Response to Referee 3

We would like to thank anonymous Referee 3 for reviewing our manuscript. These constructive comments are very important for us to improve the present manuscript. In the following, we address all comments point-by-point according to referee's comments.

General comments:

Gao and co-authors present an analysis of decadal air temperature trends against elevation to explore the case for elevation dependent warming (EDW) in the Chinese Tianshan Mountains (CTM). The authors explore this across a large domain using a recent 1km resolution product derived based upon ERA-Interim reanalysis and station data up to 3000 m a.s.l. They find that for given months and sub-domains of the CTM, EDW is evident, though is complex and not consistent or clear for all domains or seasons. The manuscript is well written in parts and explores a very interesting and relevant topic within the cryosphere. While the work has particular value to be published in the journal, I believe much more needs to be done to explain the data sources and their limitations, to convince the reader of the validity of CTMD product and therefore the uncertainty and limitations of their results as well as providing more justification and better presentation of the key findings.

General Comments I think the manuscript has promise and could be substantially improved based upon some key things.

1) The authors give general reference to their ESSD paper for details about the CMTD product, but a much stronger section of the data and methods need to be presented for this manuscript in order to summarise the key details about how the CMTD was derived, for what time scale it is processed and what the major assumptions or limitations are that might affect the analysis of EDW. It's

apparent to me that the authors are already considering these limitations etc, based upon their responses to other reviewers on the open-discussions. To the reader of this manuscript, there is not enough information presented to judge the quality of the CTMD and assess the validity of the results that are based upon it.

-Answer: Thanks a lot for the comments. The reviewer raised a very important issue as the referee 2 has pointed out before. The data set CTMD is the most important basis for EDW analysis in this study. We know that the credibility of the data set determines the reliability of EDW detection. Indeed, we did not provide much information (such as data production process) on the data set while we focused more on EDW analysis. We agree with the referee that the limitations of the CTMD should be fully demonstrated in the manuscript for better understanding of readers especially who are the potential data users. In the response to referee 2, we planned to use the Land Surface Data Assimilation System (CLDAS-V2.0) from the near real-time product data set from China Meteorological Administration to verify the higher elevations of the CTMD. However, we found this data set (in 2008-2016, we checked last time) is not available since it only begins in 2017, although it applied multiple data resources since 2007 in the data production process. Therefore, we have to seek other data sources to strengthen the verification. What we are struggling with is whether there is really a data set suitable for validating our CTMD product. Due to the lack of ground stations in high mountains (above 3500m), any other reproduce data sets (such as CRU data set at monthly and 0.5 degree spatial-temporal resolution) are flawed. We have always been very worried that the quality of CTMD seems to become an unproven issue. We appreciate that the referee 3 also pointed out the difficulty of observation acquisition. However, we agree that we should present the limitations of the CTMD without reservation in the revision.

2) I have the same issue as 1), but also for the CMA05 product. I am left

questioning the comparability of the two for the tabular information presented (the first criterion of EDW that is the regionally amplified warming). For the CMA05, all pixels are averaged to produce a temperature/warming trend for all elevations across the entirety of China? Is this dataset also derived from ERA-I? Does it include the CTM as well, or all the rest of China except the study domain? If it is all of China, this then also includes other mountain regions of the country? In general, I like the succinct and to-the-point paper, but there are a lot of important pieces of information that are missing and without them, the reader cannot gain a good appreciation of the scientific rigour and value of the authors work. Being clearer about some of those elements will greatly aid the scientific conclusions.

-Answer: Thanks a lot for the comments. The referee is right that the information on the CMA05 is not enough for the readers. We will add more details on the processes of CMA05. In this study, the CMA05 which covers the whole continental China (including the CTM) was compared to CTMD. We think the referee provides a good idea that the CMA05 without the CTM can also be compared. Thus, we will add the trend analysis using the CMA05 excluded the CTM as well as the CMA05 excluded the Tibetan Plateau (The TP is considered to be one of the most intense warming regions in China) in the section 3.1 and also update the results in Table 1 and Table 2 in the revision.

3) In some places, a justification for showing some months and not others are needed. Figures for Tmin, Tmax and Tmean all show different months, for example. Is this purely just to show the months with the strongest trends? Some work needs to go into the figures as well. I see that that has begun already based upon comments fromreviewer#2. In each figure, the authors show different scales (y-axis limits are different in Figures 2-4 and colour scales are different in each subplot for Figures 5-7), and it becomes hard for the reader to easily compare and understand them, and take away the key

message(s). See specific comments on the figures below.

-Answer: Thanks a lot for pointing this issue out. We must admit that the representative months we selected indeed have a significant warming trend. But it is not limited to these four months. We have shown the warming trend for all months in the Supplementary material. Here we want to clarify that we did not use a uniform scale (y-axis limits). We have tried. But the temperature increasing trend for some months at some elevation groups are negative. If a uniform scale used, the possible range could be -1.6 to 2 ˚C $10a^{-1}$. Thus, for some months, the box plot will appear very crowded and small, which is in a poor readable for the percentile ranges (25% to 75%). Thus, we keep the different y-axis ranges. However, the referee's comment is reasonable. We figure out a good way to show the trend comparison for all month is adding a table which including all slope and significance levels. The table is as following:

Table 3. Monthly temperature trends (℃ $10a^{-1}$) in different elevations based on CTMD from 1979–2016.

	Tmin	Tmean	Tmax
January	0.039***	0.036***	0.037***
February	0.033***	0.012	0.008***
March	0.023	0.009**	0.017***
April	0.021***	-0.02***	**0.069****
May	-0.056***	-0.022***	-0.045***
June	-0.025***	0.007	-0.046***
July	0.0	-0.017**	-0.019**
August	-0.011	**0.037****	**0.023****
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October	-0.073***	-0.018***	**0.017****
November	-0.032***	-0.031***	-0.018***
December	0.064***	**0.006****	-0.018***

Note: the bold and underlined value indicates a warming trend for higher elevations, not for the whole elevation range. More details could be found in Figure 2 to 4 and Figure S1 to S12. * denotes the significance level $p<0.1$, ** denotes the significance level $p<0.05$, and *** denotes the significance level $p<0.01$.

4) The manuscript presents a rather general discussion with little further exploration of possible mechanisms. There is a repetition of general comments

regarding, for example, the albedo's role on the surface energy balance, but this never links with why we may see EDW in certain months or why the strongest warming may occur only for Tmin in January/December and why Tmax trends or regional (east-west) temperature trends (e.g. Figure 5) might occur. A reference of Deng et al. 2019 is given, for example, but it is not elaborated upon much. Can this or other datasets or analyses regarding snow cover/albedo from MODIS tell us more about why EDW might be occurring for certain seasons/mountains/zones? I don't suggest that the authors do a full analysis of snow cover, but some additional and more in-depth discussion points are definitely required.

-Answer: Thanks a lot for the comments. The reviewer pointed a very key issue. The physical mechanism of EDW is indeed a challenge issue. The current researches are more about the hypothetical mechanism, rather than quantitative physical mechanism investigation. From our view, surface energy balance is the core mechanism. Among them, snow/ice covers that resulting in surface albedo changes may be the core influencing factors. Deng et al. (2019) did preliminary research using simple statistical analysis, which is not enough to explain the physical mechanism. That is exactly what we want to do in the future, that is, using dynamic models (e.g. WRF) to simulate the relationship between surface ground cover and near surface air temperature. The reviewer's comment is very constructive. We plan to use the remote sensing data (MODIS) to explain the possible impacts of snow/ice cover on temperature changes in the revision.

5) Finally, throughout the manuscript, the terminology of EDW and trends/gradients shifts somewhat and consistency is required throughout (following a clear initial definition). Moreover, the use of the word 'significantly' comes up a lot to refer to differences in trends across space (for the maps) and time (for seasons/months). Unless these differences are tested for significance and values reported, care should be taken for the wording and adjusted

appropriately.

-Answer: Thanks a lot for the comments. The referee 2 also pointed out the terminology problem. We admit that we did not give a very clear definition on EDW, even some misunderstanding. In the revision, we will clarify the EDW definition as well as its features. The trends indeed represent different means respect to space and temporal scale. We will specifically state in the result part in the revision.

Specific comments:

6) Abstract L26 -What are EDW 'Features'? I would consider rewording this.

-Answer: Thanks a lot for the comments. To be precise, regional warming amplification and altitude warming amplification are the two basic EDW characteristics. We will reword this part in the revision.

7) L26-27 – Please add here the time period over which CMTD was derived and analysed (1979- 2016?)

-Answer: Thanks a lot for the comments. We will add the time series 1979-2016 in the revision.

8) L28 – Statistically significant elevation dependence? Add that if so.

-Answer: Thanks a lot for the comments. We will add the statistical significances in the revision.

9) L34 – While I do not disagree that this is a likely contributor to glacier melt in the CTM, the authors do not explicitly 'explain' this link, especially as the EDW trends are not so clear for all summer months. It's possible that stronger trends in warming at high elevations in April could have a key influence on some more precipitation falling as rain, but again, the authors cannot (based upon the presented work) state this. I would rephrase this to something like "This new

evidence could partly explain the accelerated melting of glaciers in the CTM, though the mechanisms remain to be explored" or similar.

-Answer: Thanks a lot for the comments. Our conclusion may be a little bit arbitrary. We will revise this part in the revision.

Introduction

10) L36 – two 'criteria

-Answer: Thanks for pointing this out. We will revise it in the revision.

11) L50 – Current 'evidence'

-Answer: Thanks for pointing this out. We will revise it in the revision.

12) L54 – Please elaborate here and add some reasoning of seasonal significance from those studies.

-Answer: Thanks for pointing this out. We will add more information on it in the revision.

13) L58 – What is global mountain detection? Do the authors refer to detection of trends or 'observations' in general for mountain regions? Please clarify and reword.

-Answer: Thanks for pointing this out. "Global mountain detection" means the researcher investigated the temperature trends for most of large mountains over the world. We will clarify this literature in the revision.

14) L58-74 This paragraph reads rather disjointed without a clear flow or argument. Because it recounts several other instances of studies exploring EDW, the overview might be more valuable to the reader in a tabular format? I would suggest to restructure this paragraph and improve the flow of the writing.

-Answer: Thanks for pointing this out. We will restructure this paragraph and improve the flow of the writing in the revision.

15) L72-73 – Please clarify what satellite data the authors refer to and how that shows EDW/climate warming at specified elevations. How does this point fit into the context of the manuscript discussion and/or the strengths/limitations of the presented dataset?

-Answer: Thanks for pointing this out. We will check the literature in the revision.

16) L81 – Do the authors refer to 56 gridded points of a given product presented by You et al.? Please clarify and rewrite.

-Answer: Thanks for pointing this out. We will clarify this literature in the revision.

17) L87 – To me the “largest independent latitudinal mountain system” is not clear. Can the authors clarify its meaning or remove it?

-Answer: Thanks for pointing this out. We remove it in the revision.

Data and Methods

18) L109 – CTMD is briefly defined at the end of the introduction, but should be described insufficient detailed before introducing other datasets to compare to it. See my general comment about elaborating on the CTMD product, especially on its derivation and potential limitations for exploring EDW in this manuscript.

-Answer: Thanks a lot for the comments. We will add more information in the revision.

19) L111-Taking all elevations of CMA05? It is not clear how comparable these

products are (see general comment). For the CTMD product, the definition of mountain domain is all of the CTMD pixels (including low elevations)? I am left questioning whether the comparison of the CTMD and CMA05 trends are valid and how the values for Table 1 were derived for each of them. More information is required here.

-Answer: Thanks a lot for the comments. We will clarify this part and add more analysis in the revision.

20) L112 – Can the authors define what is a small large scale error? Small biases over large domains?

-Answer: Thanks for pointing this out. We will clarify this part in the revision.

21) L113 – systematic?

-Answer: Thanks for pointing this out. Yes, we will correct it in the revision.

22) L116-118 – It would be valuable to recount that winter lapse rates were not well estimated by CTMD compared to the station data as shown by Fig. 4 of Gao et al., 2018. Some mention here (or in the discussion) needs to explore the potential impact that this might have on your results. If, for example, your temperatures at the highest elevations were estimated by the station lapse rates, would they be largely different from what the CTMD gives you? Could this strongly affect the EDW trends for the highest elevations in January/December? I don't expect that the authors should use the low-elevation stations to derive the high elevation temperatures for their analyses, but some discussion on the limitations of CTMD for the current analyses are required somewhere in the manuscript.

-Answer: Thanks a lot for the comments. The reviewer is right that the limitation of CTMD should be fully demonstrated in the discussion, especially the poor simulation of lapse rate by CTMD in winter.

23) L126 – reword to ‘six-hourly timestep’

-Answer: Thanks for pointing this out. We will correct it in the revision.

24) L136-138 – fine, but maybe neaten, use of table?

-Answer: Thanks for pointing this out. We will neaten it in the revision.

25) L139 – statistical significance of the linear regression? What p-value defines your statistical significance when you use the term significant in the abstract?

-Answer: Thanks a lot for the comments. We used 0.1, 0.05, and 0.01 for p-value to define statistical significance. We add this information for Table 1 and Table 2, as well as the abstract in the revision.

26) L141- averaged is mean or median? (cf boxplots with median red line plotted)

-Answer: Thanks a lot for the comments. Yes, the boxplots show the median value. We used the mean value for consistent trend calculation.

Results

27) L150 – This needs clarification. Do the authors refer to the elevation gradient of decadal temperature trends or the gradient (slope) of the regression line that quantifies the trend in each elevation band? If referring to the latter, please use the word trend (or similar) instead to not confuse with temperature gradient/lapse rate.

-Answer: Thanks for pointing this out. We will clarify this part in the revision.

28) L174 – Why those months only? How are they ‘representative’? Representative of what? I don’t see a clear segregation of season, January and December both have negative trends for the whole domain (converse to

the CMA05), April is not as large an increase as March: : : More justification is needed. Are the authors simply showing all of the results which have more warming somewhere?

-Answer: Thanks a lot for the comments. The representative months we selected indeed have a significant warming trend. But it is not limited to these four months. We have shown the warming trend for all months in the Supplementary material. We will add more information on this part. We also add a table for Figure 2-4.

Table 3. Monthly temperature trends (℃ 10a^{-1}) in different elevations based on CTMD from 1979–2016.

	Tmin	Tmean	Tmax
January	0.039***	0.036***	0.037***
February	0.033***	0.012	0.008***
March	0.023	0.009**	0.017***
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Note: the bold and underlined value indicates a warming trend for higher elevations, not for the whole elevation range. More details could be found in Figure 2 to 4 and Figure S1 to S12. * denotes the significance level $p<0.1$, ** denotes the significance level $p<0.05$, and *** denotes the significance level $p<0.01$.

29) L176 – Is your average a Mean? Median? Note that median is displayed for boxplots.

-Answer: Thanks a lot for the comments. Because we calculated the monthly and seasonal temperature trends for each grid based on averaged 6-hourly data. Thus, we want to keep the consistent trend calculation for all parts. The boxplot shows the 25% to 75% range with the median value. The regression based on mean value reflects extra information for the whole figure.

30) L185 - Figure 3 now investigates March, April, August and September. Why are the same months not compared and what is the justification this time?

-Answer: Thanks for pointing this out. It illustrates the complexity and variability of EDW. Because the performance of different temperature type (Tmin, Tmean and Tmax) is diverse for different months. We try to select the months with the most significant temperature warming trend.

31) L193 – Months of interest for Tmean are again different.

-Answer: Thanks for pointing this out. Yes, the months of interest are different because the diverse performances for different months. We believe it is better to let the readers know which month has the intense warming trend.

32) L203 – Statistically significantly different? If so, by what test and what significance? Same comment throughout the paragraph, please clarify the significance or reword it.

-Answer: Thanks for pointing this out. We will clarify this paragraph and provide the p-value in the revision.

33) L207 – are warmer on average, the figure rather shows a higher rate of warming. Check sentence.

-Answer: Thanks for pointing this out. We reword this sentence in the revision.

Possible hypotheses and mechanisms

34) I feel that this section should be under the general header of 'discussion'. Please see general comments on this section. I believe that much more is needed for this section. It is very general and I don't go away feeling that I learned anything new.

-Answer: Thanks a lot for the comments. We will move this part to the

discussion section. We will also add some new discussion on the mechanisms, for example, the snow/ice cover changes.

35) L255 – Also the snow cover and snow albedo here affect this: : : This is mentioned in the next paragraph and the information is essentially repeated with no additional information gain.

-Answer: Thanks for pointing this out. We will reword this paragraph in the revision.

36) L264-265 – Sure, this could be a mechanism, but has there been any other studies demonstrating snow cover changes and albedo changes in the CTM? I note that the Deng paper is cited but not investigated further. Because the CTMD product is generated through station observations at lower elevations, would this not bias representation of high elevation changes? Of course, I appreciate that there are no available data at those higher elevations, but this needs to be mentioned and limitations of the dataset/study need to be linked with a more in depth interpretation of the most noteworthy results.

-Answer: Thanks a lot for the comments. We will add more discussion about the impacts of snow/ice cover on the temperature changes in the revision. It is true that there are quite few observations at higher elevation to validate the CTMD. The limitation of the CTMD will be fully demonstrated in the revision.

37) L273 – Could be? Are these model simulations of idealised conditions or did authors find this specifically for that zone? Reword to 'estimated glacier mass loss: : :'

-Answer: Thanks for pointing this out. This value is derived from a glacial model that provided by Dr. Deng (2019). We have contacted Dr. Deng that he will provide more data for our further analysis in the revision.

38) L275 – 'In summary'

-Answer: Thanks for pointing this out. We correct it in the revision.

Discussion and Conclusions

39) In my opinion, this section needs splitting into; 1) a greater discussion with section 4 (see general comment and above) and, 2) a clear and concise, separate conclusions section.

-Answer: Thanks for pointing this out. We take this suggestion and will rewrite this section in the revision.

40) L284 – 'DO' not (in the case of CTM) clearly reflect EDW. Not cannot.

-Answer: Thanks for pointing this out. We correct it in the revision.

41) L285-286 – This belongs to the previous section. The authors should elaborate whether earlier spring snow melt is significant (and quantify significance) or at least demonstrate if past work suggests that warming at those higher elevations is more likely. Comparing some general estimates of snow line elevation or from previous findings to those same elevation bands would be of value, though I'm sceptical if the CTMD product will reflect that change.

-Answer: Thanks a lot for the comments. We try to find some snow/ice cover data in spring (there is some data that be possible provided by Dr. Deng at Tianshan No. 1 Glacier station in the Urumqi River Basin in the Zone 2) and to check more literatures to validate our conclusions. The ability of CTMD will be discussed comprehensively in the revision. We still keep cautious confidence in the CTMD.

42) L288 – Replace gradients with trends unless referring specifically to the difference across the elevation bands (Figures 2-4). In general, the terminology needs clarification.

-Answer: Thanks for pointing this out. We correct it in the revision.

43) L297 – I think that this is a crucial point. Above 5000 m, there are always positive trends for minimum and some mean temperatures (Figures 2 and 4). I would like to see more discussion as to why we might expect to have a general cooling (negative) trend for the winter minimum below 3000 m. The lack of discussion regarding the mechanisms is a major drawback to the current manuscript version.

-Answer: Thanks a lot for the comments. The reviewer pointed a very important issue. It is true that the discussion on the mechanism is not enough. The land surface process plays a key role regarding the mechanism. The air at high altitudes is similar to the free atmosphere and the dry adiabatic process is dominant. In low-altitude areas, the impact of underlying surface characteristics (e.g. terrain and land cover) is more significant. We will try to improve this part in the revision.

44) L297-298 – Or could be warming as a result of snow cover depletion (feedback)?

-Answer: Thanks a lot for the comments. The melting and retreat of the snow cover will affect the surface albedo, which changes the surface energy balance. We will discuss more on the snow cover in the revision.

45) L297-302 – This reads like a results section again.

-Answer: Thanks for pointing this out. We will reword it in the revision.

Figures

46) -My general issue with the figures is the lack of standardisation (i.e. different colour and y-axis scales) and the ever changing months presented. It leaves the reader with no strong idea as to the key findings.

-I recommend maintaining the same y-axis limits to all sub-plots in Figures 2-4, labelling the months on the plots for easier interpretation.

-Answer: Thanks a lot for the comments. We have responded before. We want to clarify that we did not use a uniform scale (y-axis limits). We have tried. But the temperature increasing trend for some months at some elevation groups are negative. If a uniform scale would be used, the possible range could be -1.6 to 2 ˚C $10a^{-1}$. Thus, for some months, the box plot will appear very crowded and small, which is in a poor readable for the percentile ranges (25% to 75%). Thus, we keep the different y-axis ranges. However, the referee's comment is reasonable. We figure out a good way to show the trend comparison for all month is adding a table which including all slope and significance levels. The table is as following:

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Note: the bold and underlined value indicates a warming trend for higher elevations, not for the whole elevation range. More details could be found in Figure 2 to 4 and Figure S1 to S12. * denotes the significance level $p<0.1$, ** denotes the significance level $p<0.05$, and *** denotes the significance level $p<0.01$.

47) -For Figures 5-7, please adjust the colour scale from left (blue – negative) to right (red – positive) following the reviewer#2 comments and also set the same total scale limit for each plot (i.e. -1.5 - +1.5 C 10a-1) with 0 C trend always being the same colour (pale yellow or white). Do the authors also report

trends that are not statistically significant? If so, I would also represent these as white or blank pixels if possible. This will aid the reader's ability to interpret and compare the magnitudes of trends between sub-plots/figures as well as areas that aren't statistically significant trends.

-Answer: Thanks for the suggestion. We have revised the figures (e.g. Figure 5). We will try to set the not statistically significant values to white color in the revision.

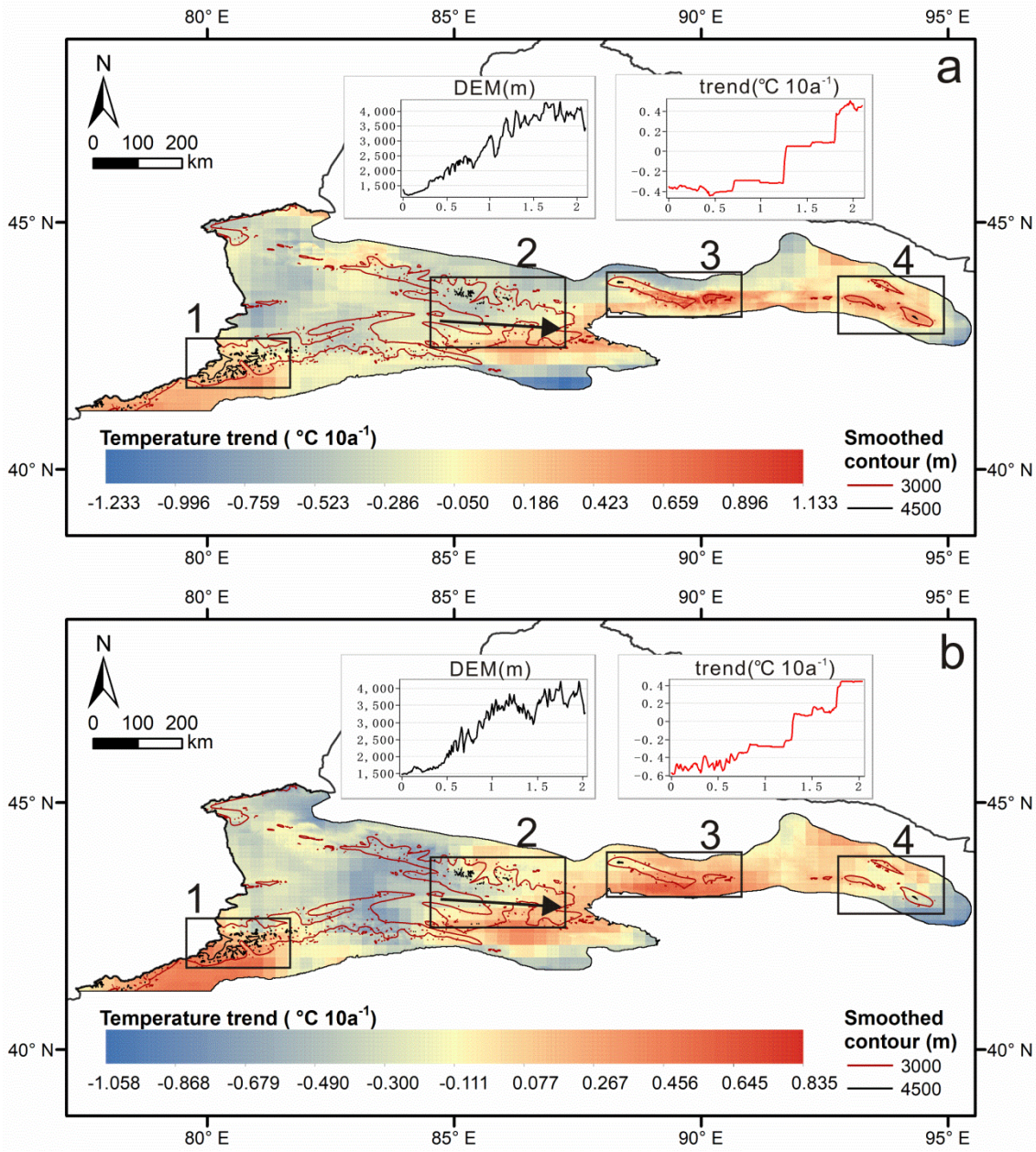

Figure 5: Monthly minimum temperature trends (a) January and (b) December for the entire CTM from 1979–2016. The top two sub-plots show the elevation and temperature

trend along the terrain profile (black arrow) in Zone 2, respectively.

48) -I would suggest adding some other figure(s) that shows the interannual variability of Tmin/Tmax/Tmean for some of the highest elevation pixels so we can better interpret how the suspected EDW warming for March/April/(or month of most interest) looks compared to some lower elevations, or compared to the 'background' change of 'non-mountain' regions shown from the CMA05, if the CMA05 and CTMD are indeed comparable (see general comment). These are the two criteria for EDW and need to be more convincingly demonstrated and discussed.

-Answer: Thanks a lot for the comments. The reviewer provides a very good suggestion. We will add more analysis on the comparison of warming trends in high altitudes and lower elevations in the revision.