Response to Reviewer #2's Comments

The manuscript was improved substantially by this revision. I have a few suggestions.

We sincerely thank for the reviewer's time and helpful suggestions on greatly improving the quality of this manuscript. As for the further comments, we have responded to all the comments point-by-point and made corresponding changes in the manuscript as highlighted in red color. Please check the responses to all the comments as below.

1) Some discussion in the response letter should be added to the manuscript.

First, in the response to my previous review comment (1), the authors described as follows: "We do agree with the reviewer that currently no single model could reproduce the BC concentrations over different regions of the Arctic well. There is a number of reasons responsible for this. First, the BC emission inventory in the Arctic is not well understood due to lacking of local activity data and emission factors, e.g. gas flaring in the oil and gas production fields, biofuel combustion, non-road transportation, etc. Secondly, the lifetime of BC in the atmosphere is sensitive to its wet deposition rates. However, different models have divergent treatment of wet scavenging parameterizations (Bourgeois et al., 2011; Liu et al., 2011), which may be not representative in the Arctic region and could result in the simulated BC concentrations ranging between several magnitudes. The mechanism of BC sinks is still not well understood in the Arctic. Last but not the least, almost all the global models used the latitude/longitude projection which has very large distortions over the polar regions and this may also affect the ability of global models simulating the air pollutants over the Arctic region. In a previous study by Shindell et al. (2008), a similar ensemble modeling study on Arctic BC was conducted. As shown in the figure below, the single model cannot reproduce the observed BC monthly variations at two sites, either. As a comparison, this study showed better model performances as seen in Figure S2a, which was due to a better global BC emission inventory and development of some key physical schemes in some global models after years. However, some similar issues as previous studies still existed, such as overestimation of BC during summer and underestimation of BC during winter. To reduce the bias from one single model, the

best way may be using the ensemble model mean as similar as those climate studies such as CMIP5 and CMIP6. This is also the goal of HTAP that collects various global model simulation results of atmospheric chemistry and uses the model ensemble results to solve the source-receptor relationship in regions of interest.". This discussion can be added to the manuscript.

Thanks for the suggestion. We have added a paragraph in Line 294 – 304.

Second, in the response to my previous review comment (4), the authors described as follows: "Matsui (2011) pointed out that Asian AN air masses were measured most frequently in the upper troposphere, with median values of 20 ng m^{-3} (410hPa) in April 2008 and 5 ng m^{-3} (353hPa) in June–July 2008. In our analysis, the contribution of 20% emission from EAS and SAS to BC in the Arctic was 1.4 ng m^{-3} (432hPa) in April 2010 and 0.7 ng m^{-3} (375hPa) in June–July 2010. If the contribution is linearly interpolated, the contribution of 100% emission from EAS and SAS to BC in the Arctic would be about 7 ng m^{-3} (432hPa) in April and 3.5 ng m^{-3} (375hPa) in June–July in 2020. In general, our results were at the same magnitude with Matsui (2011)." The authors described that the comparison between the author's study and previous studies has been added to the manuscript, but I could not find this discussion in the revised manuscript.

Thanks for the suggestion. We have added a paragraph in Line 452 – 459.

Third, in the response to my previous review comment (7), the authors described as follows: "Temporal resolution of data sources was monthly, and thus the HTAP2 emission inventory provided harmonized emission data with monthly resolution for all the air pollutants including BC. It should be noted that the emissions of international shipping and international aviation in HTAP2 were considered constant over the year." This information can be added to the manuscript.

Thanks for the suggestion. We have added it in Line 123 – 126.

Fourth, in the response to my previous review comment (10), the authors described as follows: "2 ng m^{-3} was the contribution of 20% BC emission reductions from the six

source regions to the Arctic near-surface BC concentrations. By assuming that BC is an inert particulate component, the contribution of 100% BC emissions from six regions to the Arctic near-surface BC concentrations was about five times of this value (close to 10 ng m^{-3}). The annual mean Arctic near-surface BC concentration from the BASE simulation was about 18 ng m^{-3} in 2010. By comparing the values of contribution from all six regions (10 ng m^{-3}) and BC concentration in the Arctic (18 ng m^{-3}), the impact of emissions from six regions on the Arctic near-surface BC was outstanding. It should be noted that the contributions from six regions only considered anthropogenic emissions while the contribution from biomass burning was not included in the sensitivity experiments of HTAP2. It is known that wildfires in Fast East of Russia and U.S. Alaska are important sources of BC in the Arctic region, especially in summer. Thus, the contributions from six regions to the Arctic BC should be even more dominate over the other regions by including biomass burning in RBU and NAM." I suggest the authors add these results to the manuscript.

Thanks for the suggestion. We have added a paragraph in Line 377 – 386.

Fifth, in the response to my previous review comment (17), the authors described as follows: "The scenario of HTAP2 was 20% emission reduction from all anthropogenic emission sectors. However, in reality, not all emissions sectors of a specific source region cannot be reduced by 20% at the same time. In other words, responses of Arctic surface temperature to 20% emission reductions are more suitable to be used for the comparison among different source regions but cannot be used to reflect the actual change of temperature. In addition, there are many other factors (e.g. greenhouse gases, sea ice coverage) that can affect the temperature change in the Arctic besides BC. BC may be one of the factors affecting the ambient temperature but probably not the dominant one. Thus, we didn't compare the temperature change caused by BC emission reductions from six source regions with actual temperature change.". These sentences should be added to the manuscript. The authors should clarify more why the analysis using ARTP is meaningful and where readers should focus on in this analysis.

Thanks for the suggestion. We have added a paragraph as below in Line 209 – 214.

The ARTP provide additional insight into the spatial pattern of temperature response to

inhomogeneous forcings beyond that available from traditional global metrics. Very few metrics have attempted to examine sub-global scales thus far, though some have used local information with non-linear global damage metrics (Shine et al., 2005a; Lund et al., 2012). Shindell et al. (2012) indicated that the forcing/response portion of the ARTP appeared to be relatively robust across models.

2) Please clarify why the statistics in this study are shown with ranges. What do these ranges mean? Model variability, spatial variability in the Arctic, or monthly variability?
Response: The ranges were calculated based on different statistical categories.

a) Model variability:
Lines 275 – 277: Relatively good agreement between the observation and models was found at Zeppelin, with CORs, NME, MB, and MAE of 0.59–0.83, 38.59%–142.64%, –13.53–14.97 ng m^{-3}, and 5.40–14.97 ng m^{-3}, respectively
This sentence is changed as "Relatively good agreement between the observation and models was found at Zeppelin, with CORs, NME, MB, and MAE of 0.59–0.83, 38.59%–142.64%, –13.53–14.97 ng m^{-3}, and 5.40–14.97 ng m^{-3} among the five models, respectively"

b) Monthly variability:
Lines 34 – 39: Emission reductions from East Asia (EAS) had most (monthly contributions: 0.2–1.5 ng m^{-3}) significant impact on the Arctic near surface BC concentrations while the monthly contributions from Europe (EUR), Middle East (MDE), North America (NAM), Russia-Belarus-Ukraine (RBU), and South Asia (SAS) were 0.2–1.0 ng m^{-3}, 0.001–0.01 ng m^{-3}, 0.1–0.3 ng m^{-3}, 0.1–0.7 ng m^{-3}, 0.0–0.2 ng m^{-3}, respectively.
Lines 359 – 361: The contributions of 20% BC emission reductions from all six regions to Arctic near-surface BC concentrations were 0.8–1.4 ng m^{-3} during May to October and 1.5–3.2 ng m^{-3} during November to April.
We have added "monthly" ahead of "Arctic near-surface BC concentrations" for clarification.

Lines 386 – 389: The response of Arctic near-surface monthly BC concentration was

found strongest to the 20% emission reductions from EAS with the contribution of 0.2–1.5 ng m^{-3}, accounting for 16.8%–49.0% of the total reduced BC concentrations resulting from all six source regions.

This sentence is changed as "The response of Arctic near-surface BC concentration was found strongest to the 20% emission reductions from EAS with the monthly contribution of 0.2–1.5 ng m^{-3}, accounting for 16.8%–49.0% of the total reduced BC concentrations resulting from all six source regions"

Lines 396 – 399: In addition to EAS, BC emission reduction from EUR also showed significant impacts on the Arctic near-surface monthly BC concentration with the contribution of 0.2–1.0 ng m^{-3}, accounting for 20.1%–49.0% of the total reduced BC concentrations resulting from all six source regions.

It is changed as "In addition to EAS, BC emission reduction from EUR also showed significant impacts on the Arctic near-surface BC concentration with the monthly contribution of 0.2–1.0 ng m^{-3}, accounting for 20.1%–49.0% of the total reduced BC concentrations resulting from all six source regions".

Lines 402 – 404: As for NAM and RBU, their 20% emission reductions induced moderate reductions of the monthly Arctic near-surface BC concentrations by 0.1–0.3 and 0.1–0.7 ng m^{-3}, respectively. It has been clearly indicated the ranges referred to monthly variations.

Lines 404 – 406: The contribution of 20% emission reductions from SAS to the Arctic near-surface BC concentrations was much lower of 0.0–0.2 ng m^{-3} as a significant portion of BC originating from SAS accumulated in the upper troposphere.

It is changed as "The contribution of 20% emission reductions from SAS to the Arctic near-surface BC concentrations was much lower of monthly contributions of 0.0–0.2 ng m^{-3} as a significant portion of BC originating from SAS accumulated in the upper troposphere".

Lines 637 – 640: The response of Arctic near-surface BC concentrations to 20% emission reductions from EAS and EUR was larger than other four source regions, with the monthly value of 0.2–1.5 ng m^{-3} and 0.2–1.0 ng m^{-3}, accounting for 16.8%–49.0%

and 20.1%–49.0% of the total contributions from all six regions, respectively.
It has been clearly indicated the ranges referred to monthly variations.

c) Variation of latitude bands
Line 496 – 499: In contrast, the contributions from EAS (0.3–0.4 ng m^{-3} in summer and 0.9–1.1 ng m^{-3} in winter) were higher than those from EUR (0.2–0.4 ng m^{-3} in summer and 0.4–0.9 ng m^{-3} in winter) in the other high latitudinal bands where long-range transport played the dominant role.
It is changed as "In contrast, the latitudinal contributions from EAS (0.3–0.4 ng m^{-3} in summer and 0.9–1.1 ng m^{-3} in winter) were higher than those from EUR (0.2–0.4 ng m^{-3} in summer and 0.4–0.9 ng m^{-3} in winter) in the other high latitudinal bands where long-range transport played the dominant role."

Lines 521 – 523: The statistical results of SAS indicated that the contribution in vertical appeared one peak at the 15^{th} layer (9.7 km a.s.l.) with a value of 0.45–0.48 ng m^{-3} in summer and winter.
It is changed as "The statistical results of SAS indicated that the contribution in vertical appeared one peak at the 15th layer (9.7 km a.s.l.) with values of 0.45 and 0.48 ng m–3 in summer and winter, respectively (Figure S8).".

Lines 529 – 532: The contribution of 20% emission reductions from all six source regions to BC concentrations in eight latitude bands of the Arctic near surface was 0.7–1.9 ng m^{-3} in summer and 1.8–4.1 ng m^{-3} in winter, respectively (Figure 6). The high BC peak at around 0.6–1.6 km a.s.l. (3^{rd} – 5^{th} layers) was 1.1–2.1 ng m^{-3} in summer, and 2.9–4.2 ng m^{-3} in winter.
It has been clearly indicated that the ranges referred to the variations in eight latitude bands and vertical layers in the first and second sentence, respectively.

d) time horizon (10, 20, 50, and 100 years)
In Section 3.4 "Benefit of BC emission reductions on the decrease of Arctic temperature", the ranges of temperature referred to the temperature decrease after 10, 20, 50, and 100 years.