Title: The role of snow cover on ice regime across Songhua River Basin, Northeast China (tc-2019-242)

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General comments

Dear authors,

I received the comments from referees on your revised draft. Despite your extensive revisions, one of the referees is still not convinced by the contributions of your study to the field. Please try to be clear in your discussion and conclusion how your study advances the current knowledge in the field.

Furthermore, as indicated by the referee, there is an ambiguity between between lake and river ice throughout the manuscript to the point that it is not clear which one you are reporting on (is it river ice characteristics or lake ice?) These are fundamentally two different processes of ice formation and decay. Please try to address these issues carefully.

The objectives of each data processing step are not clearly outlined. Some parameters seem to have unusual naming (such as Negative Cumulative Air Temperature which is referred to as cumulative degree day of freezing in the literature). Please chose a correct (commonly used) terminology and stick with it throughout the text.

Furthermore, there are still typos and redundancy in the writing (see my specific comments).

In the light of this criticism I have reviewed the revised version myself. Please find below my specific comments. I am asking you to address the comments (more general comments above and all of my specific comment below) and submit the revised manuscript with line-by-line responses to the comments.

Best regards,

Valentina

Response to General comments

Dear Valentina,

Thank you for your letter 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 corrections accordingly, marked as red in the manuscript.

Firstly, we presented a new geographic map of Songjiang River Basin, and supplemented the distribution of rivers in our study area. The figure clearly illustrated the hydrological stations are located on the rivers not on the lakes. Secondly, the data processing had been rewriting and linked with the objectives of our work, and you can checke in the new version of manuscript. Thirdly, we checked and updated the terminology throughout the manuscript, and removing the abbreviations. Besides, we checked typos and redundancy and modified accordingly. Last but not least, please accept the gratitude from the bottom of our heart for your extensive efforts.

Best wishes,
Qian Yang
On behalf of all authors.

Response to specific comments:

1. Abstract: 'Five typical geographic zones weridentified applying a rotated empirical orthogonal function.' -> It's not clear what is meant by five typical geographical zones. Typical of what? Also, to what data is the EOF applied?

Reply to comments: Thank you for this insightful suggestion, and we considered it carefully. In the previous version of the manuscript, the typical geographical zones were identified visually from EOF results of complete frozen duration. Our original purpose of typical geographic zones is to present a classification suitable for both ice thickness and ice phenology. Considering the limitation of the method, EOF is not a proper and reasonable method for the classification of geographic zones. Thus, we abandoned this geographic zoning method in the current version of the manuscript.

Further, we performed grouping analysis for complete frozen duration in ArcGIS software, as shown in Figure 1. We selected K means as the spatial constraints and MANHATTAN as distance method to classify the completely frozen duration. We tested the group number ranging from 2 to 15, and Figure 1 (d) illustrated the Calinski-Harabasz pseudo F-statistic as the group number increase from 2 to 15. The larger F-statistic reveals how grouping result will be more effective at distinguishing the features and variables. The group number of 2, 3 and 4 have the three most largest F-statistic of 68.24, 65.7 and 63.36. Considering the basin boundaries and topography in the Songhua River Basin, group number of 4 are the best choice for classification.

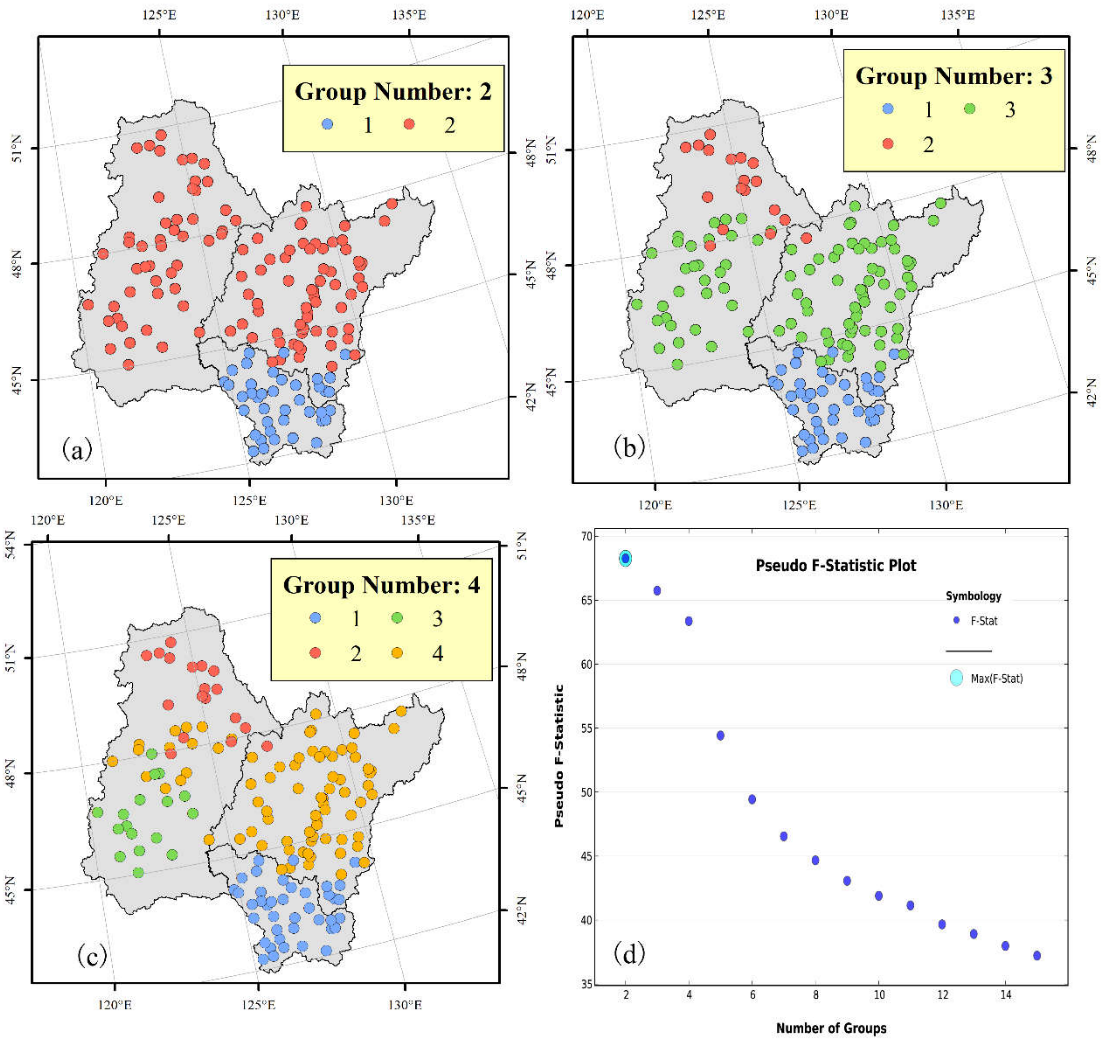

Figure 1 The grouping analysis result of complete frozen duration. (a), (b) and (c) display the spatial distribution of grouping with group number of 2, 3 and 4 namely. (d) listed Calinski-Harabasz pseudo F-statistic as the group number increase from 2 to 15.

We also performed grouping analysis for maximum ice thickness, and Figure 2 illustrated the Calinski-Harabasz pseudo F-statistic as the group number increase from 2 to 15. The F-statistic increased as the group number increase, which makes it hard to identify the best group number. Besides, the global Moran’s index of maximum ice thickness is 0.01 with z scores of 0.13 and p value of 0.89, which indicated that no cluster pattern existed for maximum ice thickness at the 95% confidence level. Therefore, we concluded that ice thickness didn’t exhibit the similar grouping cluster as complete frozen duration.

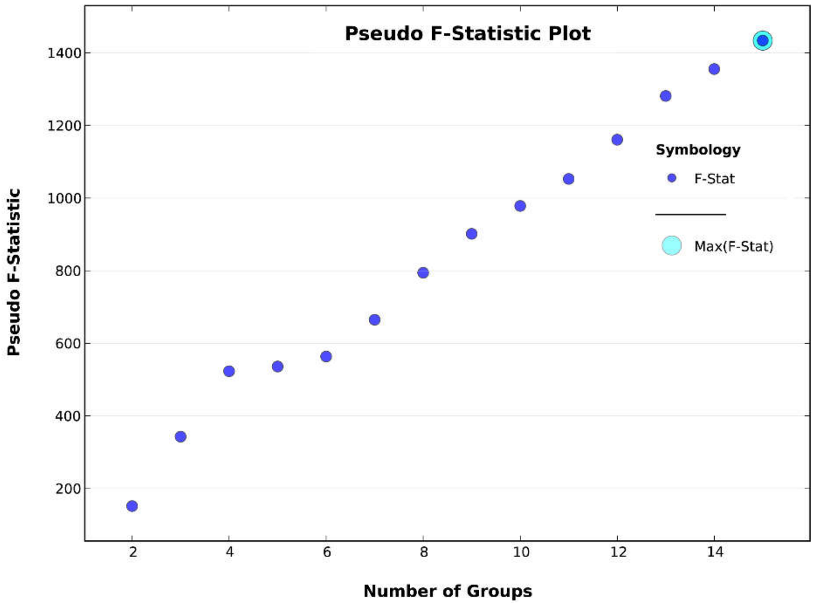

Figure 2 The Calinski-Harabasz pseudo F-statistic of grouping analysis of maximum ice thickness as the group number increase from 2 to 15.

2. Section 2.3.1: Please include more details on what data is used here, i.e. to which data is kriging applied to and what is the specific goal (in your study) that you try to achieve with the kriging. As it currently ready, the section generally describes kriging, but necessary specifics for your study/data are not given.

Reply to comments: Thank you for pointing this out, and we have improved the description of 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). The average values of five ice phenology were calculated during the periods from 2010 to 2015 and explored in the Geostatistical wizard of ArcGIS software, and the interpolation results exhibited their spatial distribution. We chose the ordinary Kriging method and set variation function as the spherical model. Moreover, isophenes connecting locations with the same ice phenology were also graphed based on interpolation results (C.R. Paramasivam, 2019). (Page 6, Line 169-176)

Reference:

[1] 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.

[2] 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

[3] C.R. Paramasivam, S. V.: An Introduction to Various Spatial Analysis Techniques. In: GIS and Geostatistical Techniques for Groundwater Science, Senapathi Venkatramanan, M. V. P., Sang Yong Chung (Ed.), Elsevier, 2019.

3. Page 2: 'The earliest ice record in the literature dates back to 150 years ago (Magnuson et al., 2000)' -> is this referring to the earliest ice record in the world or in China? Please clarify this in the sentence.

Reply to comments: Thank you for this helpful suggestion, and we updated as follows: The earliest ice record in the literature dates back to 150 years ago throughout the northern hemisphere (Magnuson et al., 2000). (Page 2 , Line 56-57)

Reference:

[1] 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.

4. Page 2, ln 49: 'At medium and large scales, ' -> provide example in km for what is considered mediium and large scales here.

Reply to comments: Thanks for your insightful suggestions, and we modified this sentence as “At medium and large scales within 25 km”. (Page 2, Line 59-60)

5. Page 2, ln 54: 'but their spatial resolutions are too large' -> do you mean too coarse? 'at small scales' -> better say at local scales (or define what is meant by small scales).

Reply to comments: We thank the reviewer for the insightful comments, and we updated as “ but their spatial resolutions are too coarse to detect ice thickness and snow depth accurately at local scales ” . (Page 3, Line 65-66)

6. Page 2, ln 60: 'include regular observations' -> not clear what is meant by regular? Do you mean continuous monitoring by automated stations?

Reply to comments: Thank you for this helpful suggestion, and the regular observation means continuous monitoring from hydrological stations. Instead, we used fixed-station observations.(Page 3, Line 71-72)

7. Page 2, ln 62: 'Ice parameters differ greatly' -> provide some examples for ice parameters here: Ice parameters, such as xxx, differ greatly

Reply to comments: Thanks for your insightful suggestions, and we modified as “Ice parameters, such as ice thickness, freeze-up and break-up dates, differ greatly from point to point on a given river”. (Page 3, Line 84-85)

8. Page 2, ln 67: 'These models consider the energy exchange and physical changes ...' -> not all of the models you listed will consider these processes but probably only 'physics-based' model. The empirical models will be focused solely on data. Please revise.

Reply to comments: We thank the reviewer for the insightful comments. The description is not clear, and we improved the sentences as “The physically-based 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.” (Page 3, Line 80-81)

9. Page 2, ln 72: 'to validate and improve accuracy and reliability. '-> to validate and improve accuracy and reliability of what?

Reply to comments: Thank you for this useful suggestion, and we modified the sentence as “Sufficient historical ice records are necessary to model the ice regime and validate the reliability of remote sensing data”. (Page 3, Line 87-88)

10. Page 3, ln 77: 'the effect of snow cover can’t be ignored.' Change 'can't ' to 'cannot'. Also provide a reference(s) for this statement.

Reply to comments: Thanks for your insightful suggestions. The usage is incorrect, and we used “cannot ”. (Page 3, Line 93)

11. Page 3, ln 78: 'snow depth outweighs air temperature during the ice forming process' -> better say 'the effect of snow depth on the ice forming process is larger than the effect of air temperature.

Reply to comments: We thank the reviewer for his/her insightful comments, and we modified as “Generally, the effect of snow depth on the ice forming process is larger than the effect of air temperature (Morris et al., 2005;Park et al., 2016). ” (Page 3, Line 93-95)

Reference:

[1] 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, MacAyeal, D. R. (Ed.), Annals of Glaciology-Series, 2005.

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, 2016

[2] 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, 2016.

12. Page 3: ln 79: Compared to other studies, the air temperature had a more significant effect on ice thickness than snow depth and was attributed to the high snowfall in the study area (Gao and Stefan, 2004).' Better say: 'In contrast to these studies, Gao and Stefan (2004) found that air temperature had a more significant effect on ice thickness formation than the snow depth.

Reply to comments: Thanks for your insightful suggestions, and we modified as “In contrast to these studies, Gao and Stefan (2004) found that air temperature had a greater effect on ice thickness formation than the snow depth.” (Page 3, Line 95-97)

Reference:

[1] Gao, S. and Stefan, H. G.: Potential Climate Change Effects on Ice Covers of Five Freshwater Lakes, Journal of Hydrologic Engineering, 9, 226-234, 2004.

13. Page 3, ln 80: 'Besides' -> change to 'Furthermore'

Reply to comments: Thank you for this helpful suggestion, and we modified as you suggested. (Page 3, Line 97)

14. Page 3, ln 83: 'ignored the changing status of ice formation processes' -> not clear what is meant by the 'changing status'. Would it be better to say 'ignored the different stages of ice formation'?

Reply to comments: Thanks for your advice, and we modified as you suggested. (Page 4, Line 100)

15. Page 3, ln 84: 'The relative influence of snow depth and air temperature on the ice regime deserves further exploration in Northeast China.' Change to: The relative influence of snow depth and air temperature on the river/lake ice regimes in Northeast China deserves more exploration.

Reply to comments: We thank the reviewer for this helpful comment, and we modified as you suggested. (Page 4, Line 101-102)

16. Page 3, ln 84-94: This paragraph repeats what has already been stated in the introduction. Please revise the whole paragraph to avoid any repetition and redundancy. Indicate the research questions and also briefly mention in very general terms (2-3 sentences) how the key questions will be answered in this study (what methods and observations you'll be using).

Reply to comments: Thanks for your insightful suggestions, and we rewrote the last part of the Introduction.This study provided a quantitative investigation of ice regime in the Songhua River Basin and potential regression models for projecting future changes in the ice regime. Remote sensing data could provide long-term and wide-range information for ice thickness and ice phenology since 1980. The work herein will provide a valuable reference for the retrieval of ice development by remote sensing. Therefore, we plan to use satellite data to enlarge our study scope in our future work. (Page 4, Line 104-111)

17. Section 2.2.1: Makes sure to indicate how many measurement site are on river ice and home many on lake ice. One of the reviewers pointed out that this has not been clearly stated.

Reply to comments: Thank you for this helpful suggestion. The hydrological station is located on the rivers, not on the lakes. Figure 3 showed the spatial distribution of hydrological stations, rivers, and lakes in the Songhua River Basins. Some are located in the neighborhood of the inflow or outflow of lakes, but not exactly on lakes. (Page 21, Line 595-601)

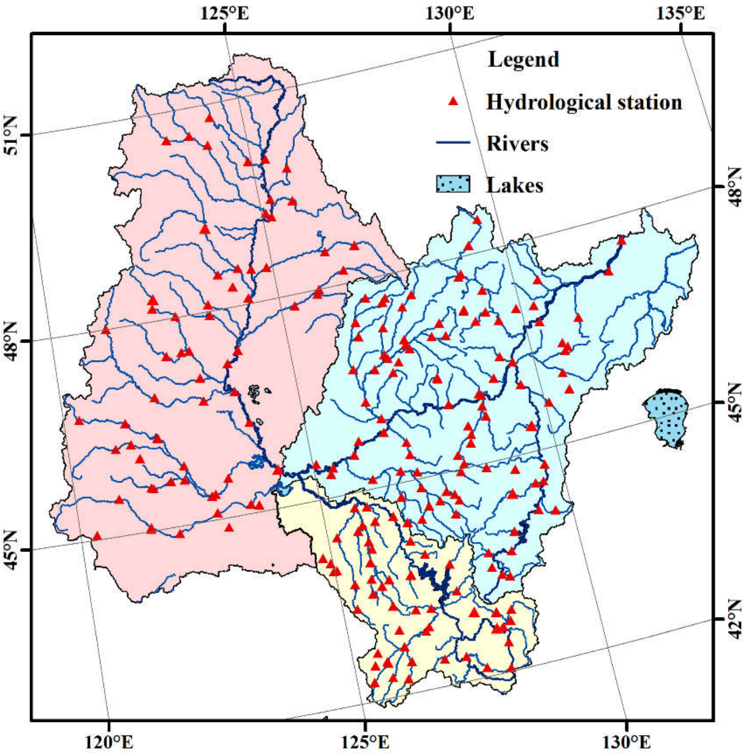

Figure 3 The distribution of hydrological stations, rivers, and lakes in the Songhua River Basin of Northeast China.

18. I would suggest removing the abbreviations here (FUS, FUE, BUS, BUE, CFD, IT, MIT, ASD) as there are too many abbreviations in the study and it is hard to keep track.

Too many abbreviations can disrupt the narrative. If you are using these abbreviations in the figures, then introduce them in the figure captions.

Reply to comments: We feel sorry for the improper usage of abbreviations. In our resubmitted manuscript, the abbreviations is removed. Thanks for your correction.

19. Page 4, Line 133: 'establish the regression model' -> it is not clear what regression model you will be establishing. Will this regression model be described later? If yes, then say 'establish a regression model, which we describe below.'

Reply to comments: Thank you for this helpful suggestion, and we modified as you suggested. (Page 5, Line 149-150)

20. Section 2.3 I suggest to provide here a short summary of overall methodology, so the readers can get a general idea of what is to follow and how it fits together. So here you would mention the key steps you will use (krigging, EOF and regression) outlining the main objective of each step. Then in each section that follows you provide more details on each step (as you have already done). Without this summary, it is very hard to comprehend why you chose to use each of this methods.

Reply to comments: Thank you for this helpful suggestion, and we added a paragraph. To start with, we analyzed the spatial pattern and mapped the cluster of rive ice phenology using Kriging, Moran's index. Then, we explored the relationship between the ice regime and the impact factors using correlation analysis. Last but not least, we established the quantitative relationship between ice thickness and snow depth, air temperature based on the Bayesian linear regression. (Page 6, Line 161-165)

21. Section 2.3.1: Please include more details on what data is used here, i.e. to which data is krigging applied to and what is the specific goal (in your study) that you try to achieve with the krigging. As it currently ready, the section generally describes krigging, but necessary specifics for your study/data are not given.

'The average values of five ice phenology indicators' -> please specify the indicators and specify how the averaging is performed (in time or space or both?)

Reply to comments: Thank you for the question, and we made it clear. For each hydrological station, the average values of five river ice phenology were calculated from the ice records from 2010 to 2015 and interpolated by Kriging method to analyze the spatial distribution of river ice phenology. The river ice phenology included freeze-up start, freeze-up end, break-up start, break-up end and completely frozen duration. (Page 6, Line 168-175)

22. Section 2.3.1: Same comment as above. Please explain why EOF is used here (what are you trying to achieve in your study) and to what data EOF method is applied.
'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.' -> you speak about the advantages of EOF which you then immediately present as problematic and therefore use the rotated EOF to solve those problems. So the section here is somewhat confusing. Please revise so that it is clear: what the advantages of rotated EOF are, and why for your specific case you chose to use rotated EOF rather than EOF.

Reply to comments: Thank you for the concerns and comments. The typical geographical zones were identified visually from EOF results of completely frozen duration. As mentions before, EOF is not a proper and reasonable method for classification in our case study. After the trial of several grouping methods, we decide using the pattern explored by Moran index, and we explained the further work for exploring spatial pattern above. (Page 6, Line 177-185)

23. Page 5: Please reduce the use of abbreviations. For example, remove BLR and ATC. Results and Discussion: due to too many abbreviations it is hard to follow the narrative. I hope this will improve with the removal of abbreviations and using the full words.

Reply to comments: Sorry for this problem, and we have removed all the abbreviations.

24. Page 5, ln 180: '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. -> is the Y data the ice thickness values on rivers or lakes? Please clarify. Also, is Y-data presented as five day moving average throughout the whole observational period? Please clarify. For many observations (points) do you have in the regression model? Do you apply any cross-validation, i.e. using section of the data for the model calibration and then another section (independent of calibration data) for validation? If you don't use any cross-validation, how do you prevent over-fitting to noise?

Reply to comments: Thank you for pointing this out, and we clarified these questions. In this paper, we treated ice thickness as the Y data values on the riverbank, and the snow depth and air temperature as X data with dataset size of 31. The ice thickness was measured on the riverbank every five days from November to March when the river was completely covered with ice with air temperature below 0℃. Y data is not the five-day moving average.

We carried out cross-validation for Bayesian linear regression using k-fold method and set K value as 5. For each iteration, a different fold is held-out for testing, and the remaining 4 subsets is used for training. The training and testing were repeated for 5 iterations, and Table 1 listed the R^2 of the training and testing process each iteration. The best Bayesian linear regression was determined when the bias between testing and training regression was smallest. (Page 7, Line 196-199; Page 12, Line 354-359)

Table 1 The cross-validation of Bayesian linear regression using k-fold method. The R^2 values of training dataset and testing dataset based on the Bayesian regression. Ice thickness was treated as dependent variables, and air temperature, snow depth on ice as independent variables. Air temperature and cumulative air temperature of freezing were considered in the model built.

Basin	Air temperature		Cumulative air temperature	
	Training	Testing	Training	Testing
NJ	0.80	0.99	0.84	0.99
	0.89	0.80	0.90	0.86
	0.84	0.92	0.89	0.82
	0.90	0.56	0.91	0.61
	0.85	0.91	0.89	0.89
SU	0.83	0.92	0.95	0.98
	0.83	0.65	0.96	0.83
	0.81	0.94	0.95	0.99
	0.84	0.79	0.95	0.93
	0.82	0.82	0.94	0.98
SD	0.80	0.96	0.82	0.98
	0.84	0.16	0.86	0.25
	0.81	0.84	0.82	0.87
	0.79	0.97	0.79	0.96
	0.81	0.80	0.82	0.83

25. Results and Discussion: due to too many abbreviations it is hard to follow the narrative. I hope this will improve with the removal of abbreviations and using the full words.

Reply to comments: Sorry again for this problem, and we have removed all the abbreviations. Thanks for your correction. (Page 20, Line 590-595)

26. Page 6, line 210: 'The general spatial trend was a tendency to advance as the latitude increased for the FUS and FUE...' Not clear what is meant by 'a tendency to advance', advance in what? Please revise.

Reply to comments: Thank you for this useful suggestion. We built the linear regression equation between the five river ice phenology and latitude. AS the latitude increased by one degree, freeze-up start and freeze-up end happened 2.56 and 2.32 days early, the break-up start and break-up end arrived 2.36 and 2.37 days late, resulting in 4.48 days decrease in completely frozen duration. This could be explained by the decreasing solar radiation with latitude influencing the ice thaw and melting processes directly. (Page 8, Line 246-251)

27. Page 6: Results from EOS -> it seems that you are visually clustering the PC results (on the map). Is that correct? If yes, please state so. Currently it reads as if you are visually identifying the modes of PC, while these are actually derived from the EOF method itself.

Reply to comments: Thank you for this useful suggestion. We found that the results obtained with REOF were probably not appropriate, and it is difficult to explain the distribution characteristics and identified the typical zones using REOF methods. Our further work has been described above.

28. Page 8, ln 259: 'an analysis of the annual changes was not conducted because the time series were not long enough' -> what is considered long enough here?

Reply to comments: We thank the reviewer for his/her insightful comments, and we removed the sentence.

29. Page 8, ln 263: 'matrix between lake ice phenology' -> what variables are use for the ice phenology? Please clarify this already in the methods section.

Reply to comments: Thank you for this helpful suggestion, and we clarified these parameters as follows:

Figure 7 displays the correlation matrix between lake ice phenology and three ground measurements with a dataset size of 120 stations. The lake ice phenology included freeze-up start, freeze-up end, break-up start, break-up end and complete frozen duration. The three ground measurements included yearly mean values of snow depth, air temperature on bank, and maximum ice thickness. (Page 10, Line 305-309)

30. Page 8, ln 281: '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.' The use of terminology here, such as 'protocol' and 'repaid', does not seem right. Please revise with

wording that is appropriate for physical processes. Start by simplifying the sentence. What do you actually try to say here?

Reply to comments: Thanks for your insightful suggestions. The sentence is hard to understand, and we kept part information: Although a uniform specification for ice regime observations was required, the inhomogeneities among different stations could not be ignored. (Page 11, Line 333-334)

31. Page 9, ln 290: 'Moreover, whether the status of river ice was steady or not also could not be neglected when studying the role of snow cover. ' Not clear what you mean by 'steady' river ice. Please clarify. Also, it is not clear how the role of snow cover is influenced by the steadiness (?) of river ice.

Reply to comments: Thanks for the doubt, and we have to admit the usage of "steady" is confusing. When the river is completely frozen, the ice cover grows as the air temperature becomes lower and lower. The ice cover wouldn't melt until next spring, and the status is steady. That's what we planned to express, and in the new manuscript, "steady" is replaced by "completely frozen ". (Page 11, Line 350-351)

32. Page 9, ln 295: 'and the snow mixes with surface ice into slush and promotes melting.' Please elaborate this a bit more as snow can turn into slush regardless of the presence of ice. Also, please briefly elaborate (add a sentence) on why would the slush promote melting.

Reply to comments: Thank you for this helpful suggestion, and we elaborate this as follows: During the ice-decay process, the lake bottom ice stops to grow, and the surface snow or ice melts, and slush forms. The speed of melting depends on the ability to absorb heat, and the slush can absorb more heat, which promotes melting. The slush often exists through multiple freeze/thaw cycles of river ice before completely disappearing. Therefore, the status of river ice could not be neglected when studying the role of snow cover. (Page 11, Line 346-350)

33. Section 3.3.2. In this section it would be interesting to relate you finding from the

regression modelling and the zones you identifies from EOF analysis. Is the model performing better or worse for different zones.

Reply to comments: Thank you for this wonderful idea. In this study, we tried to link regression modeling and the zones, but it didn't work. As we discussed above, the typical geographical zones were identified visually from EOF results of completely frozen duration, and EOF is not a reasonable method for classification. Instead, we used grouping analysis to determine the classification. Comparing the Calinski-Harabasz pseudo F-statistic with group numbers. The completely frozen duration performed were divide into four groups. However, the maximum ice thickness fails to obtain the classification. Yet, there doesn't exist a unified geographical zoning method, which is suitable for both ice phenology and ice thickness pattern analysis.

What's more, the grouping analysis used the average values of complete frozen duration for each hydrological station with dataset size of 156. The complete frozen duration only has one value within one cold season. The regression modeling used the ice thickness measured every five days. The ice thickness had 37 measurements within one cold season, and we selected 31 of 37, ranging from November to March. Only 120 of 156 stations had ice thickness measurements. In a word, complete frozen duration and regression modeling didn't share the same dataset. That's another reason we fail to achieve this idea.

34. Page 9; Ln 302: 'which is consistent with previous studies. ' Provide some references here for the studies.

Reply to comments: Thanks for your insightful suggestions. Sorry for the missing reference, and we updated the reference. Figure 9 indicates that snow depth outweighed air temperature in terms of the effect on ice thickness, which is consistent with previous studies (Sharma et al., 2019; Magnuson et al., 2000). (Page 12, Line 366-367)

Reference:

[1]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, 2019.

[2] 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.

35. Page 9, ln 305: 'was not as significant as in previous studies'. Again, provide some references here for the studies.

Reply to comments: Thank you for this kind reminder, and we added the reference. The correlation between air temperature and ice regime was not as significant as in previous studies for several reasons (Gao and Stefan, 2004). (Page 12, Line 376)

Reference:

[1] Gao, S. and Stefan, H. G.: Potential Climate Change Effects on Ice Covers of Five Freshwater Lakes, Journal of Hydrologic Engineering, 9, 226-234, 2004.

36. Page 9, line 306: 'Average air temperatures were most commonly calculated over fixed time periods at regional scales, for example as moving averages for certain time periods. ..' Are you referring to previous studies or to your study in this paragraph? It is not clear from the text.

Reply to comments: We thank the reviewer for his/her insightful comments, and we added the reference. Average air temperatures were most commonly calculated over fixed periods at regional scales, for example, as moving averages for specific periods (Yang et al., 2020; Pavelsky and Smith, 2004). (Page 12, Line 376-379)

Reference:

[1]Yang, X., Pavelsky, T. M., and Allen, G. H.: The past and future of global river ice, Nature, 577, 69-73, 2020.

[2]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, 2004.

37. Page 9, ln 310: 'Heat loss is mainly made up of sensible and latent heat exchange,'

-> do you have evidence for this from your results or are you referring to previous work. If latter, please provide reference.

Reply to comments: Thank you for this helpful suggestion. We referred to previous work, and we supplemented the reference.

Heat loss is mainly made up of sensible and latent heat exchange (Robertson et al., 1992;Beltaos and Prowse, 2009a). (Page 13, Line 385)

Reference:

[1]Robertson, D. M., Ragotzkie, R. A., and Magnuson, J. J.: Lake ice records used to detect historical and future climatic changes, Climatic Change, 21, 407-427, 1992.

[2]Beltaos, S. and Prowse, T.: River-ice hydrology in a shrinking cryosphere, Hydrological Processes, 23, 122-144, 2009a.

38. Page 9, line 315: 'dominated during the transition process.' -> the transition process of what?

Reply to comment: We thank the reviewer for his/her insightful comments. The sentence has been modified as “while cumulative air temperature dominated during the transition process between open water and completely frozen condition.” (Page 13, Line 390-392)

39. Conclusions: Please do not use any abbreviation in the conclusions are it disrupts the narrative (especially for the reader who will just read the conclusions of your study). To reiterate: use the abbreviations only in the figures if necessary.

Reply to comments: Sorry for the abbreviations again, and we modified them as you suggested.

40. Page 10, line 330: 'The peaks of snow depth and ice thickness fell behind air temperature for almost one month' -> do you mean the peaks are lagging behind the peaks in air temperature by one month? Please revise as the current sentence is somewhat ambiguous.

Reply to comments: The statement is not clear and quantitative description. We calculated the lag time. The day when ice thickness reached the maximum value was 49, 54, and 49 days later than that when air temperature reached the lowest value. (Page 10, Line 298-301)

41. Page 10, line 332: 'The yearly analysis failed to explain the relationship between ice regime and snow depth and air temperature' -> the 'yearly analysis' does not sound right. Do you want to say the you found no relationship between annual time-series of ice thickness and snow depth or air temperature?

Reply to comment: Thanks for your insightful suggestions. The sentence is confusing and we removed it.

42. Page 10, line 333: 'Based on monthly correlation analysis' -> Change to: Based on the analysis of monthly timeseries

Reply to comment: We thank the reviewer for his/her insightful comments. The sentence has been modified, as you suggested. (Page 13, Line 409-410)

43. Page 10, line 334: 'as the ice cover become steady' -> again, it is not clear what you mean by steady. Do you mean 'as the ice cover reached its maximum value for the season'?

Reply to comment: Thanks for your insightful suggestions. About "The steady status", it would be better to say the river is fully covered with ice, and the ice accumulated when the air temperature falls behind 0℃. (Page 13, Line 410)

44. Page 10, ln 335: 'Additionally, air temperature associated with ice phenology more closely than ice thickness.' Better say; the temporal variability in air temperature was more correlated with the variability in ice phenology than in ice thickness.

Reply to comment: Thank you for this helpful suggestion. The sentence has been modified as you suggested. (Page 13, Line 410-412)

45. Page 10, line 339: 'air temperature on bank and negative cumulative air

temperature.' Isn't the temperature always measured on the river bank? Please try to be consistent throughout the whole manuscript.

Reply to comment: Thanks for your insightful suggestions. The spatial distribution of hydrological stations had been illustrated in Figure 1. The hydrological stations are located on the bank of rivers rather than lakes.

46. Page 10, line 341: remove: 'rather than air temperature through the heat loss of ice formation and decay.' You are dealing with the results of an empirical model (not physics-based) so threat the results as such. You can state that the negative cumulative air temperature is acting like a proxy for the heat loss during the ice formation and decay.

Reply to comment: We thank the reviewer for his/her insightful comments. The sentence has been modified as you suggested:

Results showed that snow cover correlated with ice thickness significantly and positively during the periods when the freshwater was complete frozen. The cumulative air temperature of freezing behaved better than air temperature when building the Bayesian regression equation. The results suggested that heat exchanges between the river surface and the atmosphere dominated the ice process, and negative cumulative air temperature influenced the thickness is a more sensitive indicator of heat loss of ice growth and decay than the air temperature. (Page 13, Line 414-420)

47. Page 10, line 348: 'The work herein will provide a valuable reference for the retrieval of ice development by remote sensing.' Better say: Data analyzed in this study present a valuable reference for the remote sensing observations of river/lake ice thickness in this area.

Reply to comment: Thank you for this helpful suggestion. The sentence has been modified as you suggested. (Page 14, Line 425-426)

48. Page 10, line 349: '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 sentence is too generic. Please remove.

Reply to comment: Thanks for your insightful suggestions. The sentence has been removed. We have updated the last paragraph of the Conclusion.

This study provided a quantitative investigation of the ice regime in the Songhua River Basin and potential regression models for projecting future changes in the ice regime. Remote sensing data could provide long-term and wide-range information for ice thickness and ice phenology since 1980. The work herein will provide a valuable reference for the retrieval of ice development by remote sensing. Therefore, we plan to use satellite data to enlarge our study scope in our future work. (Page 14, Line 422-427)

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

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Abstract: The ice regime has been scarcely investigated in the Songhua River Basin of Northeast China. The regional role and trends of freshwater ice 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. We explored the role of snow depth and air temperature on the ice regime. The river ice phenology showed a latitudinal distribution and a changing direction from southeast to northwest. The cluster pattern of yearly maximum ice thickness has been measured by Global and local Moran's I. The high values clustered in the Xiao Higgan Mountain and low values clustered in the Changbai Mountain at the 95% confidence level. The maximum ice thickness over 125 cm was distributed along the ridge of Da Hagan Mountain and Changbai Mountain, and maximum ice thickness occurred most often in February and March. Six Bayesian regression models were built between ice thickness, air temperature, and snow depth in three sub-basins of the Songhua River Basin. The determine R^2 of Bayesian linear regression ranged from 0.80 to 0.95, and root mean square errors ranged from 0.08 to 0.18. 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 cumulative air temperature of freezing through the heat loss of ice formation and decay.

Keywords. River ice phenology, ice thickness, snow depth on ice, cumulative air temperature of freezing, Bayesian linear regression

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 (Lindenschmidt et al., 2017; Williams and Stefan, 2006). 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 (Beltaos and Prowse, 2009b; Magnuson et al., 2000; Sharma et al., 2019). 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 throughout the northern hemisphere (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 within 25 km, optical remote sensing data are widely used for deriving ice phenology (Šmejkalová et al., 2016; Song et al., 2014), while microwave remote sensing are used to estimate ice thickness and snow depth over ice (Kang et al., 2014; Zhang et al., 2019). 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).

Still, their spatial resolutions are too coarse to detect ice thickness and snow depth accurately at local scales. For example, the microwave satellite data of AMSR-E have a spatial resolution of 25 km, but the largest width of the 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 fixed-station 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. 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). The physically-based 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 (Rokaya et al., 2020). The reliance on information makes the physically-based model more suitable for small watershed applications within 100 km^2. The empirical model enables it possible to predict the changes in ice regime from limited climate data for larger basin applications (Yang et al., 2020). Ice parameters, such as ice thickness, freeze-up and break-up dates, differ significantly from point to point on a given river (Pavelsky and Smith, 2004), and the uneven distribution of hydrological stations poses an obstacle to spatial investigation and modeling. Sufficient historical ice records are necessary to model ice regime and validate the reliability of remote sensing data.

The ice cover of water bodies experiences three stages: freeze-up, ice growth, and break-up (Duguay et al., 2015). The ice phenology, ice thickness, and ice composition change considerably in different stages. Although air temperature dramatically influences the freeze-thaw cycle of river ice, the effect of snow cover cannot be ignored. Generally, the effect of snow depth on the ice forming process is more significant than the impact of air temperature (Morris et al., 2005; Park et al., 2016). In contrast to these studies, Gao and Stefan (2004) found that air temperature had a more significant effect on ice thickness formation than the snow depth. Furthermore, 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). Previous studies analyzed the relationship in view of spatial distributions and ignored the frozen status of ice formation processes. The relative influence of snow depth and air temperature on the freshwater ice regimes in Northeast China deserves more exploration.

To evaluate the influence of the ice regime on the regional climate and human environment, a robust investigation and quantitative analysis on ice regime are necessary, which provides helpful information for projecting future changes in the ice regime. The work is the first to present continuous river ice records of three sub-catchments of the Songhua River Basin from 2010 to 2015 and compared the spatial and temporal changes of ice phenology and ice thickness. The influence of snow cover and air temperature on the ice regime was quantitatively explored among the three sub catchments considering the frozen status of river ice.

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 (Khan et al., 2018; Zhao 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 (Chen et al., 2019; Yang et al., 2018). Temperate and cold temperate climates characterize the whole Songhua River Basin: winter is long and cold; spring is windy and dry. Annual average air temperature ranges between 3 to 5℃, while yearly precipitation ranges from 400 to 800 cm from the southeast to the northwest (Wang et al., 2018; Wang et al., 2015).

[Figure 1 is added here]

2.2 Data Source

2.2.1 Ice phenology

The ice records were obtained from the annual hydrological report, including ice phenology, ice thickness, snow depth on ice and air temperature on bank (Hydrographic bureau of Chinese Ministry of Water Resources, 2010-2015). There existed 50, 35 and 71 hydrological stations in the NJ, SU and SD basins, respectively. Five lake ice phenology were available, and the definitions are listed as below (Duguay et al., 2015; Hydrographic bureau of Chinese Ministry of Water Resources, 2015) :

- Freeze-up start is considered the first day when floating ice can be observed with temperatures below 0 ℃;
- Freeze-up end 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 is the first day when ice melting can be observed with surface ponding;
- Break-up end is the day when the surface is mainly covered by open water, and the area of open water exceed 20%;
- Complete frozen duration is the ice cover duration when the lake is completely frozen during the winter, from freeze-up end to break-up start.

2.2.2 Ice thickness

We used ice thickness, snow depth, and air temperature from 120 stations for the period ranging from 2010 to 2015, to study changes in ice thickness and establish the regression model described below. 37, 28, and 55 stations were located in the NJ, SU and SD basins, respectively. The hydrological report also provided ice thickness, snow depth on ice, and air temperature on bank every five days from November through April, totaling 37 measurements in one cold season. The yearly maximum ice thickness of the river center and the corresponding DOY were calculated from five-day records. The average snow depth ware derived from the mean of three or four measurements around the ice hole for ice thickness measurement without human disturbance (Hydrographic bureau of Chinese Ministry of Water Resources, 2015). To enhance the performance of the regression model, cumulative air temperature of freezing were derived from air temperature from November to March.

2.3 Data analysis

To start with, we analyzed the spatial pattern and mapped the cluster of rive ice phenology using Kriging and Moran's I. Then, we explored the relationship between the ice regime and the impact factors using correlation analysis. Last but not least, we established the quantitative relationship between ice thickness and snow depth, air temperature based on the Bayesian linear regression.

2.3.1 Kriging

Kriging has been widely used to spatially interpolate in situ measurements of ice phenology (Choiński et al., 2015; Jenson et al., 2007), covering freeze-up start, freeze-up end, break-up start, break-up end and complete frozen duration. The average values of five ice phenology were calculated during the periods from 2010 to 2015 and explored in the Geostatistical wizard of ArcGIS software. The interpolation results exhibited their spatial distribution. We chose the ordinary Kriging method and set variation function as the spherical model. Moreover, isophenes connecting locations with the same ice phenology were also graphed based on interpolation results (C.R. Paramasivam, 2019).

2.3.2 Moran's I

Moran's I is a measure of spatial autocorrelation developed by Patrick Alfred Pierce Moran, and spatial autocorrelation is characterized by a correlation in a signal among nearby locations in space (Li et al., 2020). We calculated the global and Anselin Local Moran's I and of completely frozen duration and ice thickness in ArcGIS software environment. The global Moran's I indicate whether the distribution of regional values is aggregated, discrete or random (Mitchell, 2005). The z-score or p-value indicates statistical significance, a positive Moran's I indicate a tendency toward clustering while a negative Moran's I indicate a tendency toward dispersion (Castro and Singer, 2006).

2.3.3 Bayesian linear regression

Ice thickness had been modelled by air temperature and snow depth using Bayesian linear regression, which has been widely used in hydrological and environmental analyses (Gao et al., 2014; Zhao et al., 2013). Bayesian linear regression 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 Bayesian linear regression 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. Using k-fold cross validation, we divided the input dataset into 5 equal subsets or folds, and treated 4 subsets as the training set and the remaining as our test set. The performance of the regression model was evaluated using the determination coefficient R^2 and the root mean square error (RMSE).

In this paper, we treated ice thickness on the river bank as the Y data, and snow depth over ice and air temperature as the X data with dataset size of 31. The ice thickness was measured on the riverbank every five days from November to March when the river was completely covered with ice with air temperature below 0 ℃. Air temperature and cumulative air temperature of freezing were considered in modeling. Additionally, the Pearson correlation was calculated to analyze the relationship among the five ice phenology events and ice-related parameters, including maximum ice thickness, snow depth on ice, and air temperature on the bank (Gao and Stefan, 1999; Williams et al., 2004).

3 Results and discussion

3.1 Spatial variations of river ice phenology

The river ice phenology was analyzed herein, included freeze-up start, freeze-up end, break-up start, break-up end, and complete frozen duration. The hydrological report supplied only one record of river ice phenology each year for all the 156 stations. For each hydrological station, the average values of five river ice phenology were calculated from the ice records from 2010 to 2015 and interpolated by Kriging method to analyze the spatial distribution of river ice phenology.

3.1.1 Freeze-up end and break-up process

Figure 2 illustrates the average spatial distribution of freeze-up start and freeze-up end and the isophenes in the Songhua River Basin of Northeast China from 2010 to 2015. Figure 3 shows the spatial distribution of the break-up start and break-up end. The corresponding statistics are listed in Table 1. Freeze-up start ranged from October 28th to

November 21st with a mean value of November 7th, and freeze-up end ranged from November 7th to December 8th with a mean value of November 22nd. Break-up start ranged from March 24th to April 20th with a mean value of April 9th, and break-up end ranged from March 31th to April 27th with a mean value of April 15th. These four parameters showed a latitudinal gradient: freeze-up start and freeze-up end decreased while break-up start and break-up end increased as the latitude increased, except in NJ. The middle part of NJ had the highest freeze-up start and freeze-up end and decreased to the southern and northern parts. 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 complete frozen duration interpolated by kriging and the isophenes in the Songhua River Basin from 2010 to 2015. Complete frozen duration ranged from 110.74 to 163.00 days with a mean value of 137.86 days, increasing with latitude. Interestingly, the isophenes of complete frozen duration had different directionality, increasing from the southeast to northwest, which could also be found in the other parameter. Both freeze-up start and freeze-up end correlated negatively with latitude, with coefficients of -0.66 and -0.53, respectively (n=156, $p < 0.001$). Break-up start, break-up end, and complete frozen duration were all positively correlated with latitude with coefficients of 0.48, 0.57, and 0.55, respectively (n=156, $p < 0.001$). We built the linear regression equations between the river ice phenology and latitude. As the latitude increased by one degree, freeze-up start and freeze-up end happened 2.56 and 2.32 day early, the break-up start and break-up end arrived 2.36 and 2.37 day late, resulting in 4.48 days decrease in complete frozen duration. This could be explained by the decreasing solar radiation with latitude influencing the ice thaw and melting processes directly.

The Global Moran's I statistic of complete frozen duration was 1.36 with z scores and p value of 2.41 and 0.02, which indicated that likelihood that complete frozen duration showed a clustered pattern was more than 95% for the whole basin. Then Anselin local

Moran's I was calculated to identify statistically significant spatial outliers for each hydrological location in Figure 4(c), and found out that 14 of 156 hydrological stations showed a statistically significant cluster of high values, 17 of 156 showed a statistically significant cluster of low values and 124 of 156 showed no significant cluster at the 95 percent confidence level. Both global and local Moran's I indicated the high values of complete frozen duration clustered along the Xiao Higgan Mountain, and the low values of complete frozen duration grouped in the Changbai Mount.

[Figure 4 is added here]

3.2 Variations of ice thickness

We explored the spatial pattern of ice thickness based on the maximum ice thickness with dataset size of 156 stations and examined the seasonal changes of ice thickness based on the time series with dataset size of 37 days.

3.2.1 Spatial patterns of ice thickness

Figure 5 illustrates the spatial distribution of the yearly maximum ice thickness of the river center and the corresponding DOY. Table 2 summarized the statistical result of maximum ice thickness and the DOY. Maximum ice thickness ranged from 12 cm to 146 cm, with an average value of 78 cm. The maximum ice thickness between 76 and 100 cm accounted for the most significant percentage of 43.33%, followed by 31.67% of maximum ice thickness between 50 and 75 cm. Five stations had maximum ice thickness more exceptional than 125 cm. The DOY of maximum ice thickness had an average value of February 21st, and maximum ice thickness mainly occurred 59 and 40 times in February and March, respectively. Four of the five highest maximum ice thickness 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 factors should be taken into 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 air temperature on bank every five days from 2010 to 2015. The variations of ice characteristics differed significantly due to time and location. Among the three basins, the NJ basin had the highest snow depth of -29.15 ± 9.99℃, followed by -25.61 ± 9.02 ℃ in the SD basin, and -22.17 ± 7.33 cm in the SU basin. The SD basin had the highest snow depth of 9.18 cm ± 3.39 cm on the average level, followed by 8.35 cm ± 4.60 cm in the SU basin,, and 8.23cm ± 3.92 cm in the NJ basin,. The changes in daily ice thickness and snow depth had a similar overall trend, while air temperature followed the opposite pattern. Both ice thickness and snow depth increased from November and reached a peak in March, then dropped at the beginning of April. The air temperature showed a distinct trend and reached the bottom in the middle of February, which is earlier than the peaks of maximum ice thickness and snow depth. In Figure 6, the day when ice thickness reached the maximum value was 49, 54 and 49 days later than that when air temperature reached the lowest value in the NJ, SU and SD basin respectively.

[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 ground measurements with a dataset size of 120 stations. The lake ice phenology events included freeze-up start, freeze-up end, break-up start, break-up end, and complete frozen duration, and the three ground measurements included yearly mean values of snow depth, air temperature on bank, and maximum ice thickness. The colour intensity and sizes of the ellipses are proportional to the correlation coefficients. Maximum ice thickness had a higher correlation with four of the five indices than snow depth and air temperature on the bank, except with freeze-up start, with which both maximum ice thickness and break-up end had the highest correlation of 0.63 ($p<0.01$, $n=120$). During the freeze-up process, two freeze-up dates had a negative association with maximum ice thickness and snow depth; during the break-up, two break-up dates had a positive correlation with maximum ice thickness and snow depth. The complete frozen duration had a positive correlation with maximum ice thickness and snow depth. The situation of air temperature was contrary to that of maximum ice thickness and air temperature. Regarding 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 and ice phenology with regression equations. The break-up process had a negative correlation with maximum ice thickness, while freeze-up had a positive correlation. Besides, the break-up process had a higher correlation with maximum ice thickness, and the break-up start had the highest correlation coefficients with the maximum ice thickness of 0.65 ($p<0.01$). Complete frozen duration also had a positive correlation with maximum ice thickness 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 specification for ice regime observations was required, the in homogeneities 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 ice thickness and snow depth and ice thickness and air temperature on bank were calculated and listed in Table 3. The correlation coefficients between ice thickness and snow depth 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 ice thickness and air temperature on bank in November and December revealed that air temperature played a more critical role in the freeze-up process. The positive correlation coefficient between snow depth and ice thickness (Table 3) showed 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 surface snow or ice melts, and slush forms. The speed of melting depends on the ability to absorb heat, and the slush can absorb more heat, which would promote melting. The slush often existed through multiple freeze/thaw cycles of river ice before completely disappearing. Therefore, the status of river ice could not be neglected when studying the role of snow cover.

[Table 3 is added here]

3.3.2 Regression modelling

We carried out cross-validation for Bayesian linear regression using k-fold method and set K value as 5. For each iteration, a different fold were held-out for testing, and the remaining 4 subsets were used for training. The training and testing were repeated for five iterations. Table 4 listed the R^2 of the training and testing process each iteration. The best Bayesian linear regression was determined when the bias between testing and training regression was the smallest, and the corresponding R^2 were marked as bold and red.

Figure 9 illustrates the scatter plot between measured and predicted ice thickness using Bayesian linear regression in three sub-basins in Northeast China. From Figure 9, the R^2 of Bayesian linear regression ranged from 0.80 to 0.95, and RMSE ranged from 0.08 to 0.18. 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 the effect on ice thickness, which is consistent with previous studies (Magnuson et al., 2000; Sharma et al., 2019). Moreover, replacing air temperature on bank with cumulative air temperature of freezing enhanced the model performance in all three basins, revealing a more important role of cumulative air temperature of freezing than air temperature. The Bayesian linear regressions just used the field measurement ranging from November to March. During this period, the river surface is completely frozen, and the air temperature that falls below 0℃ promotes the ice growth. In April, air temperature that rose above 0℃ enables the river ice to melt.

[Figure 9 is added here]

The correlation in Figure 7 between air temperature and ice regime was not as significant as in previous studies for several reasons (Gao and Stefan, 2004). Average air temperatures were most commonly calculated over fixed periods at regional scales, for example, as moving averages for specific periods (Pavelsky and Smith, 2004; Yang et al., 2020), which ignored the seasonal changes of air temperature. Our work considered this and established the regression using seasonal time series of ice thickness and air temperature. When building the Bayesian regression equation, the increasing R^2 displayed that the cumulative air temperature of freezing behaved better than the air temperature on bank, 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 (Beltaos and Prowse, 2009a; Robertson et al., 1992), which is proportional to cumulative air temperature of freezing 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 between open water and completely frozen condition.

4 Conclusions

Five river ice phenology indicators, including freeze-up end, freeze-up start, break-up end, break-up start, and complete frozen duration in the Songhua River Basin of Northeast China, have been investigated using in situ measurements for the period 2010 to 2015. The river ice phenology indicators followed the latitudinal gradient and a changing direction from southeast to northwest. The freeze-up start and freeze-up end happened 2.56 and 2.32 day early, the break-up start and break-up end arrived 2.36 and 2.37 days late, resulting in 4.48 days decrease in complete frozen duration. Both Global Moran's I with z score of 1.36 showed that complete frozen duration showed a clustered pattern at the 95% confidence level. The Anselin local Moran's I results showed that the high values of complete frozen duration clustered along the Xiao Higgan Mountain, and the low values of complete frozen duration clustered in the Changbai Mountain. The maximum ice thickness over 125 cm was distributed along the ridge of Da Hagan Mountain and Changbai Mountain, and maximum ice thickness occurred most often in February and March.

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Based on the analysis of monthly time series, snow cover played an increasingly important role as the ice cover becomes completely frozen. The temporal variability in air temperature was more correlated with the variability in ice phenology than in 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. Results showed that snow cover correlated with ice thickness significantly and positively during the periods when the freshwater was completely frozen. The cumulative air temperature of freezing behaved better than air temperature when building the Bayesian regression equation. The results suggested that heat exchanges between the river surface and the atmosphere dominated the ice process, and cumulative air temperature of freezing influenced the thickness is more sensitive indicators of heat loss of ice growth and decay than the air temperature.

This study provided a quantitative investigation of the ice regime in the Songhua River Basin and potential regression models for projecting future changes in the ice regime. Remote sensing data could provide long-term and wide-range information for ice thickness and ice phenology since 1980. The work herein will provide a valuable reference for the retrieval of ice development by remote sensing. Therefore, we plan to use satellite data to enlarge our study scope in our future work.

Author Contribution

Song K.S. and Yang Q. designed the idea of this study together. Yang Q. and Wen Z.D. wrote the paper and analyzed the data cooperatively; Hao X.H. provided valuable suggestions 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.

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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, 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

Table 4 The cross-validation of Bayesian linear regression using k-fold method. The R^2 values of training dataset and testing dataset based on the Bayesian regression. Ice thickness was treated as dependent variables, and air temperature, snow depth on ice as independent variables. Air temperature and cumulative air temperature of freezing were considered in the model building.

Basin	Air temperature		Cumulative air temperature	
	Training	Testing	Training	Testing
NJ	0.80	0.99	0.84	0.99
	0.89	0.80	0.90	0.86
	0.84	0.92	0.89	0.82
	0.90	0.56	0.91	0.61
	0.85	**0.91**	**0.89**	**0.89**
SU	0.83	0.92	0.95	0.98
	0.83	0.65	0.96	0.83
	0.81	0.94	0.95	0.99
	0.84	0.79	**0.95**	**0.93**
	0.82	**0.82**	0.94	0.98
SD	0.80	0.96	0.82	0.98
	0.84	0.16	0.86	0.25
	0.81	0.84	0.82	0.87
	0.79	0.97	0.79	0.96
	0.81	**0.80**	**0.82**	**0.83**

Figures

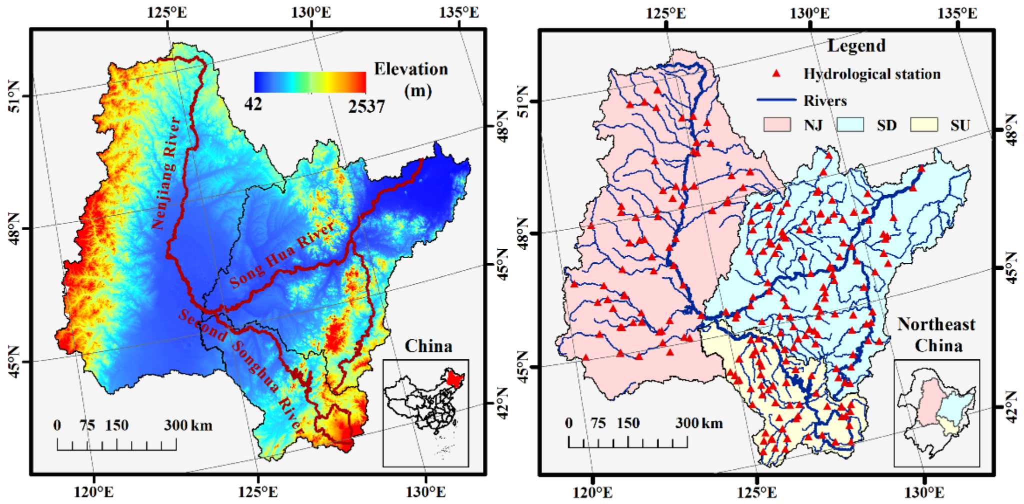

Figure 1 The geographic location of the Songhua River Basin showing (a) the elevation and (b) the location of 156 hydrological stations. The Songhua River Basin includes three sub-basins: Nenjiang River Basin (NJ), downstream Songhua River Basin (SD) and upstream Songhua River Basin (SU). Elevation data are from the Shuttle Radar Topography Mission (SRTM) with spatial resolution of 90 meters.

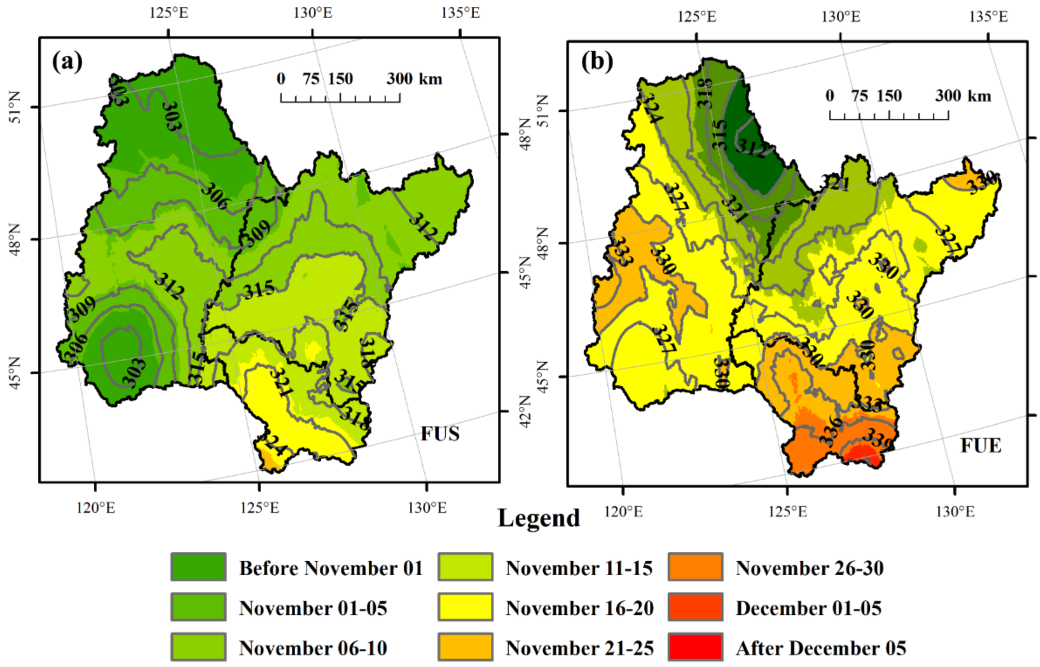

Figure 2 The average spatial distribution of freeze-up start (FUS) (a) and freeze-up end (FUE) (b) in the Songhua River Basin of Northeast China from 2010 to 2015. The number labels indicate the day of year (DOY) of the isophenes.

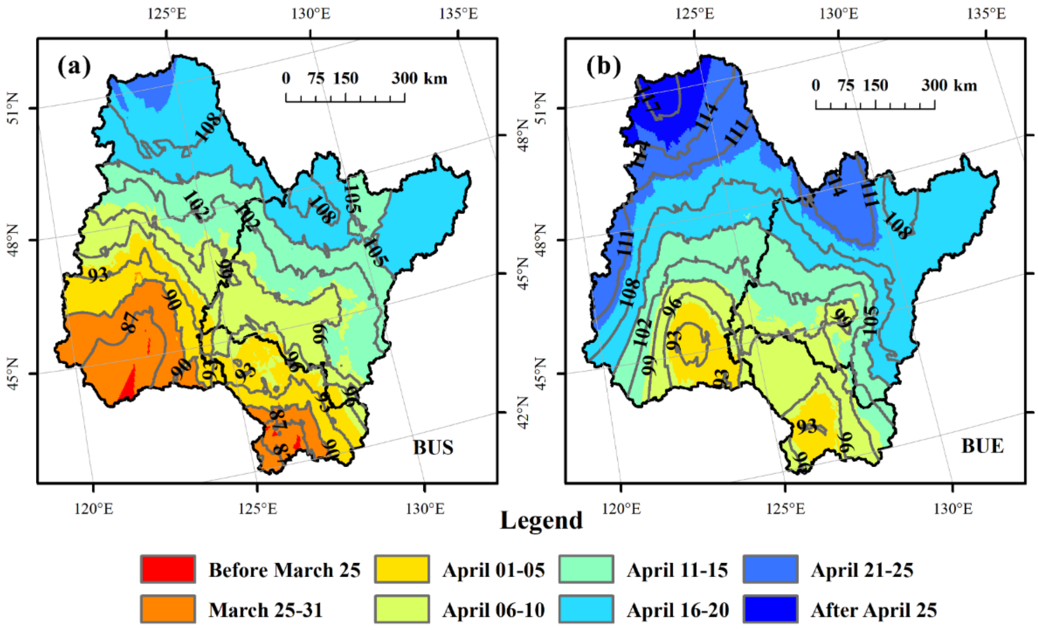

Figure 3 The average spatial distribution of break-up start (BUS) (a) and break-up end (BUE) (b) in the Songhua River Basin of Northeast China from 2010 to 2015. The number labels indicate the day of year (DOY) of the isophenes.

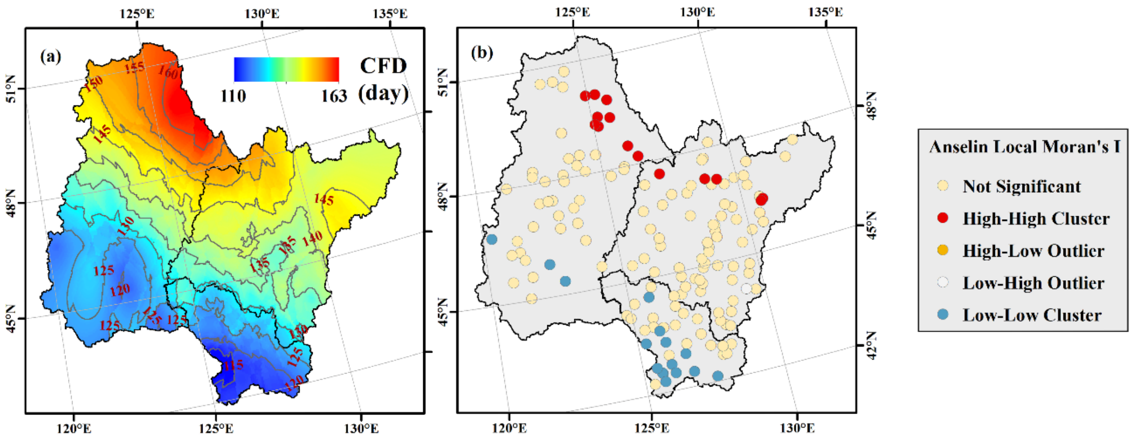

Figure 4 The spatial distribution of complete frozen duration (a) interpolated using Kriging method and Anselin local Moran's I (b) in the Songhua River Basin of Northeast China.

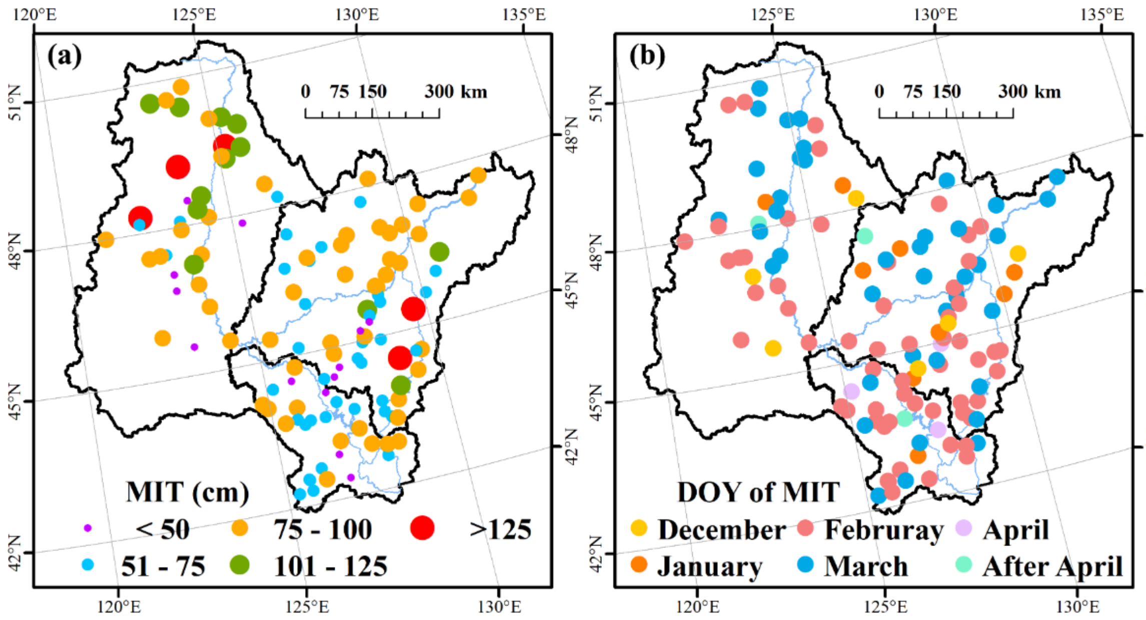

Figure 5 The spatial distribution of yearly maximum ice thickness (MIT) (a) of the river centre and the corresponding date (b).

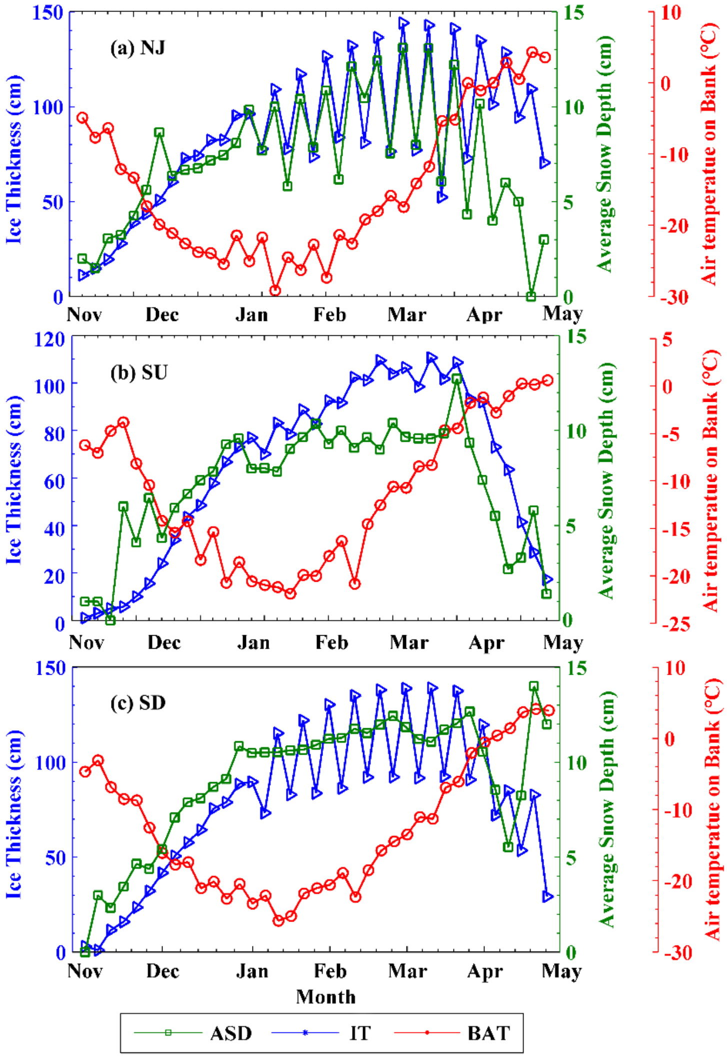

Figure 6 Average seasonal changes in ice thickness (IT), average snow depth (ASD) and air temperature on bank (BAT) from November to April for the period 2010 - 2015.

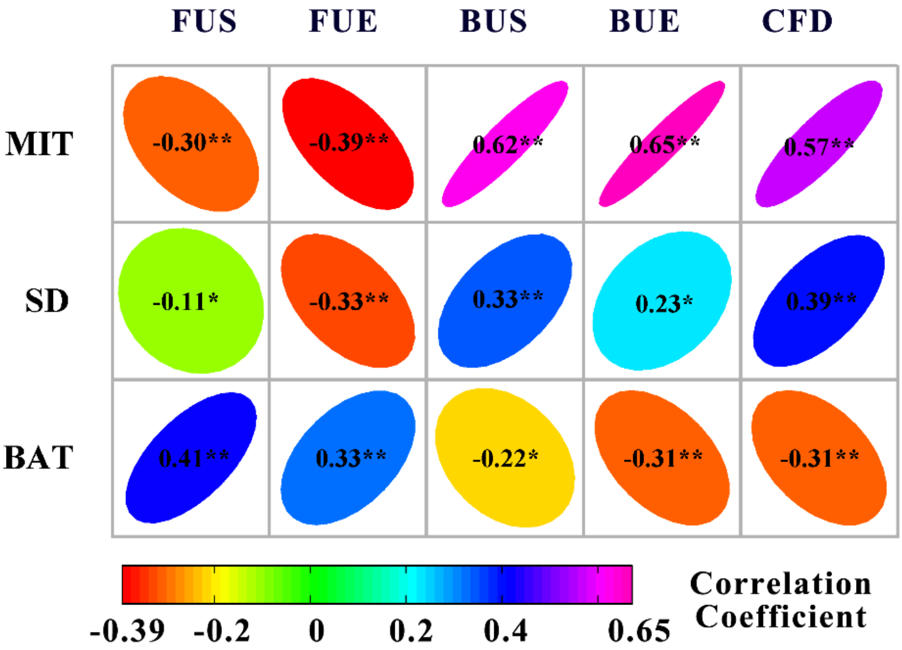

Figure 7 Correlation matrix between maximum ice thickness (MIT), average snow depth (SD) and air temperature on bank (BAT) and lake ice phenology events with data from 120 stations. The asterisk indicates the significance level of the correlation coefficients, ** means significant at 99% level ($p<0.01$),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

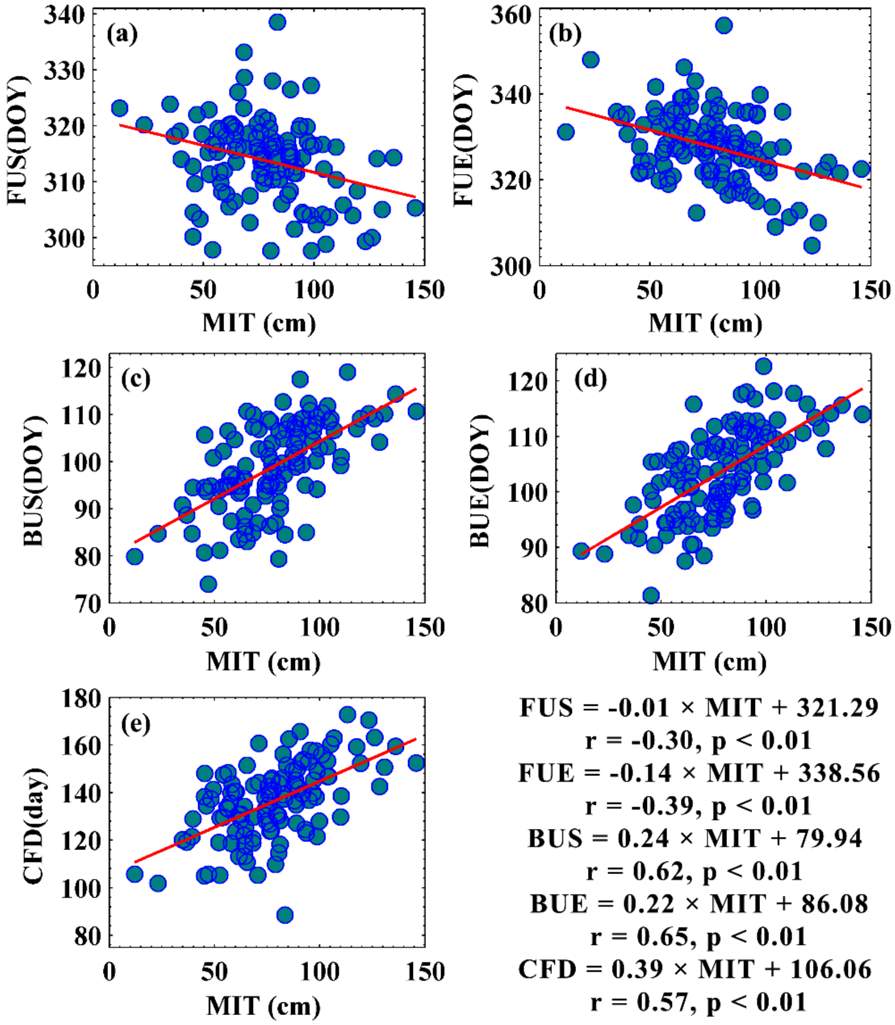

Figure 8 The bivariate scatter plots with linear regression lines between yearly maximum ice thickness (MIT) and ice phenology with dataset size of 120; r and p denote the correlation coefficient and p value of the regression line. The ice phenology events include freeze-up start (FUS), freeze-up end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

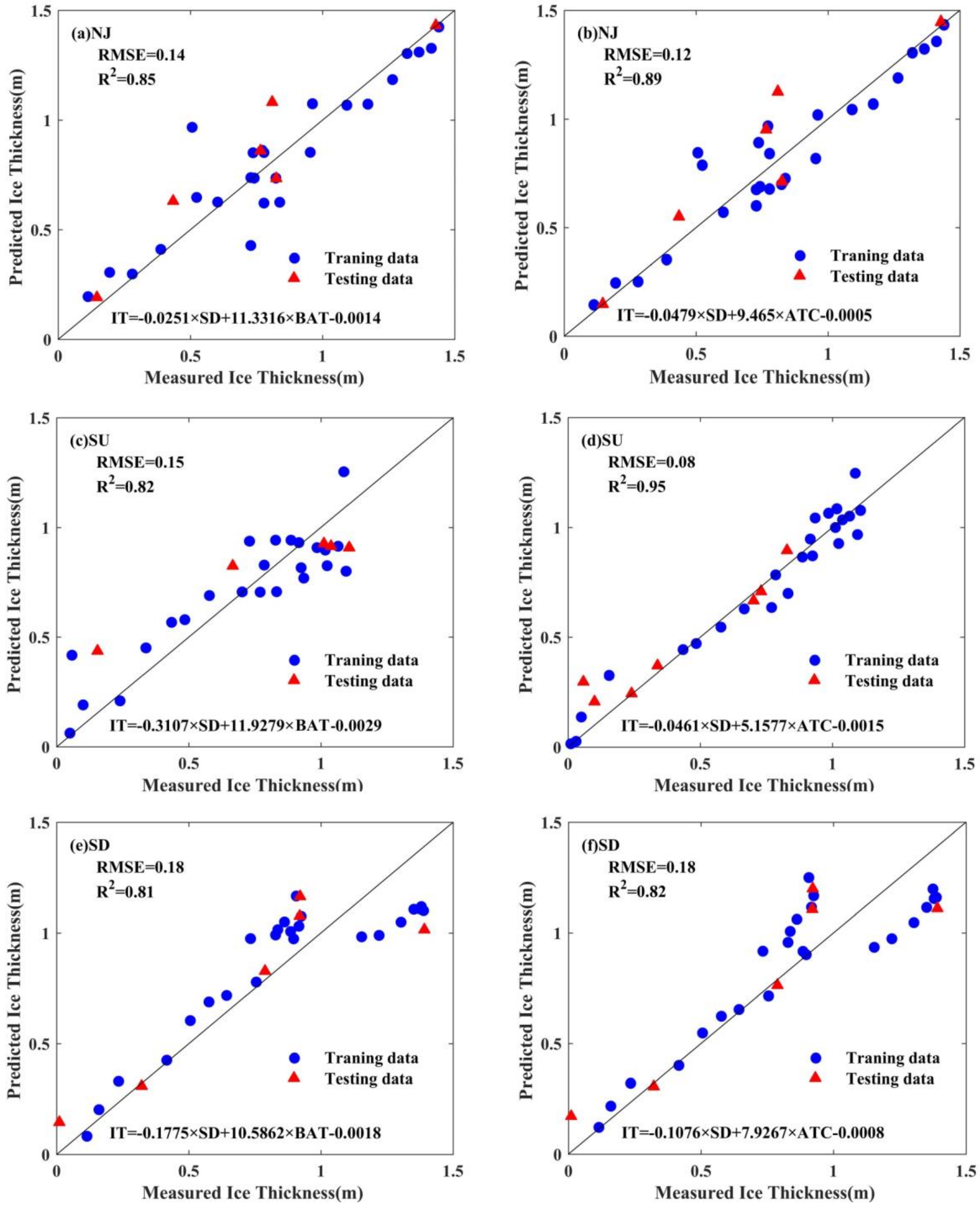

Figure 9 Scatter plots between measured and predicted ice thickness using Bayesian linear regression in three sub-basins (NJ: Nenjiang Basin, SU: upstream Songhua River Basin, and SD: downstream Songhua River Basin) in Northeast China. The model treated ice thickness as the independent variable, and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