Reply to Reviewer #3:

Thank you for the insightful comments and detailed instructions on how to improve the manuscript, and the manuscript has been revised based on the reviewer's comments. Below, the texts with italic font are the reviewer's comments, and the texts with normal font and blue color are the authors' responses.

General comments

In this study, the authors quantify the contributions of the dynamic and thermodynamic components in the observed and projected SAT anomalies under the RCP8.5 scenario. Two climate models are used (MPI-GE and CESM-LE), with respectively 100 and 40 members. The addressed questions and the methods are clearly stated. Overall, the results are presented in a coherent way. The authors show that the dynamic component accounts for most of the cold extremes during 1962-2011, while the thermodynamic changes explain most of the cold extremes in a warmer climate in 2079-2098.

Some parts should be clarified (see specific comments below) and there is a lack of discussion on the reasons which might explain the differences/similarities between the models and the observations (section 3.1) and between both models (section 3.2).

Response: Thank you for your suggestions and comments. We have addressed your questions point by point, and also added discussions on the differences/similarities between the models and the observations (section 3.1) and between both models (section 3.2). Please refer to our specific replies to the comments listed below.

Specific comments

Introduction

1. *L.60 - Please provide a reference.*

Response: We have added a reference as "A strong cold surge related to the negative phase of the Arctic Oscillation (AO) and intensified Siberian High attacked North

China during 6-8 January 2021 (Wang et al., 2021)." Please see L59-61 in the revised manuscript.

2. *L.63 - Maybe also provide the anomaly of this coldest day, such as in L.65,66 for comparison.*

Response: Thank you for your suggestion. For comparison, we added some description "The regional mean temperature in North China during 6-8 January 2021 was about 9°C lower than the average for the same period between the years 2001 and 2020." Please see L63-65 in the revised manuscript.

3. *L.70 - "The model simulations indicate that the anthropogenic influences have reduced the occurrence probability of cold extremes over eastern China with intensity stronger than the record-breaking cold extreme in January 2016 (Qian et al., 2018).": Please specify which period you are referring to? There could not have been intensities larger than the record of 2016 in the past if it is a record (the sentence is not clear).*

Response: Thank you for your suggestion. We have modified this sentence as "… the record-breaking cold extreme (since modern meteorological observations started in 1960) on 21-25 January 2016 (Qian et al., 2018)." Please see L74-75 in the revised manuscript.

Section 2.3

4. *Please justify the choice of the selection of 100 random and 150 closest SLP fields: when does it converge? Is it the same as in Deser et al. (2016), figure A2 in appendix?*

Response: Similar to Deser et al. (2016), the repeated subsampling of optimal linear combinations of analogues is done to ensure the robustness of the results. As our work is based on monthly SAT anomalies, we first randomly selected a few months as examples to examine the impact of the iterative process on the estimation (Figure A1a). The results indicate that as the number of iterations increases (approximately larger than 20), the differences in SAT anomalies among different iterations decrease. Besides, the statistics on cold extremes for the years 1986-2005 boreal winter derived from all members of CESM-LE also exhibit similar results (Figures A1b and c).

We have added a corresponding description “We repeat the subsampling procedure 100 times and average the 100 linear combinations to derive the dynamically induced SAT field in the target month. Deser et al. (2016) illustrate the importance of this iterative random selection process and the reason for the repeated subsampling procedure is to take into account the uncertainty related to internal thermodynamic variability and to ensure the robustness of the results.” Please see L153-158 in the revised manuscript.

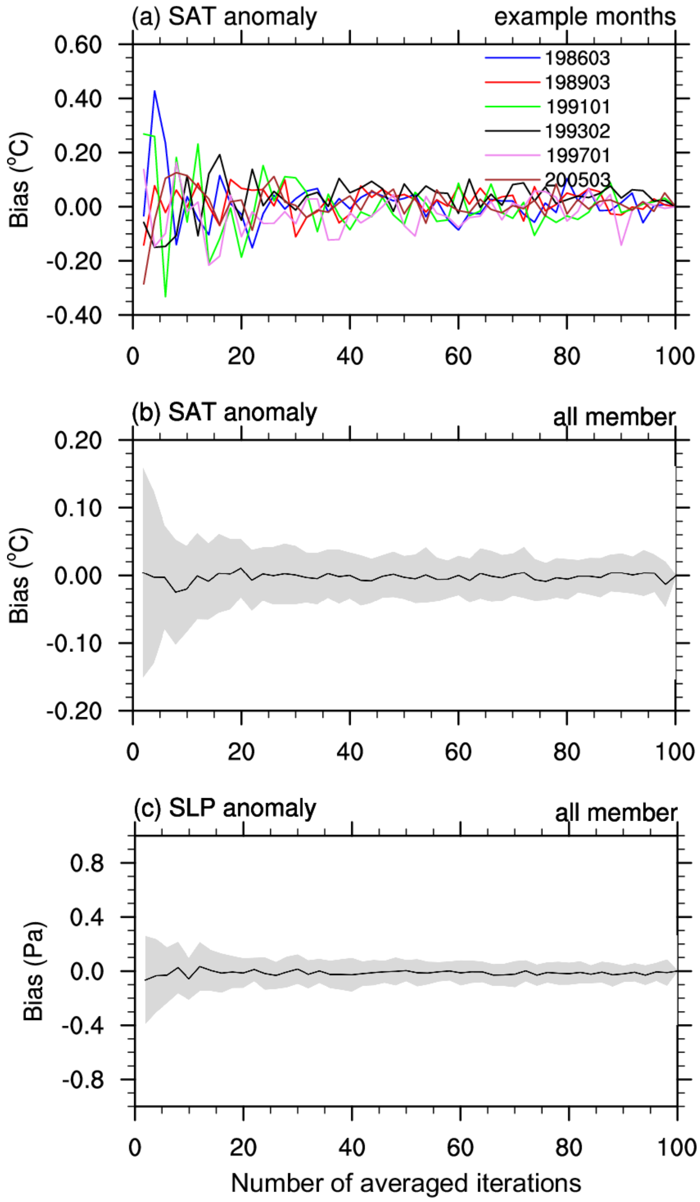

Figure A1 Differences between the results obtained at different numbers of iterations and the results obtained at 100 iterations for (a) example months selected from run 2 of CESM-LE. Subplots (b) and (c) show the result of cold extremes in 1986-2005. The shading shows the range of two standard deviations among the model members of CESM-LE.

5. *L.152 - "the internal dynamic component is obtained by subtracting the forced part from the total dynamic component.": Specify that is done for each ensemble member.*

Response: Thank you for your suggestion. We have modified this sentence as "the internal dynamic component is obtained by subtracting the forced part from the total dynamic component for each ensemble member." Please see L165-166 in the revised manuscript.

Section 2.5

6. *L.180 - "in a certain time slice": Which time slice is taken for the definition of a cold extreme?*

Response: Thank you for your suggestion, we have modified this sentence to "For a specific period, cold extremes are defined as the months in which the regional mean SAT is lower than the statistical 5th percentile of the climatological monthly SAT series during DJF in this period." Please see L196-199 in the revised manuscript.

Section 2.6

7. *L.196 - "we pull all the members together ratio rather than calculate it for each member.": Remove "ratio"? (or reformulate)*

Response: Thank you for your suggestion. We have removed "ratio". Please see L215 in the revised manuscript.

Section 3.1

8. *L.201 - First paragraph on figure 1: Please reformulate and clarify. (1) First, are you referring to observations or PiCTL simulations? (2) Why do you focus on the period 1962-2011, while the available period is 1920-2012, as mentioned L.136? (3) Explain why figure 1 shows that "this is mainly caused by the dynamically-induced internal component". What are the correlation coefficients? (4) What is the physical meaning of the sentence "this variability is the main cause of cold extremes over East Asia in the past five decades" and how do you relate this with figure 1?*

Response: Thank you for your comments. We here respond to your questions point by point.

(1) Figure 1 shows the results obtained from the observation. We have modified the first sentence of section 3.1 as "The observed winter temperature …" Please see L219 in the revised manuscript.

(2) We used data from 1920-2012 for the dynamic adjustment to make use of as much data as possible. For the analysis of the impact of dynamic and thermodynamic processes on cold extremes in East Asia, we focused on the winter period from 1962-2011. This is partly because many observational data for the study region before the 1960s were missing (Feng et al., 2004), and previous studies have shown that the significant warming in China since the 1960s can be attributed to the increase of greenhouse gases (Ding et al., 2007). In Figure 1, we not only show the cold extremes but also want to demonstrate whether external forcing has had a significant impact on the dynamic and thermodynamic parts in the past few decades. Therefore, we focused on the period from 1962-2011.

(3) We calculated the correlation coefficients between each component of the SAT anomalies and the original SAT anomalies and marked them in Figure 1. The results show that the correlation coefficient between the internal variability of the dynamic component is the highest.

(4) We modified the first paragraph of section 3.1 as "The observed winter temperature in East Asia shows obvious variability during the 1962-2011 boreal winter (Figure 1a). According to the correlation coefficients calculated between each component of the SAT anomaly and the original SAT anomaly, the SAT variability is mainly caused by the dynamically induced internal component (Figure 1b-g). The fluctuations of forced dynamic and thermodynamic components are much smaller than those of internal dynamic and thermodynamic ones (Figure 1c, d, f and g). Internal variability is the main cause of cold extremes over East Asia in the past five decades (Figure 1)." Please see L219-226 in the revised manuscript.

9. *Figure 1: Why the forced and internal parts of the thermodynamic component are not shown, but described in the methods L.168? This should be clarified.*

Response: Thank you for your comment. We have added the forced and internal parts of the thermodynamic component in Figure 1 as subplots f and g in the revised manuscript.

10. *L.210 - "especially for the cold extremes happened in recent years": Please clarify why? Looking at table 1, this is the case for 196402, 196902, 107701, 196712, 201101, 196612, so not necessarily the most recent years?*

Response: Thank you for your comment. We have reformulated the sentence to "… Compared to cold extremes in the 1960s and 1970s, the percentage contribution of the dynamic component to the cold extreme in January 2011 is higher …" Please see L233-235 in the revised manuscript.

11. *L.213 - To support the argument, the correlation coefficients could have been calculated for the different subplots, as suggested previously.*

Response: Thank you for your suggestion. We have added the correlation coefficients in Figure 1 in the revised manuscript.

12. *L.216 - "The two sets of large ensemble model simulations can well reproduce the relative contributions of the dynamic and thermodynamic components to the cold extremes during 1962-2011 boreal winter (Figure 2d-i).": Please reformulate. The relative contribution does not seem very well reproduced, as the thermodynamic component is much lower within the simulations than in the observations, and the dynamical part is much larger, especially in the North of the region (figure 2 b,c vs. e,h,f,i).*

Response: Thank you for your suggestion. We have reformulated this part as "The two sets of large ensemble model simulations can generally capture the spatial distributions of total SAT anomaly and the dynamic component of cold extremes during 1962-2011 boreal winter (Figure 2d, e, g and h), with pattern correlation coefficients higher than 0.7 in both model ensembles. However, the thermodynamic component is much weaker in the model simulations than in the observation, especially in the northern parts of East Asia (Figure 2f and i) …" Please see L241-246 in the revised manuscript.

13. *L.218 - "The SAT is significantly lower than the winter SAT climatology throughout East Asia": Considering that composites of the coldest months are selected, isn't it expected by definition?*

Response: Thank you for your comment, we have removed this sentence in the revised manuscript.

14. *L.223 - "The dynamic component accounts up to 85% and 82% of the total East Asian cold-month SAT anomaly during 1962-2011 boreal winter in the MPI-GE and the CESM-LE, respectively": Similarly, what is the percentage of the dynamic component during the whole period 1962-2011 in the observations, to compare with the simulations?*

Response: Thank you for your suggestion. We have added the corresponding description as "The dynamic component accounts for approximately 55% of the total East Asian cold-month SAT anomaly during the 1962-2011 boreal winter." Please see L232-233 in the revised manuscript.

15. *L.229 - "The cold extremes are often associated with strong East Asian winter monsoon flows, which are often accompanied with the blockings in the Urals and the intensified Siberian high.": Please provide reference(s).*

Response: Thank you for your suggestion. We have added related references as "The cold extremes are often associated with strong East Asian winter monsoon flows, which are often accompanied by the blockings in the Urals and the intensified Siberian high (Francis and Vavrus, 2012; Ma et al., 2018)." Please see L256-259 in the revised manuscript.

16. *L.235 - "there is an enhanced meandering flow pattern (Figure 3b)." Please explain why.*

Response: Previous studies indicate that the weakened zonal westerly wind tends to enhance a wavier meandering flow pattern (Walsh, 2014; Simmonds, 2015). The slowdown of the eastward propagation of Rossby waves induced by the weakened westerlies (according to the relationship between the Rossby phase speed and mean westerly wind speed) can also further enhance a broader meander (Ma et al., 2018).

We have added the related references as "there is an enhanced meandering flow pattern (Figure 3b; Walsh, 2014; Simmonds, 2015; Ma et al., 2018)." Please see L262-264 in the revised manuscript.

17. *L.236 - "The weakened westerlies may favor the blocking events, which have strong relationship with the cold extremes over East Asia.": Please provide reference(s).*

Response: Thank you for your suggestion. We have added a related reference "The weakened westerlies may favor the blocking events, which have a strong relationship with the cold extremes over East Asia (Luo et al., 2017)." Please see L265-266 in the revised manuscript.

18. *Figure 3: Plotting the climatology in contours would help to visualize the deviation or reinforcement of the dynamics with respect to the climatology. Do the models and observations have similar climatologies regarding the circulation?*

Response: Thank you for your suggestion. We have added the climatology in contours. Please see Figure 3 in the revised manuscript.

19. *Part 3.1: This part (or the discussion section) would benefit from a discussion on the differences/similarities between the observations and models obtained here for the cold extreme composites, and for total, thermodynamic and dynamic components.*

Response: Thank you for your suggestion. We have added a discussion on the differences/similarities between the observations and models as follows.

"Compared with the observation, the contribution of the dynamic component to the cold extremes is larger in the two model ensembles (Figure 2). One possible reason is that there are only 8 cold extreme samples in the observation, and the relative contributions of dynamic and thermodynamic components cannot be fully reflected by these samples. Another possible reason may be the uncertainty of local thermodynamic processes (Röthlisberger and Papritz, 2023)." Please see L249-254 in the revised manuscript.

Section 3.2

20. *L.264 - "The faster increase of thermodynamic components in northern East Asia may be caused by the snow-albedo feedback, while the reason for the faster increase in dynamic component in this region is that the influence of East Asian Winter Monsoon on northern East Asia is more evident than on other subregions." On these two aspects, please provide further explanation or cite literature.*

Response: Thank you for your suggestion. We have cited the related literature as "The faster increase of thermodynamic components in northern East Asia may be caused by the snow-albedo feedback (Fischer et al., 2011), while the reason for the faster increase in dynamic components in this region is that the influence of East Asian Winter Monsoon on northern East Asia is more evident than on other subregions (He et al., 2017)." Please see L296-300 in the revised manuscript.

21. *L.262 and second paragraph of section 3.2: it should be emphasized that it is now the thermodynamic part which plays a major role (e.g. in figure 4 a,c: it is worth noting that, in approx. the first half of the period plotted in figure 4, the dynamical component explains a larger part of the total SAT, while in approx. the second half it is the thermodynamical component, in both models.)*

Response: Thank you for your suggestion. We have added some descriptions as "It is worth noting that, the dynamic component explains a larger part of the total SAT anomaly in cold months before approximately 2040. Thereafter, the thermodynamic component is the main driver in both model ensembles (Figure 4a and c)." Please see L288-291 in the revised manuscript.

22. *L.270 - "The corresponding increases in the dynamic and thermodynamic components are 1.3 ℃ and 3.9 ℃,": Please also give the percentages to compare to L.262.*

Response: Thank you for your suggestion. We have added further descriptions such as "Statistically, the contribution of the increase in dynamic component to the total SAT increase is about 25%." Please see L304-305 in the revised manuscript.

23. *L.274 - "The thermodynamic component shows some differences (Figure 5c and f).": Specify what are these differences? What are the reasons which might explain why there are differences between both ensemble means, in the total, dynamic and thermodynamic components?*

Response: Thank you for your suggestion. We have modified this part and added a discussion as follows.

"From the perspective of spatial distribution, total SAT and its dynamic and thermodynamic components show similar changing patterns in the two sets of large ensemble model simulations, with large increases occurring in northern parts of East Asia (Figure 5). However, there are some local differences between the two models. Compared with MPI-GE, the end-of-the 21st-century increase in cold-month regional mean SAT is approximately 0.3°C higher in CESM-LE, primarily due to the thermodynamic component. The larger increase of thermodynamic components in Northeast and Southeast China in CESM-LE than in MPI-GE may be attributed to differences in thermal feedback processes, such as the snow-albedo feedback and land-surface fluxes (Seneviratne et al., 2010; Fischer et al., 2011; Röthlisberger and Papritz, 2023).” Please see L305-315 in the revised manuscript.

For the difference in local features of dynamic components between the two models, we added “There are some differences in the SLP changing patterns between the two model ensembles, particularly during cold extremes over the Eurasian region. This could be one of the possible reasons for the differences in local dynamic changes in the two model ensembles.” Please see L361-364 in the revised manuscript.

24. *L.306 - “the projected changes in SLP exhibit a positive AO-like pattern, particularly in the MPI-GE (Figure 7a and b).”: What is the correlation of the obtained pattern with the AO SLP pattern?*

Response: We have added the correlation coefficient as “the projected changes in SLP exhibit a positive AO-like pattern, especially in MPI-GE (Figure 7). The pattern correlation coefficients between the SLP changing patterns and the positive phase of AO in MPI-GE and CESM-LE are approximately 0.7 and 0.4, respectively (Figure 7a and c).” Please see L349-352 in the revised manuscript.

25. *L.311 - “Similar SLP changing pattern also occurs in cold months (Figure 7c and d)”: You might want to specify that you are now referring to the CESM-LE model? The results for this model (figure 7c,d and figure 8c,d) do not look similar to the MPI-GE model, especially comparing figures 7d and 7b, and figure 8d and 8b, where the SLP patterns during cold extremes are different over Eurasia. Comparing correlation coefficients with the AO SLP pattern could be useful for the interpretation/comparison of the different figures. Please reformulate this part.*

Response: Sorry for the typo. What we originally intended to write was “… also occurs in cold months (Figure 7b and d)”. We intended to convey that the changes of SLP in cold months are similar to that in winter mean, and have modified this part as

"The SLP changing patterns in cold months (Figure 7b and d) are similar to those in winter mean (Figure 7a and c)". Please see L356-357 in the revised manuscript.

The changing patterns of SLP in CESM-LE and MPI-GE during cold extremes are different over Eurasia, and we have added this part as "There are some differences in the SLP changing patterns between the two model ensembles, particularly during cold extremes over the Eurasian region." Please see L361-363 in the revised manuscript.

26. L.302 - "The thermodynamic change is the main contributor to the decreases in the intensity and occurrence probability of East Asian cold extremes, while the dynamic change is also contributive.": Based on figure 4 and figure 5, the dynamic component seems minor in explaining the total SAT, this should be clarified.

Response: Thank you for your comment. We have provided further clarification: "Thermodynamic component dominates the future decrease in the intensity and occurrence probability of East Asian cold extremes, while the dynamic component is also contributive. Dynamic change accounts for approximately one-quarter of the total change in the intensity of cold extremes by the end of the 21st century." Please see L342-345 in the revised manuscript.

Section 4.1

27. The 3 summarized points does not exactly correspond to the 3 questions raised at the beginning in the introduction.

Response: We have modified the 3 questions in the introduction as follows:

"(1) What are the relative contributions of the dynamic and thermodynamic effects to the East Asian cold extremes in the past several decades? (2) How will the intensity and occurrence probability of East Asian cold extremes change in the warmer future and what are the quantitative contributions of the dynamic and thermodynamic effects to the changes of East Asian cold extremes in the warmer future? (3) How will the circulation changes in the warmer future and how will this change affect cold extremes in East Asia?"

Please see L111-117 in the revised manuscript.

28. L.326 - *"especially for the cold extremes happened in recent years.": Why? Please see the comment about L.210.*

Response: We have modified this sentence as "Compared to cold extremes in the 1960s and 1970s, the percentage contribution of dynamic component to the cold extreme in recent years is higher." Please see L374-376 in the revised manuscript.

29. L.328 - *"The relative contributions of the dynamic and thermodynamic components to the cold extremes are well captured in the two model ensembles": Please reformulate the conclusion, see comment about L.216.*

Response： We have modified this sentence as "Compared with the observation, the contribution of the dynamic component to the cold extremes is more evident in the two model ensembles, and the dynamic component accounts for more than 80% of the total cold-month SAT anomalies in the past five decades." Please see L378-381 in the revised manuscript.

30. L.333 - *"In the future warm climate, the background warming is the main contributor to the decreases in the intensity and occurrence probability of East Asian cold extremes, while the circulation changes are also contributive.": The results presented in this paper (figure 4 and 5) seem to indicate that the changes in cold extreme SAT are mainly governed by the thermodynamic part; this should be emphasized (cf. comment about L.302).*

Response: Thank you for your suggestion. We have changed this sentence to "In the future warm climate, the decreases in the intensity and occurrence probability of East Asian cold extremes are dominated by thermodynamic component, while the dynamic component is also contributive." Please see L382-384 in the revised manuscript.

31. *L.335 - "Compared with the present day, the mean intensity of the East Asian cold extremes will decrease by approximately 5 ℃ at the end of the 21st century under the RCP8.5 scenario and the dynamic component contributes to a quarter of this decrease.": It should be mentioned that this is the case in the MPI-GE and CESM-LE models.*

Response: Thank you for your suggestion. We have modified this sentence to "According to MPI-GE and CESM-LE, compared with the present day, the mean intensity of the East Asian cold extremes will decrease by approximately 5°C at the end of the 21st century under the RCP8.5 scenario and the dynamic component contributes to a quarter of this decrease." Please see L384-387 in the revised manuscript.

32. *L.342 - "Positive AO-like sea level pressure pattern upward trend is projected in both of the model ensembles": This should be clarified, in line with comments on L.306 and L.311.*

Response: Thank you for your suggestion. We have modified this part as "Positive AO-like sea level pressure pattern upward trend is projected in both of the model ensembles, which is unfavorable to the occurrence of East Asian cold extremes. There are a few differences between the two-ensemble projection, particularly in the Eurasian region during cold extremes, and this could be one of the possible reasons for the local differences of dynamic components in the two model ensembles." Please see L391-396 in the revised manuscript.

Technical Corrections

33. *L.46 - Replace "concerned" by "concerning"?*

Response: Corrected. Please see L46 in the revised manuscript.

34. *L.47 - Typography: 2 commas*

Response: Corrected. Please see L47 in the revised manuscript.

35. *L.48 - Typography: "and even"*

Response: Corrected. Please see L48 in the revised manuscript.

36. L.63 - "North America" or "The north of America"

Response: Corrected. Please see L65 in the revised manuscript.

37. L.68 - Replace "if" by "while"?

Response: Corrected. Please see L70 in the revised manuscript.

References

Deser, C., Terray, L., & Phillips, A. S. (2016). Forced and internal components of winter air temperature trends over North America during the past 50 years: Mechanisms and implications. Journal of Climate, 29(6), 2237-2258. https://doi.org/10.1175/JCLI-D-15-0304.1

Ding, Y., Ren, G., Zhao, Z., Xu, Y., Luo, Y., Li, Q., & Zhang, J. (2007). Detection, causes and projection of climate change over China: an overview of recent progress. Advances in Atmospheric Sciences, 24, 954-971.

Feng S, Hu Q, Qian WH. 2004. Quality control of daily meterological data in China, 1951–2000: a new dataset. International Journal of Climatology 24: 853–870.

Fischer, E. M., Lawrence, D. M., & Sanderson, B. M. (2011). Quantifying uncertainties in projections of extremes—A perturbed land surface parameter experiment. Climate Dynamics, 37, 1381-1398.

Francis, J. A., & Vavrus, S. J. (2012). Evidence linking Arctic amplification to extreme weather in mid - latitudes. Geophysical research letters, 39(6).

He, S., Gao, Y., Li, F., Wang, H., & He, Y. (2017). Impact of Arctic Oscillation on the East Asian climate: A review. Earth-Science Reviews, 164, 48-62.

Luo, D., Yao, Y., Dai, A., Simmonds, I., & Zhong, L. (2017). Increased quasi stationarity and persistence of winter Ural blocking and Eurasian extreme cold events in response to Arctic warming. Part II: A theoretical explanation. Journal of Climate, 30(10), 3569-3587.

Ma, S., Zhu, C., Liu, B., Zhou, T., Ding, Y., & Orsolini, Y. J. (2018). Polarized response of East Asian winter temperature extremes in the era of Arctic warming. Journal of Climate, 31(14), 5543-5557. https://doi.org/10.1175/JCLI-D-17-0463.1

Qian, C., Wang, J., Dong, S., Yin, H., Burke, C., Ciavarella, A., ... & Tett, S. F. (2018). Human Influence on the Record-breaking Cold Event in January of 2016 inEastern China. [in “Explaining Extreme Events of 2016 from a Climate Perspective”]. Bulletin of the American Meteorological Society, 99(1), S118-S122. https://doi.org/10.1175/BAMS-D-17-0095.1

Röthlisberger, M., & Papritz, L. (2023). A global quantification of the physical processes leading to near‐surface cold extremes. Geophysical Research Letters, 50(5), e2022GL101670.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., ... & Teuling, A. J. (2010). Investigating soil moisture–climate interactions in a changing climate: A review. Earth-Science Reviews, 99(3-4), 125-161.

Simmonds, I. (2015). Comparing and contrasting the behaviour of Arctic and Antarctic sea ice over the 35 year period 1979-2013. Annals of Glaciology, 56(69), 18-28.

Walsh, J. E. (2014). Intensified warming of the Arctic: Causes and impacts on middle latitudes. Global and Planetary Change, 117, 52-63.

Wang, C., Yao, Y., Wang, H., Sun, X., & Zheng, J. (2021). The 2020 summer floods and 2020/21 winter extreme cold surges in China and the 2020 typhoon season in the western North Pacific.