Title: The role of snow on river ice regime across Songhua River basin, Northeast China

Qian Yang[1, 2], Kaishan Song[1], Xiaohua Hao[3], Zhidan Wen[2], Yue Tan[1,] and Weibang Li[1]

[1]Jilin Jianzhu University, Xincheng Road 5088, Changchun 130118 China; E-Mail: jluyangqian10 @hotmail.com

[2] Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Shengbei Street 4888, Changchun 130102 China; E-Mail: songks@neigae.ac.cn;

[3] Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Donggang West Road 322, Lanzhou 730000, China; E-Mail: haoxh@lzb.ac.cn;

Response to editor:

General comments:

Your paper received very critical reviews that asked for substantial revisions. Note that the criticism does not only address the presentation of your study but also the contribution of your work to the field.

Thank you for these comments and for the reviewers' comments concerning our manuscript entitled **"The role of snow cover on ice regime across Songhua River basin, Northeast China"** (tc-2019-242). Those comments are all valuable and very helpful for revising and improving our paper, as well as the important guiding significance to our work. We carefully gone through the comments and made extensive corrections accordingly, **marked as red in the manuscript**. Again, please accept the gratitude of all authors from the bottom of the heart and your suggestion enlightened us to think over more deeply than ever before.

Specific comments

1) you need to go belong the linear regression analysis of the basic parameters; if a large spatio-temporal dataset is used please consider clustering analysis and/or principal component analysis and/or Bayesian statistics.

Response: Thank you for this helpful suggestion, and we had discussed the possibilities of the three methods as blow.

We tried to analyze the distribution of complete frozen duration by method of k-means, and it is hard to explain the classification results through topography or climate features, and that's why we did not use clustering analysis.

Principal component analysis (PCA) could be used for two aspect in our work. The distribution of complete frozen duration could be decomposed by PCA, similar to the empirical orthogonal function (EOF) and rotated empirical orthogonal function (REOF). EOF and REOF focused on the eigenvector of original dataset, and PCA focused on the time coefficients, which could reflect the long-term trend of original dataset. The time coverage of our data is only five years, and is suitable for analyzing long-term trend. PCA could also be used for analyzing the relationship between ice regime and impact factors. But our work only considered two factors: air temperature and snow depth. That's why PCA were not used in our work herein.

We used Bayesian linear regression to build the equation between ice thickness and snow depth, air temperature. Two types of air temperature had been considered: the air temperature on bank and the air temperature on bank and the negative cumulative air temperature. Results, snow on ice played a dominant role when the river ice is completely frozen, followed by negative cumulative air temperature. **You can check the changes in Part 2.3.3 and 3.2.2, and we added a new Figure 9 to illustrate the results from Bayesian linear regression**

2) you need to include a literature review describing what is the current state of knowledge in the field and how your study (or objective of your study) advances the current state of knowledge in the field.

Response: Thank you for this helpful suggestion, we have updated the introduction as you suggested based on literature review and supplements new references and emphasized on the diversity knowledge on the role of snow cover during the ice process, **seen the line 47-94 of Introduction.**

The surface-based networks, including climatic and hydrological stations, have been established for tracing climate and hydrological changes in Northeast China, which are limited by the accessibility of surface-based networks and the range of filed measurement. To evaluate the influence of ice regime on regional climate and human environment, a robust investigation and quantitative analysis on ice regime is necessary, which provide helpful information for projecting future changes in the ice regime.

3) you need to provide a detailed description of the methods used (e.g. data pre and post processing, uncertainty analysis)

Response: The authors really appreciated the comments. We added some comments on the two methods we used, and also explained their application limits, reliability, and pros, and cons as well, seen in Part 2.3 (Line 143 to 185). Besides, we expanded the description of dataset we have used and used sub title to make it clear, seen in Part 2.2 (Line 112 to 141).

4) you need to expand the discussion and conclusions sections so that they reflect/include all the key results from your analysis

Response: We have significantly improved the conclusion, as you suggested, seen in **Line 328 to 350 of Conclusions.**

5) you need to pay particular attention to the language and structure of the paper: use clear sentences and logical flow, avoid grammatical and spelling errors, avoid repetitions and redundancy, and definitely proof-read the manuscript before re-submission (I would also recommend giving your manuscript to a native English speaker for proof-reading if this is possible for you)

Response:

We really appreciate your suggestion, and we adjusted the structure of this paper. We have carefully revised the manuscript according to the reviewers' comments, and used an English-language editing service Panda Edit Network (http://www.pandaedit.com/), to polish our language and writing styles. The certificate had been uploaded. We provided a comparison between the new version and the previous manuscript.

The list of improvements.

Comments	Improvements.
1) you need to go belong the linear regression analysis of the basic parameters; if a large spatio-temporal dataset is used please consider clustering analysis and/or principal component analysis and/or Bayesian statistics.	Part 2.3.3 (Line 171 to 185) Part 3.3.2 (Line 298 to 315) Figure 9 (Line 585)
2) you need to include a literature review describing what is the current state of knowledge in the field and how your study (or objective of your study) advances the current state of knowledge in the field.	Line 47-94 of Introduction.
3) you need to provide a detailed description of the methods used (e.g. data pre and post processing, uncertainty analysis)	Part 2.2 (Line 112 to 141). Part 2.3 (Line 143 to 185).
4) you need to expand the discussion and conclusions sections so that they reflect/include all the key results from your analysis	Line 328 to 350 of Conclusions.
5) you need to pay particular attention to the language and structure of the paper: use clear sentences and logical flow, avoid grammatical and spelling errors, avoid repetitions and redundancy, and definitely proof-read the manuscript before re-submission (I would also recommend giving your manuscript to a native English speaker for proof-reading if this is possible for you)	Every sentence had been checked. We provided a comparison between the new version and the previous manuscript.

Right People, Right Papers

Let Scientists Focus on Science!

EDITORIAL CERTIFICATE

This document certifies that the manuscript listed below was edited for proper English language, grammar, punctuation, spelling, and overall style by one or more of the native and subject matter expert English-speaking editors at Panda Edit Network (PEN).

Manuscript Title

The role of snow and ice thickness on river ice regime across Songhua River basin, Northeast China

Author Representative

Qian Yang, PhD

Date Issued

May 10, 2020

Editor in Chief

Cristina Milesi, PhD

北京文雅信达科技有限公司

This certificate may be verified at http://www.pandaedit.cn/. Documents receiving this certification are considered English-ready for publication; however, the author is free to further edit the manuscript and reject our edits before submission. To verify the final PEN edited version or if you have any questions or concerns about the edited document, please contact

Panda Edit Network：info@pandaedit.com

Title: The role of snow cover on ice regime across Songhua River Basin, Northeast China

Qian Yang[1, 2], Kaishan Song[1, *], Xiaohua Hao[3], Zhidan Wen[2], Yue Tan[1], and Weibang Li[1]

[1]Jilin Jianzhu University, Xincheng Road 5088, Changchun 130118 China; E-Mail: jluyangqian10 @hotmail.com

[2] Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Shengbei Street 4888, Changchun 130102 China; E-Mail: songks@neigae.ac.cn;

[3] Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Donggang West Road 322, Lanzhou 730000, China; E-Mail: haoxh@lzb.ac.cn;

Correspondence to: Song K. S. (songks@neigae.ac.cn)

Abstract: The Songhua River Basin, located in Northeast China, is an area sensitive to global warming that could be impacted by changes in lake and river ice regimes. The regional role and trends of lake and river ice of this area have been scarcely investigated and are critical for aquatic ecosystems, climate variability, and human activities. Using ice records of local hydrological stations, we examined the spatial variations of the ice phenology and ice thickness in the Songhua River Basin from 2010 to 2015 and explored the role of snow depth and air temperature on ice regime. All of five river ice phenology indicators, including freeze-up start, freeze-up end, break-up start, break-up end and complete frozen duration, showed a latitudinal distribution and a changing direction from southeast to northwest. Five typical geographic zones were identified applying a rotated empirical orthogonal function. Maximum ice thickness had a higher correlation with ice phenology, especially with the break-up process. Six Bayesian regression models were built between ice thickness, air temperature, and snow depth in three sub-basins of the Songhua River Basin. Results showed significant and positive correlations between snow cover and ice thickness when freshwater was completely frozen. Rather than by air temperature, ice thickness was influenced by negative cumulative air temperature through the heat loss of ice formation and decay.

Keywords. River ice, ice phenology, ice thickness, snow on ice, air temperature, rotated empirical orthogonal function

1 Introduction

The freeze-thaw process of surface ice of temperate lakes and rivers plays a crucial role in the interactions among the climate system(Yang et al., 2020), freshwater ecosystems (Kwok and Fahnestock, 1996) and the biological environment (Prowse and Beltaos, 2002). The presence of freshwater ice is closely associated with social and economic activities, ranging from human-made structures, water transportation, to winter recreation (Williams and Stefan, 2006;Lindenschmidt et al., 2017). Ice cover on rivers and lakes exerts large forces due to thermal expansion and could cause extensive infrastructure losses to bridges, docks, and shorelines (Shuter et al., 2012). Ice cover on waterbodies also provides a natural barrier between the atmosphere and water. Ice cover also blocks the solar radiation necessary for photosynthesis to provide enough dissolved oxygen for fish, thus can have a negative effect on freshwater ecosystems and, in extreme cases, lead to winter kill of fish (Hampton et al., 2017). Generally, the duration of freshwater ice has shown a declining trend, with later freeze-up and earlier break-up throughout the northern hemisphere. For example, freeze-up has been occurring 0.57 days per decade later and break-up 0.63 days per decade earlier during the periods of 1846-1995 (Magnuson et al., 2000;Sharma et al., 2019;Beltaos and Prowse, 2009). To evaluate the influence of ice regimes on the regional climate and human environment, and provide helpful information for regional projections of climate and ice-river floods, a robust and quantitative analysis on ice processes is necessary. Despite the growing importance of river ice under global warming, very little work has been undertaken to explain the considerable variation of ice characteristics in Northeast China, where lakes and rivers are frozen for as long as five to six months a year.

The earliest ice record in the literature dates back to 150 years ago (Magnuson et al., 2000). Ice development and ice diversity scales have been regarded as sensitive climate indicators. Ice phenology and ice thickness have been studied to gain a deeper understanding of ice processes. At medium and large scales, optical remote sensing data are widely used for deriving ice phenology (Song et al., 2014;Šmejkalová et al., 2016), while microwave remote sensing are used to estimate ice thickness and snow depth over ice (Zhang et al., 2019;Kang et al., 2014). Wide-range satellites make it possible to link ice characteristic with climate indices, such as air temperature (Yang et al., 2020) or large-scale teleconnections (Ionita et al., 2018), but their spatial resolutions are too large to detect ice thickness and snow depth accurately at small scales. For example, the microwave satellite data of AMSR-E have a spatial resolution of 25 km, but the largest width of Nenjiang River only ranges from 170 to 180 meters. The spatial resolution limits the application of satellite observations to precisely inverse ice thickness, let alone snow depth.

In terms of point-based measurements, the most commonly used ground observations include regular observations, ice charts, volunteer monitoring and field measurements (Duguay et al., 2015). Ground observations depend on spatial distribution and representation, and are limited by the accessibility of surface-based networks and the range of field measurement. Ice parameters differ greatly from point to point on a given river (Pavelsky and Smith, 2004), and the uneven distribution of hydrological stations poses an obstacle to gaining a comprehensive understanding of river ice. Various models have been implemented to derive ice phenology and ice thickness, such as physically-based models (Park et al., 2016), linear regressions (Palecki and Barry, 1986;Williams and Stefan, 2006), logistic regressions (Yang et al., 2020) and artificial neural networks (Seidou et al., 2006;Zaier et al., 2010). These models consider the energy exchange and physical changes of freshwater ice and require detailed information and data support, including hydrological, meteorological, hydraulic and morphological information. Fixed stations are normally located around the river mouth of certain rivers, so these models are limited by the input data available (Pavelsky and Smith, 2004). Both modelling and remote sensing monitoring require sufficient historical ice records to validate and improve accuracy and reliability.

The ice cover of water bodies experiences three stages during which ice phenology, ice thickness and ice composition change greatly. These stages are: freeze-up, ice growth, and break-up (Duguay et al., 2015).

Although air temperature greatly influences the freeze-thaw cycle of river ice, the effect of snow cover can't be ignored. Generally, snow depth outweighs air temperature during the ice forming process and increasing snow depth provides favourable conditions for thicker ice (Morris et al., 2005;Park et al., 2016). Compared to other studies, air temperature had a greater effect on ice thickness than snow depth and were attributed this to the high snowfall in the study area (Gao and Stefan, 2004). Besides, in situ observations at Russian river mouths where ice thickness decreased had not shown any significant correlation between ice thickness and snow depth (Shiklomanov and Lammers, 2014). Those studies analysed the relationship in view of spatial distributions and ignored the changing status of ice formation processes. The relative influence of snow depth and air temperature on the ice regime deserves further exploration in Northeast China.

The surface-based networks, including climatic and hydrological stations, have been established for tracing climate and hydrological changes in Northeast China, which are limited by the accessibility of surface-based networks and the range of filed measurement. To evaluate the influence of ice regime on regional climate and human environment, a robust investigation and quantitative analysis on ice regime is necessary, which provide helpful information for projecting future changes in the ice regime. The previous work explored the ice process in at one or more locations on a given river and ignored the changing regional pattern of ice development due to sparse location. The objectives of this study are to: (1) investigate and compare the spatial distribution of ice phenology and thickness in Northeast China; (2) quantitatively explore the influence of snow cover and air temperature on ice regime.

2 Materials and methods

2.1 Study area

The Songhua River Basin is located in the middle of Northeast China (Figure 1), and includes Jilin Province, Heilongjiang Province, and the eastern part of Inner Mongolia Autonomous Region. The Songhua River is the third-longest river in China, and has three main tributaries: Nenjiang River, Main Songhua River, and Second Songhua River (Zhao et al., 2018;Khan et al., 2018). The basins of the three tributary rivers include: Nenjiang Basin (NJ), the Downstream Songhua River Basin (SD), and the Upstream Songhua River Basin (SU) (Figure 1). The Nenjiang River has a length of 1370 km, and the corresponding drainage has an area of 2.55×10^6 thousand km^2; the Main Songhua River has a length of 939 km and the downstream catchment of the Songhua River Basin (SD) has an area of 1.86×10^6 km^2; the Second Songhua River has a length of 958 km and the upstream catchment of the Songhua River Basin (SU) has an area of 6.19×10^6 km^2 (Yang et al., 2018;Chen et al., 2019). The whole Songhua River Basin is characterized by temperate and cold temperate climates: winter is long and cold; spring is windy and dry. Annual average air temperature ranges between 3 to 5℃, while annual precipitation ranges from 400 to 800 cm from the southeast to the northwest. (Wang et al., 2015;Wang et al., 2018).

[Figure 1 is added here]

2.2 Data Source

2.2.1 Ice phenology

The hydrographic bureau of the Chinese Ministry of Water Resources has established a remarkable observation network for ice regimes. The ice records of the Songhua River Basin were obtained from the annual hydrological report, including ice phenology, ice thickness, snow depth on ice and air temperature on bank (BAT) (Annual hydrological report, 2010-2015). To analyse the spatial pattern of the ice regime, we explored five river ice parameters with the corresponding day of year (DOY) from 158 stations. We located 50, 36 and 72 stations in the NJ, SU and SD basins, respectively. For each record, five lake ice phenological events were derived from the annual hydrological report; the definitions referred to specification for observation of ice regimes in rivers and previous works (Cai et al., 2019;Yang et al., 2019;Duguay et al., 2015) :

- Freeze-up start (FUS) is considered the first day when floating ice can be observed with temperatures below 0 ℃;
- Freeze-up end (FUE) is the day when a steady ice carapace can be observed on the river, and the area of ice cover is more than 80% in the view range;
- Break-up start (BUS) is the first day when ice melting can be observed with surface ponding;
- Break-up end (BUE) is the day when the surface is mainly covered by open water and the area of open water exceed 20%;
- Complete frozen duration (CFD) is the ice cover duration when the lake is completely frozen during the winter, from FUE to BUS.

2.2.2 Ice thickness

To study seasonal changes in ice thickness (IT) and establish the regression model, we used ice thickness, snow depth and air temperature from 120 stations for the period ranging from 2010 to 2015. We used 37, 28 and 55 stations located in the NJ, SU and SD basins, respectively. The hydrological report provided ice thickness, snow depth on ice and BAT every five days from November through April, totalling 37 measurements in one cold season. The yearly maximum ice thickness (MIT) of the river centre and the corresponding DOY were calculated from five-day records. The average snow depth (ASD) was calculated from the mean of three or four measurements around the ice hole for ice thickness measurement without human disturbance. To enhance the performance of the regression model, negative cumulative air temperature was calculated from air temperature from November to March.

2.3 Data analysis

2.3.1 Kriging

Kriging has been widely used to spatially interpolate in situ measurements of ice phenology to understand its spatial distribution (Choiński et al., 2015;Jenson et al., 2007). Kriging assumes a correlation between regionalized variables and variograms that reflects randomization and structuredness of regionalized variables. It estimates unknown values based on the best linear unbiased estimator with minimal variance, expressed as:

$$\hat{Z}(s_o)=\sum_{i=1}^{N}\lambda_i Z(s_i)$$

where $\hat{Z}(s_o)$ is the estimate by kriging at an unknown point s_o, $Z(s_i)$ is the variable at a measured point s_i, N is the number of measured points. λ_i is a weight for $Z(s_i)$, and relies on the spatial arrangement of the measured values and the distance between the prediction location and the measured location (C.R. Paramasivam, 2019). The average values of five ice phenology indicators during the six years were interpolated to create isophenes, i.e., contour lines connecting locations with the same ice phenology.

2.3.2 Rotated empirical orthogonal function (REOF)

Empirical orthogonal function (EOF) decomposition is commonly used in climate and hydrological analyses (Bian et al., 2019;Yang et al., 2017). Its basic principle is to decompose the field containing *p* spatial points (variable) over time. If the sample size is *n*, then the data value x_{ij} including specific spatial point *i* and specific time *j* in the field can be regarded as the linear combination of spatial modes and temporal modes according to equation:

$$S_{b^2}^2=\frac{1}{mM}\sum_{j=1}^{M}\sum_{p=1}^{m}(b_{jp}^2-\overline{b^2})^2$$

where b_{jp} is the *j th* loading coefficient of the *p th* EOF mode.

The major advantages of the EOF method is to separate the uncorrelated components that confuse the spatial information and make it hard to interpret a physical phenomenon. In order to solve these problems, a rotated EOF (REOF) rotates the original EOF matrix into a new matrix in which the squared elements of the eigenvectors are maximum, which can better reflect changes across different geographic regions and identify correlations. This paper presented the first four load vectors of the CFD decomposed by REOF and their corresponding principal components (PC) to identify the typical geographic zones in Northeast China.

2.3.3 Bayesian linear regression

Ice thickness had been modelled by air temperature and snow depth using Bayesian linear regression (BLR), which has been widely used in hydrological and environmental analyses (Zhao et al., 2013;Gao et al., 2014). BLR treats regression coefficients and the disturbance variance as random variables, rather than fixed but unknown quantities. This assumption leads to a more flexible model and intuitive inferences (Barber, 2008). The BLR model was implemented through two models: a prior probability model considered the probability distribution of the regression coefficients and the disturbance; a posterior model predicted the response using the prior probability mentioned below. The performance of the regression model was evaluated using the determination coefficient R^2 and the root mean square error (RMSE). In this paper, the Y data were the five-day ice thickness values, and the X data included snow depth over ice and air temperature on the river bank. The calculation of the regression used the in-situ measurements from November to March and excluded the ice records of April due to unsteady ice conditions. Two types of air temperature were considered: BAT and negative cumulative air temperature (ATC). Additionally, the Pearson correlation was calculated to analyse the relationship among the five ice phenology events and ice-related parameters, including MIT, ASD, and BAT(Gao and Stefan, 1999;Williams et al., 2004).

3 Results and discussion

3.1 Spatial variations of river ice phenology

3.1.1 Freeze-up and break-up process

Figure 2 illustrates the average spatial distribution of FUS and FUE interpolated by kriging and the isophenes in the Songhua River Basin of Northeast China from 2010 to 2015. Figure 3 illustrates the spatial distribution of the BUS and BUE. The corresponding statistics are listed in Table 1. FUS ranged from October 28th to November 21st with a mean value of November 7th, and FUE ranged from November 7th to December 8th with a mean value of November 22nd. BUS ranged from March 24th to April 20th with a mean value of April 9th, and BUE ranged from March 31th to April 27th with a mean value of April 15th. These four parameters showed a latitudinal gradient: FUS and FUE decreased while BUS and BUE increased as the latitude increased, except in NJ. The middle part of NJ had the highest FUS and FUE and decreased to the southern and northern part. As the latitude decreased, the air temperature tended to increase, leading to later freeze-up and earlier break-up with shorter ice-covered duration; vice versa.

[Figure 2 is added here]

[Figure 3 is added here]

[Table 1 is added here]

3.1.2 Complete frozen duration

Figure 4(a) illustrates the average spatial distribution of CFD interpolated by kriging and the isophenes in the Songhua River Basin from 2010 to 2015. CFD ranged from 110.74 to 163.00 days with a mean value of 137.86 days, increasing with latitude. Interestingly, the isophenes of CFD had different directionality, increasing from the southeast to northwest, which could also be found in the other four ice phenologists. Both FUS and FUE correlated negatively with latitude, with coefficients of -0.66 and -0.53, respectively (n=158, $p < 0.001$). BUS, BUE and CFD were all positively correlated with latitude with coefficients of 0.48, 0.57 and 0.55, respectively (n=158, $p < 0.001$). High values indicated a delay in the ice phenology event. The general spatial trend was a tendency to advance as the latitude increased for the FUS and FUE, a tendency for delay for BUS and BUE, and a lengthening tendency for CFD. A decreasing solar radiation with latitude could explain this trend, which is directly connected with the ice thaw and melting processes.

To find the spatial distribution of ice durations, average values of CFD between 2010 and 2015 were decomposed by REOF, and the spatial distribution of the first four PC are shown in Figures 4 (c)-(f) interpolated by kriging. The first to fourth PC modes accounted for 45.89%, 13.22%, 12.62%, and 12.00%, respectively, with the cumulative variance of 83.73%. The PC data ranged from -0.22 to 0.15, and the areas with high values presented a planar distribution, which were further regarded as five typical geographic zones considering the topography of Northeast China. Zone 1, located in the Three River Plain, where Heilongjiang, Wusuli, and Songhua River converge together, was identified from the first PC. Zone 2, located around

Heaven Lake of Changbai Mountain, in the southernmost part and which has the highest elevation of 2565 m, was identified from the second PC mode. We excluded a planar distribution above Zone 2 because of the gentle terrain in the Songhua River Basin. The middle part of the Songhua River Basin accounts for a large area where no typical zones were found. The REOF was good at enhancing the high-value areas, and the PC data of this area around 0 were ignored. Zone 3, located on the eastern edge of the three basins with relatively high elevation along the ridge of Changbai Mountain, was identified from the third PC mode. Based on the fourth PC mode, Zone 4 was determined in the northernmost part along the ridge of Xiao Higgan Mountain where it meets with Da Higgan Mountain. Zone 5 almost covered the southern part of the NJ basin along the ridge of Da Higgan Mountain and appeared in the second, third, and fourth PC. The final distribution was identified from the convergence area of these three modes.

[Figure 4 is added here]

3.2 Variations of ice thickness

3.2.1 Spatial pattern of ice thickness

Figure 5 illustrates the spatial distribution of the yearly maximum ice thickness (MIT) of the river centre and the corresponding DOY. Table 2 summarized the statistical result of MIT and DOY. MIT ranged from 12 cm to 146 cm, with an average value of 78 cm. The MIT between 76 and 100 cm accounted for the largest percentage of 43.33%, followed by 31.67% of MIT between 50 and 75 cm. Five stations had MIT greater than 125 cm. Two stations were located in Zone 3 and three stations in Zone 4. The DOY of MIT had an average value of February 21st, and MIT mainly occurred 59 and 40 times in February and March, respectively. Four of the five highest MITs greater than 125 cm happened in March, which is consistent with the inter-annual changes in ice development shown in Figure 6. The results suggested that the river ice is always thickest and most steady in February or March, which is the best suitable time for human activities such as ice fishing and entertainment. The ice thickness didn't show the same latitudinal distribution as ice phenology, which suggested that more climate factor should be taken in to consideration, such as snow depth and wind.

[Figure 5 is added here]

[Table 2 is added here]

3.2.2 Seasonal changes of ice thickness

Figure 6 displays the seasonal changes of ice development using ice thickness, average snow depth on ice, and BAT every five days from 2010 to 2015. Among the three basins, NJ had the highest snow depth of -29.15 ± 9.99℃, followed by -25.61 ± 9.02 ℃ in the SD, and -22.17 ± 7.33 cm in the SU. SD had the highest snow depth of 9.18 cm ± 3.39 cm on average level, followed by 8.35 cm ± 4.60 cm in SU, and 8.23cm ± 3.92 cm in NJ. The changes in IT and ASD had similar overall trend, while BAT followed the opposite trend. Both IT and ASD increased from November and reached the peak in March, then dropped at the beginning of April. The ASD showed an obvious trend and reached the bottom in the middle of January, which is earlier than the peaks of MIT and ASD. The NJ and the SD basins underwent greater fluctuations than the SU basin, because river ice may freeze and thaw alternatively at relatively low temperatures. The changes of ice characteristics differed greatly due to time and location; an analysis of the annual changes was not conducted because the time series were not long enough.

[Figure 6 is added here]

3.3 The relationship between ice regime and climate factors

3.3.1 Correlation analysis

Figure 7 displays the correlation matrix between lake ice phenology events and three parameters, covering yearly average values of ASD, BAT, and MIT with a dataset size of 120 stations. Colour intensity and sizes of the ellipses are proportional to the correlation coefficients. MIT had a higher correlation with four of the five indices than ASD and BAT, except with FUS, with which both MIT and BUE had the highest correlation of 0.63 ($p<0.01$, $n=120$). During the freeze-up process, two freeze-up dates had a negative correlation with MIT and ASD; during the break-up, two break-up dates had a positive correlation with MIT and ASD. CFD had a positive correlation with MIT and ASD. The situation of BAT was contrary to that of MIT and ASD. Regarding to the annual changes, no significant correlation was found between snow depth and five ice phenology events in Figure 7.

[Figure 7 is added here]

Figure 8 shows the bivariate scatter plots between yearly maximum ice thickness (MIT) and five ice phenology indicators with regression equations. The break-up process had a negative correlation with MIT, while freeze-up had a positive correlation. Besides, the break-up process had a higher correlation with MIT, and BUS had the highest correlation coefficients with MIT of 0.65 ($p<0.01$). CFD also had a positive correlation with MIT of 0.55 ($P<0.01$), which means that a thicker ice cover in winter leads to a delay in melting time in spring. The break-up not only depends on the spring climate conditions, but is also influenced by ice thickness during last winter. A thicker ice cover stores more heat in winter, taking a longer time to melt in spring. The limited performance of the regression model could be attributed to the difficulties in determining river ice phenology. Although a uniform observation protocol was required, the repaid transition between frozen river and open water for two or three days with floating ice and the inhomogeneities among different stations could not be ignored.

[Figure 8 is added here]

To further explore the role of snow cover, the monthly correlation coefficients between IT and ASD, and IT and BAT were calculated and listed in Table 3. The correlation coefficients between IT and ASD increased from November to March and reached a peak of 0.75 in March when ice was thickest. This indicated an increasingly important role of snow depth on ice thickness as the ice accumulated. The higher correlation coefficients between IT and BAT in November and December revealed that BAT played a more important role in the freeze-up process. Moreover, whether the status of river ice was steady or not also could not be neglected when studying the role of snow cover.

The positive correlation coefficient between snow depth and ice thickness (Table 3) revealed two opposite effects of snow depth during ice development: during the ice-growth process, snow depth protects the ice from cold air and slows down the growth rate of ice thickness; during the ice-decay process, the lake bottom ice stops to grow, and the snow mixes with surface ice into slush and promotes melting.

[Table 3 is added here]

3.3.2 Regression modelling

Figure 9 illustrates the scatter plot between measured and predicted ice thickness using Bayesian linear regression in three sub-basins in Northeast China. R^2 ranged from 0.81 to 0.95, and RMSE ranged from 0.08 to 0.17. The model worked best in the SU basin, followed by the NJ and the SD basins. Figure 9 indicates that snow depth outweighed air temperature in terms of effect on ice thickness, which is consistent with previous studies. Moreover, replacing BAT with ATC enhanced the model performance in all three basins, revealing a more important role of ATC than BAT.

[Figure 9 is added here]

The correlation between air temperature and ice regime was not as significant as in previous studies for several reasons. Average air temperatures were most commonly calculated over fixed time periods at regional scales, for example as moving averages for certain time periods. The seasonal changes of air temperature were ignored, as well as their effects within one cold season. The negative ATC behaved better than BAT when building the Bayesian regression equation, which suggested that heat exchanges between river surface and atmosphere dominated the ice process. Heat loss is mainly made up of sensible and latent heat exchange, which is proportional to negative ATC during the cooling process. During the complete frozen duration, snow depth along with wind speed began to influence the heat exchange and ice thickening. Air temperature exerted a lesser effect on spring break-up, which is more dependent on the ice thickness and snow depth. In summary, snow depth dominated the ice process when the river was completely frozen, while cumulative air temperature dominated during the transition process.

4 Conclusions

Five river ice phenology indicators, including FUE, FUS, BUE, BUS, and CFD, in the Songhua River Basin of Northeast China have been investigated using in situ measurements for the period 2010 to 2015 using kriging and REOF methods. The FUS and FUE decreased while the BUS, BUE, and CFD increased with latitude. The five river ice phenology indicators followed the latitudinal gradient and a changing direction from southeast to northwest. The highest MIT over 125 cm were distributed along the ridge of Da Hagan Lin and Changbai Mountain, and MIT occurred most often in February and March, which indicated that this is the safest period for human activities such as navigation and winter recreation. Five typical geographic zones were identified from the first four PC modes of CFD, covering Changbai Mountain, Three River Plain, Da

Higgan Mountain, and Xiao Higgan Mountain, providing a deeper understanding of river ice distribution and its relationship with geographic locations and topography in Northeast China.

Within one cold season, ice thickness and snow depth showed similar seasonal changes, i.e. first increased and then decreased, while air temperature showed an opposite trend. The peaks of snow depth and ice thickness fell behind air temperature for almost one month. High correlation coefficients between yearly maximum ice thickness and ice phenology indicators revealed that ice phenology is closely related to ice thickness, especially in the break-up process. The yearly analysis failed to explain the relationship between ice regime and snow depth and air temperature. Based on monthly correlation analysis, snow cover played an increasingly important role as the ice cover become steady. Additionally, air temperature associated with ice phenology more closely than ice thickness.

Six Bayesian regression models were built between ice thickness and air temperature and snow depth in three sub-basins of Songhua River, considering two types of air temperature: air temperature on bank and negative cumulative air temperature. Results showed that snow cover correlated with ice thickness significantly and positively during the periods when the freshwater was completely frozen, and negative cumulative air temperature influenced the thickness rather than air temperature through the heat loss of ice formation and decay. The negative ATC behaved better than BAT when building the Bayesian regression equation, which suggested that heat exchanges between the river surface and the atmosphere dominated the ice process.

This study aimed at exploring the regional patterns of river ice development based on in situ measurements and was limited by data accessibility. Remote sensing data could provide long-term and wide-range information for ice thickness and ice phenology since 1980, expanding our study scope. The work herein will provide a valuable reference for the retrieval of ice development by remote sensing. Knowing the long-term change of river ice and the future projection could provide information for evaluating the influence of climate on social-economics, ecological environment and human activists across the riparian zones.

Abbreviations

The following abbreviations are used in this manuscript:

AMSR-E Advanced Microwave Scanning Radiometer- Earth Observing System
ASD Average Snow depth
ATC Cumulative air temperature
BAT Air temperature on bank
BLR Bayesian linear regression
BUS Break-up start
BUE Break-up end
CFD Completely frozen duration
DOY Day of year
EOF Empirical orthogonal function

FUS Freeze-up start

FUE Freeze-up end

IP Ice phenology

IT Ice thickness

NJ Nenjiang River Basin

MIT Maximum ice thickness

PC Principal component

REOF Rotated empirical orthogonal function

RMSE Root mean square error

SD Downstream Songhua River Basin

SRTM Shuttle Radar Topography Mission

SU Upstream Songhua River Basin

Author Contribution

Song K.S. and Yang Q. designed and conducted the idea of this study. Yang Q. Wen Z.D. wrote the paper and analysed the data cooperatively; Hao X.H. provided value suggestion for the structure of study and paper; Li W.B. and Tan Y. exerted efforts on data processing and graphing. This article is a result of collaboration with all listed co-authors.

Competing interest

The authors reported no potential conflict of interest.

Acknowledgments

The research was sponsored by the National Natural Science Foundation of China (41801283, 41971325, 41730104). The anonymous reviewers to improve the quality of this manuscript are greatly appreciated.

References

Barber, J. J.: Bayesian Core: A Practical Approach to Computational Bayesian Statistics, Journal of the American Statistical Association, 103, 432-433, 2008.

Beltaos, S., and Prowse, T.: River-ice hydrology in a shrinking cryosphere, 23, 122-144, https://doi.org/10.1002/hyp.7165, 2009.

Bian, Y., Yue, J., Gao, W., Li, Z., Lu, D., Xiang, Y., and Chen, J.: Analysis of the Spatiotemporal Changes of Ice Sheet Mass and Driving Factors in Greenland, Remote Sensing, 11, https://doi.org/10.3390/rs11070862, 2019.

C.R. Paramasivam, S. V.: An Introduction to Various Spatial Analysis Techniques, in: GIS and Geostatistical Techniques for Groundwater Science, edited by: Senapathi Venkatramanan, M. V. P., Sang Yong Chung, Elsevier, 23-30, 2019.

Cai, Y., Ke, C.-Q., Yao, G., and Shen, X.: MODIS-observed variations of lake ice

phenology in Xinjiang, China, Climatic Change, https://doi.org/10.1007/s10584-019-02623-2, 2019.
Chen, H., Zhang, W., Nie, N., and Guo, Y.: Long-term groundwater storage variations estimated in the Songhua River Basin by using GRACE products, land surface models, and in-situ observations, Sci Total Environ, 649, 372-387, https://doi.org/10.1016/j.scitotenv.2018.08.352, 2019.
Choiński, A., Ptak, M., Skowron, R., and Strzelczak, A.: Changes in ice phenology on polish lakes from 1961 to 2010 related to location and morphometry, Limnologica, 53, 42-49, 2015.
Duguay, C. R., Bernier, M., Gauthier, Y., and Kouraev, A.: Remote sensing of lake and river ice, 273-306 pp., 2015.
Gao, B. S., and Stefan, H. G.: Multiple linear regression for lake ice and lake temperature characterisitcs, Journal of Cold Regions Engineering, 13, 59-77, 1999.
Gao, S., and Stefan, H. G.: Potential Climate Change Effects on Ice Covers of Five Freshwater Lakes, Journal of Hydrologic Engineering, 9, 226-234, https://doi.org/doi:10.1061/(ASCE)1084-0699(2004)9:3(226), 2004.
Gao, S., Zhu, Z., Liu, S., Jin, R., Yang, G., Tan, L. J. I. J. o. A. E. O., and Geoinformation: Estimating the spatial distribution of soil moisture based on Bayesian maximum entropy method with auxiliary data from remote sensing, 32, 54-66, 2014.
Hampton, S. E., Galloway, A. W., Powers, S. M., Ozersky, T., Woo, K. H., Batt, R. D., Labou, S. G., O'Reilly, C. M., Sharma, S., Lottig, N. R., Stanley, E. H., North, R. L., Stockwell, J. D., Adrian, R., Weyhenmeyer, G. A., Arvola, L., Baulch, H. M., Bertani, I., Bowman, L. L., Jr., Carey, C. C., Catalan, J., Colom-Montero, W., Domine, L. M., Felip, M., Granados, I., Gries, C., Grossart, H. P., Haberman, J., Haldna, M., Hayden, B., Higgins, S. N., Jolley, J. C., Kahilainen, K. K., Kaup, E., Kehoe, M. J., MacIntyre, S., Mackay, A. W., Mariash, H. L., McKay, R. M., Nixdorf, B., Noges, P., Noges, T., Palmer, M., Pierson, D. C., Post, D. M., Pruett, M. J., Rautio, M., Read, J. S., Roberts, S. L., Rucker, J., Sadro, S., Silow, E. A., Smith, D. E., Sterner, R. W., Swann, G. E., Timofeyev, M. A., Toro, M., Twiss, M. R., Vogt, R. J., Watson, S. B., Whiteford, E. J., and Xenopoulos, M. A.: Ecology under lake ice, Ecol Lett, 20, 98-111, https://doi.org/10.1111/ele.12699, 2017.
Ionita, M., Badaluta, C. A., Scholz, P., and Chelcea, S.: Vanishing river ice cover in the lower part of the Danube basin - signs of a changing climate, Sci Rep, 8, 7948, https://doi.org/10.1038/s41598-018-26357-w, 2018.
Jenson, B. J., Magnuson, J. J., Card, V. M., Soranno, P. A., and Stewart, K. M.: Spatial Analysis of Ice Phenology Trends across the Laurentian Great Lakes Region during a Recent Warming Period, Limnology Oceanography, 52, 2013-2026, 2007.
Kang, K. K., Duguay, C. R., Lemmetyinen, J., and Gel, Y.: Estimation of ice thickness on large northern lakes from AMSR-E brightness temperature measurements, Remote Sensing of Environment, 150, 1-19, https://doi.org/10.1016/j.rse.2014.04.016, 2014.
Khan, M. I., Liu, D., Fu, Q., and Faiz, M. A.: Detecting the persistence of drying trends under changing climate conditions using four meteorological drought indices, Meteorological Applications, 25, 184-194, https://doi.org/10.1002/met.1680, 2018.
Kwok, R., and Fahnestock, M. A.: Ice Sheet Motion and Topography from Radar Interferometry, IEEE Transactions on Geoscience Remote Sensing, 34, 189-200, 1996.
Lindenschmidt, K.-E., Das, A., and Chu, T.: Air pockets and water lenses in the ice cover of the Slave River, Cold Regions Science and Technology, 136, 72-80, https://doi.org/10.1016/j.coldregions.2017.02.002, 2017.
Magnuson, J. J., Robertson, D. M., Benson, B. J., Wynne, R. H., Livingstone, D. M., Arai, T., Assel, R. A., Barry, R. G., Card, V., and Kuusisto, E.: Historical Trends in Lake and River Ice Cover in the Northern Hemisphere, Science, 289, 1743-1746, 2000.

Morris, K., Jeffries, M., and Duguay, C.: Model simulation of the effects of climate variability and change on lake ice in central Alaska, USA, in: Annals of Glaciology, Vol 40, 2005, edited by: MacAyeal, D. R., Annals of Glaciology-Series, 113-118, 2005.

Palecki, M. A., and Barry, R. G.: Freeze-up and Break-up of Lakes as an Index of Temperature Changes during the Transition Seasons: A Case Study for Finland, Journal of Applied Meteorology, 25:7, 893-902, 1986.

Park, H., Yoshikawa, Y., Oshima, K., Kim, Y., Ngo-Duc, T., Kimball, J. S., and Yang, D.: Quantification of Warming Climate-Induced Changes in Terrestrial Arctic River Ice Thickness and Phenology, Journal of Climate, 29, 1733-1754, https://doi.org/10.1175/jcli-d-15-0569.1, 2016.

Pavelsky, T. M., and Smith, L. C.: Spatial and temporal patterns in Arctic river ice breakup observed with MODIS and AVHRR time series, Remote Sensing of Environment, 93, 328-338, https://doi.org/10.1016/j.rse.2004.07.018, 2004.

Prowse, T. D., and Beltaos, S.: Climatic control of river-ice hydrology: a review, 16, 805-822, https://doi.org/10.1002/hyp.369, 2002.

Seidou, O., Ouarda, T. B. M. J., Bilodeau, L., Bruneau, B., and St-Hilaire, A.: Modeling ice growth on Canadian lakes using artificial neural networks, Water Resources Research, 42, 2526-2528, 2006.

Sharma, S., Blagrave, K., Magnuson, J. J., O'Reilly, C. M., Oliver, S., Batt, R. D., Magee, M. R., Straile, D., Weyhenmeyer, G. A., Winslow, L., and Woolway, R. I.: Widespread loss of lake ice around the Northern Hemisphere in a warming world, Nature Climate Change, 9, 227-231, https://doi.org/10.1038/s41558-018-0393-5, 2019.

Shiklomanov, A. I., and Lammers, R. B.: River ice responses to a warming Arctic—recent evidence from Russian rivers, Environmental Research Letters, 9, 035008, https://doi.org/10.1088/1748-9326/9/3/035008, 2014.

Shuter, B. J., Finstad, A. G., Helland, I. P., Zweimüller, I., and Hölker, F.: The role of winter phenology in shaping the ecology of freshwater fish and their sensitivities to climate change, Aquatic Sciences, 74, 637-657, 2012.

Šmejkalová, T., Edwards, M. E., and Dash, J.: Arctic lakes show strong decadal trend in earlier spring ice-out, Scientific Reports, 6, 38449, 2016.

Song, C., Huang, B., Ke, L., and Richards, K. S.: Remote sensing of alpine lake water environment changes on the Tibetan Plateau and surroundings: A review, Isprs Journal of Photogrammetry and Remote Sensing, 92, 26-37, https://doi.org/10.1016/j.isprsjprs.2014.03.001, 2014.

Wang, M., Lei, X., Liao, W., and Shang, Y.: Analysis of changes in flood regime using a distributed hydrological model: a case study in the Second Songhua River basin, China, International Journal of Water Resources Development, 34, 386-404, https://doi.org/10.1080/07900627.2018.1440538, 2018.

Wang, S., Wang, Y., Ran, L., and Su, T.: Climatic and anthropogenic impacts on runoff changes in the Songhua River basin over the last 56years (1955–2010), Northeastern China, Catena, 127, 258-269, https://doi.org/10.1016/j.catena.2015.01.004, 2015.

Williams, G., Layman, K. L., and Stefan, H. G.: Dependence of lake ice covers on climatic, geographic and bathymetric variables, Cold Regions Science Technology, 40, 145-164, 2004.

Williams, S. G., and Stefan, H. G.: Modeling of Lake Ice Characteristics in North America using Climate, Geography, and Lake Bathymetry, Journal of Cold Regions Engineering, 20, 140-167, 2006.

Yang, P., Xia, J., Zhan, C., Qiao, Y., and Wang, Y.: Monitoring the spatio-temporal changes of terrestrial water storage using GRACE data in the Tarim River basin between 2002 and 2015, Science of the Total Environment, 595, 218-228, 2017.

Yang, Q., Song, K., Hao, X., Chen, S., and Zhu, B.: An Assessment of Snow Cover Duration Variability Among Three Basins of Songhua River in Northeast China Using Binary Decision Tree, Chinese Geographical Science, 28, 946-956, https://doi.org/10.1007/s11769-018-1004-0, 2018.

Yang, Q., Song, K., Wen, Z., Hao, X., and Fang, C.: Recent trends of ice phenology for eight large lakes using MODIS products in Northeast China, International Journal of Remote Sensing, 40, 5388-5410, https://doi.org/10.1080/01431161.2019.1579939, 2019.

Yang, X., Pavelsky, T. M., and Allen, G. H.: The past and future of global river ice, Nature, 577, 69-73, https://doi.org/10.1038/s41586-019-1848-1, 2020.

Zaier, I., Shu, C., Ouarda, T. B. M. J., Seidou, O., and Chebana, F.: Estimation of ice thickness on lakes using artificial neural network ensembles, Journal of Hydrology, 383, 330-340, 2010.

Zhang, F., Li, Z., and Lindenschmidt, K.-E.: Potential of RADARSAT-2 to Improve Ice Thickness Calculations in Remote, Poorly Accessible Areas: A Case Study on the Slave River, Canada, Canadian Journal of Remote Sensing, 45, 234-245, https://doi.org/10.1080/07038992.2019.1567304, 2019.

Zhao, K., Valle, D., Popescu, S., Zhang, X., and Mallick, B.: Hyperspectral remote sensing of plant biochemistry using Bayesian model averaging with variable and band selection, Remote Sensing of Environment, 132, 102-119, https://doi.org/10.1016/j.rse.2012.12.026, 2013.

Zhao, Y., Song, K., Lv, L., Wen, Z., Du, J., and Shang, Y.: Relationship changes between CDOM and DOC in the Songhua River affected by highly polluted tributary, Northeast China, Environmental Science Pollution Research, 25, 25371-25382, 2018.

Tables

Table 1 Summary statistics of ice phenology interpolated by Kriging from 2010 to 2015. The ice phenology indicators included freeze-up start (FUS), freeze-up end (FUE), break-up start (BUS), break-up end (BUE), complete frozen duration (CFD). NJ, SD and SU represent the Nenjiang Basin, the downstream Songhua River Basin (SD) and the upstream Songhua River Basin (SU). DOY denotes day of year. Std Dev. denotes standard deviation.

Basins	Statistics	FUS (DOY)	FUE (DOY)	BUS (DOY)	BUE (DOY)	CFD (day)
NJ	**Maximum**	319.14	334.98	110.54	117.61	163.00
	Mean	307.02	324.58	98.65	106.64	139.39
	Minimum	301.41	311.30	84.53	90.40	119.11
	Std Dev.	3.91	5.69	8.16	6.80	13.22
SD	**Maximum**	321.08	334.36	110.01	102.84	154.06
	Mean	313.74	326.70	102.55	97.15	140.86
	Minimum	305.64	316.80	93.22	92.37	125.32
	Std Dev.	2.83	3.13	3.92	2.12	5.69
SU	**Maximum**	325.92	342.09	98.25	114.37	133.62
	Mean	320.39	334.35	91.93	106.43	122.61
	Minimum	313.79	327.68	83.46	95.69	110.74
	Std Dev.	2.34	3.09	3.21	4.24	4.85
Total	**Maximum**	325.92	342.09	110.54	117.61	163.00
	Mean	311.16	326.58	99.25	105.38	137.86
	Minimum	301.41	311.30	83.46	90.40	110.74
	Std Dev.	5.74	5.54	7.17	6.34	11.68

Table 2 The Frequency of yearly maximum ice thickness from November to April. The row represents different year in cold season and the column represents yearly maximum ice thickness with the unit of cm.

MIT / Month	<50	50-75	76-100	101-125	125-150
December	4	1	0	1	0
January	4	4	1	0	0
February	4	25	26	3	1
March	1	3	24	8	4
April	0	2	1	0	0
After April	0	3	0	0	0
Total	13	38	52	12	5

Table 3 Correlation coefficient between maximum ice thickness (MIT) and average snow depth (ASD), and air temperature on bank (BAT) with a dataset size of 120 stations. The asterisk indicates the significant level of correlation coefficients, ** means significant at 99% level ($p<0.01$), and * means significant at 95% level ($p<0.05$).

Correlation Coefficients	November	December	January	February	March
MIT vs. ASD	0.17	0.66*	0.53*	0.59*	0.75**
MIT vs. BAT	-0.90**	-0.80**	-0.55*	-0.30	-0.45

Figures

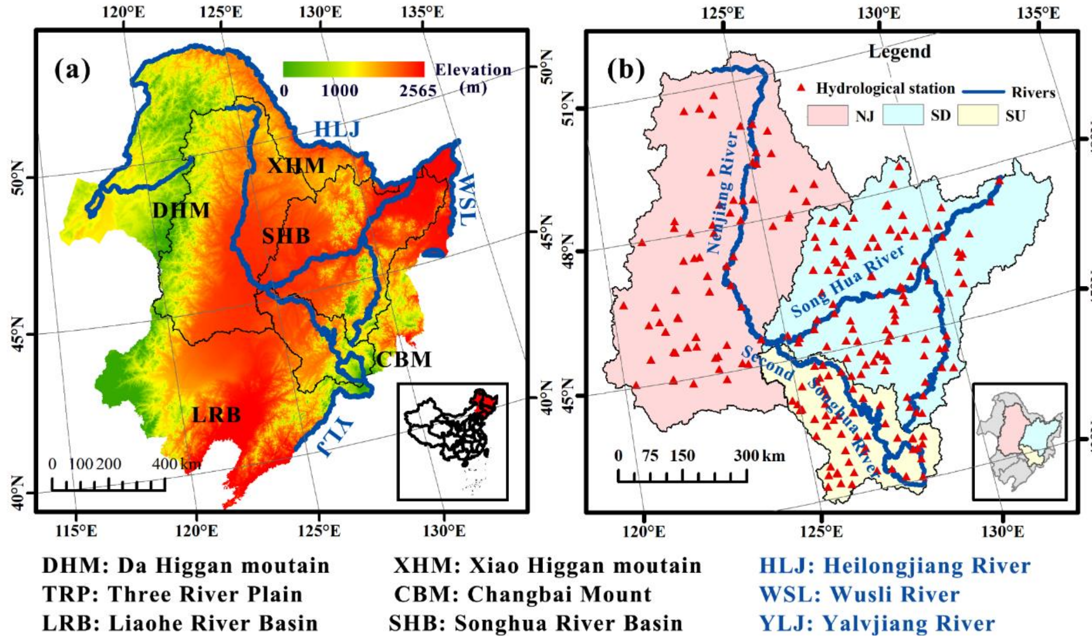


Figure 1 The geographic location of the Songhua River Basin showing (a) the elevation and (b) the location of 158 hydrological stations. The Songhua River Basin includes three sub-basins: Nenjiang River Basin (NJ), downstream Songhua River Basin (SD) and upstream Songhua River Basin (SU). Elevation data are from the Shuttle Radar Topography Mission (SRTM) with spatial resolution of 90 meters.

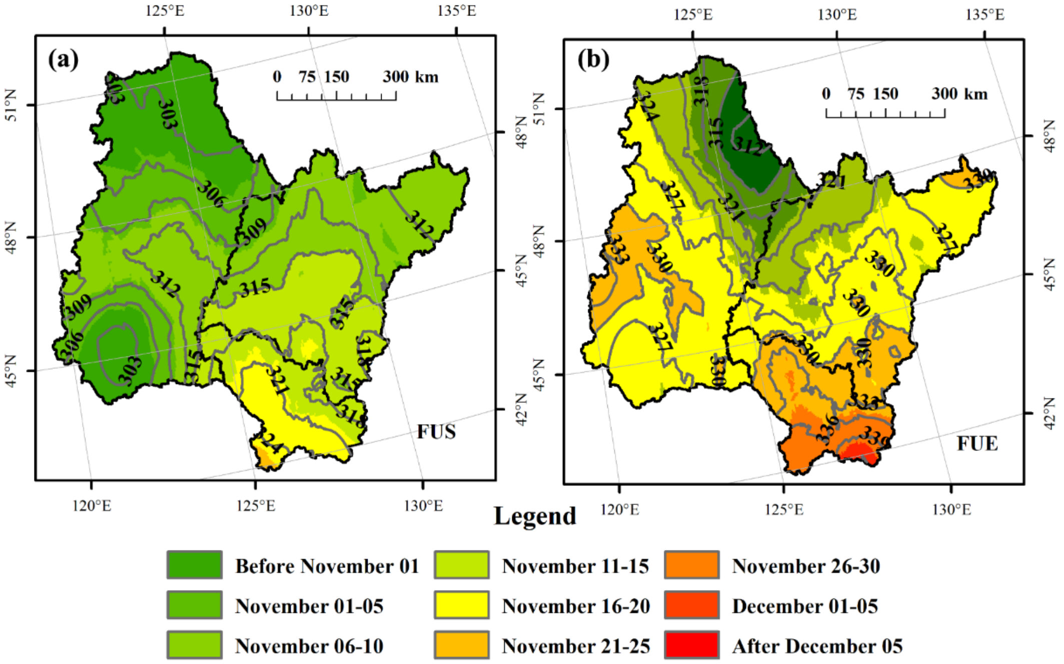


Figure 2 The average spatial distribution of freeze-up start (FUS) (a) and freeze-up end (FUE) (b) in the Songhua River Basin of Northeast China from 2010 to 2015. The number labels indicate the day of year (DOY) of the isophenes.

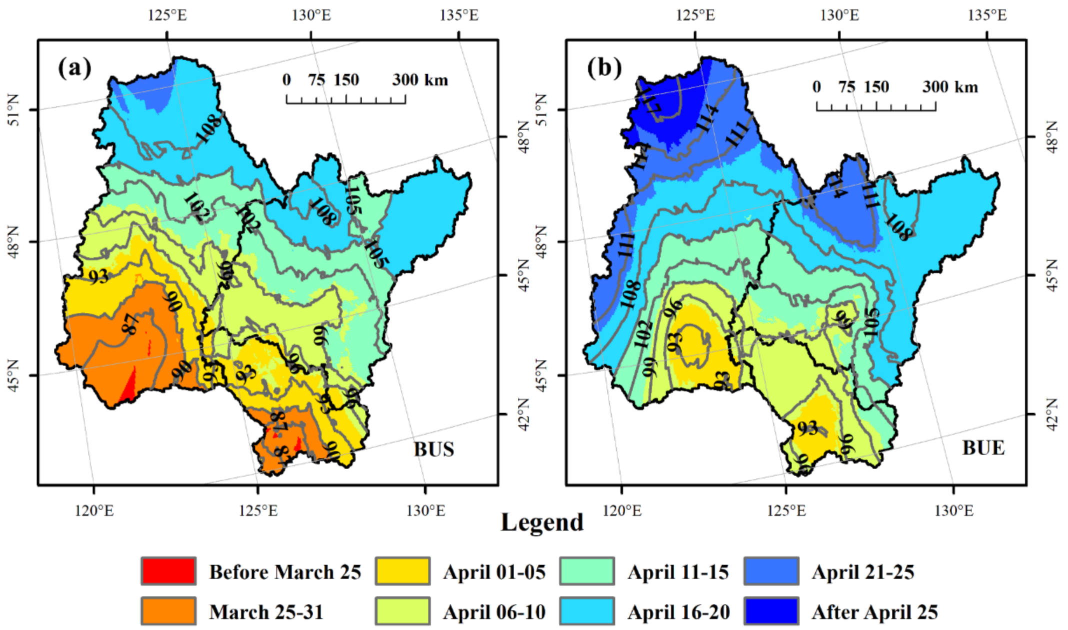


Figure 3 The average spatial distribution of break-up start (BUS) (a) and break-up end (BUE) (b) in the Songhua River Basin of Northeast China from 2010 to 2015. The number labels indicate the day of year (DOY) of the isophenes.

555

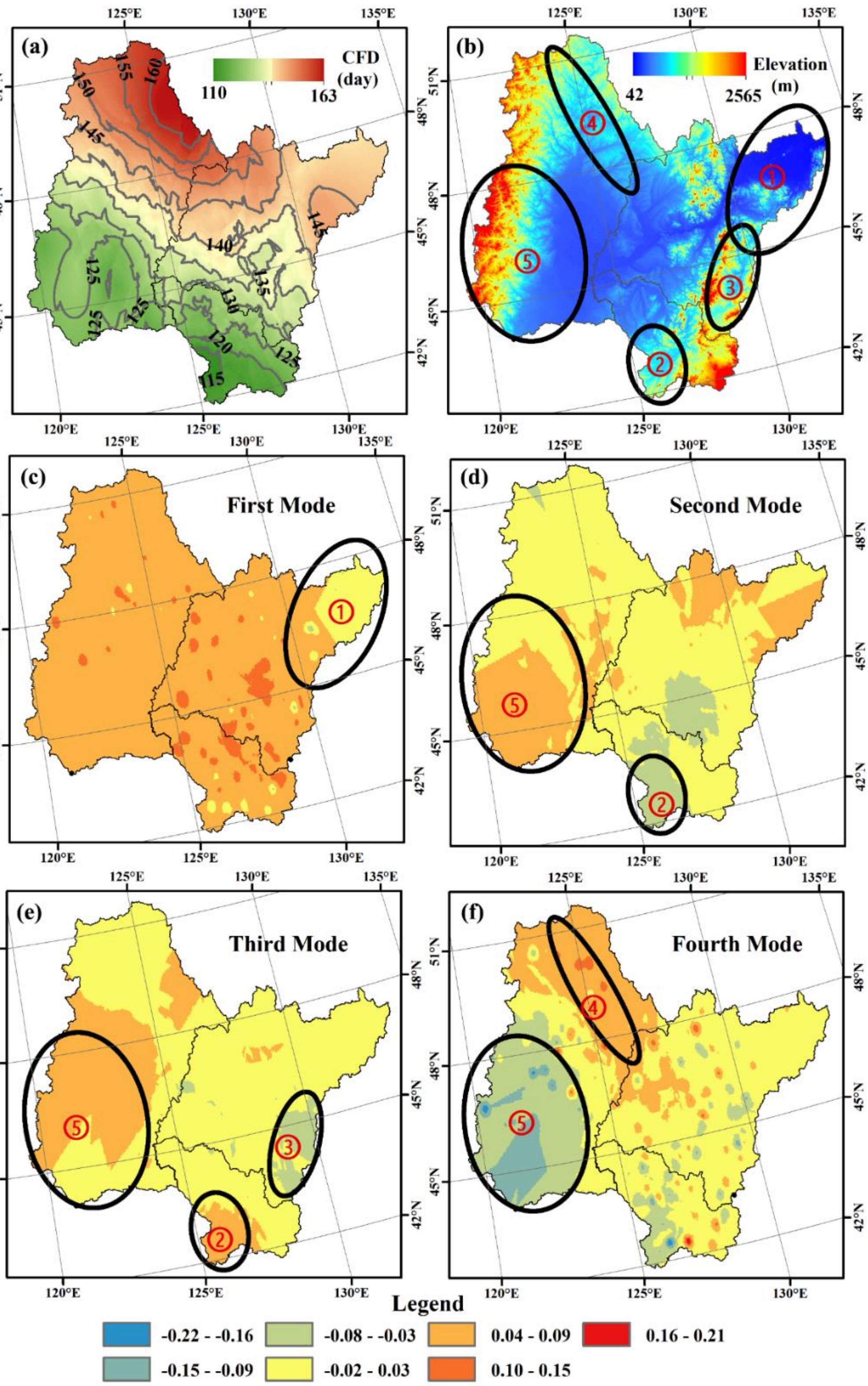


Figure 4 The spatial distribution of complete frozen duration (CFD) (a), five typical geographical zones (b), and first four principal components (c-f) decomposed by rotated empirical orthogonal function in the Songhua River Basin of Northeast China.

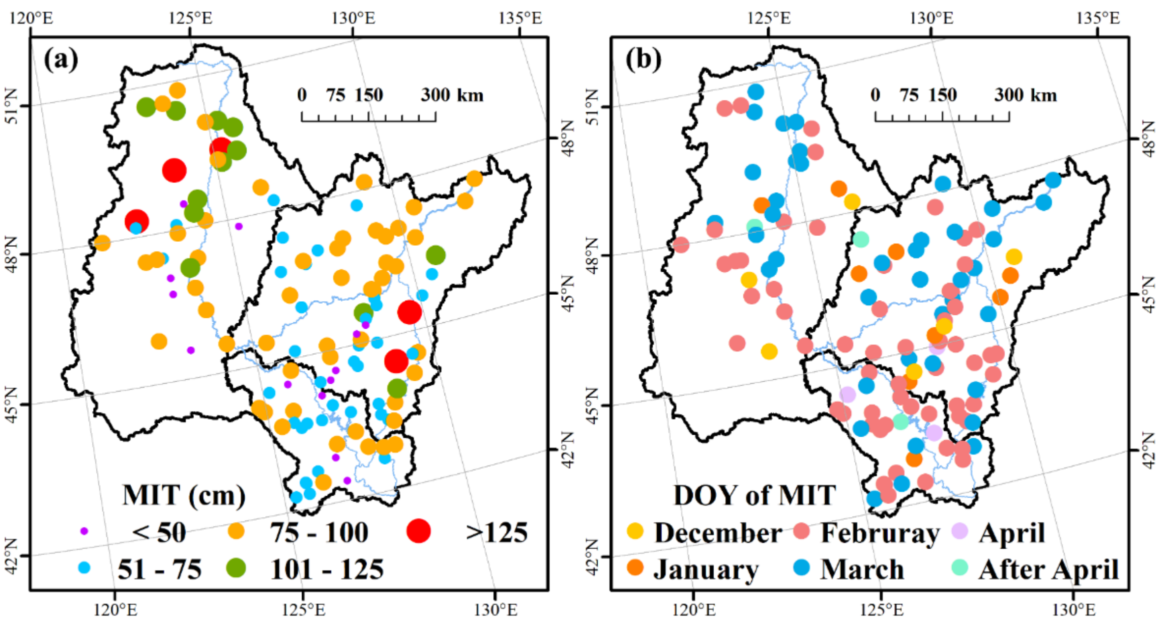


Figure 5 The spatial distribution of yearly maximum ice thickness (MIT) (a) of the river centre and the corresponding date (b).

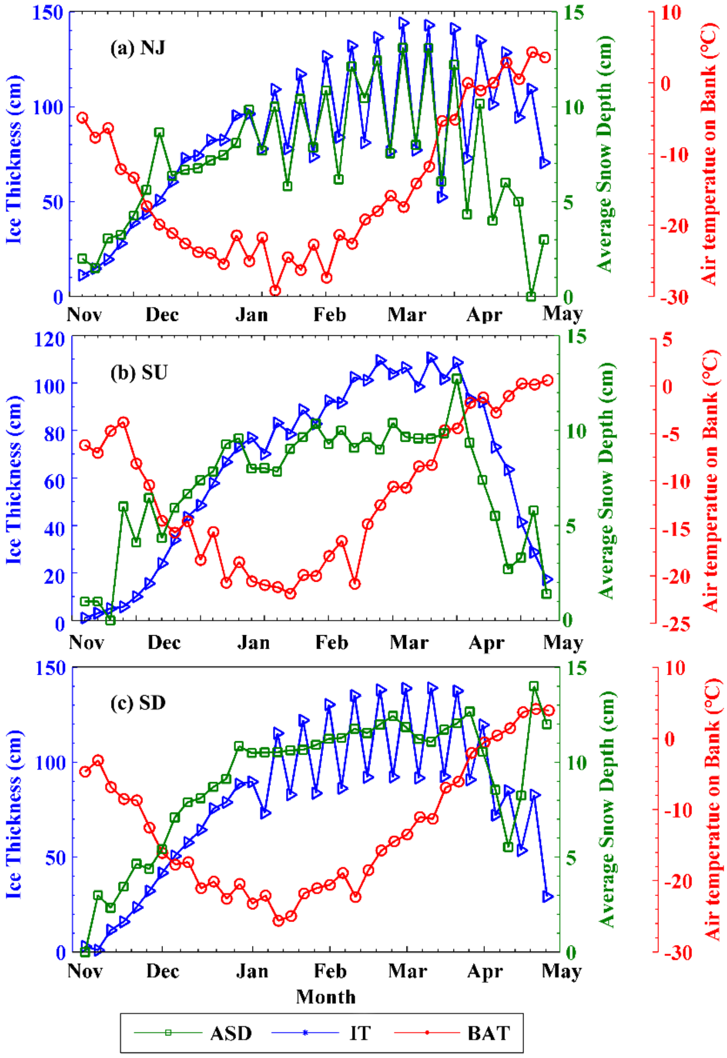


Figure 6 Average seasonal changes in ice thickness (IT), average snow depth (ASD) and air temperature on bank (BAT) from November to April for the period 2010 - 2015.

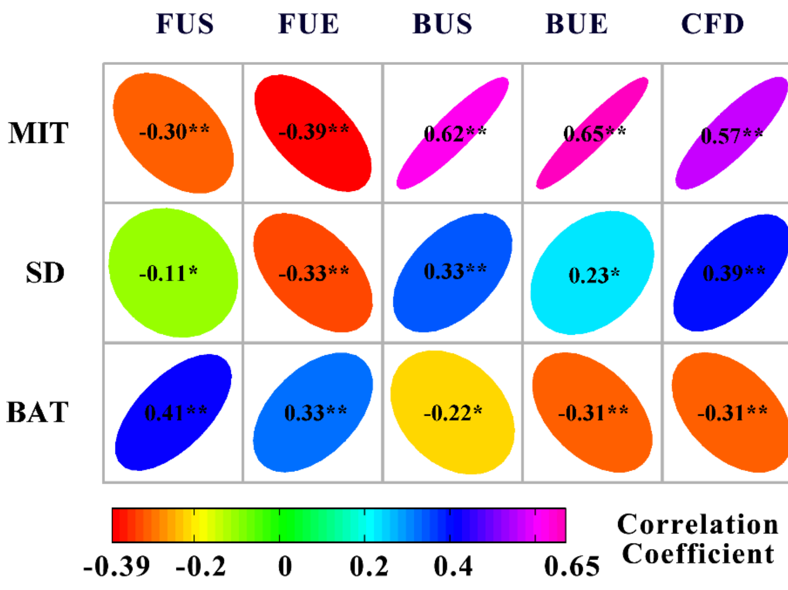


Figure 7 Correlation matrix between maximum ice thickness (MIT), average snow depth (ASD) and air temperature on bank (BAT) and lake ice phenology events with data from 120 stations. The asterisk indicates the significance level of the correlation coefficients, ** means significant at 99% level (p<0.01), and * means significant at 95% level (p<0.05).

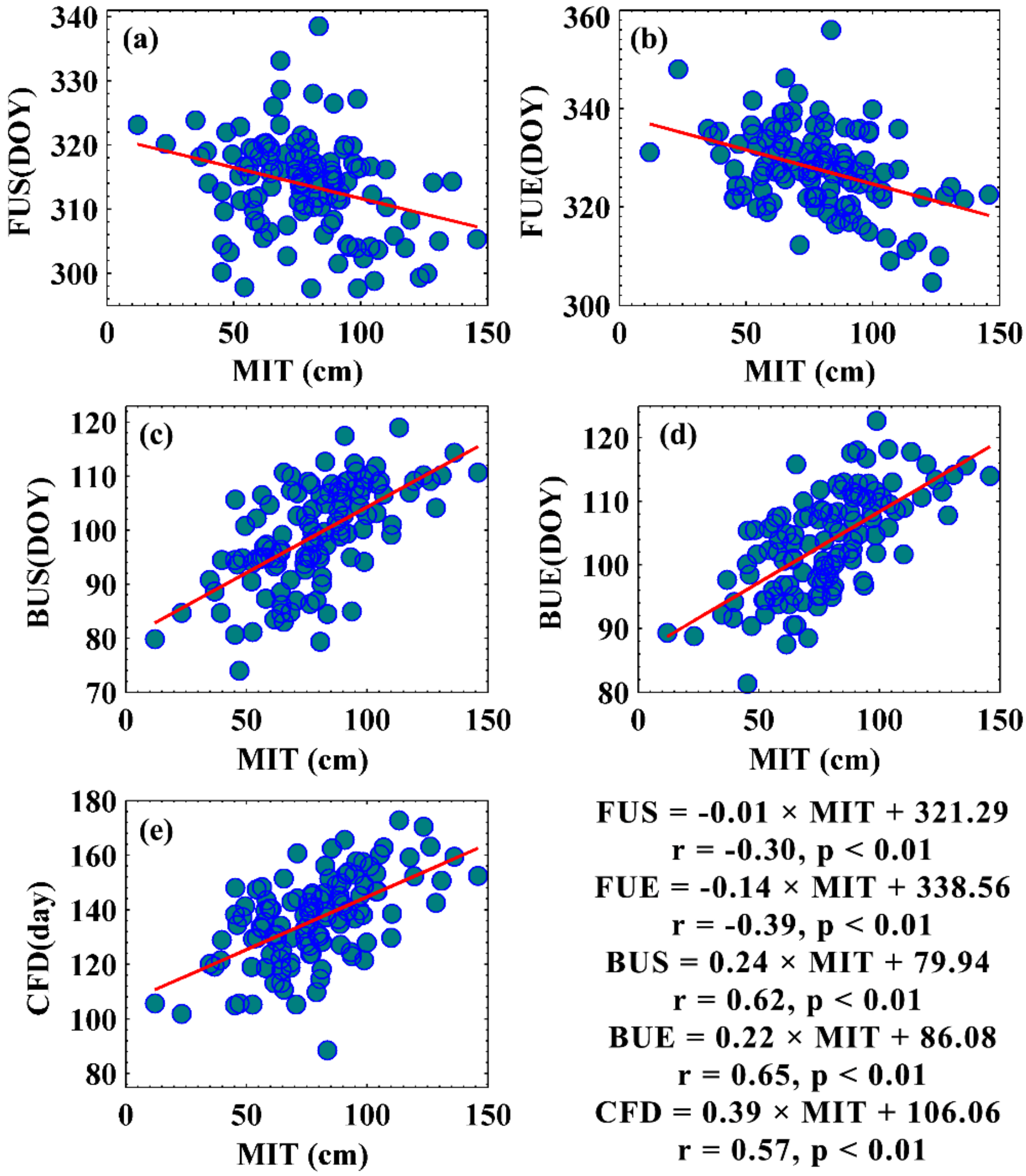


Figure 8 The bivariate scatter plots with linear regression lines between yearly maximum ice thickness (MIT) and ice phenology with dataset size of 120; r and p denote the correlation coefficient and p value of the regression line. The ice phenology events include freeze-up start (FUS), freeze-up end (FUE), break-up start (BUS), break-up end (BUE) and complete frozen duration (CFD).

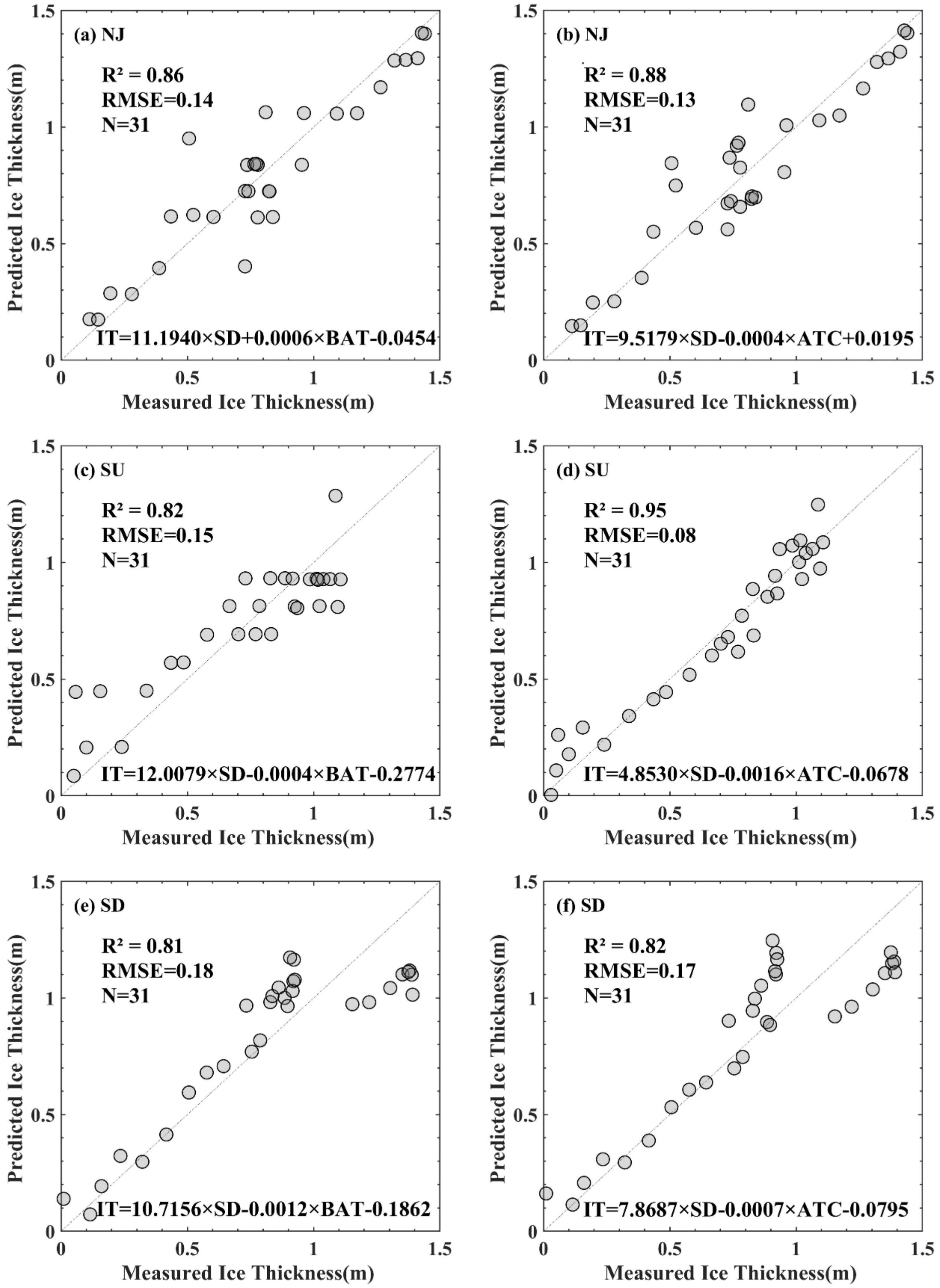


Figure 9 Scatter plots between measured and predicted ice thickness using Bayesian linear regression in three sub-basins (NJ: Nenjiang Basin, SU: upstream Songhua River Basin, and SD: downstream Songhua River Basin) in Northeast China. The model treated ice thickness as the independent variable, and snow depth and air temperature as dependent variables. Two types of air temperature were used: BAT represents air temperature on bank; ATC represents negative cumulative air temperature.

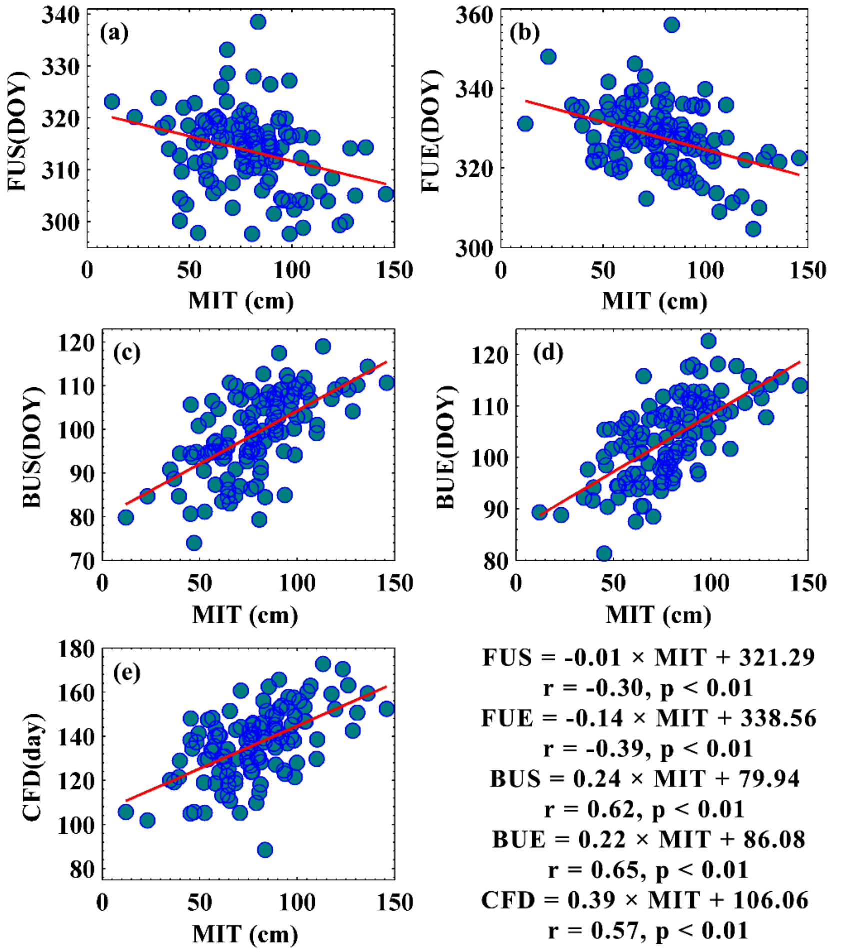


Figure 8 The bivariate scatter plots with linear regression lines between yearly maximum ice thickness (MIT) and ice phenology with dataset size of 120~~;~~, *r* and *p* denote the corresponding correlation coefficient and *p* value of ~~the~~ regression line. The ice phenology ~~events include~~includes freeze-up start (FUS), freeze-up end (FUE), break-up start (BUS), break-up end (BUE) and complete frozen duration (CFD).

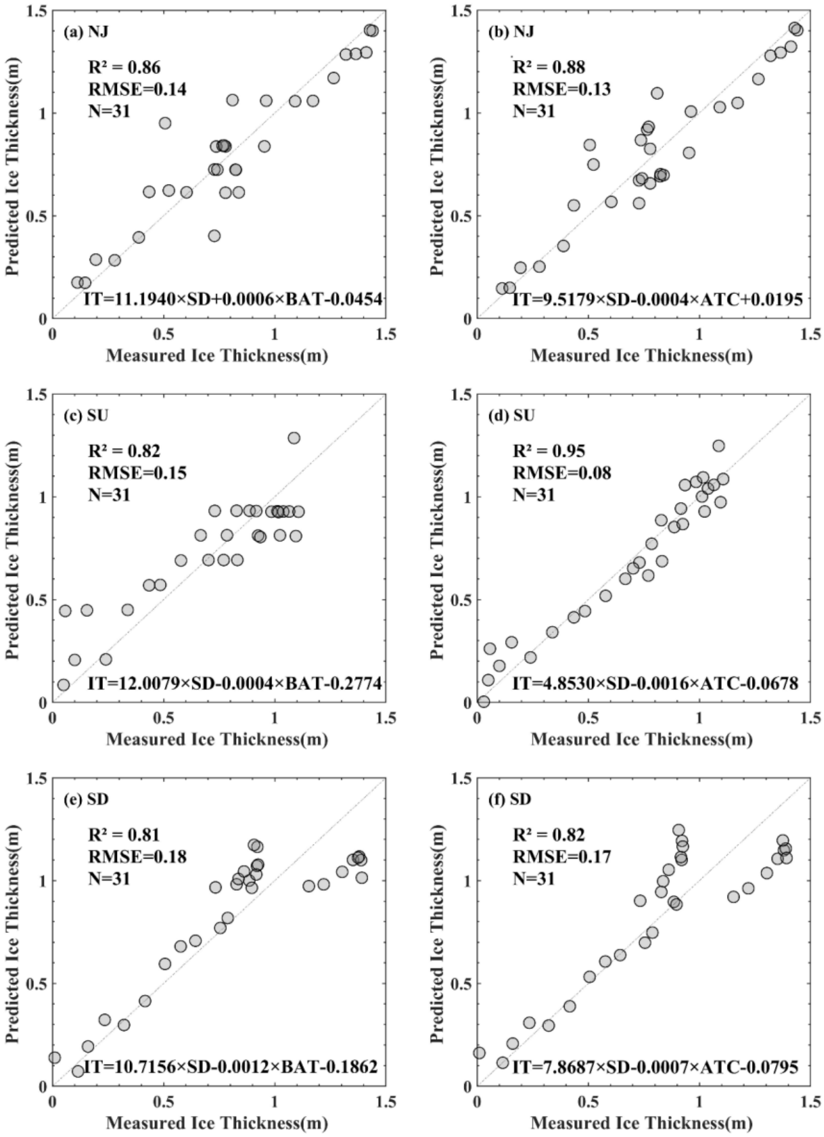
带格式的: 正文, 无

设置了格式: 字体: 倾斜

设置了格式: 字体: 倾斜

设置了格式: 字体: 倾斜

带格式的: 行距: 单倍行距


(a) NJ
R² = 0.86
RMSE=0.14
N=31
IT=11.1940×SD+0.0006×BAT-0.0454
(b) NJ
R² = 0.88
RMSE=0.13
N=31
IT=9.5179×SD-0.0004×ATC+0.0195
(c) SU
R² = 0.82
RMSE=0.15
N=31
IT=12.0079×SD-0.0004×BAT-0.2774
(d) SU
R² = 0.95
RMSE=0.08
N=31
IT=4.8530×SD-0.0016×ATC-0.0678
(e) SD
R² = 0.81
RMSE=0.18
N=31
IT=10.7156×SD-0.0012×BAT-0.1862
(f) SD
R² = 0.82
RMSE=0.17
N=31
IT=7.8687×SD-0.0007×ATC-0.0795
Predicted Ice Thickness(m)
Measured Ice Thickness(m)

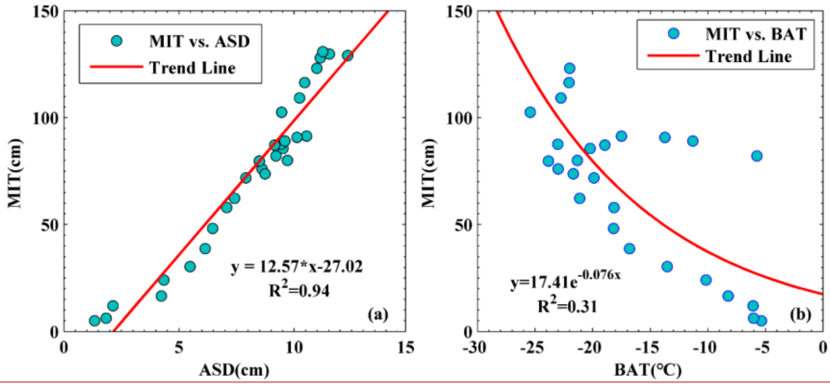


Figure 9 The scatter plot between maximum ice thickness (MIT), average snow depth (ASD) and air temperature on bank (BAT) and the corresponding trend line. The data was selected under the criteria with air temperature below 2°C and snow depth less than 20 cm.

~~Figure 9 Scatter plots between measured and predicted ice thickness using Bayesian linear regression in three sub-basins (NJ: Nenjiang Basin, SU: upstream Songhua River Basin, and SD: downstream Songhua River Basin) in Northeast China. The model treated ice thickness as the independent variable, and snow depth and air temperature as dependent variables. Two types of air temperature were used: BAT represents air temperature on bank; ATC represents negative cumulative air temperature.~~

设置了格式: 字体: 加粗

设置了格式: 字体: +西文正文 (Times New Roman), 字体颜色: 自动设置

带格式的: 无, 行距: 单倍行距

设置了格式: 字体颜色: 自动设置

The comparision between the new version and the previous manuscript

Abstract: ~~The~~ Songhua River ~~Basin, located in Northeast China,~~basin is ~~an area~~a sensitive area to global warming in Northeast China that could be ~~impacted~~indicated by changes in lake and river ice ~~regimes~~development. The regional role and trends of ~~lake and river~~ ice characteristics of this area have been scarcely investigated ~~and~~, which are critical for aquatic ~~ecosystems~~ecosystem, climate variability, and human activities. ~~Using~~Based on the ice ~~records~~record of ~~local~~ hydrological stations, we examined the spatial variations of the ice phenology and ice thickness in ~~the~~ Songhua River ~~Basin~~basin in Northeast China from 2010 to 2015 and explored the role of ice thickness, snow ~~depth~~ during ice-on and ~~air temperature on ice regime~~ice-off process. All ~~of~~ five river ice phenology ~~indicators,~~ including freeze-up start, freeze-up end, break-up start, break-up end and complete frozen duration~~,~~ showed ~~a~~ latitudinal distribution and a changing direction from southeast to northwest~~. Five typical~~, and five typically geographic zones were identified ~~applying a~~based on rotated empirical orthogonal function. Maximum ice thickness had a higher correlation with ~~ice phenology, especially with the break-up process. Six Bayesian~~five parameters than that of average snow depth and air temperature on bank. A linear regression ~~models were built~~function was established between ice thickness~~,~~ and snow depth on ice and indicated ice thickness was closely associated with snow depth on ice. The air temperature~~, and snow depth in three sub-basins of the Songhua River Basin. Results showed~~ had higher correlation with ice phenology and influenced the lake ice phenology significantly, and snow cover did not show significant ~~and positive correlations between~~correlation with the ice phenology. However, snow cover ~~and~~correlated with ice thickness significantly and positively during the periods when the freshwater ~~was~~is completely frozen. ~~Rather than by air temperature, ice thickness was influenced by negative cumulative air temperature through the heat loss of ice formation and decay.~~

Keywords. River ice, ice phenology, ice thickness, snow on ice, air temperature, rotated empirical orthogonal function

1 Introduction

~~The freeze-thaw process of surface ice of temperate lakes and rivers plays a crucial role in the interactions among the climate system(Yang et al., 2020), freshwater ecosystems (Kwok and Fahnestock, 1996) and the biological environment (Prowse and Beltaos, 2002). The presence of freshwater ice is closely associated with social and economic activities, ranging from human-made structures, water transportation, to winter recreation (Williams and Stefan, 2006;Lindenschmidt et al., 2017). Ice cover on rivers and lakes exerts large forces due to thermal expansion and could cause extensive infrastructure losses to bridges, docks, and shorelines (Shuter et al., 2012). Ice cover on waterbodies also provides a natural barrier between the atmosphere and water. Ice cover also blocks the solar radiation necessary for photosynthesis to provide enough dissolved oxygen for fish, thus can have a negative effect on freshwater ecosystems and, in extreme cases, lead to winter kill of fish~~ The freeze and thaw process of surface ice of temperate lakes and rivers plays crucial roles in the interaction among climate system (Stephanie and Stefan Heinz, 2006), freshwater ecosystem (Kwok and Fahnestock, 1996) and biological environment. The existence of freshwater ice closely associate with social and economic activities ranging from human-made structures, water transportation to

设置了格式: 字体: 非加粗
设置了格式: 字体颜色: 红色
设置了格式: 字体颜色: 红色
设置了格式: 突出显示
设置了格式: 突出显示
设置了格式: 突出显示
设置了格式: 突出显示
设置了格式: 字体颜色: 红色
带格式的: 行距: 单倍行距

winter recreation (Lindenschmidt et al., 2017; Williams and Stefan, 2006). The ice cover on rivers and lakes has exerted large forces due to thermal expansion and could cause extensive loss of the human-made structures, such as bridges, docks, shorelines, and so on (Shuter et al., 2012). Furthermore, ice cover on waterbodies provide a natural barrier between the atmosphere and the water and blocks the solar radiation necessary for photosynthesis and enough dissolved oxygen for fish, which have a negative effect on freshwater ecosystem, in extreme cases, leading to winter kills of fishes (Hampton et al., 2017; Xing et al., 2009). Generally, the frozen duration of freshwater ice has a shorten trend with later freeze-up and earlier break-up throughout the northern hemisphere, *i.e.*, with freeze-up date 0.57 days per decade later and 0.63 days per decade earlier during the periods of 1846-1995 (~~Hampton~~Magnuson et al., ~~2017~~2000; Sharma et al., 2019)~~. Generally, the duration of freshwater ice has shown a declining trend, with later freeze-up and earlier break-up throughout the northern hemisphere. For example, freeze-up has been occurring 0.57 days per decade later and break-up 0.63 days per decade earlier during the periods of 1846-1995 (Magnuson et al., 2000;Sharma et al., 2019;Beltaos and Prowse, 2009). To evaluate the influence of ice regimes on the regional climate and human environment, and provide helpful information for regional projections of climate and ice-river floods, a robust and quantitative analysis on ice processes is necessary. Despite the growing importance of river ice under global warming, very little work has been undertaken to explain the considerable variation of ice characteristics in Northeast China, where lakes and rivers are frozen for as long as five to six months a year.~~

~~The earliest ice record in the literature dates back to 150 years ago (Magnuson et al., 2000). Ice development and ice diversity scales have been regarded as sensitive climate indicators. Ice phenology and ice thickness have been studied to gain a deeper understanding of ice processes. At medium and large scales, optical remote sensing data are widely used for deriving ice phenology (Song et al., 2014;Šmejkalová et al., 2016), while microwave remote sensing are used to estimate ice thickness and snow depth over ice .~~. Changes in ice characteristics and phenology have been considered as a sensitive proxy for global warming, which could be attributed to characteristics of water bodies, climate changes, and river discharges (Duguay et al., 2010). Northeast China belongs to one of the most intense areas for climate changes (Piao et al., 2010), but limited work has been carried out on analyzing the considerable variation of ice characteristics in Northeast China, where the lakes and rivers are frozen as long as five to six months.

Along with ice phenology, ice thickness is also considered as a meaningful indicator for regional and global climate changes. Various models have been implemented to derive ice phenology and ice thickness, such as physically-based models, hydrodynamic models, regression models, radiation transfer model, and so on (Duguay et al., 2015). These models considered the energy exchange and physical changes of freshwater ice and required detailed ice measurements, which were carried out around the river mouth and specific rivers (Duguay et al., 2003). Most commonly used ice observations include regular observation, ice charts, volunteer monitoring and field measurements (Duguay et al., 2015). The uneven distribution of hydrological stations limits the expansion of field measurement to regional and global applications. Remote sensing data have been widely used in deriving ice phenology, and ice thickness (~~Zhang~~Brown and Duguay, 2010; Dörnhöfer and Oppelt, 2016; Šmejkalová et al., ~~2019;Kang~~2016; Song et al., 2014)~~. Wide-range satellites~~

设置了格式: 字体颜色: 自动设置

~~make it possible to link ice characteristic with climate indices, such as air temperature (Yang et al., 2020) or large-scale teleconnections (Ionita et al., 2018), but their spatial resolutions are too large to detect ice thickness and snow depth accurately at small scales. For example, the microwave satellite data of AMSR-E have a spatial resolution of 25 km, but the largest width of Nenjiang River only ranges from 170 to 180 meters. The spatial resolution limits the application of satellite observations to precisely inverse ice thickness, let alone snow depth.~~

~~In terms of point-based measurements, the most commonly used ground observations include regular observations, ice charts, volunteer monitoring and field measurements (Duguay et al., 2015). Ground observations depend on spatial distribution and representation, and are limited by the accessibility of surface-based networks and the range of field measurement. Ice parameters differ greatly from point to point on a given river (Pavelsky and Smith, 2004), and the uneven distribution of hydrological stations poses an obstacle to gaining a comprehensive understanding of river ice. Various models have been implemented to derive ice phenology and ice thickness, such as physically-based models (Park et al., 2016), linear regressions~~ , and its inability is limited by the temporal and spatial resolution of remote sensing image. Not only modeling but also remote sensing monitoring requires sufficient historical ice records to validate and improve the accuracy and reliability. Most commonly used ice observations include regular observation, ice charts, volunteer monitoring and field measurements (Duguay et al., 2015). If the sample size of ice records is big enough, monitoring spatiotemporal variations of ice characteristics and the regional trend is essential and feasible, which could provide the potential for analyzing the ice phenology in specific waterbodies.

The most commonly vertical structure of ice cover is made up of congelation ice, snow-ice, snow, and water (Leppäranta, 2010). The ice cover of waterbodies is experiencing three stages: freeze-up, ice growth, and break-up, during which ice phenology, ice thickness, and ice composition changes greatly (Duguay et al., 2015). The effect of snow depth and air temperature on ice thickens has been analyzed based on numerous models, such as regression models (Palecki and Barry, 1986; Williams and Stefan, 2006), thermodynamic ice model (Ménard et al., 2002b), and artificial neural networks (~~Palecki and Barry, 1986;Williams and Stefan,~~Seidou et al., 2006; Zaier et al., 2010)~~, logistic regressions (Yang et al., 2020) and artificial neural networks (Seidou et al., 2006;Zaier et al., 2010). These models consider the energy exchange and physical changes of freshwater ice and require detailed information and data support, including hydrological, meteorological, hydraulic and morphological information. Fixed stations are normally located around the river mouth of certain rivers, so these models are limited by the input data available (Pavelsky and Smith, 2004). Both modelling and remote sensing monitoring require sufficient historical ice records to validate and improve accuracy and reliability.~~

~~The ice cover of water bodies experiences three stages during which ice phenology, ice thickness and ice composition change greatly. These stages are: freeze-up, ice growth, and break-up (Duguay et al., 2015). Although air temperature greatly influences the freeze-thaw cycle of river ice, the effect of snow cover can't be ignored. Generally, snow depth outweighs air temperature during the ice forming process and increasing snow depth provides favourable conditions for thicker ice (Morris et al., 2005;Park et al., 2016). Compared to other studies, air temperature had a greater effect on ice thickness than snow depth and were attributed this~~

设置了格式: 字体颜色: 自动设置

~~to the high snowfall in the study area (Gao and Stefan, 2004). Besides, in situ observations at Russian river mouths where ice thickness decreased had not shown any significant correlation between ice thickness and snow depth (Shiklomanov and Lammers, 2014). Those studies analysed the relationship in view of spatial distributions and ignored the changing status of ice formation processes. The relative influence of snow depth and air temperature on the ice regime deserves further exploration in Northeast China.~~

. The most commonly vertical structure of ice cover consists of congelation ice, snow-ice, snow and water (Leppäranta, 2010). Snow depth on ice and air temperature mainly controls the total ice thickness covering congelation ice and snow-ice. Snow on ice is a good insulator and has two-fold effects: during the freeze-up process and ice growth, the timing and amount of snow directly influence the ice thickness and promote ice thickening; during the break-up process, the snow has a lower light-transmitting property and prevents the ice from melting. Generally, snow depth plays a more crucial role than air temperature (Morris et al., 2005) and increasing snow depth provide favorable condition for thicker ice cover. In comparison with other works, the air temperature had more effect on ice thickness than snow depth and attributed this to the high snowfall of study area (Gao and Stefan, 2004). Whether snow depth or air temperature is the primary factor influencing ice formation and decay deserves further exploring in Northeast China.

The surface-based networks, including climatic and hydrological stations, have been established for tracing climate and hydrological changes in Northeast China, which are limited by the accessibility of surface-based networks and the range of filed measurement. ~~To evaluate the influence of ice regime on regional climate and human environment, a robust investigation and quantitative analysis on ice regime is necessary, which provide helpful information for projecting future changes in the ice regime.~~ The previous work explored the ice process in at one or more locations on a given river and ignored the changing regional pattern of ice development ~~due to sparse location.~~. The objectives of this study are to~~:~~ (1) ~~investigate~~examine and compare ~~the spatial distribution of~~ ice phenology ~~and~~ dynamics of three sub-basins of Songhua River from 2010 to 2015; (2) explore the relationship between ice thickness ~~in Northeast China; (2) quantitatively~~and ice phenology; (3) explore the ~~influence of snow cover~~primary factor influencing ice process and ~~air temperature on~~ ice ~~regime.~~ thickness.

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

带格式的: 行距: 单倍行距

2 Materials and methods

2.1 Study area

~~The~~ Songhua River Basin ~~is~~(119°25′-134°00′E, 41°41′-51°38′N) located in the middle of Northeast China (Figure 1~~), and includes~~) involving Jilin Province, Heilongjiang Province, and ~~the~~ eastern part of Inner Mongolia Autonomous Region. The Songhua River (SHR) is the third-longest river in China, ~~and has~~covering three main ~~tributaries~~streams: Nenjiang ~~River, Main,~~, Songhua River, and Second Songhua River ~~(Zhao et al., 2018;Khan et al., 2018). The basins~~ (Zhao et al., 2018). According to the spatial distribution of ~~the~~ three ~~tributary~~ rivers~~-~~' basin, the corresponding basins include~~:~~ Nenjiang Basin (NJ), the Downstream Songhua River Basin (SD), and the Upstream Songhua River Basin (SU~~)~~), namely (Figure 1). The ~~Nenjiang River~~NJ has a length of 1370 km, and the corresponding drainage has an area of 2~~.~~,55 $\times 10^6$ thousand km^2; the ~~Main~~

~~Songhua River~~MSR has a length of 939 km and the catchment named downstream ~~catchment of the~~ Songhua River Basin (SD) has an area of 1.86 $\times 10^6$ km^2; the ~~Second Songhua River has~~ SSHR have a length of 958 km and the ~~upstream~~ catchment ~~of the~~ named upstream Songhua River Basin (SU) has an area of 6.19$\times 10^6$ km^2. ~~(Yang et al., 2018;Chen et al., 2019).~~(Yang et al., 2018). The whole ~~Songhua River Basin is characterized~~SHR is featured by temperate and cold temperate ~~climates: winter is~~climate with long and cold~~; spring is~~ winter and windy and dry~~. Annual average~~ spring. The air temperature ~~ranges between~~has annual average values of 3 to 5℃, ~~while annual~~and the precipitation ranges from 400 to 800 cm from the southeast to the ~~northwest.~~west ~~(Wang et al., 2015;Wang et al., 2018)~~(Wang et al., 2015).

[Figure 1 is added here]

2.2 Data Source

~~**2.2.1 Ice phenology**~~

The ~~hydrographic bureau of~~in-situ lake ice records were available provided by the Chinese Ministry of Water Resources ~~has established a remarkable observation network for ice regimes. The ice records of the Songhua River Basin were obtained~~ from ~~the annual hydrological report~~2010 to 2015, including ice phenology, ice thickness, snow depth on ice and air temperature on bank (BAT) (Annual hydrological report, 2010-2015). ~~To analyse the spatial pattern of the ice regime, we explored five river ice parameters with the corresponding day of year (DOY) from 158 stations. We located 50, 36 and 72 stations in the NJ, SU and SD basins, respectively. For each record, five lake ice phenological events were derived from the annual hydrological report; the definitions referred to specification for observation of ice regimes in rivers and previous works (Cai et al., 2019;Yang et al., 2019;Duguay et al., 2015) :~~Ice phennolgoy from 158 stations were ananlyzed in this paper, with 48, 36 and 71 stations located in NJ, SU and SD basins.

~~Freeze~~In-situ measurements provide five lake ice phenological events: freeze-up start (FUS~~)~~), freeze-up end (FUE), break-up start (BUS), break-up end (BUE) and complete frozen duration (CFD), and the definition are provided by specification for observation of ice regime in rivers (2015) as follows:

- FUS is considered as the first day when ~~floating~~ ice can be observed~~.~~;
- FUE is considered as the day when the surface is mainly covered by ice with ~~temperatures below 0 ℃~~open water less than 20% of view range;
- ~~Freeze-up end (FUE) is the day when a steady ice carapace can be observed on the river, and the area of ice cover is more than 80% in the view range;~~
- ~~Break-up start (~~BUS~~)~~ is considered as the first day when ice ~~melting can be observed with surface ponding;~~ began to melt;
- ~~Break-up end (~~BUE~~)~~ is considered as the day when the surface is mainly covered by open water ~~and the~~with ice area less than 20% of ~~open water exceed 20%;~~view range.
- ~~Complete frozen duration (CFD)~~-CFD is the ice cover duration between FUE and BUS when the lake is completely frozen during the winter~~, from FUE to BUS.~~.

设置了格式: 非上标/ 下标
带格式的: 正文, 无
设置了格式: 字体颜色: 自动设置
带格式的: 行距: 单倍行距
设置了格式: 字体: 倾斜, 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置, 突出显示
设置了格式: 字体颜色: 自动设置, 突出显示
设置了格式: 字体颜色: 自动设置, 突出显示
带格式的: 正文, 缩进: 首行缩进: 2 字符, 无项目符号或编号
设置了格式: 字体颜色: 自动设置, 突出显示
设置了格式: 字体颜色: 自动设置, 突出显示
带格式的: 正文, 缩进: 首行缩进: 2 字符, 无项目符号或编号
设置了格式: 字体颜色: 自动设置, 突出显示
设置了格式: 字体颜色: 自动设置, 突出显示
设置了格式: 字体颜色: 自动设置, 突出显示
设置了格式: 字体颜色: 自动设置, 突出显示
带格式的: 正文, 缩进: 首行缩进: 0.71 厘米, 无项目符号或编号
设置了格式: 字体颜色: 自动设置, 突出显示
设置了格式: 字体颜色: 自动设置, 突出显示
设置了格式: 字体颜色: 自动设置, 突出显示
设置了格式: 字体颜色: 自动设置, 突出显示
设置了格式: 字体颜色: 自动设置, 突出显示
设置了格式: 字体颜色: 自动设置, 突出显示
设置了格式: 字体颜色: 自动设置, 突出显示
设置了格式: 字体颜色: 自动设置, 突出显示
设置了格式: 字体颜色: 自动设置

~~**2.2.2 Ice thickness**~~

~~To study seasonal changes in ice thickness (IT) and establish the regression model, we used ice thickness, snow depth and air temperature from 120 stations for the period ranging from 2010 to 2015. We used 37, 28 and 55 stations located in the NJ, SU and SD basins, respectively. The hydrological report provided ice thickness, snow depth on ice and BAT every five days from November through April, totalling 37 measurements in one cold season.~~ The yearly maximum ice thickness (MIT) of the river ~~centre and~~ center was involved in this paper, as well as the corresponding ~~DOY were calculated from five~~ day ~~records.~~of year (DOY) and air temperature on bank (BAT). The average snow depth (ASD) ~~was~~is calculated from the mean values of ~~three~~3 or ~~four~~4 measurements around the ice hole for ice thickness measurement without human disturbance. ~~To enhance the performance of the regression model, negative cumulative air temperature was calculated from air temperature from November to March.~~ The measurement was carried out every five days and lasted from November to April in cold season every year, totally 37 measurements in one cold season. MIT and ASD from 120 of 158 stations were avalible herein with 55, 28 and 37 stations in the SD, SU, and NJ respectively.

2.3 Data analysis

2.3.1 ~~Kriging~~

~~Kriging has been widely used to spatially interpolate in situ measurements of ice phenology to understand its spatial distribution (Choiński et al., 2015;Jenson et al., 2007). Kriging assumes a correlation between regionalized variables and variograms that reflects randomization and structuredness of regionalized variables. It estimates unknown values based on the best linear unbiased estimator with minimal variance, expressed as:~~

$$\hat{Z}(s_o)=\sum_{i=1}^{N}\lambda_i Z(s_i)$$

~~where $\hat{Z}(s_o)$ is the estimate by kriging at an unknown point s_o; $Z(s_i)$ is the variable at a measured point s_i; N is the number of measured points. λ_i is a weight for $Z(s_i)$, and relies on the spatial arrangement of the measured values and the distance between the prediction location and the measured location (C.R. Paramasivam, 2019). The average values of five ice phenology indicators during the six years were interpolated to create isophenes, i.e., contour lines connecting locations with the same ice phenology.~~

~~2.3.2~~ Rotated empirical orthogonal function (REOF)

Empirical orthogonal function (EOF) decomposition is commonly used in ~~climate~~the climatic and hydrological ~~analyses~~analysis (Bian et al., 2019; Yang et al., 2017)~~. Its~~, whose basic principle is to decompose the field containing p spatial points (variable) to decompose over time. If the sample size is n, then the data value x_{ij} including specific spatial point i and specific time j in the field can be regarded as the linear combination of spatial ~~modes~~function S_{ik} and ~~temporal modes according to~~time function t_{kj} (k = 1,2,..., p), and the equation~~:~~ is listed as below.

带格式的: 缩进: 首行缩进: 2 字符
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
带格式的: 行距: 单倍行距
设置了格式: 字体: 宋体
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置

$$\cancel{S_{b^2}^2 = \frac{1}{mM}\sum_{j=1}^{M}\sum_{p=1}^{m}(b_{jp}^2 - \overline{b^2})^2}$$

~~where~~ $x_{ij} = s_{ik} \times t_{kj}$

Rotated empirical orthogonal function~~b_{jp} is the *j th* loading coefficient of the *p th* EOF mode.~~

~~The major advantages of the EOF method is to separate the uncorrelated components that confuse the spatial information and make it hard to interpret a physical phenomenon. In order to solve these problems, a rotated EOF~~ (REOF) rotates the original EOF matrix ~~into~~to a new matrix ~~in which~~that the squared elements of ~~the~~ eigenvectors are maximum, which ~~can better~~could reflect ~~changes across~~ the change of different geographic regions and correlation distribution.

$$S_{b^2}^2 = \frac{1}{mM}\sum_{j=1}^{M}\sum_{p=1}^{m}(b_{jp}^2 - \overline{b^2})^2$$

b_{jp} is the *j th* loading coefficient of the *p th* EOF mode.~~identify correlations. This~~ The paper presented the first four load vectors of ~~the~~ CFD decomposed by REOF and their corresponding principal components ~~(PC)~~ to identify the typical geographic zones in Northeast China.

2.3.~~3 Bayesian linear regression~~2 Kriging

As a spatial interpolation, Kriging has been widely used to produce the spatial distribution of ice phenology based on in-situ measurement (Choiński et al., 2015; Jenson et al., 2007). Kriging estimate the unknown values based on best linear unbiased estimator with minimal variance, is expressed as:

$$\hat{Z}(s_o) = \sum_{i=1}^{N}\lambda_i Z(s_i)$$

~~Ice thickness had been modelled by air temperature and snow depth using Bayesian linear regression (BLR), which has been widely used in hydrological and environmental analyses (Zhao et al., 2013;Gao et al., 2014). BLR treats regression coefficients and the disturbance variance as random variables, rather than fixed but unknown quantities. This assumption leads to a more flexible model and intuitive inferences (Barber, 2008). The BLR model was implemented through two models: a prior probability model considered the probability distribution of the regression coefficients and the disturbance; a posterior model predicted the response using the prior probability mentioned below. The performance of the regression model was evaluated using the determination coefficient R^2 and the root mean square error (RMSE). In this paper, the Y data were the five-day ice thickness values, and the X data included snow depth over ice and air temperature on the river bank. The calculation of the regression used the in-situ measurements from November to March and excluded the ice records of April due to unsteady ice conditions. Two types of air temperature were considered: BAT and negative cumulative air temperature (ATC). Additionally, the Pearson correlation was calculated to analyse the relationship among the five ice phenology events and ice-related parameters, including MIT, ASD, and BAT(Gao and Stefan, 1999;Williams et al., 2004).~~

域代码已更改
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
域代码已更改
设置了格式: 字体颜色: 自动设置
带格式的: 左
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置
设置了格式: 字体颜色: 自动设置

~~**3 Results and discussion**~~

~~3.1 Spatial variations of river~~where $\hat{Z}(s_o)$ is the estimate by Kriging at an unknown point s_o, $Z(s_i)$ is the variable at a measured point s_i, N is the amount of measured point. λ_i is a weight for $Z(s_i)$, and relies on the arrangement of measured values and the distance between the prediction location and measured location(C.R. Paramasivam, 2019). Average values of fiver ice phenology during the six years were used to interpolate and to create the isophenes that were contour lines connecting locations with the same ice phenology.

2.3.3 Partial least squares regression

Partial least squares regression predicts the response of Y to X data. The method decomposes the X and Y data into scores and loadings and makes the correlation between different scores maximum. In this paper, Y data is maximum ice thickness, and X data includes snow depth on ice and air temperature on bank. Besides, Pearson correlation was conducted to analyze the relationship among five ice phenology and ice-related parameters, including MIT, ASD, and BAT (Gao and Stefan, 1999; Williams et al., 2004).

3 Result and Discussion

Five ice phenology

~~3.1.1 Freeze-up~~ and ice thickness described the ice condition during the freeze-up process and break-up process, and the relation between ice phenology, ice thickness, and snow depth and air temperature on bank were analyzed herein.

3.1 Spatial distribution of ice process

3.1.1 The spatial distribution of ice phenology

Figure 2 illustrates the ~~average~~ spatial distribution of FUS and FUE interpolated by ~~kriging~~Kriging and the ~~isophenes~~isosphere in the Songhua River ~~Basin~~basin of Northeast China from 2010 to 2015. Figure 3 illustrates the spatial distribution of the BUS and BUE. The corresponding statistics are listed in Table 1. FUS ranged from October 28th to November 21st with ~~a~~the mean value of November 7th, and FUE ranged from November 7th to December 8th with ~~a~~the mean value of November 22nd. BUS ranged from March 24th to April 20th with ~~a~~the mean value of April 9th, and BUE ranged from March 31th to April 27th with ~~a~~the mean value of April 15th. These four parameters showed ~~a~~ latitudinal ~~gradient~~distribution: FUS and FUE decreased while BUS and BUE increased as the latitude increased~~,~~ except in NJ. The middle part ~~of~~on NJ had the highest FUS and FUE and decreased to the southern and northern part~~. As the latitude decreased, the air temperature tended to increase, leading to later freeze-up and earlier break-up with shorter ice-covered duration; vice versa.~~ ~~[~~, which could be observed from the DOY of isophane. BUS and BUE of the middle NJ didn't show a similar pattern in Figure ~~2~~3.

[Figure 2 and 3 is added here]

域代码已更改

域代码已更改

域代码已更改

域代码已更改

域代码已更改

域代码已更改

带格式的: 正文

带格式的: 正文, 无

~~[Figure 3 is added here]~~

[Table 1 is added here]

带格式的: 正文, 无

~~**3.1.2 Complete frozen duration**~~

Figure 4(a) illustrates the ~~average~~ spatial distribution of CFD interpolated by ~~kriging~~Kriging and the ~~isophenes~~isosphere in the Songhua River ~~Basin~~basin from 2010 to 2015. CFD ranged from 110.74 to 163.00 days with ~~a~~the mean value of 137.86 days, ~~increasing with~~which increased from south to north as the latitude increased. Interestingly, the ~~isophenes~~isophere of CFD had ~~different directionality,~~a changing direction increasing from the southeast to northwest, which could also be found in the other four ice ~~phenologists~~phenology. Both FUS and FUE negatively correlated ~~negatively~~ with latitude, with coefficients of -0.66 and -0.53, ~~respectively~~namely (n=158, $p < 0.001$). All of BUS, BUE and CFD ~~were all positively correlated~~have positive coefficients with latitude with ~~coefficients~~values of 0.48, 0.57 and 0.55~~,~~ respectively (n=158, $p < 0.001$). High values indicated ~~a~~appearance delay ~~in the~~for ice phenology~~ event.~~ The general spatial trend ~~was a tendency to~~ could be seen that the FUS and FUE tended to advance as the latitude increased ~~for the FUS and FUE, a tendency for delay for BUS and BUE, and a lengthening tendency for~~, BUS and BUE tended to delay, and CFD~~. A~~ tended to prolong. The decreasing solar radiation ~~with latitude~~ could explain this trend due to increasing latitude, which ~~is~~ directly connected with the ice thaw and melting ~~processes.~~process.

[Figure 4 is added here]

带格式的: 正文, 无

To find the spatial distribution of ice durations, ~~average values of CFD between 2010 and 2015 were~~CFD is decomposed by REOF from 2010 to 2015, and the spatial distribution of ~~the~~ first ~~four~~to fourth PC mode are shown in Figures ~~4~~3 (c~~)-(~~) to 3 (f) interpolated by ~~kriging~~Kriging. The first to fourth principal component (PC) modes ~~accounted~~account for 45.89%, 13.22%, 12.62%, and 12.00%, respectively, with the ~~cumulative~~accumulative variance of 83.73%. The PC mode data ranged from -0.22 to 0.15, and the ~~areas~~area with high values presented a planar distribution, which were further regarded as five typical geographic zones considering the topography of Northeast China. Zone 1~~,~~ was located in the Three River Plain, where Heilongjiang, Wusuli, and Songhua River converge together, ~~was~~ identified from the first PC mode. Zone 2~~,~~ was located around Heaven Lake of Changbai ~~Mountain,~~mountain, which was located in the southernmost part ~~and which has~~with the highest elevation of 2565 ~~m, was~~meters, identified from the second PC mode. We excluded a planar distribution above Zone 2 from these zones because of the gentle terrain in the Songhua River ~~Basin~~basin. The middle part of the Songhua River Basin accounts for a large area where no typical zones were found. The REOF was good at enhancing the high-value areas, and the PC mode data of this area around 0 were ignored. Zone 3~~,~~ was located on the eastern edge of the three basins with relatively high elevation along the ridge of Changbai ~~Mountain, was~~mountain, identified from the third PC mode. Based on the fourth PC mode, Zone 4 was determined in the northernmost part along the ridge of Xiao Higgan Mountain, where ~~it meets~~meet with Da Higgan Mountain. Zone 5 almost covered the southern part of the NJ basin along the ridge of Da Higgan Mountain and appeared in the second, third, and fourth PC. The final distribution was identified from the convergence area of these three modes.

~~[Figure 4 is added here]~~

带格式的: 正文, 无

3.1.2 ~~Variations~~The spatial distribution of ice thickness

~~**3.2.1 Spatial pattern of ice thickness**~~

Figure 5 illustrates the spatial distribution of ~~the~~ yearly maximum ice thickness (MIT) of the river ~~centre~~center and the corresponding day of year (DOY~~.~~). Table ~~2~~1 summarized the statistical result of MIT and the DOY. MIT ranged from 12 cm to 146 cm, with an average value of 78 cm. The MIT between 76 and 100 cm accounted for the largest percentage of 43.33%, followed by 31.67% of MIT between 50 and 75 cm. Five stations had the MIT ~~greater~~over than ~~125 cm~~125cm. Two stations were located in Zone 3, and three stations in Zone 4~~. The~~, respectively. DOY of MIT had an average value of February 21st, and MIT mainly occurred 59 and 40 times in February and March, respectively. Four of the five highest MITs ~~greater than~~over 125 cm happened in March, which is consistent with ~~the~~ inter-annual changes in ice development ~~shown~~ in Figure 6. The results suggested ~~that~~ the river ice is always thickest and most steady in February or March, which is the best suitable time for human activities such as ice fishing and entertainment. ~~The ice thickness didn't show the same latitudinal distribution as ice phenology, which suggested that more climate factor should be taken in to consideration, such as snow depth and wind.~~

[Figure 5 is added here]

~~[Table 2 is added here]~~

~~**3.2.2 Seasonal changes of ice thickness**~~

Figure 6 displays the ~~seasonal~~interannual changes of ice development using maximum ice thickness, average snow depth on ice, and ~~BAT every five days from 2010 to 2015.~~air temperature on bank. Among ~~the~~ three basins, NJ had the highest snow depth of -29.15 ± 9.99°C, followed by -25.61 ± 9.02 °C in the SD, ~~and~~then -22.17 ± 7.33 cm in the SU. SD had the highest snow depth of 9.18 cm ± 3.39 cm on average level, followed by 8.35 cm ± 4.60 cm in SU, ~~and~~then 8.23cm ± 3.92 cm in NJ. The changes in ~~IT~~MIT and ASD had similar overall trend, while ~~BAT~~air temperature on bank followed the opposite trend. Both ~~IT~~MIT and ASD ~~increased from~~went up since November and reached the peak in ~~March~~Marth, then dropped at the ~~beginning~~begging of April. The ASD showed an obvious trend and reached the bottom in the middle of January, which is earlier than the peaks of MIT and ASD. The NJ and the SD ~~basins~~ underwent greater fluctuations than the SU ~~basin~~, because river ice may freeze and thaw alternatively ~~at~~under, relatively low ~~temperatures~~temperature. The changes of ice characteristics differed greatly due to time and location~~; an~~ (Hawley et al., 2018); analysis ~~of the~~on annual changes ~~was~~had not been conducted because the time series were not long enough.

[Figure 6 is added here]

3.~~3~~2 The relationship between ice ~~regime~~development and ~~climate~~the impact factors

~~**3.3.1 Correlation analysis**~~

3.2.1 The influence of ice thickness on ice phenology

Figure 7 ~~displays~~display the correlation matrix between lake ice phenology ~~events~~ and three parameters~~,~~ covering ~~yearly average values of~~ ASD, BAT, and MIT with a dataset size of 120 ~~stations~~. Colour intensity

带格式的: 正文, 3 级, 行距: 单倍行距

带格式的: 正文, 无

设置了格式: 突出显示

设置了格式: 突出显示

设置了格式: 突出显示

设置了格式: 突出显示

设置了格式: 突出显示

设置了格式: 突出显示

设置了格式: 突出显示

设置了格式: 突出显示

设置了格式: 突出显示

带格式的: 正文, 无

带格式的: 行距: 单倍行距

and ~~sizes~~the size of the ~~ellipses~~ellipse are proportional to the correlation coefficients. MIT had a higher correlation with four of the five indices than that of ASD and BAT~~,~~ except ~~with~~ FUS, ~~with~~among which ~~both~~ MIT and BUE had the highest correlation of 0.63 (p<0.01, n=120). During the freeze-up process, two freeze-up dates had a negative correlation with MIT and ASD; during the break-up dates, two break-up dates had a positive correlation with MIT and ASD. CFD had a positive correlation with MIT and ASD. The situation of BAT ~~was~~is contrary to that of MIT and ASD. ~~Regarding to the annual changes, no significant correlation was found between snow depth and five ice phenology events in Figure 7.~~

~~[Figure 7 is added here]~~

Figure 8 shows the bivariate scatter plots between yearly maximum ice thickness (MIT) and five ice phenology ~~indicators with regression equations. The~~. From Figure 7, the break-up process had a negative correlation with MIT, while the freeze-up had a positive correlation. Besides, the break-up process had a higher correlation with MIT, and BUS had the highest correlation coefficients with MIT of 0.65 (p<0.01). CFD also had a positive correlation with MIT ~~of~~ with r =0.55 (P<0.01~~), which~~). It means that ~~a~~ thicker ice cover in winter ~~leads~~lead to ~~a delay in~~ melting time tend to delay in spring. ~~The break-up not only depends on the spring climate conditions, but is also influenced by ice thickness during last winter. A thicker~~Thick ice cover ~~stores more~~stored high heat in winter, ~~taking~~which takes a longer time to melt in spring. ~~The limited performance of the regression model could be attributed to the difficulties in determining river ice phenology. Although a uniform observation protocol was required, the repaid transition between frozen river and open water for two or three days with floating ice and the inhomogeneities among different stations could not be ignored.~~

[Figure 7 is added here]

[Figure 8 is added here]

带格式的: 正文, 无

~~To further explore the role~~

3.2.2 The influence of snow and air temperature on ice thickness

Snow cover~~,~~ and air temperature are considered the two most domain climate factors influencing the ~~monthly~~ ice process of freshwaters (Ménard et al., 2002b). Regarding to the annual changes, no significant correlation ~~coefficients~~had been found between ~~IT~~ snow depth and five ice phenology in Figure 7. The interannual changes of correlation coefficients between MIT and ASD, ~~and IT and~~ BAT were ~~calculated and listed~~shown in Table 3~~. The~~ with a dataset size of 37. We calculated the means of MIT, ASD, and BAT from 120 stations on a specific day, 37 days during one cold season. The correlation coefficients between ~~IT~~MIT and ASD increased from November to March and reached a peak of 0.75 in March when the ice ~~was~~is thickest~~.~~ around the year. This indicated an ~~increasingly important~~increasing import role of snow depth on ice thickness as the ice accumulated. The higher correlation coefficients between ~~IT~~MIT and BAT in November and December revealed that the BAT played a more important role in the freeze-up process. ~~Moreover,~~ Besides, we found the relationship between these three parameters relied on whether the status of river ice is steady or not. We excluded the data of April in Table 2 because the river melts and refreeze alternatively during April, and the status of river ice was not steady and accurate enough.

Moreover, the regression equation between MIT, ASD, and BAT had been built up to quantificationally analyze their relationship. Figure 9(a) shows the scatter plot between MIT and ASD, and a linear regression function was ~~steady or not also could not be neglected when studying the role of snow cover.~~ found between MIT and ASD with a mean root square of 0.94. This showed that snow played a crucial role in the river ice decay and formation, which is consistent with previous works (Duguay et al., 2003; Ménard et al., 2002a). The positive correlation coefficient between snow depth and ice thickness ~~(~~both in Table ~~3)~~2 and revealed two opposite effects of snow depth during ice development: during the ice-growth process, the snow depth protects the ice from cold air and ~~slows~~slow down the growth rate of ice thickness~~; during the ice-decay process, the lake~~ (Adams and Roulet, 1980); during ice-decay process, the bottom of lake ice ~~stops~~stopped to grow, and the snow ~~mixes~~mixed with surface ice into ~~slush~~slushing and ~~promotes~~promoted the melting process.

~~[Table 3~~

[Figure 9 is added here]

Figure 9~~3.3.2 Regression modelling~~

~~Figure 9 illustrates the scatter plot between measured and predicted ice thickness using Bayesian linear regression in three sub-basins in Northeast China. R^2 ranged from 0.81 to 0.95, and RMSE ranged from 0.08 to 0.17. The model worked best in the SU basin, followed by the NJ and the SD basins. Figure 9 indicates that snow depth outweighed air temperature in terms of effect on ice thickness, which is consistent with previous studies. Moreover, replacing BAT with ATC enhanced the model performance in all three basins, revealing a more important role of ATC than BAT.~~

~~[Figure 9 is added here]~~

~~The correlation between air temperature and ice regime was not as significant as in previous studies for several reasons. Average air temperatures were most commonly calculated over fixed time periods at regional scales, for example as moving averages for certain time periods. The seasonal changes of air temperature were ignored, as well as their effects within one cold season. The negative ATC behaved better than BAT when building the Bayesian regression equation, which suggested that heat exchanges between river surface and atmosphere dominated the ice process. Heat loss is mainly made up of sensible and latent heat exchange, which is proportional to negative ATC during the cooling process. During the complete frozen duration, snow depth along with wind speed began to influence the heat exchange and ice thickening. Air temperature exerted a lesser effect on spring break-up, which is more dependent on the ice thickness and snow depth. In summary, snow depth dominated the ice process when the river was completely frozen, while cumulative air temperature dominated during the transition process.~~

(b) shows the scatter plot between MIT and BAT, and an exponential function was built between MIT and BAT with a mean root square of 0.31. A monotonic function with a decreasing trend could not explain the relationship between MIT and BAT due to low R^2. Regarding interannual changes in Figure7, there existed a time lag between the peaks of MIT and BAT. The correlation coefficients of BAT exhibited a decreasing trend from November to March, which indicated a stronger role of BAT in the freeze-up process. Higher

带格式的: 正文, 无

设置了格式: 字体: 加粗

设置了格式: 字体颜色: 自动设置

correlation coefficients of average SD, the existence of ice was more dependent on snow depth especially when the ice is thick and steady enough. The surface snow and ice melted and refroze alternatively throughout the whole ice development, particularly for the snow seen in Figure 6. Comparing the results in Table 3 and Figure 6, the air temperature had a higher correlation with ice phenology than ice thickness. The SD has a higher correlation with FUE, BUS, and CFD in Figure 6, which described the completely frozen status of a lake with thickest ice cover. Therefore, lake ice phenology closely correlated with air temperature while ice thickness correlated with snow depth.

4 ~~Conclusions~~Conclusion

Five river ice phenology ~~indicators~~, including FUE, FUS, BUE, BUS, and CFD, had been investigated in the Songhua River Basin of Northeast China ~~have been investigated~~ using in-situ ~~measurements for~~measurement by the ~~period 2010 to 2015 using kriging~~method of Kriging and REOF ~~methods~~. The FUS and FUE decreased as while the BUS, BUE, and CFD increased ~~with~~as the latitude~~. The five~~ increased. Five river ice phenology ~~indicators followed~~showed the latitudinal ~~gradient~~distribution and a changing direction from southeast to northwest. The highest MIT over ~~125 cm~~125cm were distributed along the ridge of Da Hagan Lin and Changbai ~~Mountain~~Mount, and MIT occurred most often in February and March, which indicated ~~that this is the safest period for~~ human activities such as navigation and winter recreation are safest. Five typical geographic zones were identified from the first four PC modes of CFD, covering Changbai ~~Mountain~~Mount, Three River Plain, Da Higgan Mountain, and Xiao Higgan Mountain, ~~providing~~which provide a deeper understanding of ~~river~~rive ice distribution and ~~its~~the relationship with geographic locations and topography in Northeast China.

The interannual changes of MIT, ASD, and BAT are analyzed based on their time series. Within one cold season, ~~ice thickness~~MIT and ~~snow depth~~ASD showed similar ~~seasonal~~interannual changes~~, i.e. first that~~ firstly increased and then decreased, while ~~air temperature~~ BAT showed an opposite trend~~. The~~, the peaks of ~~snow depth~~ASD and ~~ice thickness fell~~MIT fall behind ~~air temperature~~BAT for almost one month. High correlation coefficients between ~~yearly maximum ice thickness~~MIT and five ice phenology ~~indicators~~ revealed ~~that~~ ice phenology ~~is closely~~closed related to ice thickness~~, especially in the break-up process. The yearly analysis failed to explain the relationship between ice regime and snow depth~~. MIT and ~~air temperature. Based on monthly~~ASD had as high correlation ~~analysis, snow cover played an increasingly important role as the ice cover become steady. Additionally, air temperature~~ coefficients as 0.95 ($p < 0.05$) when the air temperature under freezing point, which means snow cover influence the ice thickness significantly. The correlation analysis was carried out under two cases, including geographic distribution and interannual changes, and BAT has been found more associated with ice phenology ~~more closely~~ than ice thickness~~.~~

~~Six Bayesian regression models were built between ice thickness and air temperature and snow depth in three sub-basins of Songhua River, considering two types of air temperature: air temperature on bank and negative cumulative air temperature. Results showed~~ and snow depth. We conclude that snow ~~cover correlated with ice thickness significantly and positively during~~ depth is the ~~periods when the freshwater was completely~~

带格式的: 行距: 单倍行距

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

~~frozen, and negative cumulative air temperature influenced the thickness rather than air temperature through the heat loss of ice formation and decay. The negative ATC behaved better than BAT~~ primary factor influencing the ice process when ~~building the Bayesian regression equation, which suggested that heat exchanges between the river surface and the atmosphere dominated the ice process.~~compared with air temperature.

~~This study aimed~~The work presented aims at exploring the regional ~~patterns~~pattern of ~~river~~rive ice development based on the in-situ ~~measurements~~measurement and ~~was~~are limited by the data accessibility. Remote sensing data could provide long-term and wide-range information for ice thickness and ice phenology since 1980, ~~expanding~~which will expand our study ~~scope~~scopes. The work herein will provide a valuable reference for the retrieval of ice development by remote sensing. ~~Knowing the long-term change of river ice and the future projection could provide information for evaluating the influence of climate on social-economics, ecological environment and human activists across the riparian zones.~~The relationship between ice thickness and air temperature can't be simulated by a linear regression model, degree-day model, or radiation transmission model considering the thermal process of ice thawing and melting will be used in future work.

Abbreviations

The following abbreviations are used in this manuscript:

~~AMSR-E Advanced Microwave Scanning Radiometer- Earth Observing System~~
ASD Average Snow depth
~~ATC Cumulative air temperature~~
BAT Air temperature on bank
~~BLR Bayesian linear regression~~
BUS Break-up start
BUE Break-up end
CFD Completely frozen duration
~~DOY Day of year~~
EOF Empirical orthogonal function
FUS Freeze-up start
FUE Freeze-up end
~~IP Ice phenology~~
~~IT Ice thickness~~
NJ Nenjiang River Basin
MIT Maximum ice thickness
PC Principal component
REOF Rotated empirical orthogonal function
~~RMSE Root mean square error~~
SD Downstream Songhua River Basin
~~SRTM Shuttle Radar Topography Mission~~

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

带格式的: 行距: 单倍行距

SU~~-~~ Upstream Songhua River Basin

Author Contribution

带格式的: 行距: 单倍行距

Song K.S. and Yang Q. designed and conducted the idea of this study. Yang Q. Wen Z.D. wrote the paper and ~~analysed~~analyzed the data cooperatively; Hao X.H. provided value suggestion for the structure of study and paper; Li W.B. and Tan Y. exerted efforts on data processing and graphing. This article is a result of collaboration with all listed co-authors.

Competing interest

带格式的: 行距: 单倍行距

The authors reported no potential conflict of interest.

Acknowledgments

带格式的: 行距: 单倍行距

The research was sponsored by the National Natural Science Foundation of China (41801283, 41971325, 41730104). The anonymous reviewers to improve the quality of this manuscript are greatly appreciated.

References

带格式的: 行距: 单倍行距

域代码已更改

~~Barber, J. J.: Bayesian Core: A Practical Approach to Computational Bayesian Statistics, Journal of the American Statistical Association, 103, 432-433, 2008.~~

~~Beltaos, S., and Prowse, T.: River-ice hydrology in a shrinking cryosphere, 23, 122-144, https://doi.org/10.1002/hyp.7165, 2009.~~

Adams, W. and Roulet, N.: Illustration of the roles of snow in the evolution of the winter cover of a lake, Arctic, 33, 1980.

Bian, Y., Yue, J., Gao, W., Li, Z., Lu, D., Xiang, Y., and Chen, J.: Analysis of the Spatiotemporal Changes of Ice Sheet Mass and Driving Factors in Greenland, Remote Sensing, 11, ~~https://doi.org/10.3390/rs11070862, 2019.~~2019.

带格式的: 正文

Brown, L. C. and Duguay, C. R.: The response and role of ice cover in lake-climate interactions, Progress in Physical Geography, 34, 671-704, 2010.

C.R. Paramasivam, S. V.: An Introduction to Various Spatial Analysis Techniques~~, in~~. In: GIS and Geostatistical Techniques for Groundwater Science, ~~edited by:~~ Senapathi Venkatramanan, M. V. P., Sang Yong Chung~~,~~ (Ed.), Elsevier, ~~23-30, 2019.~~

~~Cai, Y., Ke, C. Q., Yao, G., and Shen, X.: MODIS-observed variations of lake ice phenology in Xinjiang, China, Climatic Change, https://doi.org/10.1007/s10584-019-02623-2, 2019.~~

~~Chen, H., Zhang, W., Nie, N., and Guo, Y.: Long-term groundwater storage variations estimated in the Songhua River Basin by using GRACE products, land surface models, and in-situ observations, Sci Total Environ, 649, 372-387, https://doi.org/10.1016/j.scitotenv.2018.08.352,~~ 2019.

带格式的: 正文

Choiński, A., Ptak, M., Skowron, R., and Strzelczak, A.: Changes in ice phenology on polish lakes from 1961 to 2010 related to location and morphometry, Limnologica, 53, 42-49, 2015.

Dörnhöfer, K. and Oppelt, N.: Remote sensing for lake research and monitoring – Recent advances, Ecological Indicators, 64, 105-122, 2016.

Duguay, C. R., Bernier, M., Gauthier, Y., and Kouraev, A.: Remote sensing of lake and river ice, ~~273-306 pp.,~~ 2015.

带格式的: 正文

Duguay, C. R., Flato, G. M., Jeffries, M. O., Ménard, P., Morris, K., and Rouse, W. R.: Ice-cover variability on shallow lakes at high latitudes: model simulations and observations, Hydrological Processes, 17, 3465-3483, 2003.

Duguay, C. R., Prowse, T. D., Bonsal, B. R., Brown, R. D., Lacroix, M. P., and Ménard, P.: Recent Trends in Canadian Lake Ice Cover, Hydrological Processes, 20, 781-801, 2010.

Gao, B. S~~.,~~. and Stefan, H. G.: Multiple linear regression for lake ice and lake temperature characterisitcs, Journal of Cold Regions Engineering, 13, 59-77, 1999.

带格式的: 正文

Gao, S~~.,~~. and Stefan, H. G.: Potential Climate Change Effects on Ice Covers of Five Freshwater Lakes, Journal of Hydrologic Engineering, 9, 226-234, ~~https://doi.org/doi:10.1061/(ASCE)1084-0699(2004)9:3(226), 2004.~~2004.

~~Gao, S., Zhu, Z., Liu, S., Jin, R., Yang, G., Tan, L. J. I. J. o. A. E. O., and Geoinformation: Estimating the spatial distribution of soil moisture based on Bayesian maximum entropy method with auxiliary data from remote sensing, 32, 54-66, 2014.~~

Hampton, S. E., Galloway, A. W., Powers, S. M., Ozersky, T., Woo, K. H., Batt, R. D., Labou, S. G., O'Reilly, C. M., Sharma, S., Lottig, N. R., Stanley, E. H., North, R. L., Stockwell, J. D., Adrian, R., Weyhenmeyer, G. A., Arvola, L., Baulch, H. M., Bertani, I., Bowman, L. L., Jr., Carey, C. C., Catalan, J., Colom-Montero, W., Domine, L. M., Felip, M., Granados, I., Gries, C., Grossart, H. P., Haberman, J., Haldna, M., Hayden, B., Higgins, S. N., Jolley, J. C., Kahilainen, K. K., Kaup, E., Kehoe, M. J., MacIntyre, S., Mackay, A. W., Mariash, H. L., McKay, R. M., Nixdorf, B., Noges, P., Noges, T., Palmer, M., Pierson, D. C., Post, D. M., Pruett, M. J., Rautio, M., Read, J. S., Roberts, S. L., Rucker, J., Sadro, S., Silow, E. A., Smith, D. E., Sterner, R. W., Swann, G. E., Timofeyev, M. A., Toro, M., Twiss, M. R., Vogt, R. J., Watson, S. B., Whiteford, E. J., and Xenopoulos, M. A.: Ecology under lake ice, Ecol Lett, 20, 98-111, ~~https://doi.org/10.1111/ele.12699, 2017.~~2017.

带格式的: 正文

~~Ionita, M., Badaluta, C. A., Scholz, P., and Chelcea, S.: Vanishing river ice cover in the lower part of the Danube basin – signs of a changing climate, Sci Rep, 8, 7948, https://doi.org/10.1038/s41598-018-26357-w, 2018.~~

Hawley, N., Beletsky, D., and Wang, J.: Ice thickness measurements in Lake Erie during the winter of 2010–2011, Journal of Great Lakes Research, 44, 388-397, 2018.

Hydrographic bureau of Chinese Ministry of Water Resources, 2010-2015. Annual hydrological report: hydrological data of Heilongjiang River Basin. (in Chinese)

Jenson, B. J., Magnuson, J. J., Card, V. M., Soranno, P. A., and Stewart, K. M.: Spatial Analysis of Ice Phenology Trends across the Laurentian Great Lakes Region during a Recent Warming Period, Limnology Oceanography, 52, 2013-2026, 2007.

带格式的: 正文

~~Kang, K. K., Duguay, C. R., Lemmetyinen, J., and Gel, Y.: Estimation of ice thickness on large northern lakes from AMSR-E brightness temperature measurements, Remote Sensing of Environment, 150, 1-19, https://doi.org/10.1016/j.rse.2014.04.016, 2014.~~

~~Khan, M. I., Liu, D., Fu, Q., and Faiz, M. A.: Detecting the persistence of drying trends under changing climate conditions using four meteorological drought indices,~~

~~Meteorological Applications, 25, 184-194, https://doi.org/10.1002/met.1680, 2018.~~

Kwok, R~~.,~~, and Fahnestock, M. A.: Ice Sheet Motion and Topography from Radar Interferometry, IEEE Transactions on Geoscience Remote Sensing, 34, 189-200, 1996.

带格式的: 正文

Leppäranta, M.: Modelling the Formation and Decay of Lake Ice, 2010.

Lindenschmidt, K.-E., Das, A., and Chu, T.: Air pockets and water lenses in the ice cover of the Slave River, Cold Regions Science and Technology, 136, 72-80, ~~https://doi.org/10.1016/j.coldregions.2017.02.002, 2017.~~2017.

带格式的: 正文

Magnuson, J. J., Robertson, D. M., Benson, B. J., Wynne, R. H., Livingstone, D. M., Arai, T., Assel, R. A., Barry, R. G., Card, V., and Kuusisto, E.: Historical Trends in Lake and River Ice Cover in the Northern Hemisphere, Science, 289, 1743-1746, 2000.

Ménard, P., Duguay, C. R., Flato, G. M., and Rouse, W. R.: Simulation of ice phenology on Great Slave Lake, Northwest Territories, Canada, Hydrological Processes, 16, 3691-3706, 2002a.

Ménard, P., Duguay, C. R., Pivot, F. C., Flato, G. M., and Rouse, W. R.: Sensitivity of Great Slave Lake ice cover to climate variability and climatic change, New Zealand, 2nd–6th December 2002b.

Morris, K., Jeffries, M., and Duguay, C.: Model simulation of the effects of climate variability and change on lake ice in central Alaska, USA, ~~in:~~ Annals of Glaciology, ~~Vol~~ 40~~, 2005, edited by: MacAyeal, D. R., Annals of Glaciology Series~~, 113-118, 2005.

带格式的: 正文

Palecki, M. A~~.,~~, and Barry, R. G.: Freeze-up and Break-up of Lakes as an Index of Temperature Changes during the Transition Seasons: A Case Study for Finland, Journal of Applied Meteorology, 25:7, 893-902, 1986.

~~Park, H., Yoshikawa, Y., Oshima, K., Kim, Y., Ngo-Duc, T., Kimball, J. S., and Yang, D.: Quantification of Warming Climate-Induced Changes in Terrestrial Arctic River Ice Thickness and Phenology, Journal of Climate, 29, 1733-1754, https://doi.org/10.1175/jcli-d-15-0569.1, 2016.~~

~~Pavelsky, T. M., and Smith, L. C.: Spatial and temporal patterns in Arctic river ice breakup observed with MODIS and AVHRR time series, Remote Sensing of Environment, 93, 328-338, https://doi.org/10.1016/j.rse.2004.07.018, 2004.~~

~~Prowse, T. D., and Beltaos, S.: Climatic control of river-ice hydrology: a review, 16, 805-822, https://doi.org/10.1002/hyp.369, 2002.~~

Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., Liu, C., Tan, K., Yu, Y., Zhang, T., and Fang, J.: The impacts of climate change on water resources and agriculture in China, Nature, 467, 43-51, 2010.

Seidou, O., Ouarda, T. B. M. J., Bilodeau, L., Bruneau, B., and St-Hilaire, A.: Modeling ice growth on Canadian lakes using artificial neural networks, Water Resources Research, 42, 2526-2528, 2006.

带格式的: 正文

Sharma, S., Blagrave, K., Magnuson, J. J., O'Reilly, C. M., Oliver, S., Batt, R. D., Magee, M. R., Straile, D., Weyhenmeyer, G. A., Winslow, L., and Woolway, R. I.: Widespread loss of lake ice around the Northern Hemisphere in a warming world, Nature Climate Change, 9, 227-231, ~~https://doi.org/10.1038/s41558-018-0393-5, 2019.~~2019.

~~Shiklomanov, A. I., and Lammers, R. B.: River ice responses to a warming Arctic—recent evidence from Russian rivers, Environmental Research Letters, 9, 035008, https://doi.org/10.1088/1748-9326/9/3/035008, 2014.~~

Shuter, B. J., Finstad, A. G., Helland, I. P., Zweimüller, I., and Hölker, F.: The role of winter phenology in shaping the ecology of freshwater fish and their sensitivities to climate change, Aquatic Sciences, 74, 637-657, 2012.

带格式的: 正文

Šmejkalová, T., Edwards, M. E., and Dash, J.: Arctic lakes show strong decadal trend in earlier spring ice-out, Scientific Reports, 6, 38449, 2016.

Song, C., ~~Huang, B~~Bo, H., Ke, L., ~~and~~ Richards, K. S. J. I. J. o. P., and Sensing, R.: Remote sensing of alpine lake water environment changes on the Tibetan Plateau and surroundings: A review, Isprs Journal of Photogrammetry ~~and~~ Remote Sensing, 92, 26-37, ~~https://doi.org/10.1016/j.isprsjprs.2014.03.001,~~ 2014.

~~Wang, M., Lei, X., Liao, W., and Shang, Y.: Analysis of changes in flood regime using a distributed hydrological model: a case study in the Second Songhua River basin, China, International Journal of Water Resources Development, 34, 386-404, https://doi.org/10.1080/07900627.2018.1440538, 2018.~~

Specification for observation of ice regime in rivers (SL59-2015)，Ministry of water resources of the People's Republic of China，pp.52, 2015.

Stephanie, J. and Stefan Heinz, G.: Indicators of climate warming in minnesota : Lake ice covers and snowmelt runoff, Climatic Change, 75, 421-453, 2006.

Wang, S., Wang, Y., Ran, L., and Su, T.: Climatic and anthropogenic impacts on runoff changes in the Songhua River basin over the last 56years (1955–2010), Northeastern China, Catena, 127, 258-269, ~~https://doi.org/10.1016/j.catena.2015.01.004, 2015.~~2015.

带格式的: 正文

Williams, G., Layman, K. L., and Stefan, H. G.: Dependence of lake ice covers on climatic, geographic and bathymetric variables, Cold Regions Science Technology, 40, 145-164, 2004.

Williams, S. G~~.,~~., and Stefan, H. G.: Modeling of Lake Ice Characteristics in North America using Climate, Geography, and Lake Bathymetry, Journal of Cold Regions Engineering, 20, 140-167, 2006.

Xing, F., Stefan, H. G., Williamson, C. E., Saros, J. E. G., Vincent, W. F., and Smol, J. P.: Simulations of climate effects on water temperature, dissolved oxygen, and ice and snow covers in lakes of the contiguous U.S. under past and future climate scenarios, J Limnology Oceanography, 54, 2359-2370, 2009.

Yang, P., Xia, J., Zhan, C., Qiao, Y., and Wang, Y.: Monitoring the spatio-temporal changes of terrestrial water storage using GRACE data in the Tarim River basin between 2002 and 2015, Science of the Total Environment, 595, 218-228, 2017.

带格式的: 正文

Yang, Q., Song, K., Hao, X., Chen, S., and Zhu, B.: An Assessment of Snow Cover Duration Variability Among Three Basins of Songhua River in Northeast China Using Binary Decision Tree, Chinese Geographical Science, 28, 946-956, ~~https://doi.org/10.1007/s11769-018-1004-0, 2018.~~2018.

~~Yang, Q., Song, K., Wen, Z., Hao, X., and Fang, C.: Recent trends of ice phenology for eight large lakes using MODIS products in Northeast China, International Journal of Remote Sensing, 40, 5388-5410, https://doi.org/10.1080/01431161.2019.1579939, 2019.~~

~~Yang, X., Pavelsky, T. M., and Allen, G. H.: The past and future of global river ice, Nature, 577, 69-73, https://doi.org/10.1038/s41586-019-1848-1, 2020.~~

Zaier, I., Shu, C., Ouarda, T. B. M. J., Seidou, O., and Chebana, F.: Estimation of ice thickness on lakes using artificial neural network ensembles, Journal of Hydrology, 383, 330-340, 2010.

带格式的: 正文

~~Zhang, F., Li, Z., and Lindenschmidt, K. E.: Potential of RADARSAT-2 to Improve Ice Thickness Calculations in Remote, Poorly Accessible Areas: A Case Study on the Slave River, Canada, Canadian Journal of Remote Sensing, 45, 234-245,~~

~~https://doi.org/10.1080/07038992.2019.1567304, 2019.~~
~~Zhao, K., Valle, D., Popescu, S., Zhang, X., and Mallick, B.: Hyperspectral remote sensing of plant biochemistry using Bayesian model averaging with variable and band selection, Remote Sensing of Environment, 132, 102-119, https://doi.org/10.1016/j.rse.2012.12.026, 2013.~~
Zhao, Y., Song, K., Lv, L., Wen, Z., Du, J., and Shang, Y.: Relationship changes between CDOM and DOC in the Songhua River affected by highly polluted tributary, Northeast China, Environmental Science Pollution Research, 25, 25371-25382, 2018.

带格式的：正文

Tables

Table 1 ~~Summary statistics~~Statistics summary of ice phenology interpolated by Kriging from 2010 to 2015. The ice phenology ~~indicators included~~including freeze-up start (FUS), freeze-up end (FUE), break-up start (BUS), break-up end (BUE), the complete frozen duration (CFD). NJ, SD and SU represent the Nenjiang ~~Basin~~basin, the downstream Songhua River ~~Basin~~basin (SD) and the upstream Songhua River ~~Basin~~basin (SU). DOY denotes day of year. Std Dev. denotes standard deviation.

Basins	Statistics	FUS (DOY)	FUE (DOY)	BUS (DOY)	BUE (DOY)	CFD (day)
NJ	Maximum	319.14	334.98	110.54	117.61	163.00
	Mean	307.02	324.58	98.65	106.64	139.39
	Minimum	301.41	311.30	84.53	90.40	119.11
	Std Dev.	3.91	5.69	8.16	6.80	13.22
SD	Maximum	321.08	334.36	110.01	102.84	154.06
	Mean	313.74	326.70	102.55	97.15	140.86
	Minimum	305.64	316.80	93.22	92.37	125.32
	Std Dev.	2.83	3.13	3.92	2.12	5.69
SU	Maximum	325.92	342.09	98.25	114.37	133.62
	Mean	320.39	334.35	91.93	106.43	122.61
	Minimum	313.79	327.68	83.46	95.69	110.74
	Std Dev.	2.34	3.09	3.21	4.24	4.85
Total	Maximum	325.92	342.09	110.54	117.61	163.00
	Mean	311.16	326.58	99.25	105.38	137.86
	Minimum	301.41	311.30	83.46	90.40	110.74
	Std Dev.	5.74	5.54	7.17	6.34	11.68

Table 2 The Frequency of yearly maximum ice thickness from November to April. The row represents different year in cold season and the column represents yearly maximum ice thickness with the unit of cm.

Month \ MIT	<50	50-75	76-100	101-125	125-150
December	4	1	0	1	0
January	4	4	1	0	0
February	4	25	26	3	1
March	1	3	24	8	4
April	0	2	1	0	0
After April	0	3	0	0	0
Total	13	38	52	12	5

Table 3 Correlation coefficient between maximum ice thickness (MIT~~) and~~), average snow depth (ASD~~),~~) and air temperature on bank (BAT) with ~~a~~ dataset size of 120~~ stations~~. The asterisk indicates the significant level of correlation coefficients, ** means significant at 99% level (p<0.01), and * means significant at 95% level (p<0.05).

~~Correlation Coefficients~~CC	November	December	January	February	March
MIT vs. ASD	0.17	0.66*	0.53*	0.59*	0.75**
MIT vs. BAT	-0.90**	-0.80**	-0.55*	-0.30	-0.45

Figures

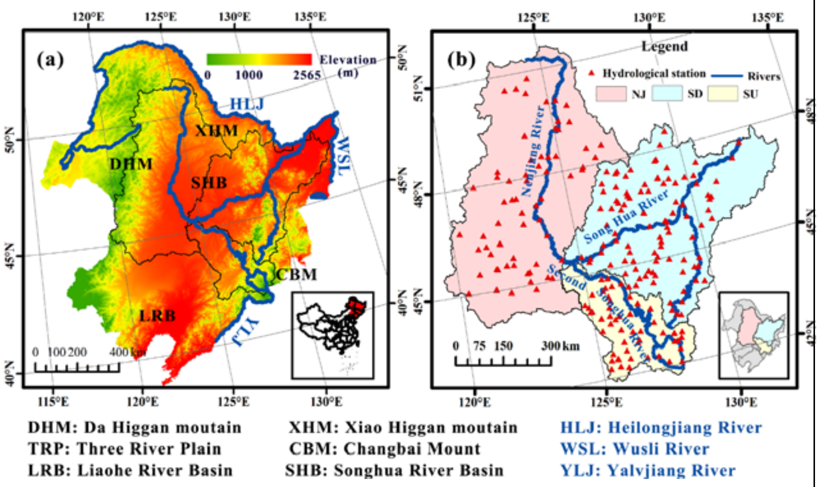


Figure 1 The geographic location of ~~the~~ Songhua River Basin showing ~~(a) the elevation and (b) the location of~~ 158 hydrological stations. The ~~Songhua River Basin~~basin includes three ~~sub~~ basins: Nenjiang River Basin (NJ), downstream Songhua River Basin (SD) and upstream Songhua River Basin (SU). ~~Elevation data are from the~~The elevation is provided by Shuttle Radar Topography Mission (SRTM) with spatial resolution of 90 meters.

带格式的: 行距: 单倍行距

带格式的: 1 级, 段落间距段前: 12 磅, 段后: 8 磅, 行距: 单倍行

带格式的: 1 级, 段落间距段前: 12 磅, 段后: 8 磅, 行距: 单倍行

带格式的: 行距: 单倍行距

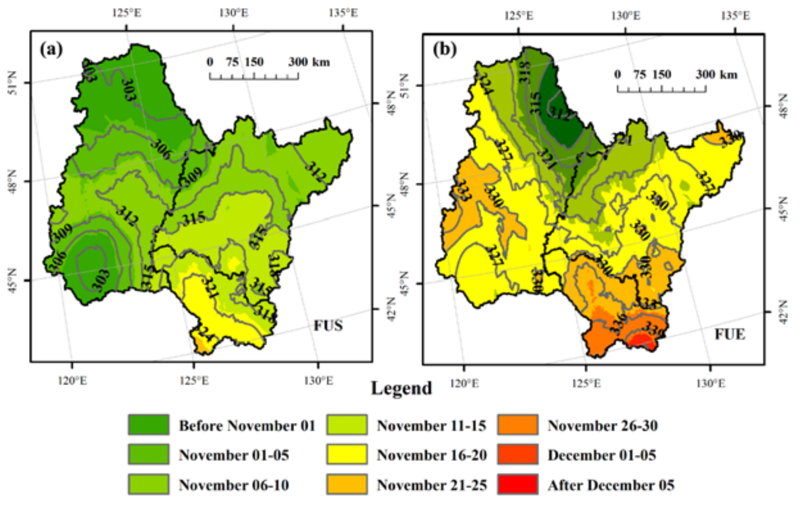


Figure 2 The ~~average ~~spatial distribution of freeze-up start (FUS) (a) and freeze-up end (FUE) (b) in the Songhua River ~~Basin~~basin of Northeast China from 2010 to 2015. The number ~~labels indicate~~labelled indicates the day of year (DOY) of ~~the isophenes~~isophene.

设置了格式: 字体颜色: 红色

设置了格式: 字体颜色: 红色

带格式的: 无, 行距: 单倍行距

带格式的: 行距: 单倍行距

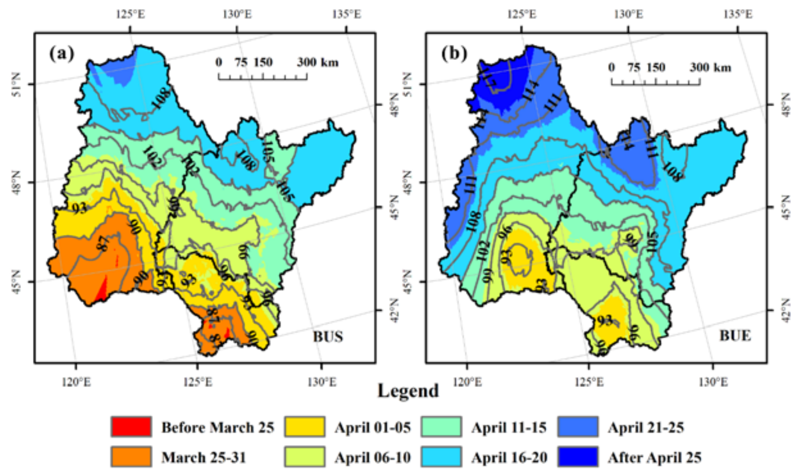


Figure 3 The ~~average ~~spatial distribution of break-up start (BUS) (a) and break-up end (BUE) (b) in the Songhua River ~~Basin~~basin of Northeast China from 2010 to 2015. The number ~~labels indicate~~labelled indicates the day of year (DOY) of ~~the isophenes~~isophene.

设置了格式: 字体颜色: 红色

设置了格式: 字体颜色: 红色

带格式的: 无, 行距: 单倍行距

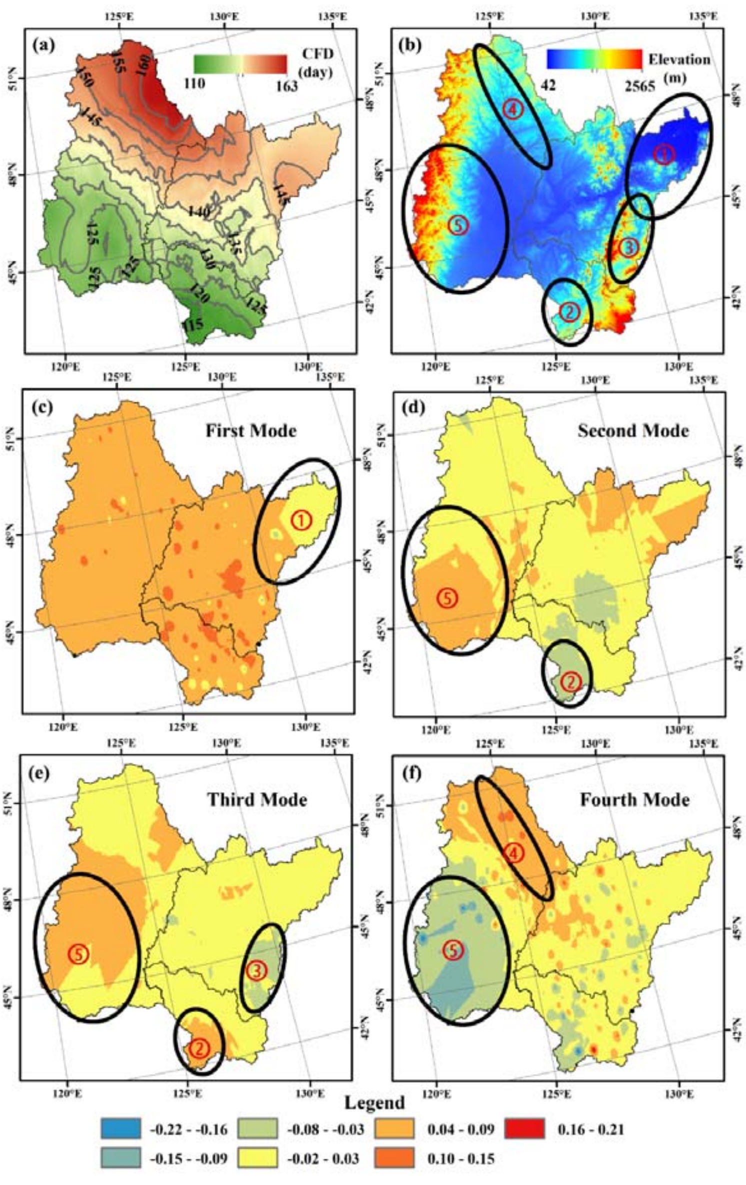


Figure 4 The spatial distribution of complete frozen duration (CFD) (a), five typical geographical zones (b), and ~~first~~fist four principal components (c-f) of decomposed by rotated empirical orthogonal function (REOF) in the Songhua River ~~Basin~~basin of Northeast China.

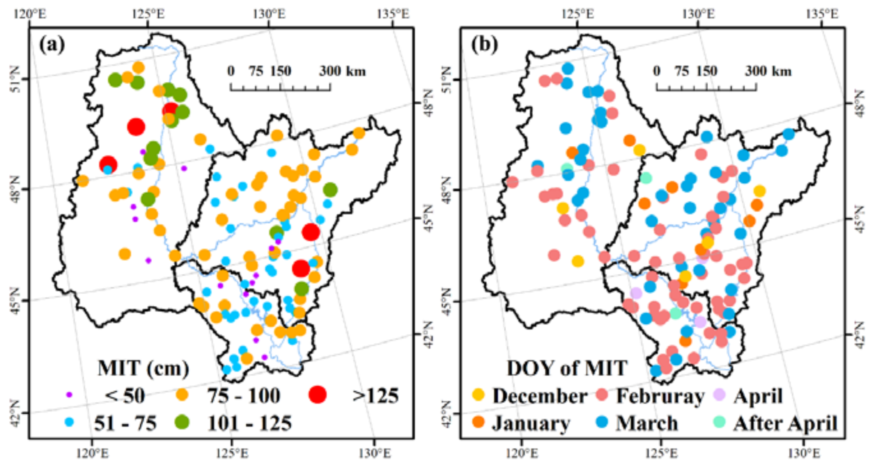
带格式的: 行距: 单倍行距

带格式的: 无, 行距: 单倍行距

设置了格式: op_dict_text2, 字体: Times New Roman

设置了格式: op_dict_text2, 字体: +西文正文 (Times New Roman)

设置了格式: 字体: +西文正文 (Times New Roman)



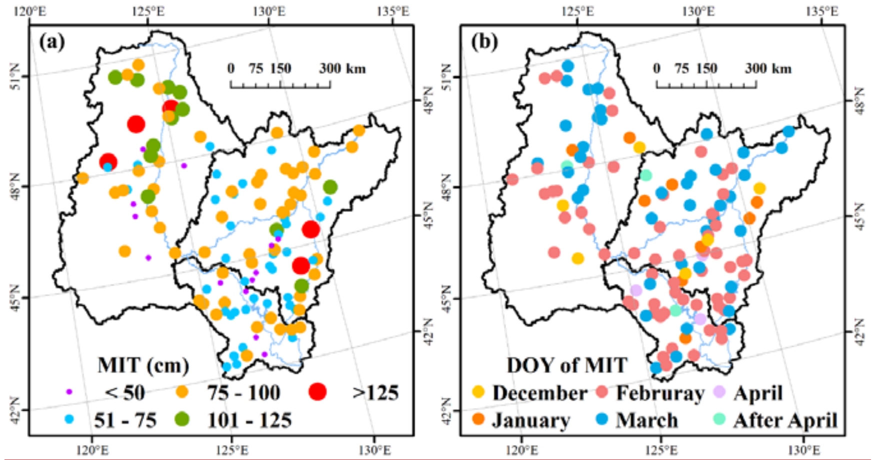
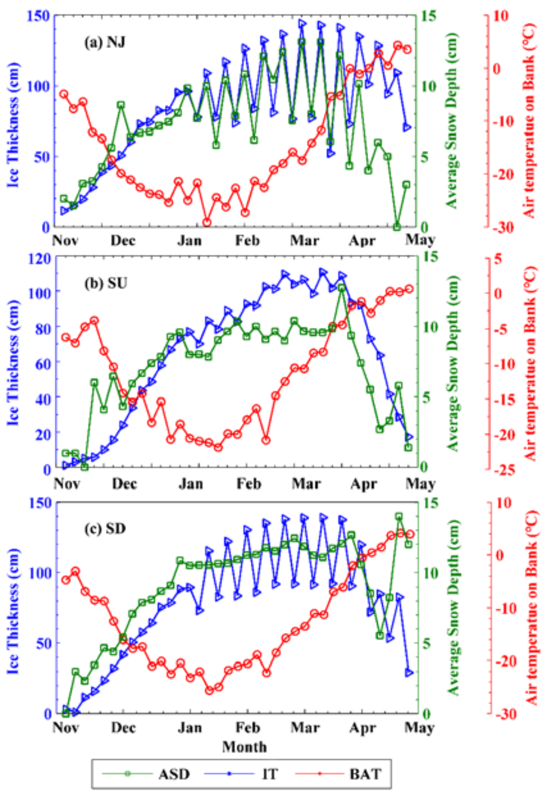


Figure 5 The spatial distribution of yearly maximum ice thickness (MIT) (a) of ~~the~~ river centre and the corresponding date (b).

带格式的: 正文, 无, 段落间距段后: 0.5 行


(a) NJ
(b) SU
(c) SD
Ice Thickness (cm)
Average Snow Depth (cm)
Air temperatue on Bank (°C)
Nov
Dec
Jan
Feb
Mar
Apr
May
Month
ASD
IT
BAT

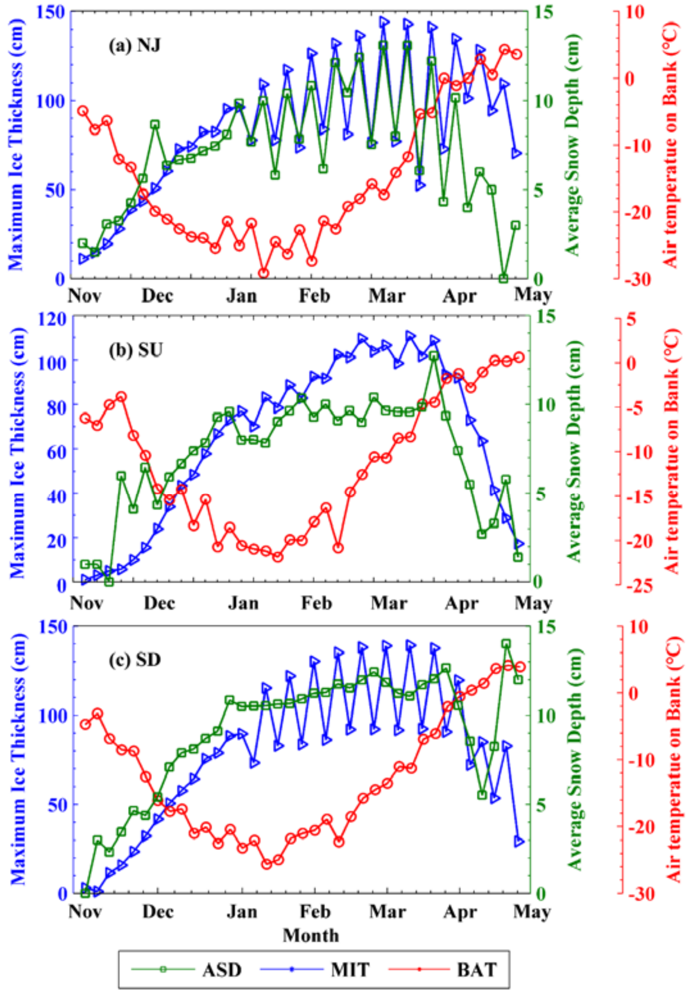


Figure 6 ~~Average seasonal changes in~~The time series of yearly maximum ice thickness (~~IT~~MIT), average snow depth (ASD) and air temperature on bank (BAT) from November to April ~~for the period~~during 2010~~–~~-2015.

带格式的: 无, 行距: 单倍行距

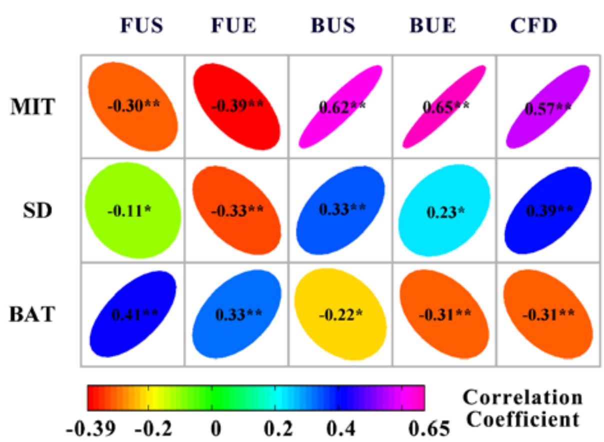


Figure 7 Correlation matrix between maximum ice thickness (MIT), average snow depth (ASD) and air temperature on bank (BAT) and lake ice phenology ~~events~~ with ~~data from~~ dataset size of 120 ~~stations~~. The asterisk indicates the ~~significance~~significant level of ~~the~~ correlation coefficients, ** means significant at 99% level ($p<0.01$), and * means significant at 95% level ($p<0.05$).

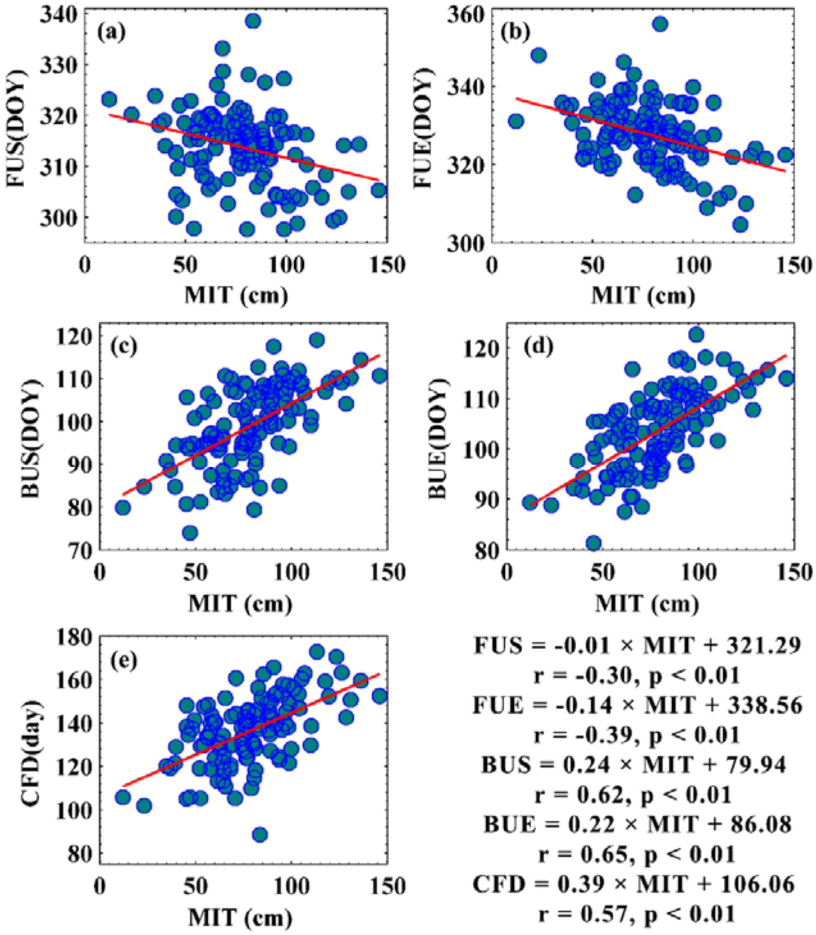
带格式的: 段落间距段后: 0.5 行, 行距: 单倍行距

带格式的: 行距: 单倍行距

带格式的: 无, 行距: 单倍行距

设置了格式: 上标

设置了格式: 上标



(a)
FUS(DOY)
MIT (cm)
(b)
FUE(DOY)
MIT (cm)
(c)
BUS(DOY)
MIT (cm)
(d)
BUE(DOY)
MIT (cm)
(e)
CFD(day)
MIT (cm)
FUS = -0.01 × MIT + 321.29
r = -0.30, p < 0.01
FUE = -0.14 × MIT + 338.56
r = -0.39, p < 0.01
BUS = 0.24 × MIT + 79.94
r = 0.62, p < 0.01
BUE = 0.22 × MIT + 86.08
r = 0.65, p < 0.01
CFD = 0.39 × MIT + 106.06
r = 0.57, p < 0.01

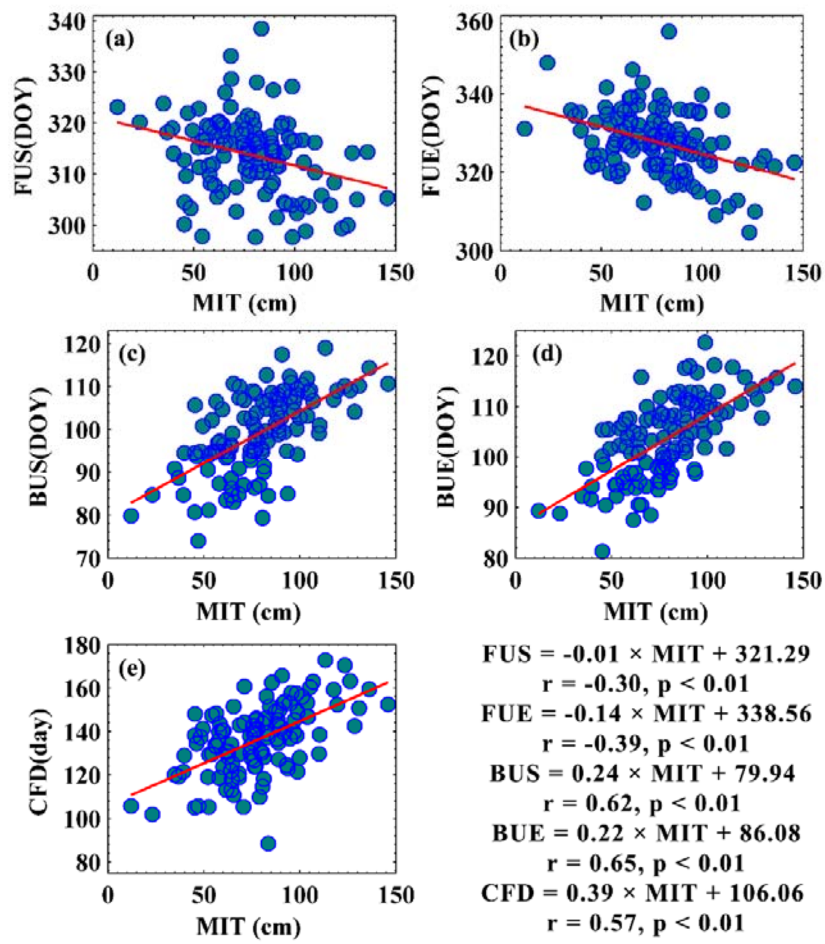
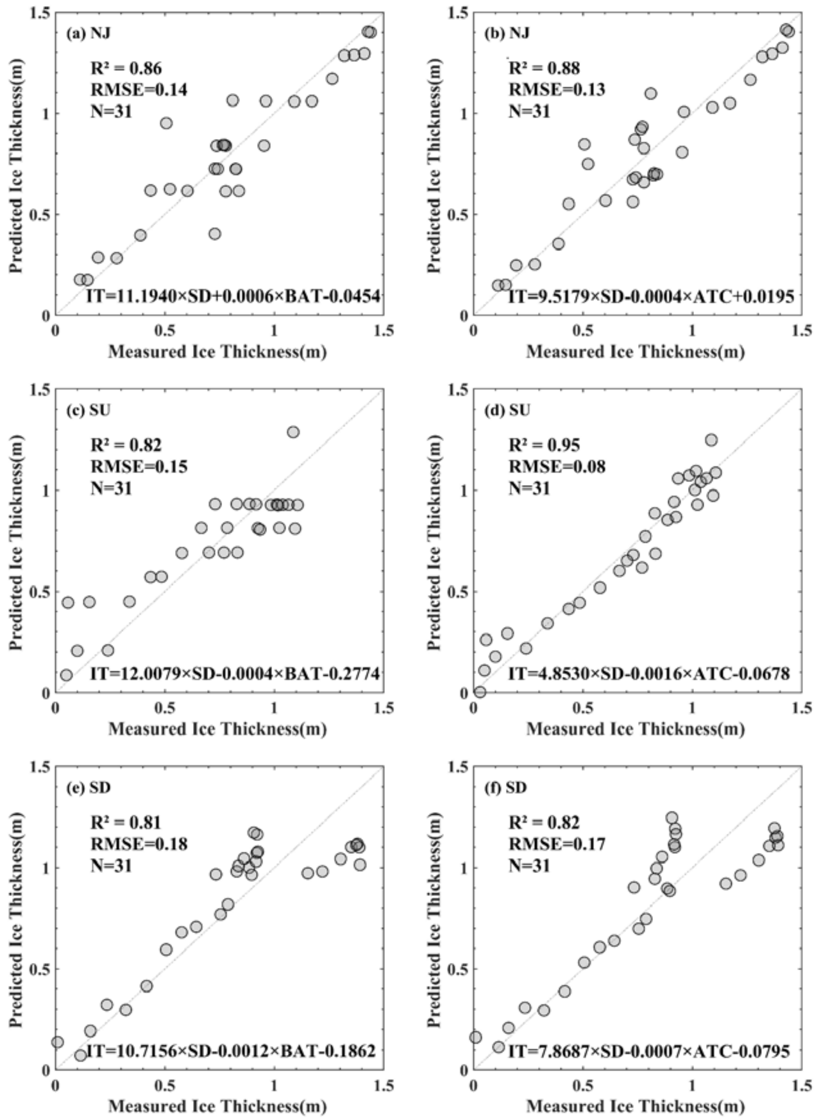


Figure 8 The bivariate scatter plots with linear regression lines between yearly maximum ice thickness (MIT) and ice phenology with dataset size of 120~~;~~, *r* and *p* denote the corresponding correlation coefficient and *p* value of ~~the~~ regression line. The ice phenology ~~events include~~includes freeze-up start (FUS), freeze-up end (FUE), break-up start (BUS), break-up end (BUE) and complete frozen duration (CFD).

带格式的: 正文, 无
设置了格式: 字体: 倾斜
设置了格式: 字体: 倾斜
设置了格式: 字体: 倾斜
带格式的: 行距: 单倍行距



(a) NJ
R² = 0.86
RMSE=0.14
N=31
IT=11.1940×SD+0.0006×BAT-0.0454
(b) NJ
R² = 0.88
RMSE=0.13
N=31
IT=9.5179×SD-0.0004×ATC+0.0195
(c) SU
R² = 0.82
RMSE=0.15
N=31
IT=12.0079×SD-0.0004×BAT-0.2774
(d) SU
R² = 0.95
RMSE=0.08
N=31
IT=4.8530×SD-0.0016×ATC-0.0678
(e) SD
R² = 0.81
RMSE=0.18
N=31
IT=10.7156×SD-0.0012×BAT-0.1862
(f) SD
R² = 0.82
RMSE=0.17
N=31
IT=7.8687×SD-0.0007×ATC-0.0795
Predicted Ice Thickness(m)
Measured Ice Thickness(m)

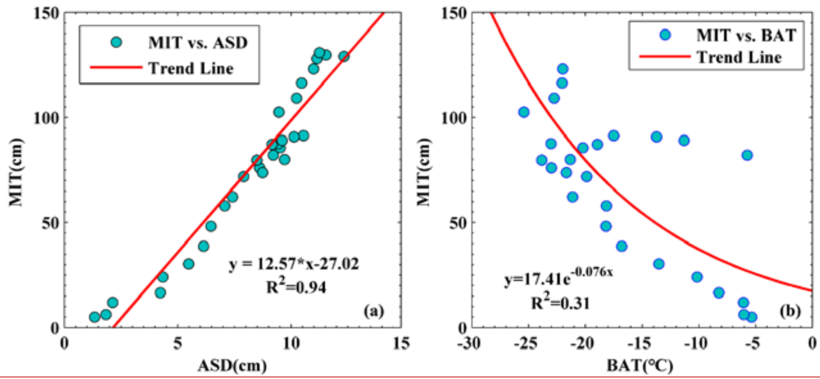


Figure 9 The scatter plot between maximum ice thickness (MIT), average snow depth (ASD) and air temperature on bank (BAT) and the corresponding trend line. The data was selected under the criteria with air temperature below 2°C and snow depth less than 20 cm.

~~Figure 9 Scatter plots between measured and predicted ice thickness using Bayesian linear regression in three sub basins (NJ: Nenjiang Basin, SU: upstream Songhua River Basin, and SD: downstream Songhua River Basin) in Northeast China. The model treated ice thickness as the independent variable, and snow depth and air temperature as dependent variables. Two types of air temperature were used: BAT represents air temperature on bank; ATC represents negative cumulative air temperature.~~

设置了格式: 字体: 加粗

设置了格式: 字体: +西文正文 (Times New Roman), 字体颜色: 自动设置

带格式的: 无, 行距: 单倍行距

设置了格式: 字体颜色: 自动设置