

## **Response to Review #2**

General comments: Haze pollution is for the time being a serious problem for China. The prediction of haze pollution is highly-relevant to the society. The manuscript explored the linkage between the number of haze days in China and the change in autumn sea ice extent in the Beaufort Sea and analyze the potential mechanism. I find the manuscript is scientifically interesting and fits the scope of ACP. However, major revision is needed before it can be accepted for publication in ACP

Major comment:

**1. the cause and effect are not convincing in this manuscript. There are quite some places authors used ‘induced’. Correlation/regression can not tell what is cause and what is the effect.**

*Reply:*

(1) To verify the proposed causality, numerical experiments were designed by the public CESM-LE datasets. **A new section “5. Causality verification by CESM-LE experiments” and a new Figure 16 was added in the manuscript.**

The CESM-LE simulations were completed by the fully coupled CESM model, thus the interactions among sea ice, sea temperature and atmosphere can be contained. In the numerical experiment, all available CESM-LE members were included and different amplitudes of sea ice anomalies were composited, thus the uncertainty from the internal variability were largely reduced.

In this experiment, **the linkages between the BSISO and the haze pollution in the North China also exist in CESM-LE simulations.** Meanwhile, the corresponding physical mechanisms were also well reproduced by the large ensemble members. Details can be found in the following revision.

(2) In the old version, in addition to the correlation analysis, the composite results were also included, such as Figure 4 and 16 (17 now). In Figure 4, every years with significant BSISO anomalies were analyzed to find the corresponded haze conditions. Furthermore, a typical case (i.e., 2015) was studied to confirm the proposed relationship.

*Revision:*

**5. Causality verification by CESM-LE experiments**

The connection between the haze pollution in North China and ASI, and associated physical mechanisms were statistically analyzed. To confirm the causality, numerical experiments were designed with the public CESM-LE datasets. To be consistent with the observational results, the variables from CESM-LE from 1979 to 2015 are employed, which was combined by the historical simulation during 1979–2005 and the data during 2006–2015 from the future representative concentration pathway 8.5 (RCP8.5 scenario) forcing simulation. 35 CESM-LE ensemble members were used here. The CESM-LE simulations were completed by the fully coupled CESM model, thus the interactions among sea ice, sea temperature and atmosphere can be contained. **The years when the sea ice anomalies concentrated in the west of the Beaufort Sea were selected and the differences between the positive BSISO and negative BSISO years were identified as the responses to the sea ice anomalies.** In the numerical experiment, all available CESM-LE members were included and different amplitudes of sea ice anomalies were composited, thus the uncertainty from the internal variability were largely reduced.

In Figure 16a, the sea ice anomalies were obvious in the key region. The maximum of the difference in sea ice concentration was more than 35% (Figure 16a). In the following November, the accumulated sea ice favored increased SST over the Gulf of Alaska (Figure 16b), which is in good accordance with the observed results. Although there were weaker, but negative SST responses in Bering Sea, the positive SST anomalies extended southwards and enhanced the air-sea interaction. In terms of the corresponding atmospheric circulations with regard to anomalous BSISO, the composite difference was also consistent with the observed results. The anti-cyclonic anomalies of the geopotential height at 500hPa were also well reproduced by the model in the early winter (Figure 16c). On the lower troposphere, there were also anomalous anticyclone over North China and Northeast China, which induced anomalous southerlies (Figure 16d) and weakened the cold air from the high latitude. Furthermore, the moist air condition (Figure 16c) and lower boundary layer (Figure

16d) were also verified to be significantly connected with the positive BSISO anomalies. **Consistent with the observed results, the linkages between the BSISO and the haze pollution in the North China also exist in CESM-LE simulations.** Meanwhile, the corresponding physical mechanisms were also well reproduced by the large ensemble members. The performances of numerical models in the mid-high latitude were consistently limited, however, the results from CESM-LE here successfully captured major features and general physical processes as expected. Consequently, the robustness of the proposed connections and physical mechanisms were strongly confirmed.

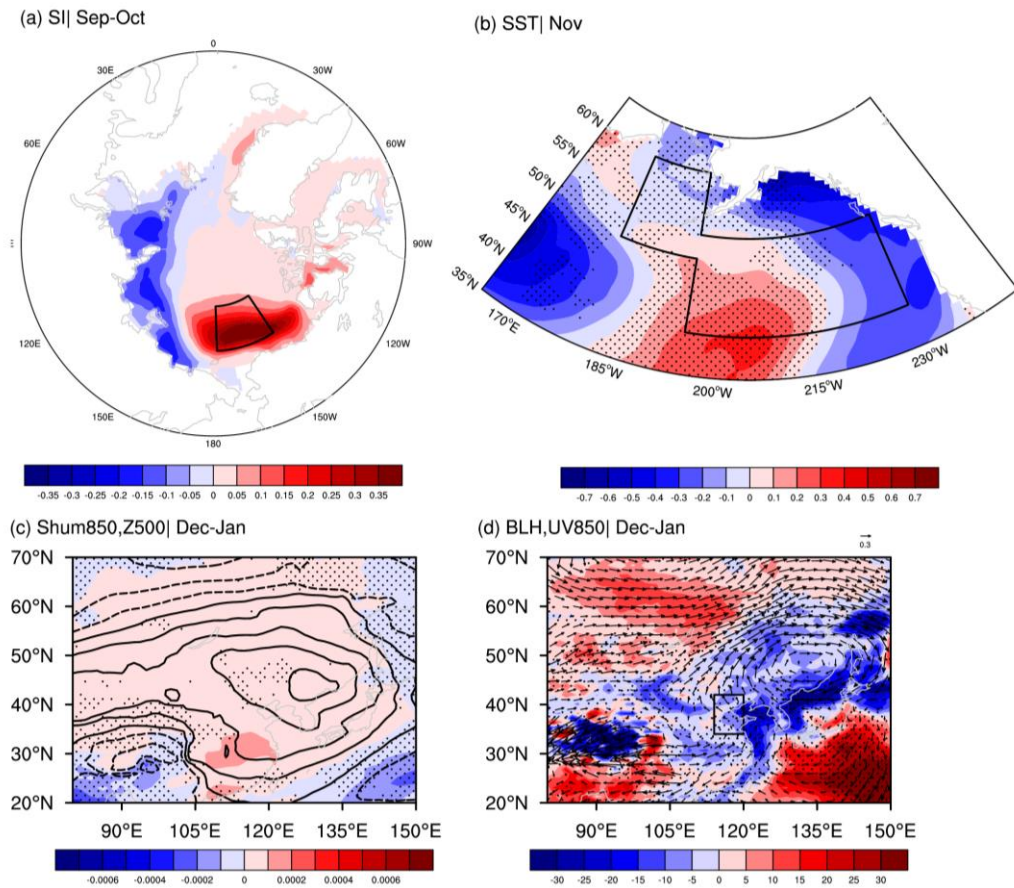


Figure R1. Composite difference of (a) September-October sea ice concentration, (b) sea surface temperature in November, (c) geopotential height (contour) at 500 hPa, specific humidity at 850 hPa in December-January, (d) BLH (shading), wind (arrow) at 850 hPa in December-January. The black box in panel (a) represents the location of the Beaufort Sea, and in panel (b) it represents the BA area. Results are based on 35 ensembles of CESM-LE simulations. The black dots indicate that mathematical sign of the changes with shading from more than 50% of the members are consistent with the ensemble mean.

**2. Why can not directly link the SST anomalies in the Bering Sea and the number of haze days over NCP?**

***Reply:***

Certainly, there was directly link between the November SST anomalies and the number of haze days in December and January. There are two reasons why we link the number of haze days and the September-October sea ice. (1) As an efficient driver, the September-October sea ice was one month in advance of the November SST, which **supports sufficient time gap to make the seasonal prediction in the real-time operation**. That is, in November, we may gain the sea ice September-October data and run the statistical seasonal prediction models. (2) The goal of this manuscript is to reveal the connection between the sea ice and the haze pollution in the early winter. Our studies **not only reveal the link between the SST and haze, but also deepen the understanding the impacts of the sea ice on the haze** by taking the SST anomalies as a bridge.

Detailed comments:

**1. What is the difference between ‘Arctic region’ (Line 23) and ‘Arctic area’ (Line 25)?**

***Reply:***

The presentations were coalesced to “Arctic region”.

***Revision:***

~~tremendous concerns from global climate change scientists.~~ During the past few years, the increase of surface air temperature has been distinctly amplified in the Arctic ~~area region(i.e., the Arctic Amplification feature)~~ and approximately

**2. Line 23, I do not understand why authors highlighted ‘February 2018’ since no data from 2018 is used in the manuscript.**

***Reply:***

In the old version, we mentioned ‘February 2018’ to emphasize the importance of Arctic sea ice. Now, to focus on the scientific issue, the associated texts were deleted.

**Revision:**

~~In February 2018, the highest temperature near the Arctic region was above the freezing point (Jason, 2018), raising tremendous concerns from global climate change scientists.~~ During the past few years, the increase of surface air temperature has been distinctly amplified in the Arctic area region(i.e., the Arctic Amplification feature) and approximately

**3. Line 24, Does the authors mean the Arctic amplification intensified only during past few years?**

**Reply:**

Our presentation was confusing. We did not mean the Arctic amplification intensified. We wanted to introduce that the increase of surface air temperature has been distinctly amplified in the Arctic region and lead to the definition of Arctic amplification.

The confusing texts have been revised.

**Revision:**

~~tremendous concerns from global climate change scientists.~~ During the past few years, the increase of surface air temperature has been distinctly amplified in the Arctic area region(i.e., the Arctic Amplification feature) and approximately twice as large as the average increase in global warming, which was called the Arctic Amplification (Zhou, 2017). ~~Recently,~~

**4. Line 26, What the authors mean by ‘Recently’?**

**5. Line 26, ‘Arctic sea ice decreases rapidly since the satellite era, in particular, after year 2000’.**

**Reply:**

According to the advice of the reviewer, detailed comments 4 &5 were revised together.

**Revision:**

...Arctic sea ice (ASI) decreases rapidly since the satellite era, in particular, after the year of 2000 (Gao et al., 2015)...

twice as large as the average increase in global warming, which was called the Arctic Amplification (Zhou, 2017). ~~Recently,~~ the Arctic sea ice (ASI) decrease~~d rapidly due to the Arctic Amplification and reached a record low in September 2012~~since the satellite era, in particular, after the year of 2000 (Gao et al., 2015). The ~~loss-change~~ of ASI, associated with changed the

**6. Line 27, ‘the change of ASI’**

***Reply:***

According to the advice of the reviewer, the errors were revised.

***Revision:***

...The change of ASI, associated with changed reflection of solar radiation and the exchange of energy and fresh water, could remotely connect with the climate in the Northern Hemisphere, especially the winter climate in Eurasia...

**7. Line 30, remove ‘variability’**

***Reply:***

According to the advice of the reviewer, the errors were revised.

***Revision:***

...especially the winter climate in Eurasia...

**8. Line30, sea ice is a component in climate system, is not an external driver**

***Reply:***

According to the advice of the reviewer, the errors were revised.

***Revision:***

climate in the Northern Hemisphere, especially the winter climate ~~variability~~ in Eurasia (Liu et al., 2007; Wang and Liu, 2016). ~~As an efficient external driver in the high latitudes,~~ ~~t~~The decreased ASI over the Barents–Kara Seas in late autumn stimulated a planetary-scale ~~Rossby~~ wave train in early winter (Honda et al., 2009; Kim et al., 2014) and transported its

**9. Line 40, it is better if the authors can provide a brief definitions for dust, sandstorm and haze.**

***Reply:***

The brief definitions for dust, sandstorm and haze were provided.

***Revision:***

...The dust (dry particles suspended in air after strong wind) and sandstorm (strong wind carrying sand) over North China, types of weather that are sensitive to wind, also showed close relationships with the variation of ASI after the mid-1990s (Fan et al., 2017)...

...Haze (polluted particulate aerosols suspended in air), also being sensitive to wind, frequently occurred under calm and static weather conditions...

**10. Line 45, ‘long-term trend of haze’ is not clear. Long-term trend of number of haze days, or intensity of haze, or periods of haze?**

**11. Line 46, the same as above ‘the trend of haze pollution’**

**12. Line 50, the same as above, ‘correlation with the haze’**

**13. Line51, the same as above, ‘different variations in haze days’**

**14. Line 52, ‘between the autumn sea ice cover in Beaufort Sea and the number of haze days in winter’**

**15. Line54. ‘number of haze days varied differently during early (December-January) and late (February) winters’**

***Reply:***

The presentation “haze days” was confusing and should be **the number of the haze days**. Detailed comments 10–15 were revised together.

***Revision:***

Haze (polluted particulate aerosols suspended in air), also being sensitive to wind, frequently occurred under calm and static weather conditions, i.e., small surface winds and strong thermal inversion (Yin et al., 2015; Ding and Liu, 2014; Chen and Wang, 2015; Cai et al., 2017; Gao and Chen, 2017). For the long-term trend of number of haze days, human activities are the recognized and fundamental driver (Li et al., 2018; Yang et al. 2016; Chen et al., 2018; Zhang et al., 2018), but the rapid ASI decline also contributed to the trend of number of haze days ~~haze-pollution~~ in the North China Plain after 2000 (Wang and Chen 2016<sup>7</sup>). For the ~~interannual~~ ~~interdecadal~~ variations, the impacts of ASI on the number of haze days ~~haze~~ in the east of China were emphasized by observational analyses (Wang et al., 2015) and numerical studies (Li et al. 2017). By the sensitive experiments, Li et al. (2017) emphasized the impacts of ASI anomalies on haze pollution in North China, but deemphasized the role of ENSO (He et al., 2019). From 1979–2012, the ASI loss led to a northward shift of the East Asia jet stream and weak East Asian winter monsoons, indicating a strongly negative correlation with the number of haze ~~day~~ ~~haze~~ in the east of China (Wang et al. 2015). However, the first mode of the Empirical Orthogonal Function (EOF) in Yin and Wang (2016a) presented different variations of number of haze days ~~haze-days~~ in the south and north of the Yangtze River. The positive relationship between the autumn sea ice in the Beaufort Sea and the number of haze days in winter ~~haze days~~ was briefly revealed without sufficient physical explanations but contributed to the prediction of number of haze days ~~in winter~~ ~~haze days~~ (Yin and Wang 2016b, 2017b). The number of haze days in early winter (December-January) ~~haze days~~ also varied differently with that in February ~~haze days~~ (figure omitted), ~~indicating a variant modulating mechanism from~~

## 16. Line 54', 'suggesting a potential different driving mechanism'

### *Reply:*

According to the advice of the reviewer, the errors were revised.

### *Revision:*

...The number of haze days in early winter (December-January) also varied differently with that in February (figure omitted), suggesting a potential different driving mechanism...

## 17. Line 56, similar as No. 14

### *Reply:*

The presentation “haze days” was confusing and should be the number of the haze days.



***Revision:***

...Thus, an open question still existed, i.e., the connections between Beaufort Sea ice (BSI) and the number of haze days in early winter in the North China Plain (NCP: 34–42°N, 114–120°E) and the associated physical mechanisms...

**18. Line 80', 'The HDJ was stable during 1979 to 2012 and decreased during 1993 to 2009'**

***Reply:***

According to the advice of the reviewer, the confusing presentation were revised.

***Revision:***

...The HDJ<sub>NCP</sub> was stable during 1979 to 1992 and decreased from 1993 to 2009...

**19. Line 80, 'The HDJ showed a strong upward trend after 2009'**

***Reply:***

According to the advice of the reviewer, the confusing presentation were revised.

***Revision:***

...After 2009, the HDJ<sub>NCP</sub> showed a strong upward trend...

**20. Line 85, 'what is the threshold for pollution in China'?**

***Reply:***

The threshold was supplemented.

***Revision:***

...still exceeded the threshold of pollution in China (i.e., 75 µg/m<sup>3</sup>)...

**21. Line 84, what is the meaning of 'synoptic process of haze were weaker'? How to judge this?**

***Reply:***

The “synoptic processes of haze” was not accurate. According to the advice of the reviewer, the confusing presentation were revised.

“synoptic processes of haze”→”the concentrations of PM<sub>2.5</sub>”

**Revision:**

The daily maximum of area-mean PM<sub>2.5</sub> in 2015 is shown in Figure 2b and was above 100  $\mu\text{g}/\text{m}^3$ . The ~~synoptic processes of haze concentrations of PM<sub>2.5</sub>~~ were relatively ~~weaker~~lower in January 2016 than those in December but still exceeded the threshold of pollution in China (*i.e.*, 75  $\mu\text{g}/\text{m}^3$ ). On 23 December, the most disastrous haze occurred, and the area-mean

**22. Line 90, there are number of places the authors used haze days. I believe that authors mean ‘number of haze days’.**

**Reply:**

The haze days were revised to the “number of haze days” throughout the MS.

**Revision:**

of China by modulating the large-scale atmospheric circulations and local meteorological conditions. Furthermore, the opposite pattern of ~~number of haze days~~haze days in the east of China was revealed in Figure 1. To confirm the response of

**23. Line 97, the correlation cannot tell which causes which.**

**24. Line 101, ‘correspond’ instead of ‘induce’. Again, correlation cannot tell which causes which**

**26. Line 103, ‘response’ is not accurate here**

**27. Line 108, SST and sea ice concentration in general co-varies. Correlation can not tell which causes which. Authors can also check the surface heat flux.**

**28. Line 108, ‘induced’ is not correct here.**

**30. Line 110, correlation can not tell ‘change of BS sea ice’ can lead to SST anomalies over the BS and GA. ‘induced’ is not correct here.**

**32. Line 123, how authors can conclude the change in atmosphere circulation is a response to change in sea ice by correlation?**

**33. Line 125, ‘induced’ again**

**34. After line 125, authrs used correlation to conclude the sea ice change-leading to atmosphere change-leading to SST change in number of places of the manuscript.**

***Reply:***

Detailed comments 23, 24, 26–28, 30, 32–34 concentrated on the meaning of the correlation method and were similar with the Major comment 1.

(1) During the statistical analysis sections, the presentations, like “induce”, “response”, were modified.

(2) To verify the proposed causality, numerical experiments were designed by the public CESM-LE datasets. **A new section “5. Causality verification by CESM-LE experiments” and a new Figure 16 was added.**

(3) Analysis about the surface heat flux was done in Figure 9. As follows:

...the reduction of  $WSPD_{RS1}$  resulted in a warmer sea surface over the Gulf of Alaska (Figure 9a). Due to the weakening of the water evaporation, the latent heat release slowed down both in the Bering Sea and the Gulf of Alaska, which conserved more thermal energy in the sea surface (Figure 9b). In addition, the upper anti-cyclonic circulations, with clear sky, facilitated more shortwave solar radiation onto the sea surface. The absorbed and stored thermal energy, which was connected with the heavy positive BSISO anomalies, heated the sea surface over the Gulf of Alaska in November, i.e., positive  $SST_{GA}$  anomalies.

***Revision:***

**(1) 5. Causality verification by CESM-LE experiments**

The connection between the haze pollution in North China and ASI, and associated physical mechanisms were statistically analyzed. To confirm the causality, numerical experiments were designed with the public CESM-LE datasets. To be consistent with the observational results, the variables from CESM-LE from 1979 to 2015 are employed, which was combined by the historical simulation during 1979–2005 and the data during 2006–2015 from the future representative concentration pathway 8.5 (RCP8.5 scenario) forcing simulation. 35 CESM-LE ensemble members were used here. The CESM-LE simulations were completed by the fully coupled

CESM model, thus the interactions among sea ice, sea temperature and atmosphere can be contained. **The years when the sea ice anomalies concentrated in the west of the Beaufort Sea were selected and the differences between the positive BSISO and negative BSISO years were identified as the responses to the sea ice anomalies.** In the numerical experiment, all available CESM-LE members were included and different amplitudes of sea ice anomalies were composited, thus the uncertainty from the internal variability were largely reduced.

In Figure 16a, the sea ice anomalies were obvious in the key region. The maximum of the difference in sea ice concentration was more than 35% (Figure 16a). In the following November, the accumulated sea ice favored increased SST over the Gulf of Alaska (Figure 16b), which is in good accordance with the observed results. Although there were weaker, but negative SST responses in Bering Sea, the positive SST anomalies extended southwards and enhanced the air-sea interaction. In terms of the corresponding atmospheric circulations with regard to anomalous BSISO, the composite difference was also consistent with the observed results. The anti-cyclonic anomalies of the geopotential height at 500hPa were also well reproduced by the model in the early winter (Figure 16c). On the lower troposphere, there were also anomalous anticyclone over North China and Northeast China, which induced anomalous southerlies (Figure 16d) and weakened the cold air from the high latitude. Furthermore, the moist air condition (Figure 16c) and lower boundary layer (Figure 16d) were also verified to be significantly connected with the positive BSISO anomalies. **Consistent with the observed results, the linkages between the BSISO and the haze pollution in the North China also exist in CESM-LE simulations.** Meanwhile, the corresponding physical mechanisms were also well reproduced by the large ensemble members. The performances of numerical models in the mid-high latitude were consistently limited, however, the results from CESM-LE here successfully captured major features and general physical processes as expected. Consequently, the robustness of the proposed connections and physical mechanisms were strongly confirmed.

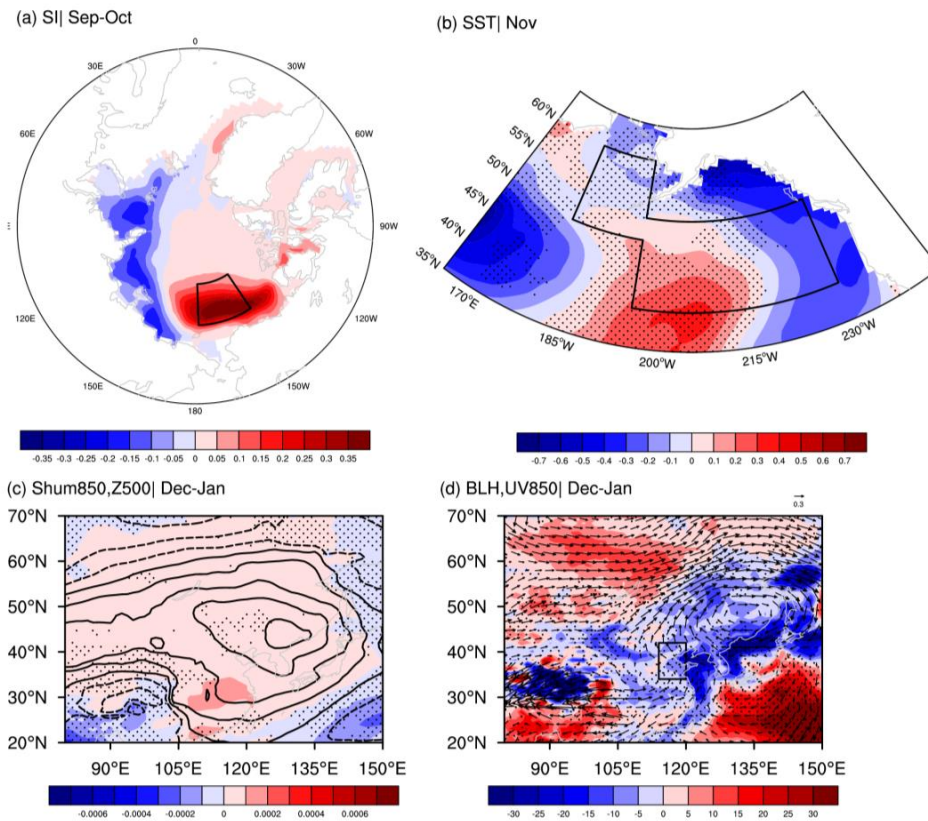


Figure R1. Composite difference of (a) September-October sea ice concentration, (b) sea surface temperature in November, (c) geopotential height (contour) at 500 hPa, specific humidity at 850 hPa in December-January, (d) BLH (shading), wind (arrow) at 850 hPa in December-January. The black box in panel (a) represents the location of the Beaufort Sea, and in panel (b) it represents the BA area. Results are based on 35 ensembles of CESM-LE simulations. The black dots indicate that mathematical sign of the changes with shading from more than 50% of the members are consistent with the ensemble mean.

(2)

deviation). During 65% of these years, the significant BSISO anomalies corresponded induced HDJ<sub>NCP</sub> anomalies with the same mathematical sign. There were no significantly opposite responses of HDJ<sub>NCP</sub> ( $|\text{HDJ}_{\text{NCP}}| > 0.8 \times \text{its standard deviation}$ ) to the BSISO anomalies. Furthermore, the relationship seemed to be enhanced after the mid-1990s. The same mathematical signs of the anomalies appeared more frequently, and the intensity of the responses was also amplified.

The heavy-positive sea ice anomalies, with high albedo, can efficiently reflect solar radiation and restore more fresh water, which could influence the local and adjacent SST. The correlation coefficients between BSISO and the simultaneous and subsequent SST were computed (Figure 5). Because of efficient reflections of the solar radiation, the locally negative SST anomalies, located near the west of the Beaufort Sea (70–81°N, 166°E–138°W), were induced by associated with the heavy-positive BSISO anomalies in October. In the following two months, these negative SST anomalies could not be sustained, i.e., these anomalous responses disappeared in November. However, the induced-positive SST anomalies in the Bering Sea (49–60°N, 165°W–180°W) and the Gulf of Alaska (40–52°N, 130°W–165°W) appeared in October and were

**25. Line 102, can authors perform sliding correlation to indicate the enhanced connection after mid-1990?**

**Reply:**

The sliding (21-yr running) correlation was plotted in Figure R2. It is obvious that the correlation coefficient was insignificant before 2000, but became significant then. The correlation coefficient during 1980–1997 was 0.11, but was 0.55 during 1998–2015. Furthermore, the number of years when the anomalies of HDJ<sub>NCP</sub> and BSISO with the same mathematical sign (NY<sub>SMS</sub>) were counted and those with significant amplitudes (i.e.,  $|\text{anomalies}| > 0.8 \times \text{its standard deviation}$ ) among the NY<sub>SMS</sub> values were extracted and termed NY<sub>SA</sub>. Compared to P1, both NY<sub>SMS</sub> and NY<sub>SA</sub> significantly increased during P2. Specifically, there were 8 (0) NY<sub>SMS</sub> (NY<sub>SA</sub>) years before the mid-1990s, which dramatically increased to 13 (5) years during 1998–2015 (Figure R3).

To answer the reasons for the change of the relationship, a paper titled “Enhanced Contributions of Beaufort Sea Ice to Early-winter Haze Days in North China after the mid-1990s” was prepared.

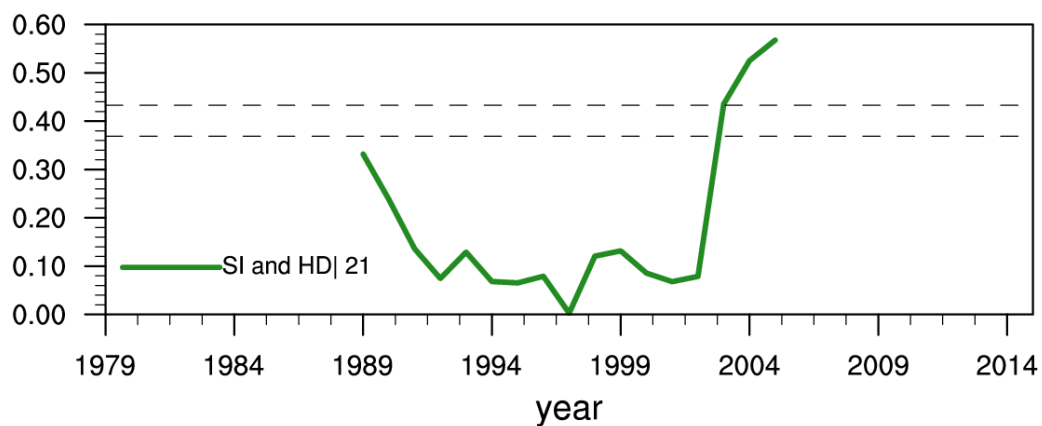


Figure R2. The 21-yr running correlation coefficient between BSISO and HDJ<sub>NCP</sub>

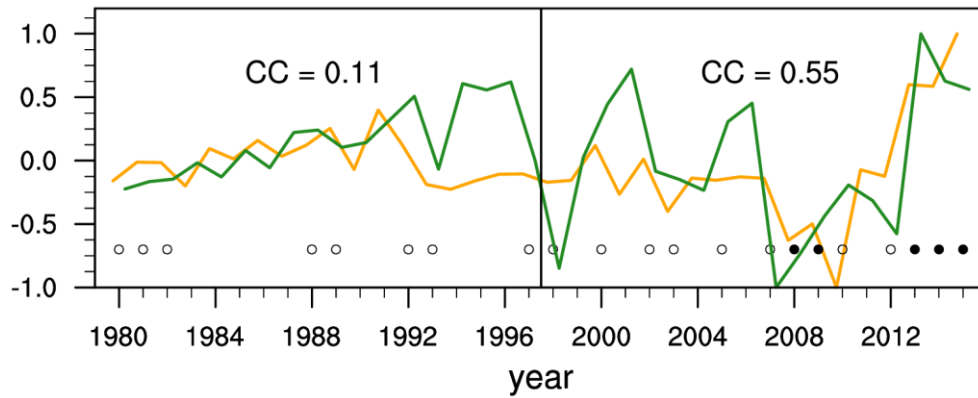


Figure R3. The variation in normalized  $HDJ_{NCP}$  (orange) and BSISO (green) from 1980 to 2015 after the removal of the linear trend. The “○” indicates the anomalies of  $HDJ_{NCP}$  and BSISO with the same mathematical sign. The “●” indicates the anomalies of  $HDJ_{NCP}$  and BSISO with significant amplitudes (i.e.,  $|anomalies| > 0.8 \times its\ standard\ deviation$ ).

**29. Line 109, Do authors have any idea why negative SST anomalies disappear in November?**

**Reply:**

This question was not the mainly concerned issue of this manuscript, but we tried to provide a reasonable guess.

The disappearing of the negative SST anomalies in November connected with the change of the atmospheric circulations and can be explained by Figure 6 in the manuscript. (1) The September-October negative SST anomalies in the west of Beaufort Sea co-varied with the positive sea ice anomalies. (2) According to many previous studies, the signal of the ice in the polar region cannot persistent for long time by itself. **Its influence should delivery via the change of the atmospheric circulations.** (3) In Figure R4 (i.e., Figure 6 in the MS), the distribution and intensity of the atmospheric circulations associated with BSISO was different in September-October and November both near surface and in the mid-troposphere. (4) In November, the local atmospheric circulation associated with positive BSISO was the significant pressure gradient between an anti-cyclonic and a cyclonic circulation (Figure R4), which **weakened the release of the surface heat flux and did not maintain the negative SST anomalies in November.**

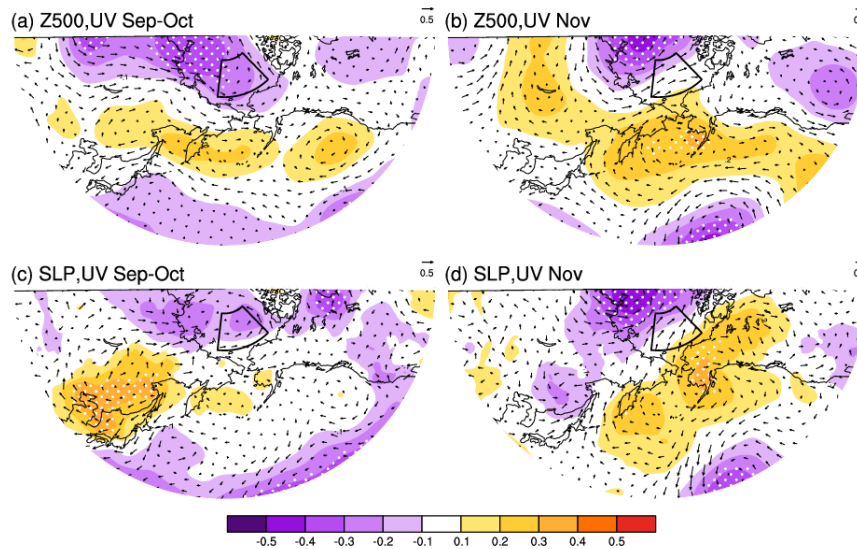


Figure R4. The CC between BSISO and September-October (a) geopotential height (shading), wind (arrow) at 500 hPa, (c) SLP (shade), and surface wind (arrow); and November (b) geopotential height (shading), wind (arrow) at 500 hPa, (d) SLP (shade), and surface wind (arrow) from 1979 to 2015, after detrending. The white dots indicate CCs exceeding the 90% confidence level (t test). The black box in (a–d) represents the location of the Beaufort Sea.

**31. Line 118, why authors cannot directly link the SST anomalies over BS and GA to HDJ?**

**Reply:**

Detailed comments 31 was similar with the Major comment 1.

Certainly, there was directly link between the November SST anomalies and the number of haze days in December and January. There are two reasons why we link the number of haze days and the September-October sea ice. (1) As an efficient driver, the September-October sea ice was one month in advance of the November SST, which **supports sufficient time gap to make the seasonal prediction in the real-time operation.** That is, in November, we may gain the sea ice September-October data and run the statistical seasonal prediction models. (2) The goal of this manuscript is to reveal the connection between the sea ice and the haze pollution in the early winter. Our studies **not only reveal the link between the SST and haze, but also deepen the understanding the impacts of the sea ice on the haze** by taking the SST anomalies as a bridge.