

Dear Dr. K ääb and Dr. Gruber,

Thank you very much for providing us the opportunity to improve our paper based on the referees' valuable comments. We have revised the manuscript according to the reviewers' comments and suggestions. Enclosed please find the revised manuscript, responses to the referees, as well as a list of changes. The responses are marked blue. We hope these revisions have improved our manuscript to make it suitable for publication in "The Cryosphere." If you have any questions or concerns about this paper, please don't hesitate to let me know. We look forward to hearing from you soon.

Sincerely yours,

Tingjun Zhang

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The summary of the changes and responses to Referees' comments are listed below. The page, line, and figure numbers refer to our revised manuscript. The changes have been indicated in the paper using bold font.

We thank Dr. Elchin Jafarov for his detailed and insightful review of the discussion paper. We have addressed all the comments and made the suggested changes in the revised version of our manuscript. Our point-by-point replies (in blue) to the comments are listed below.

1. I would suggest to change the 'non-climatic factors' to 'environmental factors' everywhere in the manuscript.

Response: Thank you for this suggestion. We have changed 'non-climatic factors' to 'environmental factors' everywhere in the manuscript.

2. The current version of the paper requires further improvements in language, flow and science.

Response: We have revised the language and further improved the grammar and wording throughout the manuscript.

3. I enjoyed the discussion on snow depth and vegetation and was disappointed that discussion on soil moisture and soil organic matter relationship with SFD was missing.

Response: Thanks for this important reminder. We have explained these additional variables in detail in question 38 (3). Regarding soil moisture and organic matter: we agree that soil moisture and organic matter are two important factors influencing soil freeze depth. Based on previous research, soil moisture and organic matter have significant impacts on active layer thickness (Zhang et al., 1998, Jafarov and Schaefer, 2016). However, we analyze the soil freeze depth based on observational data, and unfortunately we cannot get observational soil moisture and organic matter datasets. If we used remote sensing data or analyzed products, there are many potential errors, e.g., remotely sensed soil moisture can only "see" the top 0–10 cm, the resolution of

the data is coarse, the accuracy is not good, etc.

4. L32. Out of 24% of permafrost affected soils in Northern Hemisphere how many falls in Tibetan Plateau? How much of the area in Tibetan Plateau permafrost-affected (i.e. has an active layer) and how much is seasonally frozen ground (i.e. no permafrost)?

Response: The latest estimates show that permafrost, seasonally frozen ground, and unfrozen ground cover areas of  $1.06 \times 10^6$  km<sup>2</sup> (40% of the Tibetan Plateau),  $1.46 \times 10^6$  km<sup>2</sup> (56% of the Tibetan Plateau), and  $0.03 \times 10^6$  km<sup>2</sup> (1% of the Tibetan Plateau), respectively, excluding glaciers and lakes which cover the remaining 3% (Zou et al., 2016). Permafrost regions occupy about  $22.79 \times 10^6$  km<sup>2</sup> (approximately 24%) of the exposed land surface of the Northern Hemisphere (Zhang et al., 2003). Thus, combining with these dataset, permafrost of Tibetan Plateau occupies about 4.65% of the permafrost of Northern Hemisphere.

5. L56. ...feedbacks to climate change... please cite Abbott et al., (2016).

Response: Thank you, we have added this new reference. Please see L62.

6. Overall the flow in the Data and Methods section needs to be improved. Authors used different datasets (air temp., DEM, snow, etc). All these datasets are in different spatial resolutions. It is not clear to me what was the resolution of the final product and how authors dealt with all these different resolutions.

Response: Thank you! We agree. We reformulated this part to clarify. Daily air temperature, daily ground temperature, daily soil temperature, NDVI, snow depth, mean monthly gridded air temperature (MMGAT), DEM, datasets are used in this study. Generally:

(1) Daily air and ground temperature data are used to estimate air/ground freezing/thawing index, and mean annual air temperature (MAAT), and mean annual ground surface temperature (MAGST) at the point scale;

(2) Daily soil temperature is used to estimate soil freeze depth in the point scale;

(3) Snow depth data are used to correlate soil freeze depth and snow depth in point scale.

(4) DEM is with 1-km spatial resolution, which is helpful for improve the MMGAT resolution and accuracy.

(5) Mean monthly gridded air temperature (MMGAT) data with  $0.5^\circ \times 0.5^\circ$  resolution is combined with the 1-km resolution DEM and monthly lapse rates to obtain a  $1 \text{ km} \times 1 \text{ km}$  temperature dataset (the detail process can be seen in L152-159), which is then used to obtain soil freeze depth in the regional scale with 1-km resolution.

(6) NDVI data is with 8-km spatial resolution, which is used to analyze the relationship with soil freeze depth in the point scale. We obtained NDVI value based on the latitude and longitude information from stations.

7. L78-80. Provide a web-link (reference) to the CMA dataset.

Response: ok, we added the website in L96.

8. L95-103. Is it possible to divide the entire domain to several classes (subregions) with somewhat similar temperatures?

Response: Thanks, this is a good suggestion. The datasets used in the manuscript are just to estimate the freezing index. We worry that if we divide the entire domain to several subregions based on our subjective ideas, it may result in uncertainties or errors because we did not find any existing. Further, this was not one of the goals of this manuscript but we think that this would be a great idea for a future collaboration, perhaps based on some objective criteria and multivariate methodologies (PCA, clustering).

9. L104-107. DEM is finer resolution than MMGAT. Was it extrapolated to 0.5 deg or 0.5 deg was interpolated? Please clarify.

Response: MMGAT was interpolated to the DEM's finer resolution. More detail can be found in L150-159: To improve the original  $0.5^\circ \times 0.5^\circ$  MMGAT data to a 1-km resolution, spatial interpolation was used in conjunction with monthly lapse rates and the 1-km resolution DEM (e.g., Willmott and Matsuura, 1995; Gruber et al., 2012). The data processing steps are to (1) calculate the average monthly atmospheric lapse rate based on all available meteorological stations across China and their elevations; (2) bring each average monthly gridded air temperature value to a reference level (elevation of 0 m) using the average monthly lapse rate; (3) apply a Kriging interpolation to the reference-level adjusted MMGAT; and (4) bring the gridded reference-level air temperature back to the DEM-gridded height. Based on more than 800 sites, we evaluated the interpolated MMGAT against the observational monthly air temperatures, and find that the regression coefficient is almost 1.0 with a minimum of 0.98 in April.

10. L109-112. Is the snow depth (SD) dataset available online? Provide a reference. More description is required. What is an overall snow distribution/max depth? How the SD was extrapolated? How accurate is that extrapolation (include uncertainties)? Where there more snow where is less? It would ice to know how this SD compares with MODIS or Globsnow products?

Response: The daily snow depth dataset is unfortunately not available publicly online, but we have added a reference in L128. In this study, we estimated the annual maximum snow depth based on the methodology described in L131–134. We only used daily snow depth observations, but no remotely sensed data. Because the goals of this study did not include the comparison between the observational snow depth and MORGIS or Globsnow products, we did not undertake this comparison.

11. NDVI. Provide a description similarly to the SD (see previous comment). Note, the Resolution is 8km. How it was used (extrapolated interpolated)?

Response: We added some discussion in the methods section on L139-140: “These data were used to assess the influence of vegetation on soil freeze depth. We extracted the NDVI values corresponding to the stations’ latitude and longitude coordinates.”

12. L118-120. Provide an uncertainty number associated with the interpolation.

Response: We revised this paragraph as follows (L142–149): “Missing data often present a potential problem for analyzing and averaging time series. Therefore, if fewer than five days were missing in a given month, filling in missing daily air temperatures was based on highly correlated neighboring sites using linear regression. Missing daily mean ground surface temperatures were estimated through linear regression with the daily mean air temperature at the same station. Based on the daily air temperature, we also calculate the mean monthly air temperature and mean annual air temperature (MAAT). The interpolated results are strongly correlated with observations, as indicated by regression coefficients larger than 0.95.”

13. L124-125. Did you use 2 DEM datasets? Previously it was 30m, here 1 km?

Response: We used the GTOPO30 DEM data with a resolution of 30 arc-seconds, which is equal to 1 km. We revised this paragraph, please see L120-126: “Considering the complex terrain across China and the impacts of elevation on air temperature, we also used the global 30 arc-second elevation dataset (GTOPO30; <https://lta.cr.usgs.gov/GTOPO30>) as the digital elevation model (DEM) for this study to further improve the MMGAT resolution. GTOPO30 was derived from several raster and vector sources of topographic information. Across China, the elevation ranges from –152 to 8752 m (Figure 1). Based on this DEM, we spatially interpolate the MMGAT data to the DEM’s 30 arc-second (1-km) resolution.”

14. L131. More than 800 sites should go to the description of the monthly gridded air temperature

Response: Thanks! Yes. In this study, more than 800 sites of daily air temperature are used to evaluate the monthly gridded air temperature. Please see the L157-159 “Based on more than 800 sites, we evaluated the interpolated MMGAT against the observational monthly air temperatures, and find that the regression coefficient is almost 1.0 with a minimum of 0.98 in April.”

15. L137. Need to improve flow and rearrange. Repeating the met. station description. Move this sentence to the 2.1.3.

Response: Thanks! Based on your suggestions, we rewrote the “Data and Methods” section. We hope it is better now with an improved flow.

16. L141-143. Snow description should be moved to the 2.1.5. What about snow thermal properties?

Response: Thank you, we have moved it to section 2.1.5. We did not consider the snow thermal properties in our study, because we do not have this dataset.

17. L148. Provide a formula for F<sub>la</sub>.

Response: We have added the formula in the methods section L160-174.

18. L149. What dataset was used for soil thermal conductivities? Are they all constant and a one number or they change based on region and soil type?

Response: In this study, we used the simple Stefan Solution, which applies the edaphic factor, representing soil thermal conductivity, soil bulk density, water content, and latent heat of fusion. Thus, the soil thermal conductivity is different at each station. Further, it is difficult to obtain the soil thermal conductivity at the regional scale. The simple Stefan Solution can be efficient in applying estimated soil freeze depth at the regional scale.

19. L152. Similarly, to conductivities, which dataset was used for soil moisture content?

Response: As above regarding question 18, the edaphic factor included soil moisture content as part of the simple Stefan Solution.

20. L154-156. Complex sentence. I suggest to simplify it or split to two.

Response: Thank you, we split the sentences into two, please see L185-188: “However, based on the SFD and annual freezing index at each observational site, we can quantify the relationship between these two parameters (Figure 2). We find a strong and statistically significant correlation of  $R=0.87$ .”

21. L162. This is an important factor that has been referred in afterwards in the paper. State more clearly why it is important and what it tell us about SFD or permafrost.

Response: We describe the importance of soil freeze depth across China in the introduction, please see L46-75. For SFD or permafrost, please see L107-109 where we explain that “we combine the potential maximum soil seasonal freeze depth in permafrost regions, and maximum soil freeze depth in SFG.”

22. L162-211. Make a workflow chart and refer to it while describing the workflow.

Response: Great suggestion—we made such a workflow chart, introducing how to estimate soil freeze depth using Stefan solution (Fig. 1):

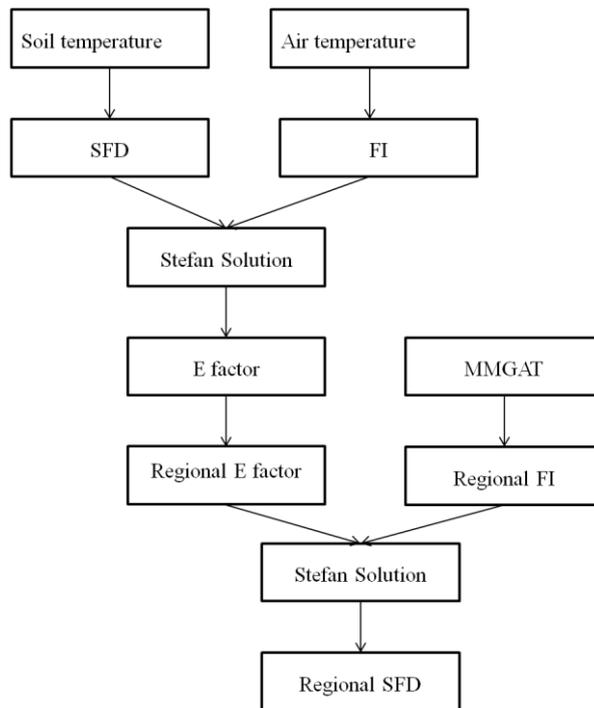


Fig. 1. Flowchart describing how to estimate SFD at the regional scale.

23. L205. ...Stefan method – reference the equation.

Response: We added equation 4 in L190.

24. L215. ...Figure 4. What are the corresponding uncertainties?

Response: As an estimate of the uncertainty of SFD, we provide the standard deviation at each site across China (Fig. 2 below), please see L222-227 “Figure 5 shows the standard deviation of SFD at each site across China. It varies from 0.00–0.27 m. The standard deviation of SFD is generally less than 0.03 m south of 35°N, except on the Tibetan Plateau. In northeastern China, the standard deviation changes between 0.06 m and 0.15 m. In the northwest, it is generally 0.06–0.12 m. On the Tibetan Plateau, the standard deviation varies from less than 0.09 m, but can be greater than 0.18 m at some sites.”

Another SFD uncertainty is the comparison between observational SFD and simulated SFD, Fig. 3 (in the manuscript) have shown it.

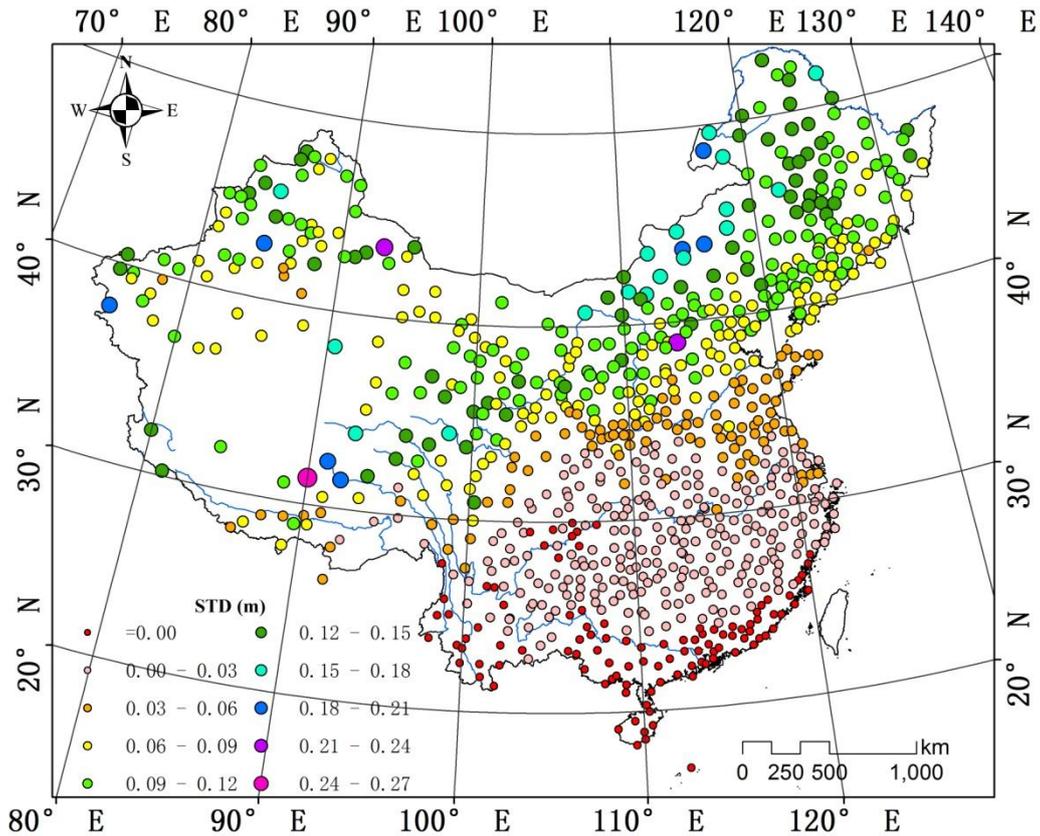


Fig. 2. The standard deviation of SFD across China.

25. L232. By calculating the anomalies for the whole region you average a lot of data. That is why it would be nice to divide the region on several classes, as I suggested above, and calculate anomalies for each subregion separately.

Response: Please see our response below, regarding your comment #38. While it would be interesting to calculate the anomalies of SFD in subregions, there would be different numbers of observational sites in each subregion. Further, we can see the SFD trend in different subregions in Fig. 4c. Here, we just want to provide the time-series of SFD trend in China as a whole, because this has not previously been done and represents a new result.

For the sub-regional averaged SFD changes in different sub-regions, we have added it in discussion part 4.2. Please see the detail explanation in L383-397.

26. 3.2. Section. Again within the subregions it could be easier to quantify changes in spatial variability.

Response: Thanks for your nice suggestion. We discussed the SFD changes in different sub-regions, based on climate zones standard. Please see the detail in L383-397.

27. L263-264. Belongs to discussion. Results section should only include the results description.

Response: Thanks! We add one sentence here, and discuss the relationship between

air temperature and SFD in the other sections. Please see L259-261 “Therefore, air temperature is possibly one of the important factors that influence soil freeze depth in these areas. More detailed discussion is provided in sections 3.3 and 4.1.”

28. L310—311. Rewrite that sense.

Response: We rewrote this, “Similarly, soil freeze/thaw depth changes also have destabilizing effects on engineering structures, such as on improperly constructed infrastructure”.

29. L314. What are pros and cons of using Stefan method?

Response: Soil freeze depth are affected by so many variables, such as soil moisture, soil density, soil texture, thermal conductivity etc. It is difficult or impossible to obtain these parameters in the regional scale. While simple Stefan method provide a catch-all E factor to representing these parameters as a whole. Thus, it is advantage estimating soil freeze depth in the regional scale. Further, this method is successfully using the related study (Zhang et al., 2005; Park et al., 2016).

Except these advantages, some disadvantages are also exist. Due to the catch-all E factor including so many parameters, it limit the accuracy of soil freeze depth comparing with observational dataset. But the uncertainties can be accepted by us (question 24).

30. L317-319 Combine two sentences for better flow.

Response: Thanks! We combined into one sentences, see L315-317 “SFD variability is susceptible to climate warming and environmental change, and is affected by variables including air temperature, ground surface temperature, freezing/thawing index, and vegetation.”.

31. L336. I would not say that TI can influence the ground temperature, because TI is an indicator rather than a factor.

Response: Good point, we revised it as follows in L334: “Thus TI is a potential indicator of SFD, indirectly affecting soil temperature”

32. L340. “snow structure” do you mean snow metamorphism?

Response: “snow structure” is the terminology from Park et al. (2015). Based on the reference, it means snow cover, snow depth, and snow density. However, snow structure can include more properties, such as snow type (Zhong et al., 2014), snow days, snow water equivalent, grain size, and so on.

33. L343. Authors did not find any relationship between SND and SFD. This confirms other findings, similarly Jafarov and Schaefer (2016) did not find any correlation between SND and ALT.

Response: Yes, we agree; in this study, the relationship between SFD and SND is negative, but not statistically significant. Thus, we further analyze the possible reasons in L336-349. Jafarov and Schaefer (2016) ‘s result make us more confidence

for this result. We have cited this reference in this study.

34. L344. Do not need 'the' before snow depth.

Response: Thanks! We delete it.

35. L344-350. Consider drawing plots of thermal offset ( $T_{\text{surface}} - T_{\text{air}}$ ) vs. SND. This could reveal the relationship between offset and snow depth.

Response: We estimated the relationship between snow depth and thermal offset ( $T_{\text{surface}} - T_{\text{air}}$ ) across China (Fig. 3 below). It shows that there is a statistically significant negative correlation between snow depth and thermal offset, though this relationship is mostly caused by some potential outliers. Although there is a slight negative correlation, we focus on soil freeze depth and snow depth in this study. Soil freeze depth is not only at the surface, but also below ground. It is thus more complex and needs further research.

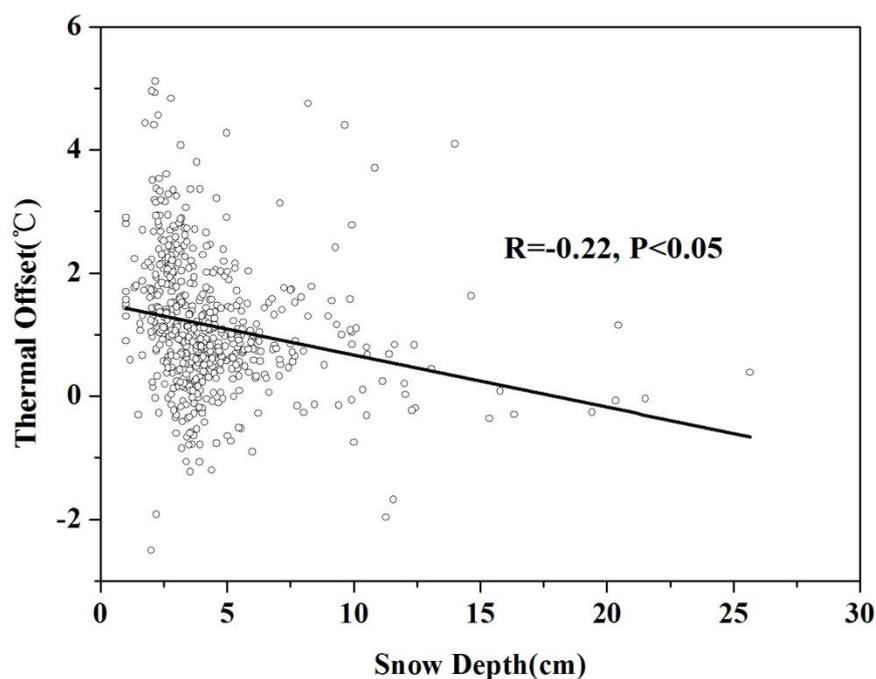


Fig. 3. Correlation between snow depth and thermal offset (difference between ground surface temperature and air temperature).

36. L351. Consider adding a plot of negative correlation of NDVI and SFD.

Response: Thank you—the negative correlation between NDVI and SFD is in Fig. 11.

37. L355. ...via different physical mechanism. Which mechanism?

Response: We apologize for this confusing sentence, and have revised it as follows (see L353-354): "... via different physical mechanisms (Snyder et al., 2004), e.g. changes in the surface albedo....."

38. Some of the conclusion could be moved to the abstract, especially statistics. If you divide your domain on subregions then you could better quantify the variability, and departures from mean in each subregion. This could improve the conclusion. Also which of the non-climatic or environmental factor influences SFD at most, and which one influences at least? Bringing in the influence of soil moisture and organic matter could strengthen the overall message.

Response: Great suggestions—we added these conclusions and statistics to the abstract, please see L24–31: “Investigating potential climatic and environmental driving factors of soil freeze depth variability, we find that mean annual air temperature and ground surface temperature, air thawing index, ground surface thawing index, and vegetation growth are all negatively associated with soil freeze depth. Changes in snow depth are not correlated with soil freeze depth. Air and ground surface freezing index are positively correlated with soil freeze depth. Comparing these potential driving factors of soil freeze depth, we find that freezing index and vegetation growth are more strongly correlated with soil freeze depth, while snow depth is not significant.”

Sub-region problem: this is a very good suggestion for spatial analysis. Thus, based on the potential driving variables of SFD, we divide China into five climate zones, which is powerful used in the related study (Zheng et al., 2010). Please see L383-397. Hopefully, you can agree with us.

Regarding soil moisture and organic matter: we agree that soil moisture and organic matter are two important factors influencing soil freeze depth. Based on previous research, soil moisture and organic matter have significant impacts on active layer thickness (Zhang et al., 1998, Jafarov and Schaefer, 2016). However, we analyze the soil freeze depth based on observational data, and unfortunately we cannot get observational soil moisture and organic matter datasets. If we used remote sensing data or analyzed products, there are many potential errors, e.g., remotely sensed soil moisture can only “see” the top 0–10 cm, the resolution of the data is coarse, the accuracy is not good, etc.

39. Figure 2. Why the linear relationship was chosen? It looks quadratic or exponential to me.

Response: Based on previous studies (Nelson and Outcalt, 1987; Shiklomanov et al., 2002; Zhang et al., 2005; Park et al., 2016), the relationship between soil freeze depth and freezing index was suggested to be linear.

40. Figure 3 c and d. Change y axis ‘station number’ to ‘number of stations’ Also it would nice to see the relationship between SFD and elevation and SFD and latitude.

Response: Thanks! We revised this as suggestged.

For the relationship between SFD and elevation and latitude, we do have figures but we were not sure whether they should be included. We provide them below, and

could add them to the paper if you and the editors believe they add to our findings:

“To explore the spatial features of SFD, we classify the meteorological stations as either eastern or western based on 110 °E longitude. Figure 4 represents the correlations between SFD and latitude and altitude in the eastern and western parts. In the east, we find an exponential relationship between SFD and latitude, and a linear relationship with altitude, with both being statistically significant. The SFD value ranges from 0.0 m to less than 3.5 m, varying with latitude more so than with altitude. Thus, SFD was mainly affected by latitude in the east of China. In the west, SFD is near 0.0 m with altitude higher than 1000m, because these sites are located in the Yunnan-Guizhou Plateau, but with lower latitude. Similarly, SFD is related statistically significantly with altitude and latitude in west, where altitude was the main factor affecting SFD.”

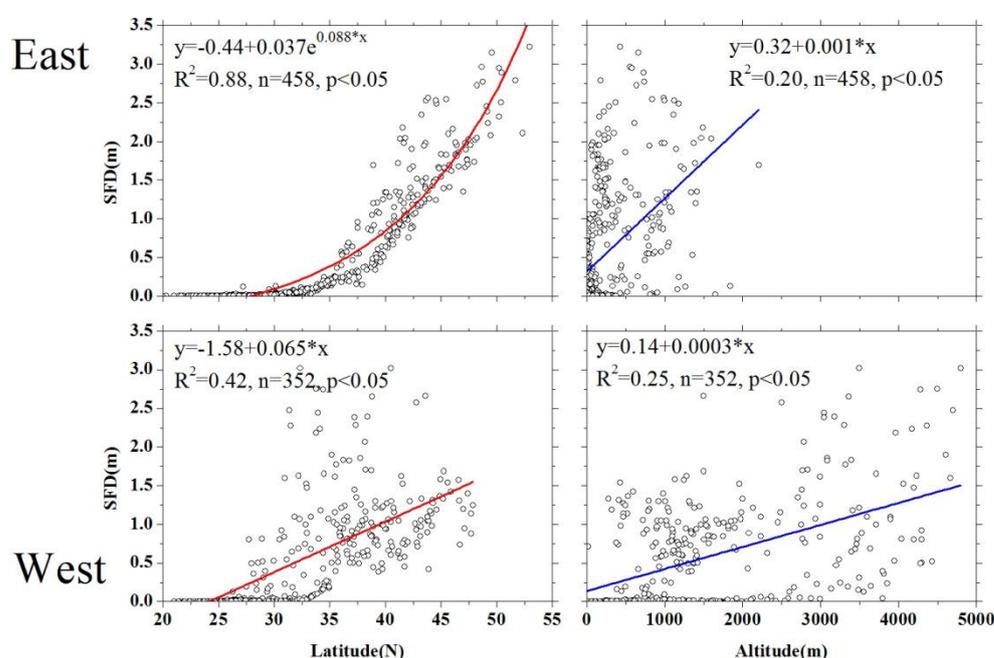


Fig. 4. The relationship between SFD and latitude and altitude in the east and west of China, as divided by 110 °E longitude.

41. Figure 6 spatial variability. I suggest to choose different color bar (BlueWhiteRed), where 0 is blue, white in the middle, and red is 4.5m. This should improve the contrast and make it visually easier to understand.

Response: Thanks! We revised the color bar.

42. Figure 7 is that the rate of change or a total change?

Response: Figure 8 (original figure 7) shows the rate of SFD change during 1950-2010 across China.

43. Figure 8. If the goal is to show the correlation, consider plotting SFD vs. MAGST

and then MAAT, and so on.

Response: The goal of figure 9 (original figure 8) is not only for the correlation, but also to show the variability of SFD, MAGST, MAAT, etc.

44. Figure 9 and 10. Change y axis 'station number' to 'total number of stations'. Similarly, to Fig. 8 consider SFD vs. SND and NDVI and then you can colormap those points that will have the best correlation and analyze which years are those.

Response: ok, we revised these figures, please see new figures 10 and 11.

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