated from the magnitude of the detected change in the reflectance of the coarse spatial resolution image between t_m and t_n and the prediction moment t_p;

$$T_k = \frac{1 / \left| \sum_{j=1}^{w}\sum_{i=1}^{w} C(x_j, y_i, t_k) - \sum_{j=1}^{w}\sum_{i=1}^{w} C(x_j, y_i, t_p) \right|}{\sum_{k=m,n}\left(1 / \left| \sum_{j=1}^{w}\sum_{i=1}^{w} C(x_j, y_i, t_k) - \sum_{j=1}^{w}\sum_{i=1}^{w} C(x_j, y_i, t_p) \right|\right)}, (k = m, n) \tag{2}$$

where $C(x_j, y_i, t_k)$ and $C(x_j, y_i, t_k)$ denote the image element values of similar pixel contributing to the predicted pixel; v_i is the conversion coeffects; T_k is the known time, including T_m and $T_n$image elements (x_i, y_i) within the moving window of the coarse spatial resolution image at the reference moment t_k and prediction moment t_p, respectively.

3.3 The extraction of length and angle for quantitative analysis of linear structures

The In the beginning, the Landsat-GOCI fusedfusion images were transformed into binary images. The We extracted the original linear network was extracted by the method of Canny edge detection algorithm, (Canny, 1986) and then conducted edge detection was carried out to remove the outer boundaries (Canny, 1986). The morphological processing, including opening, filling, and eroding sequentially, was implemented for the inner part of the linear network, including opening, filling, and eroding sequentially. Then, we dividedthe linear structure was derived from the largest connected domain of inner parts into two paths, and the linear network without boundaries, and the length is calculated by the shortest path was considered the final length.of the largest connected domain. We connected the northmost and southmost ends into a straight line. The angle was determined as the north-south connection line and the northfollowed the definition of wind direction along the clockwise direction.above. We compared the auto-extraction and visual interpretation in our previous work (Hao et al., 2021). Regarding(Hao et al., 2021). The R^2 values of the length and angle of linear structures, 0.96 and 0.98, and proved the good performance of auto-extraction performed well with an R^2 value of 0.96 and 0.98, respectivelyalgorithm.

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4 Results

4.1 The performance of ESTARFM model

We predicted the fine images from two pairs of fine Landsat and coarse GOCI data to fill the data gap caused by the low revisit frequency of the Landsat. The two known pairs of data in the freeze-up process were captured on November 6, 2018, and December 8, 2018, and 53 fine ESTARFM fusion images were predicted from coarse GOCI images. The two known pairs of data of the break-up process were captured on February 26, 2019, and April 15, 2019, and 43 fine ESTARFM fusion images were predicted. Figure 3 displayscompares the comparisonspatial distribution of the original images and predicted images on November 22, 2018. The two related pairs of Landsat and GOCI were captured on November 6, 2018, and December 8, 2018. The predicted image keptIn the predicted images, the texture of the ground objects, which is was maintained, and enlargement figures in Figure 3 (c) and Figure 3 (d) clearly display the distribution of linear structure. The predicted images were well consistent with the original images. We also enlarged part of the linear structure, showing, and indicate a good fusion effect. of ESTARFM. Figure 4 illustrates the scatter plots along the 1:1 line of the actual and estimatedpredicted reflectance values andalong the corresponding statical results1:1 line. The R^2 had the value ofis 0.93, which indicated935, indicating that the predicted image was highly correlated with the actual image. Besides, we compared the reflectance values of original images and predicted images on November 22, 2018. The result showed that the range of estimatedThe ranges of predicated and actual images waswere consistent; the mean of their mean reflectance values waswere both 0.10 ± 0.03. The performance of the ESTARFM results was limited by (1) the limited image pairs available during the cold season from 2018 to 2019; (2) the time lag between the predicted and actual images; (3) the inconsistency of capture time between the predicted images and two pairs of input images (Lu et al., 2019; Liu et al., 2018). Therefore, the ESTARFM fusion images had a good performance and providedcan provide reliable materials for further exploration.

[Figure 3 and 4 is added here]

We predicted the fine images from two pairs of fine Landsat and coarse GOCI data to fill the data gap caused by the low revisit frequency of Landsat. The high R^2 between actual and predicted images was 0.935 on November 28, 2018, which proved that the fusion images are consistent with the remote sensing data. Liu (2018) et al. pointed out that when validating the ESTARFM model, a 4-day time lag between fusion and validation results may lead to errors in the analysis of the results. The time lag in our study ranged from 5.5 to 12.5 hours for Landsat and GOCI, and the assumption that the lake ice will not change dramatically in a short period. The performance of ESTARFM results was limited by: (1) Only three image pairs were available during the cold seasons; (2) the time lag between the prediction and verification images; (3) the inconsistency between the predicted time and two input pairs (Lu et al., 2019; Liu et al., 2018). The ESARFAM model predicted the reflectance using a linear model and assumes that the reflectance changes steadily during the fusion process (Liu et al., 2018). These limitations need to be considered in our future work.

4.2 The changes in surface morphology

We extracted the surface morphology of Chagan Lake from 96 fusion images during the cold season ~~of~~from 2018~~-~~ to 2019.
Figure 5 displays the spatial changes ~~of~~in the linear structure ~~on~~of Landsat images ~~during~~in the freeze-up and break-up ~~process.~~
~~Figure S3~~processes. Figures A1 and ~~Figure S4 presented~~A2 present the original images ~~from~~of the GOCI with a resolution of
500 ~~meters~~m, the fusion images ~~from~~of the Landsat and GOCI with a spatial resolution of 30 ~~meters~~m, the network structure
~~of surface morphology,~~ and the ~~surface morphology during~~linear structure in the freeze-up and break-up ~~process, which~~
~~provide~~processes, providing more details of the extraction process. The linear structure ~~on image~~ appeared on images from
southeast to northwest, lasting from November 22, 2018, to November 30, 2018. The linear structure disappeared from ~~the~~
northwest to southeast, lasting from March 15 ~~to March 24, 2019. ~~, 2019, to March 24, 2019. Figure 6 shows the average daily
lengths of ice ridges based on the Landsat and GOCI remote sensing data. We monitored the growth and recession process of
the linear structure via 96 Landsat-GOCI fusion images and monitored the stable process via four Landsat images. The growth
stage lasted for 9 days, from November 22, 2018, to November 30, 2018. The ice ridges had a length range of 5211.17–
18042.15 m and an average value of 12680.32 ± 4472.37 m, extending from southeast to northwest. The azimuth angles of the
ice ridges in the growth stage ranged from 331.54° to 338.17°, with an average value of 334.38° ± 2.08°. The lengths in the
stable process ranged from 21052.78 m to 21227.53 m with an average value of 21141.57 ± 68.26 m, and the angles changed
from 335.15° to 335.77° with an average value of 335.48 ± 0.20° The recession stage lasted for 10 days, from March 15, 2019,
to March 24, 2019. The ice ridges had a length range of 19178.18–5924.03 m and an average value of 13288.59 ± 4907.89 m,
disappearing from northwest to southeast. The azimuth angles of the ice ridges in the recession stage ranged from 329.84° to
336.16°, with an average value of 332.90° ± 2.54°. The changing rates in the growth and recession stages were 1425.66 and
1325.42 m per day, respectively, indicating that growth was slightly faster than recession. The large-scale ~~fracture~~structure
extending from northwest to southeast ~~that~~ repeatedly appeared on Landsat images since 1986, which has been reported in our
previous work ~~(Hao et al., 2021).~~(Hao et al., 2021).

[Figure 5 is added here]

~~Figure 6 shows the average daily length of ice ridges from Landsat and GOCI remote sensing data. It can be seen that the ice~~
~~ridge changes in the winter of 2018-2019 can be divided into three processes, including the growth process, stable process,~~
~~and recession process. The growth stages lasted from November 22 to November 30, a total of 9 days. The length of the ice~~
~~ridge changed from 5211.17 meters to 18042.15 meters with an average value of 12680.32 ± 4472.37 meters, extending from~~
~~the southeast to the northwest. The average azimuth angle of the ice ridges during the growth process was 334.38° ± 2.08°~~
~~ranging from 331.54° to 338.17°. The recession lasted from March 15, 2019, to March 24, 2019, a total of 10 days. The length~~
~~of the ice ridge changed from 19178.18 meters to 5924.03 meters with an average value of 13288.59 ± 4907.89 meters,~~
~~disappearing from northwest to southeast. The average azimuth angle of the ice ridges during the recession process was 332.90°~~
~~± 2.54° ranging from 329.84° to 336.16°. The changing growth and recession process rate were 1425.66 and 1325.42 meters~~
~~per day, which suggests the growth is slightly faster than the recession process.~~

[Figure 6 is added here]

4.3 The field investigation

~~The lake ice process is governed by the complex interaction of hydraulics, thermodynamics, and mechanics. The heat loss caused by decreasing air temperature exceeds the heat gained from the surface water in the late autumn and early winter. When the water temperature falls below the freezing point, the cooling water provides a beneficial condition for ice crystals. Then the volume of lake ice expands and the amount increases, followed by ice formation. The average freeze-up date of Chagan Lake was November 12 during the 12 recent cold seasons from 2010 to 2022, which has been listed in Table S1 (Hao et al., 2021).~~ Considering the safety of traveling ~~safety~~ on ice, we conducted two ~~thorough~~field investigations during the two recent cold seasons, ~~on~~from December 30 to 31, 2020, and January 2 to 4, 2022, respectively. We divided the lake area into three regions according to the surface morphology of lake ice. Region 1 was distributed along the linear structures. The surface of lake ice is uneven, and ice fractures and ice ridges were widely distributed. Region 2 was distributed along the northeastern coast, where the Ice and Snow Fishing and Hunting Cultural Tourism Festival of Chagan Lake has been held at the end of December each year. Region 3 covered the southern part of Chagan Lake. The lake ice in Regions 2 and Region 3 was flat and smooth, and snow cover was sporadically distributed. The color of lake ice along the linear structure was distinguished from lake ice in the neighborhood. We infer that the frozen time of linear structure was later than the lake ice in the neighborhood. The difference between ice fractures and ice ridges was the vertical height. Ice ridges were elevated sections formed on the upper and lower surfaces of lake ice, consisting mainly of ridge sails and keels. We located ten sampling points along the linear structure on the satellite images and collected field photos of ice ridges and fractures, ~~as shown in~~ (Figure 1~~.~~). We further verified the large-scale fractures on the images as ice ridges. ~~More interesting is that we both discovered ice balls along the southwest coast of Chagan Lake in the two years, as shown in Figure 7. The ice ball piled above the ice surface in the winter of 2020, and the ice was so uneven that the cars had difficulties traveling on the ice surface. However, the ice ball in 2022 was frozen beneath the ice surface, and the surface was relatively smooth.~~

We also measured the ice ~~thickness~~thicknesses and water ~~depth~~depths of ~~each~~16 sampling ~~point, presented in~~points (Figure 7~~.~~). The ice ~~thickness~~thicknesses in the winter of ~~2022~~2021 ranged from 437.55 mm to 668.25 mm, with an average value of 582.24 ± 58.14 mm. ~~We divided into three regions: Region 1 was distributed along the ice ridges; Region 2 was distributed along the north-eastern coast; Region 3 covered the southern part of Chagan Lake.~~ The average ~~values~~ice thicknesses of ~~regions~~Regions 1, 2, and 3 were 551.58 ~~mm~~, 547.75 ~~mm~~, and 645.74 mm~~.~~, respectively. The average water depths of Regions 1, 2, and 3 were 3.48, 2.99, and 3.00 m, respectively. Among the three regions, ~~the ice thickness~~Region 2 had the smallest ~~value.~~average values of ice thickness and water depth. The ~~difference~~differences in water depth between ~~summer~~the fall of 2021 and ~~winter~~the winner of 2021 ~~varied from 0 to 0.2 m with~~had an average value of 0.12 ± 0.05 m. ~~This indicated that winter's~~ and a maximum value of 0.2 m. The water depth ~~is~~in winter was lower than ~~summer's, but the differences were not significant enough to explain what we observed from the satellite.~~that in fall, and the decreasing water level also was a cause of lake ice fracturing in winter (Leppäranta, 2015). The ice features first formed in the ~~southeast coast's~~nearshore area of the

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southeast coast, where the water depth was relatively ~~shallower~~smaller than that in other regions in Figure 7. The ice ~~thickness~~thicknesses and water ~~depth~~depths showed spatial coherence with the surface morphology~~, especially with the ice thickness. ~~.

[Figure 7 is added here]

4.4 The climate condition

~~As shown in Figure 8, we analysed~~Lake ice processes are governed by the complex interaction of hydraulics, thermodynamics, and mechanics. The heat loss due to the decreasing air temperature exceeds the heat gained from surface water in late fall and early winter. When the water temperature falls below the freezing point, the cooled water provides a beneficial condition for ice crystals. Then, the volume of lake ice expands, and the amount increases, followed by the formation of ice. We analyzed the wind ~~rose~~roses and daily average and maximum ~~wind~~wind speeds from November 1, 2018, to April 15, 2019~~.~~ (Figure 8). The freeze-up and break-up dates of Chagan Lake in the cold season of 2019 ~~are~~derived from MODIS LST products were November ~~17~~14, 2018, and March ~~22~~24, 2019, respectively. The ice ridges appeared on November 22, 2018, 5 days ~~later than~~after the freeze-up date; they disappeared on March 24, 2019, ~~2 days later than~~and were consistent with the break-up date. The ~~temporal resolution of MODIS LST products is eight days~~domain wind in the growth process was NW, WNW, W, and ~~can explain the time difference. We also found that~~WSW; the ~~WSW (247.5°)~~domain wind in the stable process was WNW, WSW, and NNE; the domain wind in the recession process was NW, WNW, and WSW. WNW and WSW direction ~~had a relatively high frequency~~was the domain wind direction for all three stages. The frequency ~~of WSW~~in the WSW direction in the growth, stability, and recession stages was 22.22%, 30%, and 14.23~~% for the growth, stable, and disappearing processes.~~%, respectively. The ~~angle~~angles between the WSW direction and ice ridges ~~was~~were 87.98°, 86.88°, and 85.4~~°~~40° for the three stages. The nearly perpendicular relationship was consistent with our previous study ~~(Hao et al., 2021). Moreover, the three quartiles of daily average speed were 3.52 m/s, and those~~ (Hao et al., 2021). Our previous used the yearly average values of wind from 2013 and 2020, and the work herein just exploited the wind in the cold season from 2018 to 2019. Besides, the wind speed also contributed to the formation of ice cracks and ridges. The daily average wind speed in the growth process ~~(3.88 m/s)~~ and recession process ~~(was 3.88 m/s and~~ 3.63 m/s~~)~~, and the average values for the whole cold season were ~~more prominent than the three quartiles. The three quartiles of~~ 2.97 m/s. Both the daily maximum wind speed ~~were 6.92 m/s, and those of~~in the growth process ~~(7.05 m/s)~~ and recession process ~~(6.86 m/s) were close to the three quartiles.~~was 3.88 m/s and 3.63 m/s 7.05 m/s and 6.86 m/s, and the average values for the whole cold season were 5.65 m/s. Not only daily average values but also the maximum value was higher than the average level and revealed that the changing processes of ice fractures and ridges require relatively strong action of wind. Therefore, wind ~~speed~~speeds and ~~direction~~directions played ~~a~~ crucial ~~role~~roles in the development of ice ridges.

[Figure 8 is added here]

~~To explain the existence of ice balls, we checked the changes in air temperature, precipitation, wind speed, and wind direction of Lake Chagan around the freeze-up periods from 2010 to 2021, as shown in Figure 9. The freeze-up dates were provided by~~

375

380 **[Figure 9 is added here]**

5 Discussion

The lake ice experiencedexperiences different phasestypes during the freezing and thawing cycle, including the phases of ice crystalcrystals, frazil ice, nails, pancake ice, and ice layer. The lake ice began to freeze in shallow water areas and expanded to the lake centre until the lake was completely frozen.layers (Leppäranta, 2015). Lake ice deformed under the combined

385 influence of thermodynamics and hydrodynamics, resulting in lead, cracks, and ice ridges. The lake ice expanded and contractedexpands and contracts as the air temperature roserises and droppeddrops during the cold seasonseasons. The temperature difference between night and day results in lake ice'sthe thermal expansion and contractscontract of lake ice, which differ significantly within a given lake. Furthermore, long and narrow cracks then happenedare generated and were likely to evolve into ice ridges under the pressure when the lake ice bulked, collidedbulk, collides, and piledpiles up. The view

390 rangedefinitions of lake ice are limited traditional by the view ranges of field measurement and had difficulty identifying the spatial distribution of ice ridges. In this work, we proposed an algorithm to detect the high lightenedmeasurements, and satellite remote sensing provides a new perspective for surface morphology in a larger-scale observation. The large-scale linear structure basedhas been found on remote sensing images. The recurrent linear structure on a large scale during the cold season from 2018 to 2019. Similar phenomena have also been found in lakes and reservoirs in Northeast China (Liu et al., 2018b).

395 In our previous work, we used 4 Landsat 8 OLI images to monitor the monthly changes due to the limitation of temporal resolution (Hao et al., 2021). In this study, we took advantage of the hourly revisit of the GOCI and generated 53 and 43 ESTARFM fusion images in the freeze-up and break-up processes, respectively. This makes it possible to explore the linear structure in detail. The recurrent large-scale linear structure was further verified as ice fractures and ice ridges in the fieldwork. The ice ridges were supposed to happen in the area with thinner ice thickness. During the field investigation, we measured the

400 ice thickness along the linear structure. We compared it with the other regions (Figure 7), and the difference of ice thickness is not significant to support this. The spatial scales of ice fractures and ice ridges is a changeling work when considering the data source. The UAV is suitable to monitor the lake ice fractures at small scales (0-100m), and the satellite sensors are suitable to monitor the ice ridges at large scales (10-100 km), both of which required a thorough investigation of ice thickness in

Chagan Lake by combingare suitable to monitor the in-situ measurement and remote sensing monitoring. horizon changes of the lake ice surface.

The development of seasonalBesides the thermal forces, the lake ice isfractures and ridges are also a dynamic process, and the under the control of mechanical forces. The wind above ice covers and water currents beneath ice covers force the shift of ice bulk. During (Tan et al., 2012). Wang et al. (2006) compared the machinal changes of leads and ice covers based on modelling results and satellite monitoring (Wang et al., 2006; Leppäranta, 2010) and revealed the influence of winds on the drift of ice. In the freeze-up process, the windwinds and water flowcurrents can push the ice toward the shore, preventing the ice covercovers from freezing; duringin the break-up process, the wind couldcan break the ice covercovers and accelerate the melting. The lake ice fractures were mainly controlled by thermal forces, and the ice ridges were mainly controlled by mechanical forces. The ice ridges underwent three stages during the cold season of 2018, during 2019, in which the wind directiondirections and speedspeeds exhibited remarkable differences in Figure 8. . The ice ridges grew from southeast to northwest with an average direction of 334.38° and decayed from northwest to southeast with an average direction of 332 ° .

The direction of ice ridges is nearly perpendicular to .90°. The WSW (247.5 °), which direction frequently happened forin all three periodsstages, revealing the crucial role of windwinds in the development of ice ridges. However, more aspects should be considered. More interestingly, theThe direction of the ice ridges was nearly perpendicular to the WSW direction of(247.5°), which followed the principal laws of mechanics. The air temperature created a cold environment for the ice cover to freeze, the wind provided a mechanical force for the ice bulk to shift, and ice ridges and ice fractures formed. In addition, the direction of the ice ridges had a similar shape to the southwest shoreline, and the stable shoreline geometry could explain the recurrent ice ridges with a specific direction, which had beenwas reported in previous studies (Leppäranta, 2015). (Leppäranta, 2015). We also discovered the spherical ice ball in the neighbourhood of the southeast coast, and this rare geographic scenic attracted our interest, which has been reported in Finland, Japan, and so on (Case, 1906; Loewe, 1949; Langlois, 1965; Eisen et al., 2003; Kawamura et al., 2009). From Figure 9, the occurrence of ice ball needs to meet the strict requirements of climate conditions together during the frozen process: (1) the air temperature varies up and down the freezing point and can meet the freezing conditions; the temperature cannot be lower than -10 ℃. Otherwise, the ice will directly freeze completely; (2) sufficient snowfall is necessary to provide material sources for the emergence of ice balls, snow and water mixed and frozen together, the final ice balls formed under the continuous washing of wind and waves; (3) wind speed is large enough to push the rolling spherical ice to southwest coast only if the wind direction was northeast before freezing, and then ice balls aggerated the nearshore areas (Xie et al., 2022(in Chinese)). During the past decade, only the cold season of 2020 and 2021 could meet all three conditions, and we, fortunately, discovered these ice balls during the field investigation.

Linear structures are common natural phenomena on the surfaces of sea ice and lake ice and profoundly influence light transfer and ice ecology. Lake ice ridges alter surface roughness and light transfer and contribute to the thickness and volume of ice. People in cold regions have skilfully taken advantage of frozen ice covers for fishing, food storage, and commercial

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transportation. The capacity and stability of floating ice can be evaluated by the ice thickness and the spatial distribution of ice fractures and ridges (Tan et al., 2012). Generally, 30 cm is the thickness suggested for safe human activities on the ice (Leppäranta, 2015). Ice fractures and ice ridges potentially threaten human activities. In the field investigations, we measured the ice thicknesses along the linear structure when the ice covers were steady. The ice thicknesses along the ice ridges were supposed to be thinner than in other areas (Leppäranta, 2015), but no significant difference in ice thickness had been found in our field measurements. Thus, the surface morphology of lake ice would be a reliable sign of dangerous traveling. Besides, we monitored the horizon changes in lake ice ridges using optical satellite images but ignored the vertical heights of ice ridges, which need to consider in future work.

6 Conclusion

We generated high spatial-temporal remote sensing data ~~from~~of the Landsat and GOCI using ~~the~~ ESTARFM~~, and filled~~ to fill the gap ~~for~~in the fine monitoring of lake ice ~~dynamic~~dynamics in Lake Chagan. We compared the reflectance of the fusion ~~image~~images and the original ~~image~~images on November 22, 2018. The ~~scatter plot was centred around 1:1 with the~~ R^2 value ~~of 0.93, which indicated~~between the actual images and predicted ~~image was~~images is up to 0.935, indicating the predicted images were highly correlated with the actual ~~image. Besides~~images. Moreover, the ~~predicted image kept~~consistency of the ~~ground objects'~~texture ~~consistent with~~of the ground objects was maintained between the predicated images and the original images. Therefore, the ESTRAFM fusion images provided reliable materials for further exploration.

We ~~proposed the automatic extraction and~~ calculated the ~~length~~lengths and the ~~angle~~angles of ~~the~~ linear structure on the fusion images in the freeze-up and break-up processes during the cold season from 2018 to 2019. Based on the satellite ~~stages~~images, the linear structure experienced growth, stability, and ~~decay.~~recession stages. The growth ~~lasted nine days, just four days later than the freeze-up date from MODIS; The decay process~~stage lasted for 9 ~~and~~ days ranging from November 22 to November 30, 2018. The recession stage lasted for 10 days~~, just two days earlier than the break-up date.~~ ranging from March 15 to March 22, 2019. From southeast to northwest, the linear structure was 5211.17 to 18042.15 ~~meters~~m long during growth; from northwest to southwest, it disappeared. The average length of the ice ridges ~~during~~in the ~~fully~~completely frozen period was 21141.57 ± 68.36 m. The average azimuth angle was 335.48° ± 0.23°.

We ~~carried out several~~performed field investigations and verified the linear structure ~~of the~~as ice ridges~~, along which we also discovered spherical ice balls. .~~. The direction of the ice ~~ridge~~ridges was nearly perpendicular to the southwest wind direction, which is the dominant wind direction ~~with high frequency.~~in winter. The deformation of ~~the~~ surface morphology was related to the meteorological conditions before the freeze-up process, including ~~wind, snowfall,~~winds and air ~~temperate~~temperatures. This work ~~demonstrates~~demonstrated the capability of monitoring large-scale surface morphology using multi-source remote sensing. ~~We need to simulate the flow field using the hydrodynamic model~~ and ~~explore the relationship between the hydrodynamic field~~ has profound implications for traveling safety on ice and ice engineering. We also plan to extend our findings to other large lakes in China and fill the knowledge gap of the surface morphology of ~~the~~ lake ice ~~in the future.~~.

470

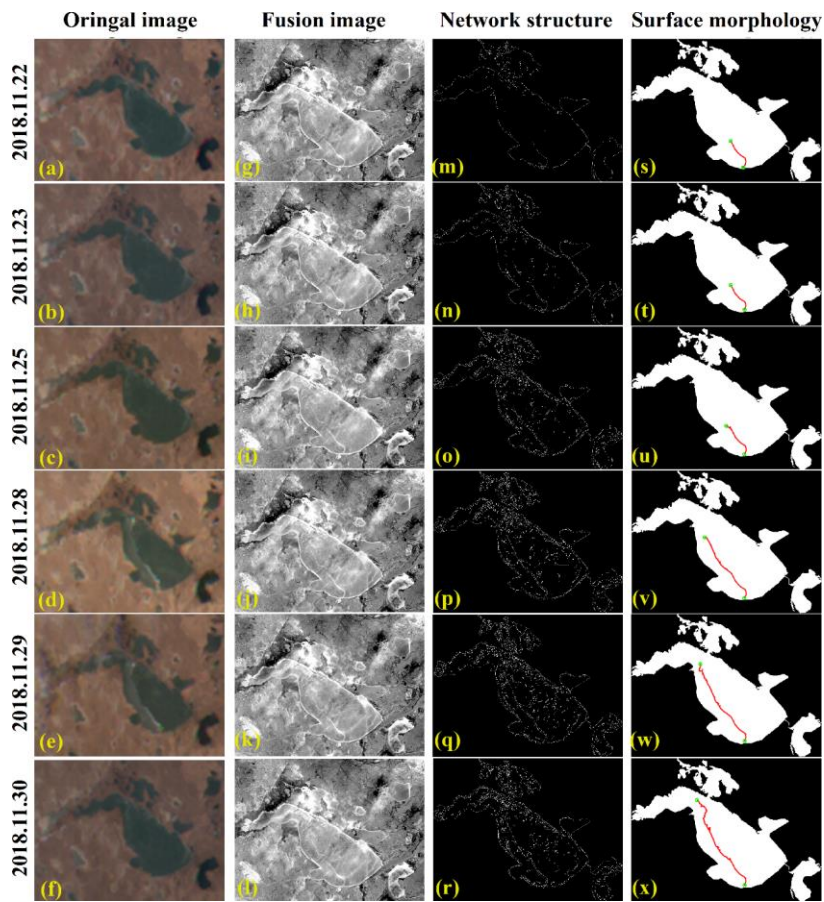
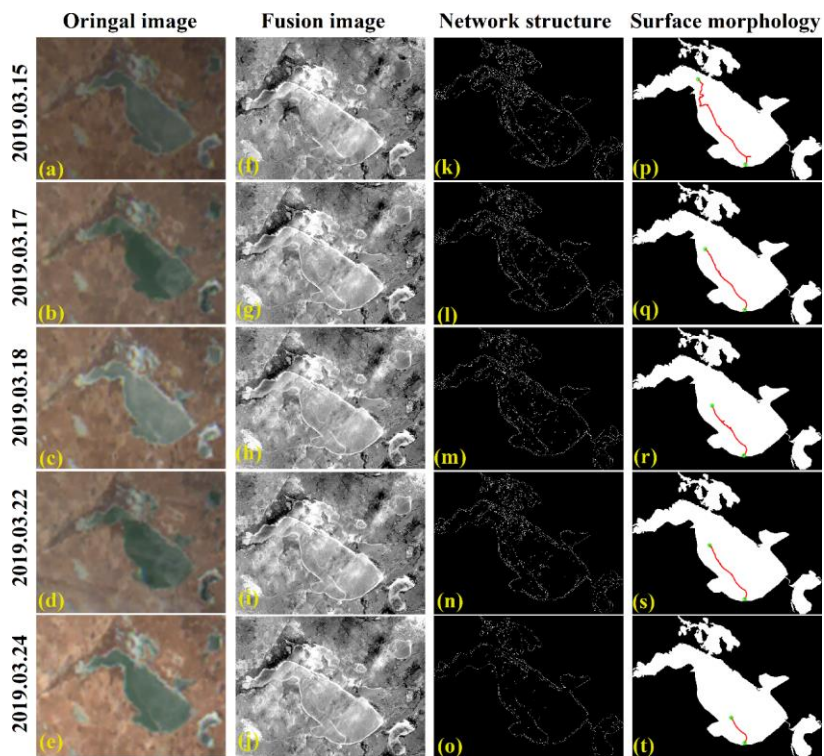



Figure A1 The changes of ice ridges during the freeze-up process from November 22 to November 30, 2019: (a-f) the original images from GOCI; (g-l) the fusion images from Landsat and GOCI; (m-r) the network structure of surface morphology; (s-x) the surface morphology.

475 Figure A2 The changes of ice ridges during the break-up process from March 15 to March 24, 2019: (a-e) the original images from GOCI; (f-j) the fusion images from Landsat and GOCI; (k-o) the network structure of surface morphology; (p-t) the surface morphology.

Data availability

All raw data can be provided by the corresponding authors upon request.

480 **Author contribution**:

YQ, XF, and LZJ planned the field investigation; SXG and LWB processed the remote sensing data; FC and LN analyzed the data; YQ and SKS wrote the manuscript draft; HXH, LZJ, WZD, and LG reviewed and edited the manuscript.

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Tables

Table 1Table 1 The comparison of band range between GOCI and Landsat. The selected bands for merging Landsat and GOCI are marked with red.

Band	GOCI		Landsat 8 OLI	
	Band centre (nm)	Bandwidth (nm)	Band centre (nm)	Bandwidth (nm)
Band 1	402-422	20	443-453	20
Band 2	433-453	20	450-515	65
Band 3	480-500	20	525-600	75
Band 4	545-565	20	630-680	50
Band 5	650-670	20	845-885	40
Band 6	675-685	10	1560-1660	100
Band 7	735-755	20	2100-2300	200
Band 8	845-885	40	500-680	180

Table 2 The usage of GOCI images from November 2018 to March 2019.

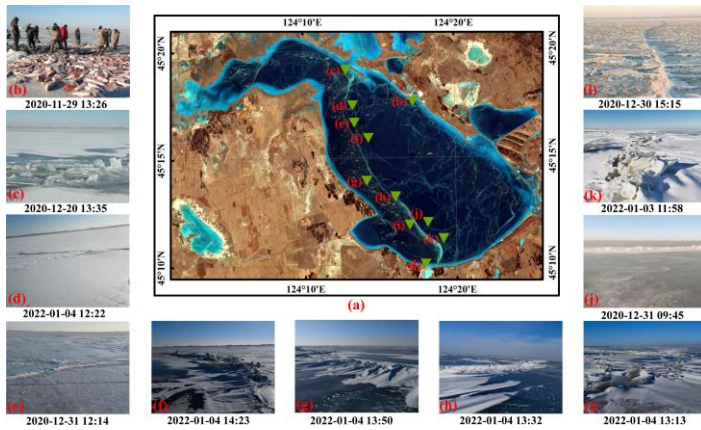
Date	Image number	Date	Image number
2018.11.21	1	2019.03.14	1
2018.11.22	8	2019.03.1516	60
2018.11.23	7	2019.03.1617	08
2018.11.24	0	2019.03.1718	8
2018.11.25	8	2019.03.1819	80
2018.11.26	0	2019.03.1920	0
2018.11.27	7	2019.03.2021	0
2018.11.28	8	2019.03.2122	04
2018.11.29	8	2019.03.2223	48
2018.11.30	7	2019.03.2324	87
2019.03.1315	18	2019.03.24Total	796

Figures

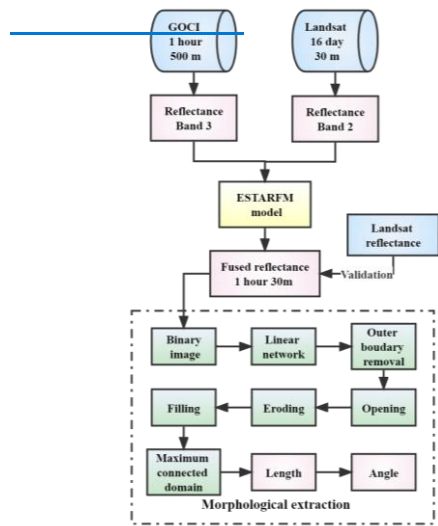
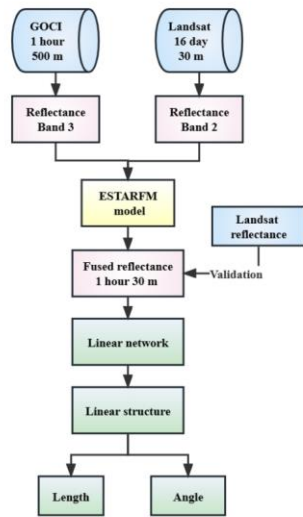
Figure 1 The spatial distribution of Chagan Lake and field photographs. Figure 1 (a) is provided Landsat 8 OLI on February 10, 2019 with the band composite: R(5) + G(4) + B(3). Figure 1 (b) shows the fishing activities of Chagan. Figure 1(c)-()- (h) displays the field photographs along the linear structure observed from the satellite imagescaptured in our two recentfield investigations.

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Figure 2 The ~~flowchart of the methodology~~workflow of this study.
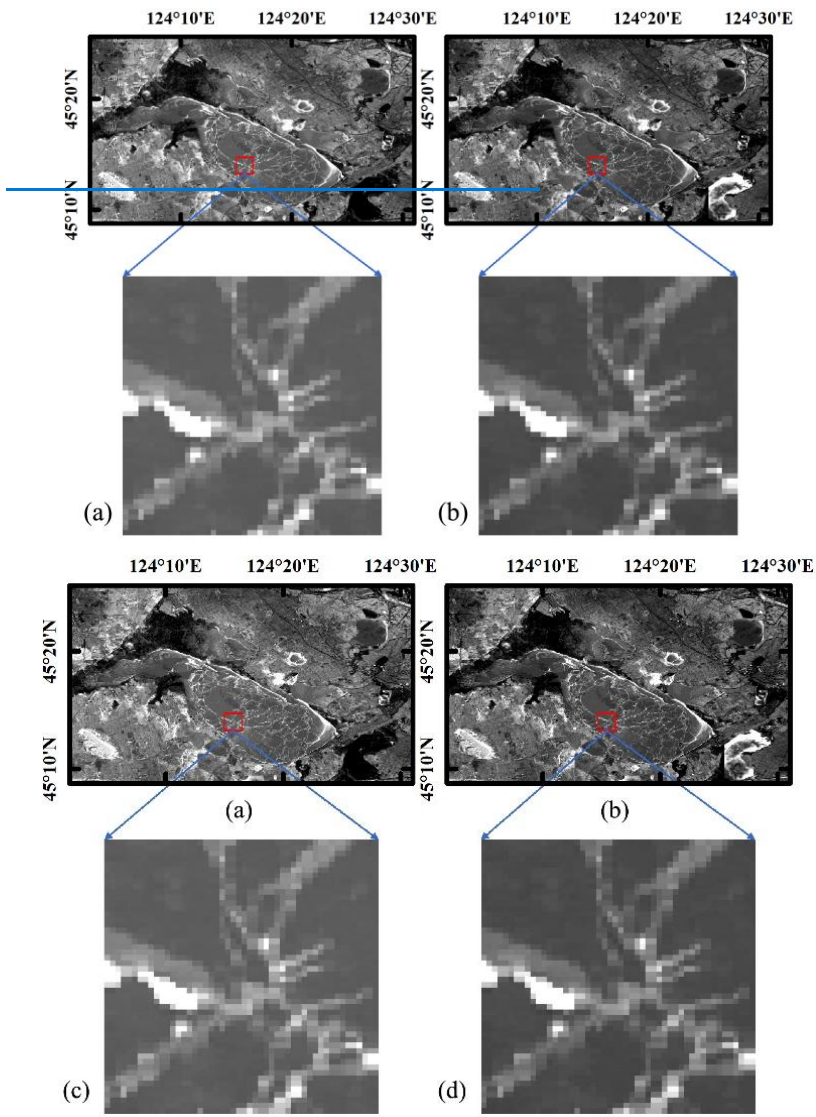
Figure 3 The ~~actual~~ **image** ~~comparison of Landsat 8 OLI (a) and ESTARFM (b)~~ **observed** on November 22, 2018. ~~(a) and its prediction images by the ESTARFM (b). The lower row images (c) and (d) display the enlargement figure of red rectangle in upper row images (a) and (b).~~

Image	**Landsat**	**Fusion image**
Mini.	-0.16	-0.09
Max.	0.65	0.46
Mean	0.10	0.10
SD	0.03	0.03

Statistical results
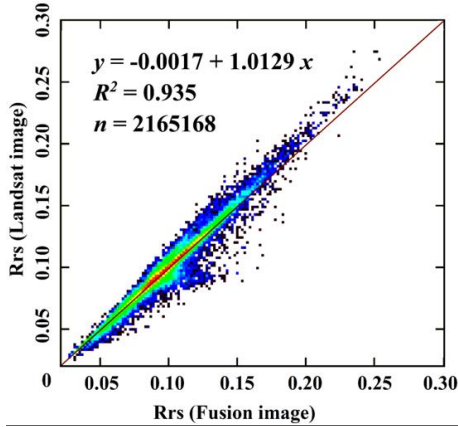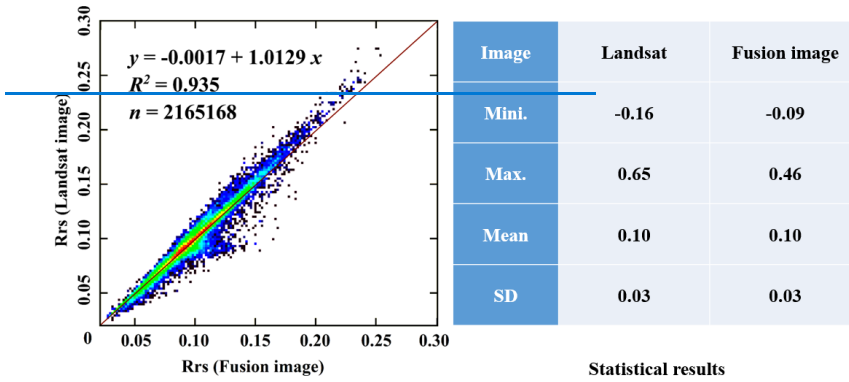
Figure 4 ~~The observed~~ Scatter plot of the real and the predicted **reflectance** ~~values and estimated value~~by the ESTARFM **for the blue band** ~~using ESTARFM: .~~ The capture date was November 22, 2018.

2018-11-22 **2018-11-23** **2018-11-25**

2018-11-28 **2018-11-29** **2018-11-30**

2019-03-15 **2019-03-17** **2019-03-18**

2019-03-22 **2019-03-24**
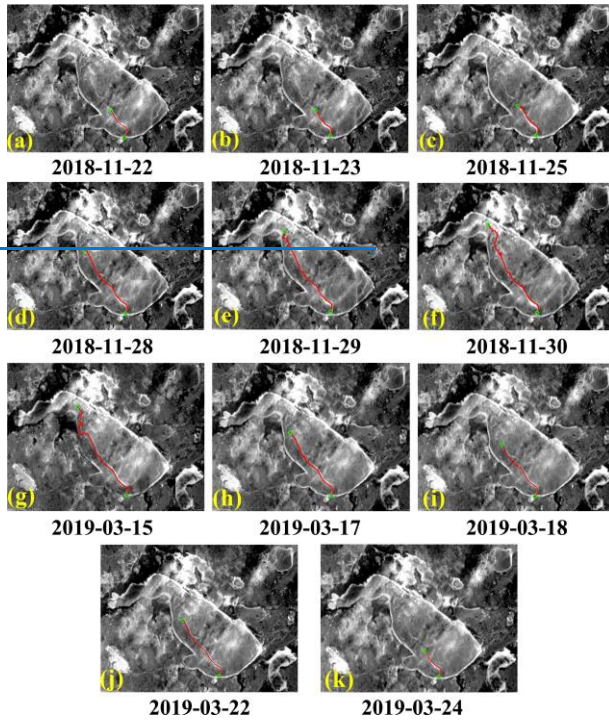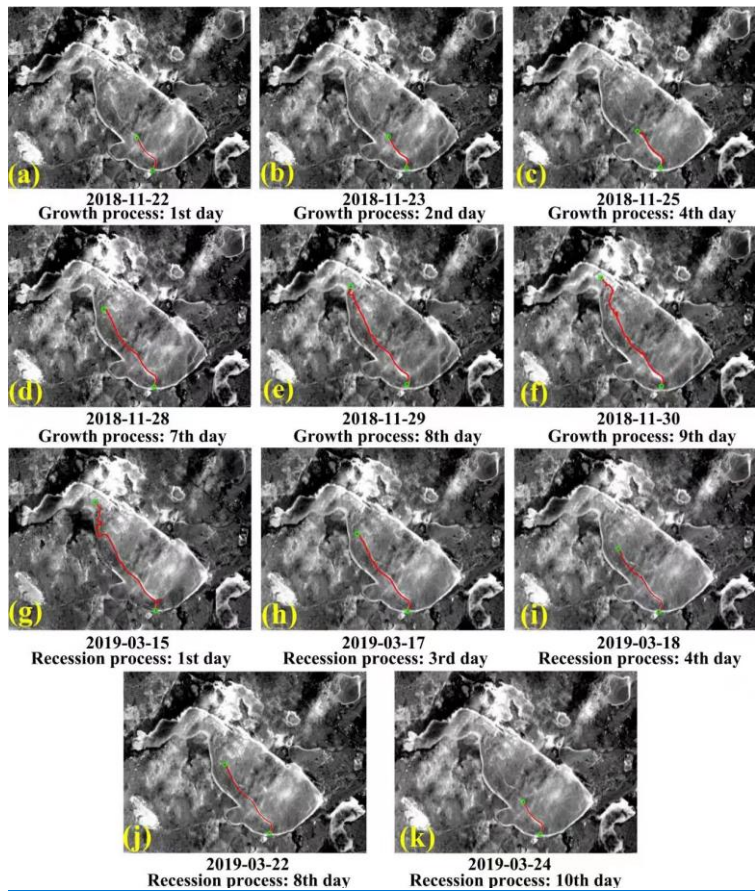
Figure 5 The ~~growth~~spatial **and** ~~decay process~~temporal changes **of** ~~ice ridges derived from the~~linear structure on **fusion** ~~data~~ images **of Lake Chagan during the cold season** ~~from~~of **2018** ~~to~~ **2019.**
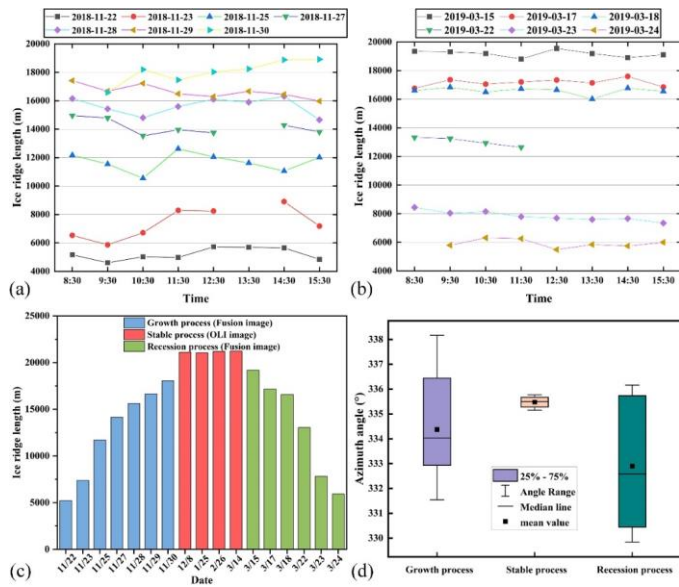
Figure 5̶6 The changes of ice ridges during the cold season of 2018-2019: (a̶)̶ ̶(̶f̶)̶ ̶d̶i̶s̶p̶l̶a̶y̶s̶)̶ length changes during **the growth process from November 22,̶ ̶2̶0̶1̶8̶,̶ to November 30, 2018;̶ ̶F̶i̶g̶u̶r̶e̶ ̶5̶(̶g̶)̶-̶(̶k̶)̶ ̶d̶i̶s̶p̶l̶a̶y̶s̶ measured from 53 ESTARFM fusion images; (b) length changes during the d̶e̶c̶a̶y̶recession process l̶a̶s̶t̶e̶d̶ from March 15 to M̶a̶r̶c̶h̶ 24, 2019, measured from 43 ESTARFM fusion images; (c) the daily average length; (d)the angles of ice ridges in different stages.**

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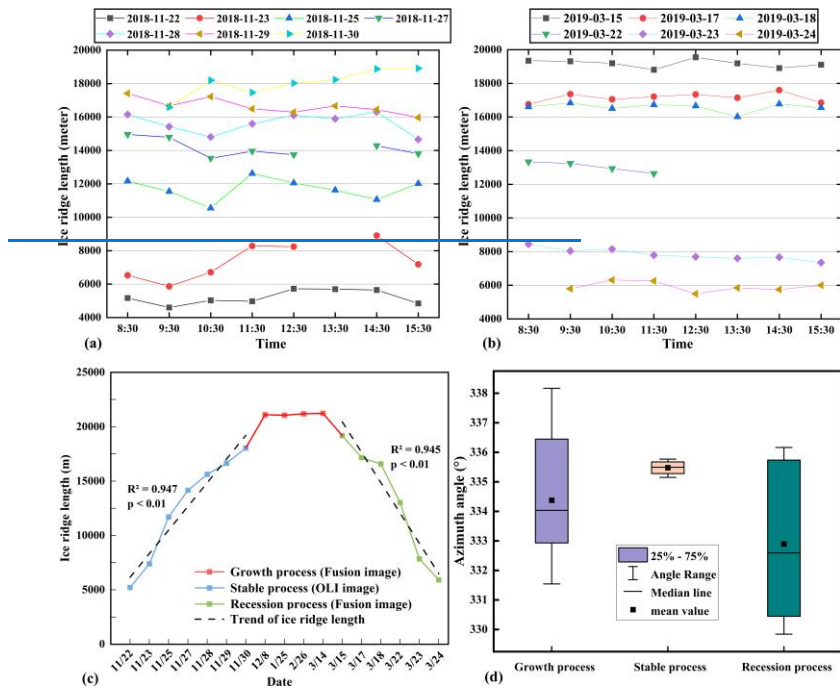


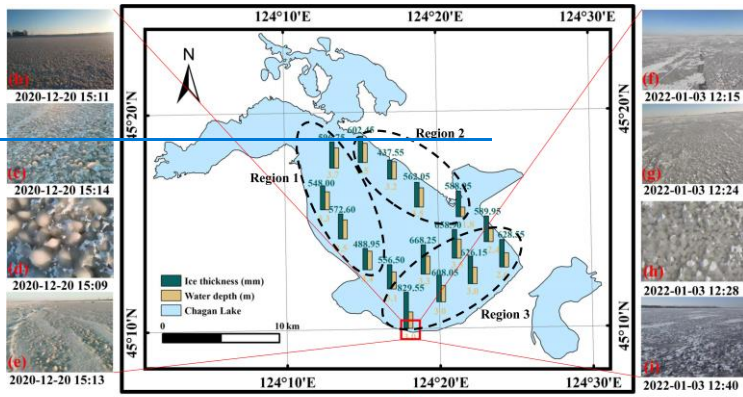
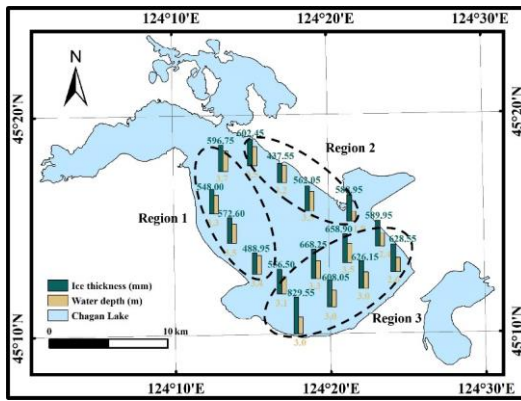
Figure 6 The length changes of ice ridges from November 2018 to March 2019. The length and angle during the growth and recession process were extracted from Landsat-GOCI fusion data, and that of the stable process was extracted from Landsat data.

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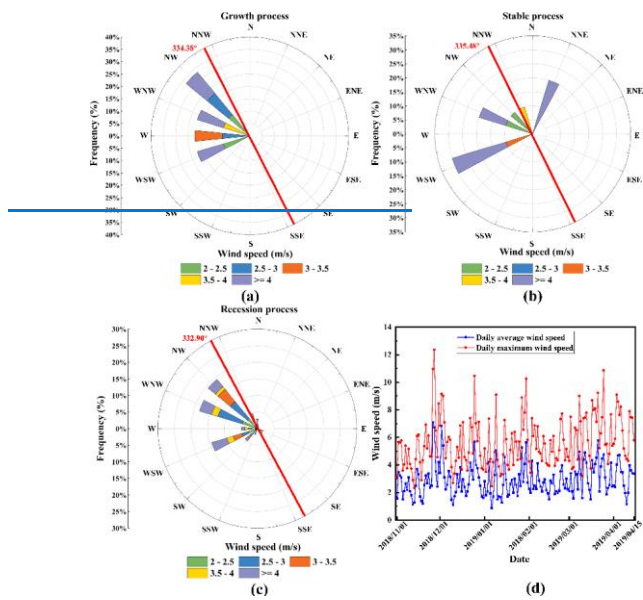
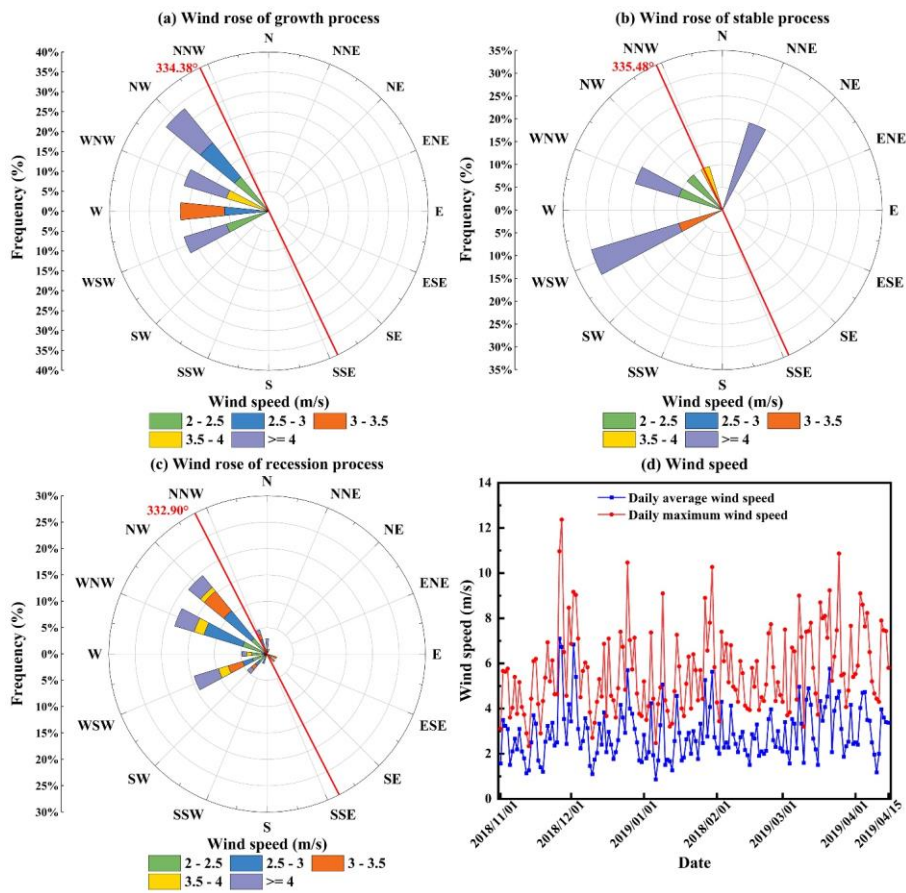
Figure 7 The ice thickness (mm) and water depth (m) of Chagan Lake was measured during the periods from January 2 to 4, 2022, and the field photograph..

835 **Figure 8 The wind ~~rose~~field of Chagan Lake during the cold season of 2018: (a) growth process from November 22, 2018, to November 30, 2018; (b) stable process; (c) recession process from March 15 to March 24, 2019; (4) daily average and maximum weed speed from November 1, 2018, to April 15, 2019.**

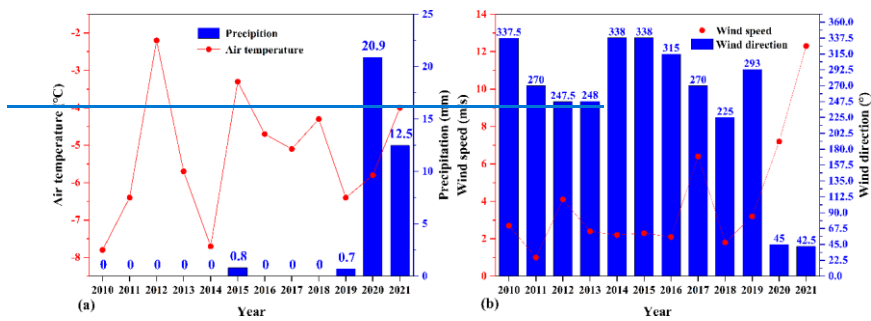



Figure 9 The changes of climate changes around the freeze-up process from 2010 to 2022: (a) air temperature (°C) and precipitation (mm); (b) wind speed (m/s) and wind direction (°). The average values are calculated a week before and after the freeze-up date derived from MODIS.

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