Responses to Referees' Comments

Effects of Arctic stratospheric ozone changes on spring precipitation in the northwestern United States
(ACP-2018-414)

Xuan Ma, Fei Xie, Jianping Li, Xinlong Zheng, Wenshou Tian,
Ruiqiang Ding, Cheng Sun, and Jiankai Zhang

September 2018

Response to Referee 1

This study examines the relationship between springtime Arctic lower stratospheric ozone concentrations and precipitation anomalies over the northwestern United States (Washington and Oregon). Using observations and WACCM model simulations (with various prescriptions of ozone and SSTs), the authors link Arctic lower stratospheric ozone depletion to precipitation increases over the northwestern United States. Their model simulations indicate that prescribing both the ozone and SSTs is necessary to recover the observed relationship in the model.

The premise of this study is very interesting … using Arctic lower stratospheric ozone anomalies to predict springtime precipitation. However, as written, I don't find the manuscript to meet the standards of an ACP publication for the following reasons: 1) most of the observed correlations are based upon statistical significance at the 90% confidence level, 2) the authors fail to account for the role of stratospheric dynamic variability (sudden stratospheric warmings) in their analysis, 3) many of the figures (and associated text) simply repeat the same information, and most importantly 4) no physical mechanism is provided to explain why lower stratospheric ozone anomalies impact the North Pacific circulation (but not the North Atlantic circulation) and in particular how they can excite SST anomalies (which seem opposite to those that would be forced by the lower tropospheric wind anomalies). For these reasons, I am inclined to recommend that the paper be rejected at this point and encourage the authors to resubmit their interesting analyses after they have addressed some of these issues.

Response: We thank the reviewer for taking the time to assess the manuscript and for highlighting important issues and providing helpful comments and suggestions to improve the manuscript. We have revised the manuscript carefully according to the reviewer's comments. The 95% confidence level is now used throughout the paper. Some less-important figures have been removed. We apologize for the lack of clarity in places, which led the reviewer to feel that the manuscript overemphasized the influence of ozone on stratosphere and troposphere coupling.

At the same time, we are grateful for the important references provided by the reviewers; the new references, including Black et al. (2005, 2006, 2009); Gabriel et al. (2007); Gillett et al. (2009); Nowack et al. (2015, 2017, 2018); McCormack et al. (2011); WMO (2003) and Zhang et al. (2018), have been cited in the revised manuscript. Please see the following detailed point-by-point responses:

Major Comments:

1. Winters with sudden stratospheric warmings and strong stratospheric polar vortices are caused by natusral wave-driven dynamic variability (lines 67-68), and thus chemical ozone depletion will only occur when the Arctic stratosphere is not dynamically active (strong stratospheric polar vortex years). So, Arctic stratospheric ozone (ASO) depletion is only relevant in years when the dynamics precondition the Arctic stratosphere for it to potentially occur. It's not immediately apparent to me what advantage looking at ozone (compared to polar stratospheric temperature anomalies) provides for tropospheric teleconnections. In other words, if instead of using ozone as a criteria for the years selected in Table 2, you used the strength of the stratospheric polar vortex, would you get the same patterns? Or, another way of stating this, are the years with positive ASO anomalies associated with sudden stratospheric warmings and/or early seasonal breakdowns of the stratospheric polar vortex? The paper is framed as if ozone is the predominant cause of NH stratospheric circulation anomalies. In reality, the ozone-induced stratosphere-troposphere connections should be secondary in importance to those driven by stratospheric dynamics in the NH. In the SH, where year-to-year dynamic variability is weaker, the ozone-induced stratosphere-troposphere connections.

Response: Thanks for the comment. We agree with the reviewer's opinion that the spring ASO variations are related to changes in the winter Arctic stratospheric vortex (SPV). The strength of the SPV can affect ASO, and then ASO affects tropospheric teleconnection and precipitation in the northwestern United States (indirect effect of SPV). The strength of the SPV may also have a direct leading effect on tropospheric teleconnection and precipitation in the northwestern United

States. There is a tight coupling between dynamical modes of variability and ASO. In this study, we have not thought of a better way to separate the two effects on precipitation. Thus, the thrust of this study is to at least recognize that the ASO changes may affect precipitation in the northwestern United States. From the analysis of observational data, we find that the ASO has a leading relationship with spring precipitation in the northwestern United States. In addition, this relationship can be reproduced in simulations by abnormal ASO forcing. This implies that the variations in spring ASO can force the observed tropospheric circulation and precipitation anomalies in the northwestern United States.

Figure R1 shows the correlation coefficients between the February SPV (multiplied by –1) index and April 200 hPa zonal wind and precipitation variations (Fig. R1a and b), and between March ASO and April 200 hPa zonal wind and precipitation (Fig. R1c and d). The SPV index is defined as the strength of the stratospheric polar vortex, following Zhang et al. (2018). Although the patterns of correlation coefficients in Fig. R1 are similar, the ASO variations are much closer than the SPV to the variations in 200 hPa zonal wind and precipitation. Fig. R1 indicates indirect and direct effects of winter SPV on spring tropospheric climate. Since the coupling between dynamical and radiative processes in spring is strong, the connection between winter SPV and spring tropospheric circulation seems weaker than that between the spring ASO and tropospheric circulation.

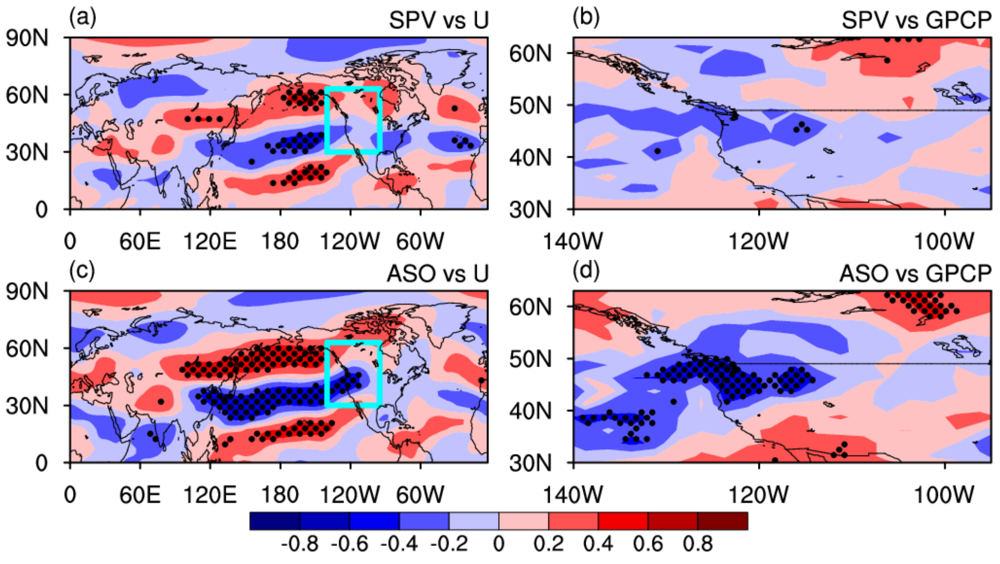


Figure R1. (a) Correlation coefficients between the February –SPV (10^5 K m^2 kg^{-1} s^{-1}) index defined by Zhang et al. (2018) and April zonal wind variations at 200 hPa for 1984–2016. (b) Correlation coefficients between February –SPV index and April precipitation variations. (c) and (d) As for (a) and (b), but between March ASO and April 200 hPa zonal wind and April precipitation variations. Dots denote significance at the 95% confidence level, according to Student's *t*-test. The long-term linear trend and seasonal cycle in all variables were removed before the correlation analysis. The ASO data are from SWOOSH, zonal wind from NCEP2, and precipitation from GPCP.

We apologize for the lack of clarity that led the reviewer to feel that the manuscript overemphasized the influence of ozone on stratosphere and troposphere coupling in spring. In this study, we want to state that the ASO changes possibly influence precipitation in the northwestern United States, emphasizing the influence of stratospheric ozone on tropospheric regional climate. The direct and indirect impacts of SPV on precipitation in the northwestern United States and the effect of the strong coupling between dynamical and ozone variability are indeed important issues that we will examine in future work.

We have made this point clearer in the revised manuscript. The Fig. R1 and relevant discussion have been added to the discussion section in the revised manuscript. See lines 368–388.

References:

Zhang J., et al.: Stratospheric ozone loss over the Eurasian continent induced by the polar vortex shift, Nat. Commun., 9, 206, 2018.

2. The authors state that ASO recovery will cause the northwestern United States to become drier in the future (lines 19–20, lines 203–205). The analysis in this study is based entirely on detrended ozone anomalies (year-to-year variability). If the authors wish to make this argument, they will need to convincingly show that 1) springtime ASO has trended downward in recent years and 2) northwestern US precipitation has *trended upward during April over the same time interval (independent of concurrent variability in ENSO and the PDO).*

Response: Thank you for this hint. We removed this statement in the revised paper which might be too hasty. We think this issue should be a very interesting study and we will continue to work on it.

3.1 Prior studies have argued that stratospheric circulation anomalies can couple down into the troposphere with a spatial pattern similar to the Northern Annular Mode (NAM) or North Atlantic Oscillation (NAO) (lines 70-71). Yet, the authors' analysis shows a poleward circulation shift over the North Pacific, but not the North Atlantic. Some discussion needs to be provided about why the authors' results are different than those documented in previous studies. It would be nice to compare the patterns shown in Figs. 3–7 with those associated with the NAM/NAO.

Response: Thank you for this comment. In spring, stratospheric circulation anomalies, related to ASO changes, couple down into the troposphere with a spatial pattern similar to the North Pacific Oscillation (NPO). This is consistent with previous studies based on simulations (Smith et al., 2014; Calvo et al., 2015) and observations (Xie et al., 2016, 2017; Ivy et al., 2017). Stratospheric circulation anomalies that couple down into the troposphere with a spatial pattern similar to the Northern Annular Mode (NAM) or North Atlantic Oscillation (NAO) occur mainly in winter. The different pathways of stratospheric circulation anomalies from the stratosphere to troposphere may be associated with different seasons or different processes. This topic is also worthy of further study.

The text has been revised as follows (lines 67–71 in the revised manuscript):

"*Comparing with the effect of the winter stratospheric dynamical processes on the tropospheric North Atlantic Oscillation (NAO) and the incidence of extreme weather events (Baldwin and Dunkerton, 2001; Black et al., 2005, 2006, 2009), the depletion of spring ASO can cause circulation anomalies that influence the North Pacific Oscillation.*"

Following the reviewer's suggestion, the patterns (Figs. 3–7 in the initial

manuscript) associated with the April NAO are shown in Figs. R2–4. Figure R2 shows that the NAO index is significantly correlated with precipitation variations in the central United States in April (not in the northwestern United States in our study). The zonal winds and geopotential height changes related to the NAO index are located mainly over the North Atlantic and North America in April (Fig. R3). An anomalous anticyclone is forced over the western United States, but the region of significant correlation is located mainly over Canada (Fig. R4).

Considering the length of the article, the number of figures, and the relevance of the content, the results in Figs. R2–4 are not included in the revised manuscript.

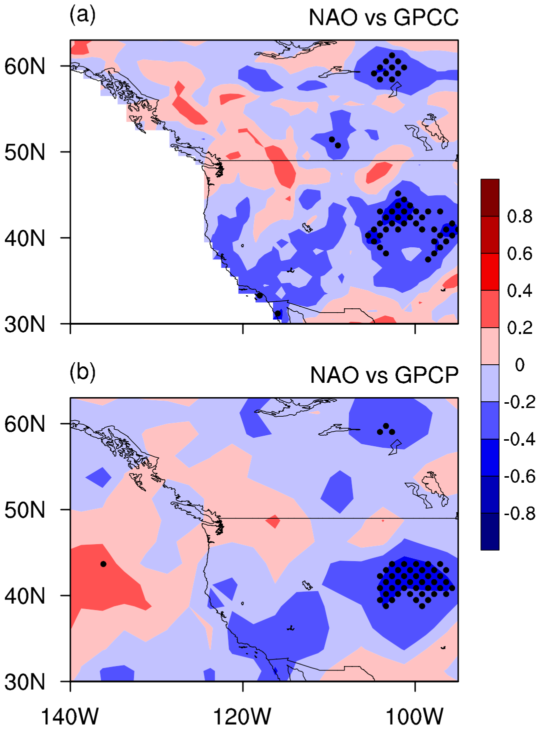


Figure R2. Correlation coefficients between NAO index and precipitation variations in April based on GPCC (a) and GPCP (b) rainfall for the period 1984–2016. Dots denote significance at the 95% confidence level, according to Student's *t*-test. The long-term linear trend and seasonal cycle in all variables were removed before the correlation analysis. The NAO index is from the NOAA Climate Prediction Center (CPC).

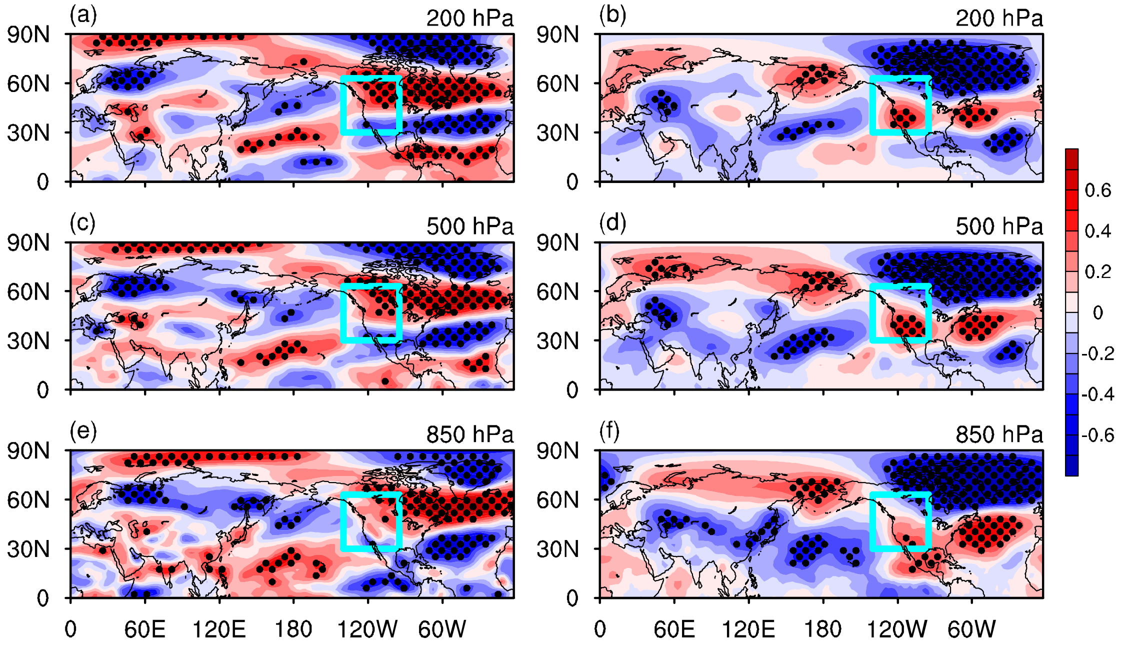


Figure R3. Correlation coefficients between NAO index and zonal wind variations in April over the period 1984–2016 at 200 hPa (a), 500 hPa (c), and 850 hPa (e). Dots denote significance at the 95% confidence level, according to Student's *t*-test. The blue square indicates the area shown in Fig. R2. Before performing the analysis, the seasonal cycle and long-term linear trend were removed from the original datasets. (b, d, f) As for (a, c, e), but for geopotential height. The NAO index is from the NOAA Climate Prediction Center (CPC), and wind and geopotential height are from NCEP2.

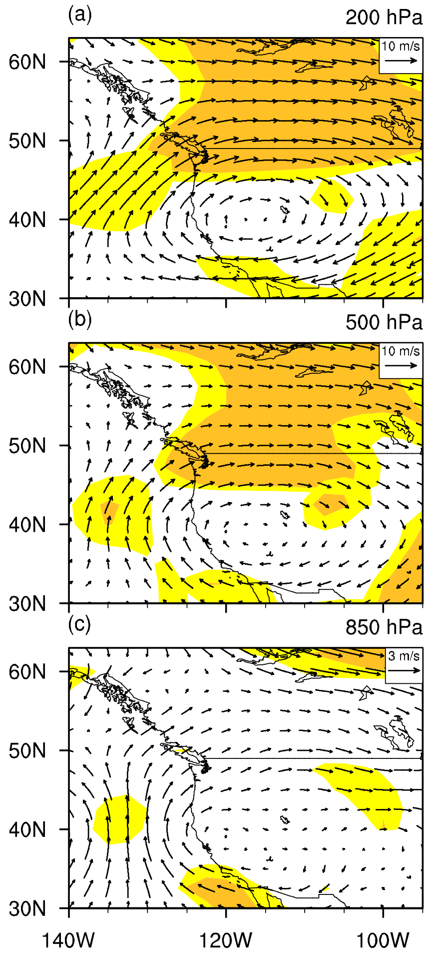


Figure R4. Differences in composite April winds (vectors, m/s, from NCEP2) between positive and negative NAO anomaly events at 200 hPa (a), 500 hPa (b), and 850 hPa (c) for 1984–2016. Colored regions are statistically significant at the 90% (light yellow) and 95% (dark yellow) confidence levels. The seasonal cycle and long-term linear trend were removed from the original dataset. The NAO anomaly events are selected based on Table R1 below.

Table R1. Positive (left column) and negative (right column) NAO anomaly events in April for the period 1984–2016. Positive and negative April NAO anomaly events are defined using a normalized time series of April NAO variations from 1984 to 2016. Values larger than 1 standard deviation are defined as positive NAO anomaly events, and those below –1 standard deviation are defined as negative NAO anomaly events.

Positive NAO anomaly events	Negative NAO anomaly events
1987, 1990, 1992, 2011	1988, 1995, 1997, 1998, 1999, 2008, 2010

References:

Calvo, N., Polvani, L. M., and Solomon, S.: On the surface impact of Arctic stratospheric ozone extremes. Environ. Res. Lett., 10, 094003, 2015.

Baldwin, M. P. and Dunkerton, T. J.: Stratospheric harbingers of anomalous weather regimes. Science, 294, 581–584, doi:10.1126/science.1063315, 2001.

Black, R. X., Mcdaniel. B. A., Robinson, W. A.: Stratosphere Troposphere Coupling during Spring Onset. J. Climate, 19, 4891-4901, 2005.

Black, R. X. and Mcdaniel, B. A.: SubMonthly polar vortex variability and stratosphere-troposphere coupling in the Arctic. J. Climate, 22, 5886-5901, 2009.

Black, R. X., Mcdaniel, B. A.: The Dynamics of Northern Hemisphere Stratospheric Final Warming Events. Journal of the Atmospheric Sciences, 64, 2932-2946, 2006.

Ivy, D. J., Solomon, S., Calvo, N., and Thompson, D. W.: Observed connections of Arctic stratospheric ozone extremes to Northern Hemisphere surface climate. Environ. Res. Lett., 12, 024004, 2017.

Smith, K. L. and Polvani, L. M.: The surface impacts of Arctic stratospheric ozone anomalies. Environ. Res. Lett., 9, 074015, 2014.

Xie, F., Li, J., Tian, W., Fu, Q., Jin, F.-F., Hu, Y., Zhang, J., Wang, W., Sun, C., Feng, J., Yang, Y., and Ding, R.: A connection from Arctic stratospheric ozone to El Niño-Southern Oscillation. Environ. Res. Lett., 11, 124026, 2016.

Xie F., Li, J., Zhang, J., Tian, W., Hu, Y., Zhao, S., Sun, C., Ding, R., Feng, J, and Yang, Y.: Variations in North Pacific Sea Surface Temperature Caused by Arctic Stratospheric Ozone Anomalies. Environ. Res. Lett., 12, 114023, 2017.

3.2 Additionally, given that the SST anomalies shown in Fig. 10 strongly resemble the Pacific Decadal Oscillation (PDO), the same patterns should be examined for the PDO and ENSO. With such a small sample size of years used in the analysis (Table 2), the authors could simply be sampling concurrent SST variability. Given that most previous studies on this subject see the strongest anomalies in the North Atlantic sector, the fact that all of the anomalies are in the Pacific in this study makes me concerned that Pacific

SST variability is being aliased into the analysis.

Response: We thank the reviewer for this comment. Figure R5 shows the correlation coefficients between April SST variations and (Fig. R5a) April precipitation in the northwestern United States, (Fig. R5b) March ASO, (Fig. R5c) April PDO, and (Fig. R5d) April Nino 3.4 indices. Figure R5a and R5b are Fig. 10 in the initial manuscript. Comparing Fig. R5a with Fig. R5b–d, the pattern of correlation coefficients in Fig. R5a is closer to the pattern shown in Fig. R5b (ASO and SST).

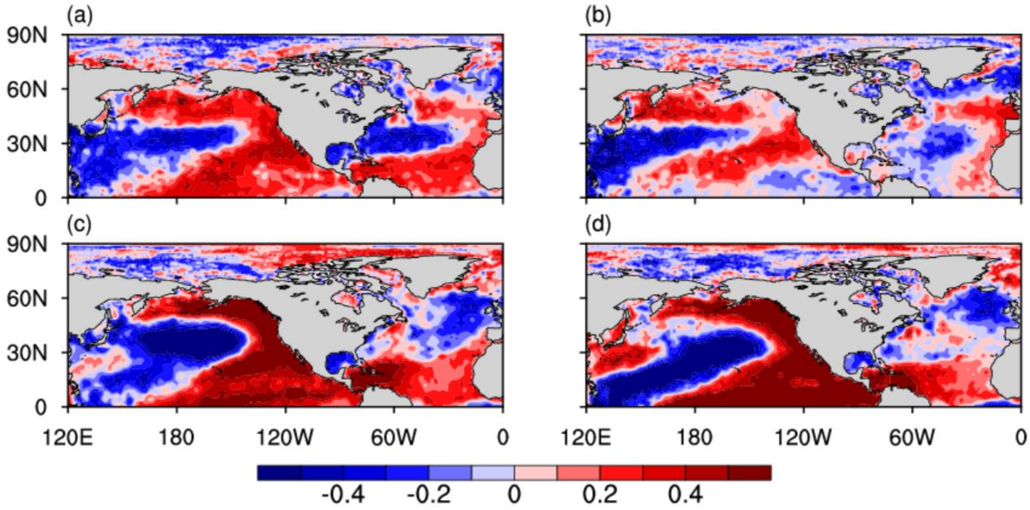


Figure R5. Correlation coefficients between April SST variations and (a) April precipitation in the northwestern United States, (b) March ASO, (c) April PDO, (d) and April Nino 3.4 indices for 1984–2016. Before performing the analysis, the seasonal cycle and linear trend were removed from the original datasets.

To provide a more quantitative answer to the question, Table R2 lists the spatial correlation coefficients between Fig. R5a and the patterns in Fig. R5b–d. The highest spatial correlation coefficient is obtained for the patterns in Fig. R5a and Fig. R5b. Table R3 further lists the correlation coefficients between the time series of April precipitation in the northwestern United States and March ASO, April PDO, and April Nino 3.4 indices. The highest correlation coefficient is between precipitation and ASO. The above results indicate that the SST anomalies shown in Fig. 10a in the initial manuscript are more likely related to ASO.

The mechanism by which March ASO variations affect April SST in the North Pacific was studied in detail by Xie et al. (2017) using observational data and model simulations. For a full response to this question, please see point #6 below.

Table R2. Spatial correlation coefficients for the patterns over the North Pacific only (124.5°E–100.5°W, 20.5°N–65.5°N) in Fig. R5a–d.

Patterns	**–ASO (Fig. R5b)**	**PDO (Fig. R5c)**	**ENSO (Fig. R5d)**
Precipitation (Fig. R5a)	**0.72**	**0.40**	**0.31**

Table R3. Correlation coefficients between time series of April precipitation in the northwestern United States, and March ASO, April PDO, and April Nino 3.4 indices for 1984–2016.

Time series	**–ASO**	**PDO**	**ENSO**
Precipitation	**0.55**	**0.25**	**0.20**

Reference:

Xie F., Li, J., Zhang, J., Tian, W., Hu, Y., Zhao, S., Sun, C., Ding, R., Feng, J, and Yang, Y.: Variations in North Pacific Sea Surface Temperature Caused by Arctic Stratospheric Ozone Anomalies. Environ. Res. Lett., 12, 114023, 2017.

4. As a related point, variations in March ASO should be linked closely to the timing of the seasonal breakdown of the NH stratospheric polar vortex. Black has examined this issue in detail in a series of papers (e.g., Black et al. 2006). Again, the authors need to better contextualize their results in the context of the past literature, which emphasizes the North Atlantic.

Response: Thanks very much for the comment. After reading the literatures

provided by reviewer, we realized that there are indeed many omissions in this manuscript. In the revised version, we made up for these missing knowledge points. Those some important references are also cited.

5. A consistent measure of statistical significance needs to be provided throughout the paper. Some figures show a 90% level, others a 95% level, and some show no significance at all (model results). 90% is a fairly weak threshold for statistical significance (1 in 10 chance that the point is significant by chance). I would recommend using the 95% level, or at least showing both the 90% and 95% levels (as is shown in Fig. 6).

Response: Thank you for this comment. In the revised paper, we used 95% confidence level throughout the paper and added significance test to the model results.

6.1 Related to point #3 above, how can we be sure that the SST anomalies in Fig. 10 are in fact caused by the stratospheric anomalies? They seem inconsistent with the wind anomalies in Fig. 4 (enhanced air-sea fluxes and cooling should occur in regions of enhanced westerlies). Some physical mechanism linking ASO to the SST anomalies needs to be provided.

Response: Thanks very much for the important comment. Xie et al. (2017) have recently explained why the ASO has a lagged impact on the sea surface temperature in the North Pacific mid–high latitudes (Fig. R6). They found that the stratospheric circulation anomalies caused by ASO changes can rapidly extend to the lower troposphere in the Northern Hemisphere high latitudes; however, the lower troposphere high-latitude circulation anomalies take about 1 month to propagate to the North Pacific mid-latitudes. The key findings of Xie et al. (2017) are as follows:

Xie et al. (2017) used composite analysis and wave ray theory to understand the lagged process. Figure R7 shows the composite changes in circulation on a daily time scale during ASO decrease and increase events (this is Figure 3 in Xie

et al. 2017). Figure R7a and b indicate that the composite Arctic stratospheric circulation anomalies during ASO anomaly events propagate downward to the high latitudes of the lower troposphere in a few days. The anomalies reaching the troposphere continue to propagate meridionally toward the northern lower and middle latitudes along the 180° to 120°W longitude zone (Fig. R7c and d). This southward propagation takes about 1 month. This phenomenon can be seen in both the ASO decrease and increase events (Fig. R7a/c and b/d).

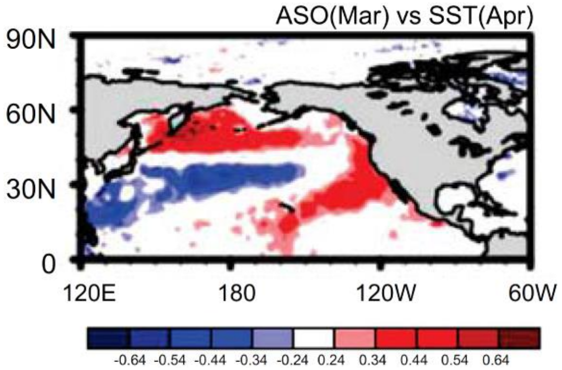
To study in more detail the horizontal propagation of circulation anomalies, the ray paths of waves at 850 hPa generated by the perturbed circulation over the region 60°–90°N and 180°–120°W in March are shown in Fig. R8 (Figure 4 in Xie et al. (2017), who found that the circulation anomalies over the region 60°–90°N and 180°–120°W have the strongest simultaneous correlation with the ASO changes). The wavenumbers along these rays are between 1 and 3. The wave ray paths represent the climate teleconnections; i.e., the propagation of stationary waves in realistic flows. The calculation of the wave ray paths and application of the barotropic model are described in detail by Li et al. (2015) and Zhao et al. (2015). Xie et al. (2017) found that the Rossby waves generated by the perturbed circulation over the north polar lower troposphere in March mainly propagate southward to the central North Pacific after about 1 month (they propagate to the northern North Pacific in about 15 days). The wave ray paths are in good agreement with the composite analysis in Fig. R7.

Figures R6-8 imply that ASO changes take at least 1 month to influence North Pacific circulation and SST. For more details, see Xie et al. (2017).

Figure R9 shows the April 850 hPa zonal wind anomalies during negative ASO anomalies events and the corresponding climatology. It is found that the westerly in the middle North Pacific is significantly enhanced during negative ASO anomalies events. It agreed with Fig. R10 that a negative SST anomaly is found in the middle North Pacific. In addition, the SST anomalies forced by ASO also can be explained by NPO anomalies. As mentioned above, the variations in ASO relate to NPO anomalies. Alexander et al. (2010) and Yu and Kim (2011) reported that

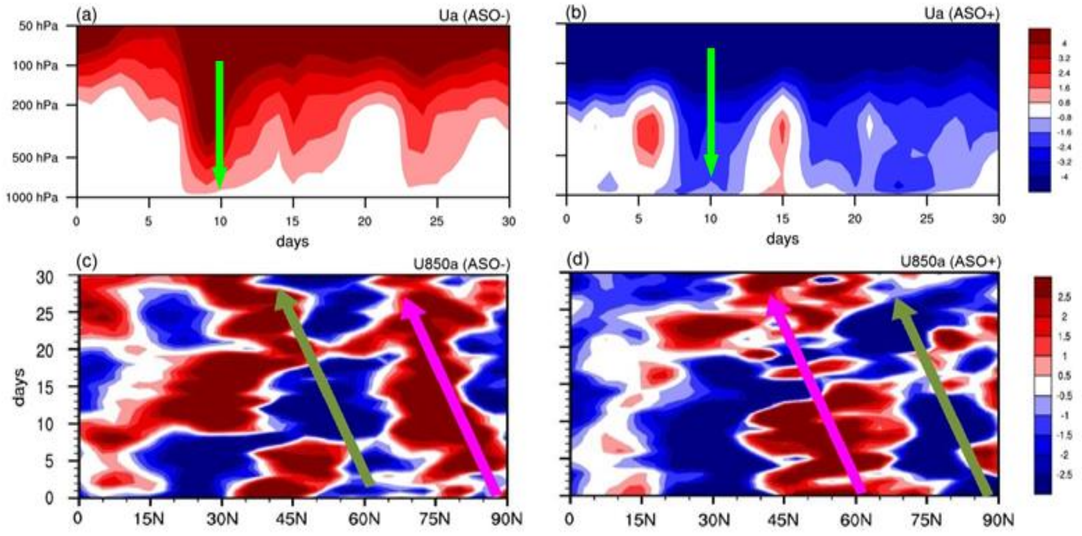
anomalous surface wind associated with the NPO can force a tripole-like pattern of the surface heat flux anomalies in the North Pacific, which in turn induces a tripole SSTA pattern there (including a dipole SSTA pattern of the Victoria Mode (VM) in the North Pacific poleward of 20°N).

The further proof from full-couple climate-ocean model please sees the next Response.



(Figure 6c in Xie et al. 2017)

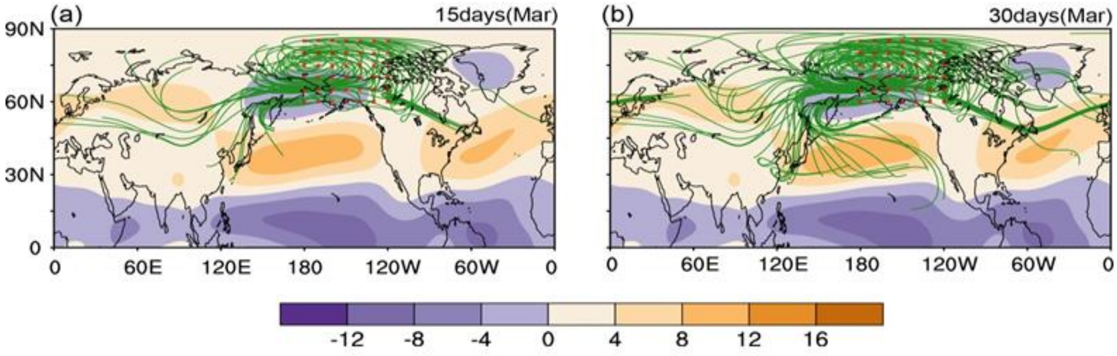
Figure R6. Correlation coefficients in March for 1979–2015 between –ASO and SST a month later. Only regions above the 95% confidence level are colored. The ASO data are from MERRA2, SST from HadSST.



(Figure 3 in Xie et al. 2017)

Figure R7. Time–height cross-section of composite daily variations in zonal wind (averaged over 60°–90°N, 180°–120°W) and latitude–time cross-section of composite daily variations in

zonal wind at 850 hPa (averaged over 180°–120°W) during ASO decrease events (a) and (c) and increase events (b) and (d) in March from 1979 to 2015. Winds are from NCEP2. The pink and green arrows indicate the propagation pathways of circulation anomalies.



(Figure 4 in Xie et al. 2017)

Figure R8. Ray paths (green lines) at 850 hPa in March after the circulation was perturbed for 15 days (a) and 30 days (b). Red dots denote wave sources in the region 60°–90°N, 180°–120°W. The wavenumbers along these rays are in the range 1–3. Color shading indicates the climatological flow.

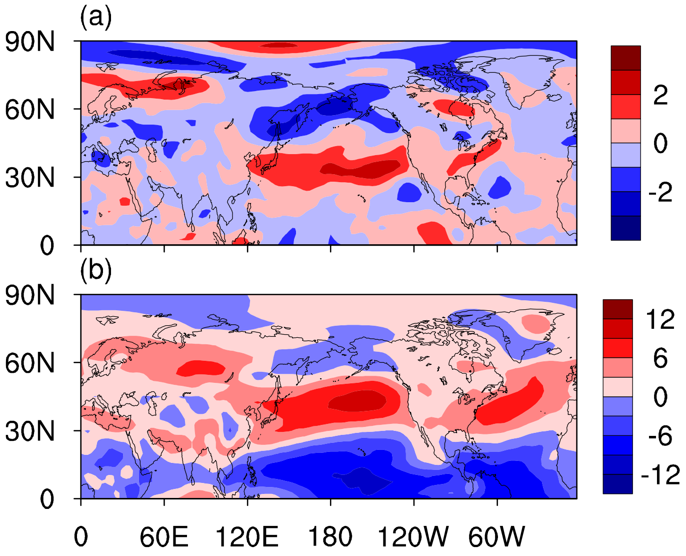


Figure R9. (a) April zonal wind anomalies during negative ASO anomalies events and (b) the climatology of the zonal wind in April at 850 hPa. The negative ASO anomalies events is based on Table 2 in the manuscript. Zonal wind is from NCEP2.

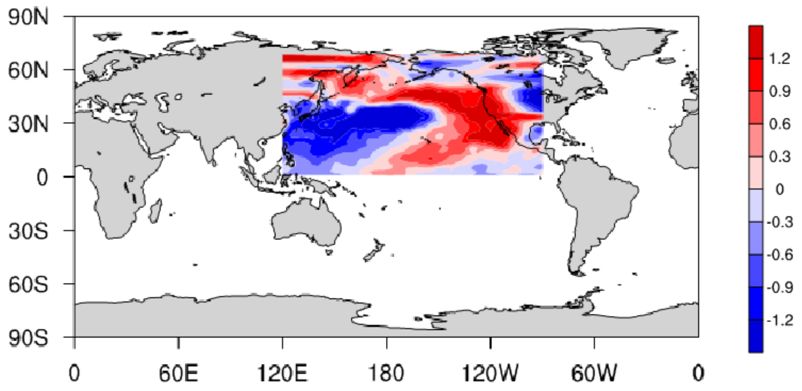


Figure R10. Composite SST anomalies during negative ASO anomaly events.

References:

Alexander, M. A., Vimont, D. J., Chang, P., and Scott, J. D.: The impact of extratropical atmospheric variability on ENSO: Testing the seasonal footprinting mechanism using coupled model experiments. J. Clim., 23, 2885–2901, 2010.

Li Y. J., Li J., Jin F-F, and Zhao S.: Interhemispheric propagation of stationary rossby waves in a horizontally no uniform background flow. J. Atmos. Sci. 72, 3233–3256, 2015.

Xie F., Li, J., Zhang, J., Tian, W., Hu, Y., Zhao, S., Sun, C., Ding, R., Feng, J, and Yang, Y.: Variations in North Pacific Sea Surface Temperature Caused by Arctic Stratospheric Ozone Anomalies. Environ. Res. Lett., 12, 114023, 2017.

Yu, J.-Y., and Kim, S. T.: Relationships between extratropical sea level pressure variations and the central Pacific and eastern Pacific types of ENSO. J. Clim., 24, 708–720, 2011.

Zhao S., Li J., and Li Y. J.: Dynamics of an interhemispheric teleconnection across the critical latitude through a southerly duct during boreal winter. J. Clim. 28, 7437–7456, 2015.

6.2 Without prescribing ASO anomalies in a fully coupled model (with interactive SSTs), it's difficult to conclusively establish that the SST anomalies can in fact be forced by ASO.

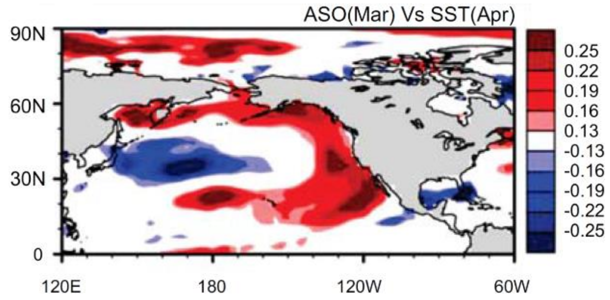
Response: To further confirm the leading effect of ASO on North Pacific SST, Xie et al. (2017) used the National Center for Atmospheric Research's Community Earth System Model (CESM) version 1.0.6 to simulate this process, which is a fully

coupled global climate model that incorporates an interactive atmosphere (CAM/WACCM) component, ocean (POP2), land (CLM4), and sea ice (CICE). For the atmospheric component, they used the Whole Atmosphere Community Climate Model (WACCM), version 4 (Marsh et al 2013), which has a finite volume dynamical core and it extends from the surface to approximately 140 km. For their study, they disabled the interactive chemistry.

The transient experiment (E1) performed by CESM with the fully coupled ocean incorporating both natural and anthropogenic external forcings, including spectrally resolved solar variability (Lean et al 2005), transient greenhouse gases (GHGs) (from scenario A1B of IPCC 2001), volcanic aerosols (from the Stratospheric Processes and their Role in Climate (SPARC) Chemistry–Climate Model Validation (CCMVal) REF-B2 scenario recommendations), a nudged quasi-biennial oscillation (QBO) (the time series in CESM is determined from the observed climatology over the period 1955–2005), and specified ozone forcing derived from the CMIP5 ensemble mean ozone output. E1 is a historical simulation covering the period 1955–2005. All the forcing data used in their study are available from the CESM model input data repository.

The experiment E1, covering the period 1955–2005 and with the specified ASO forcing applied to the CESM, captures the leading effect of the specified ASO anomalies on the North Pacific (Fig. R11). The VM-like pattern SST anomalies that appear over the North Pacific in April. This simulated result is similar to the observations (Figs. R6 and R10). Note that the ozone forcing is specified in the simulation and SST is output; therefore, the relationship between ASO and SST variations could only be caused by North Pacific SST anomalies related to the ASO changes.

More descriptions of the lagged impact of ASO on North Pacific SST anomalies shown in Xie et al. (2017) are added in the revised paper. Please see lines 284–290.



(Figure 7d in Xie et al. 2017)

Figure R11. Correlation coefficients between the specified –ASO in March and SST in April for the period 1955–2005 in the model simulation experiment. Only regions above the 95% confidence level are colored. All quantities were detrended before correlation.

Minor Revisions:

7. The following sentence structure used in the abstract (and elsewhere in the paper) is very difficult to read: "An increase (decrease) .... results in enhanced (weakened) ... but weakened (enhanced) ... facilitating (impeding) ..." Please consider eliminating the words in parentheses, or using a difficult format to convey this information. It's confusing to discuss both polarities (both an increase and decrease in ozone) within the same sentence structure.

Response: Thanks for the comment. We have used a new format to convey this information in the whole manuscript.

8. Line 37: The circulation changes mostly occurred in the late 20th century, not the early 21st century, as the ozone hole was increasing in size from the 1980s until around the year 2000. Since that time, the ozone hole has stabilized in size, and may in fact be starting to recover (see Solomon et al. 2017).

Response: Revised. Thanks.

9. Lines 44–45. See Fig. 3 in Kang et al. (2011). The precipitation changes associated with Antarctic stratospheric ozone depletion are more accurately described as an increase in the subtropics and high latitudes, and a decrease at mid-latitudes.

Response: Revised. Thank you.

10. Lines 55–57: This explanation of the surface temperature anomalies associated with Antarctic ozone depletion is not consistent with previous literature. See discussion in Thompson et al. (2011) and the references therein. The surface temperature anomalies are linked to how the poleward circulation shift associated with the ozone hole affects localized wind patterns (and associated thermal advection) at each location.

Response: We thank the reviewer for this comment. We have modified this section as follows (lines 38-41 in the revised manuscript):

"*The poleward circulation shift would cause surface temperature anomalies by affecting localized wind patterns and associated thermal advection (Son et al., 2010; Thompson et al. 2011; Feldstein, 2011).*"

References:

Thompson, D. W. J., Solomon, S., Kushner, P.'J., England, M. H., Grise, K. M., and Karoly, D. J.: Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change, Nature Geosci., 4, 741–749, doi:10.1038/NGEO1296, 2011.

11. Line 110: The vertical pressure range (100–50 hPa) contradicts that in footnote #2 of Table 1 (150–50 hPa). Please correct.

Response: Corrected. Thanks.

12. Line 142: If SSTs are specified, the term "coupled" here is misleading. Follow convention in the literature, I would recommend using the term "coupled" only if the atmosphere model is fully coupled to an interactive ocean model.

Response: Removed the term "coupled". Thanks.

13. Line 148: This statement seems to contradict the statement on line 143. The model has middle atmospheric chemistry, yet the model does not include interactive chemistry. This needs to be clarified.

Response: Thanks for the comment. There are two schemes to run WACCM4, one is WACCM4-MOZART (including interactive chemistry), and one is WACCM4-GHG (disable interactive chemistry). Our study used the latter scheme. We are sorry that it is not clear here. It has been revised in the revised manuscript.

14. Lines 151, 154: The text refers to a reference period of 1980–2015, while Table 1 refers to a reference period of 1995–2005. This needs to be clarified and standardized throughout the paper.

Response: Revised. Thanks.

15. Line 164: I would use "break down" rather than "rupture" here to be consistent with terminology in previous literature.

Response: Revised. Thanks.

16. Line 167: This lead time is not unique to NH stratospheric ozone perturbations. It is consistent with the tropospheric anomalies associated with NH sudden stratospheric warmings (Baldwin and Dunkerton 2001) and SH stratospheric ozone depletion (Thompson and Solomon 2002).

Response: Thanks for this comment. Here, we added the some content in the revised paper. See lines 165-169 in the revised manuscript.

> ***"These studies pointed out that the changes in ASO affect the tropospheric climate with a lead of about 1–2 months, which is similar to the troposphere response to the Northern Hemisphere sudden stratospheric warmings (Baldwin and Dunkerton 2001; Black et al., 2005, 2006, 2009) and Southern Hemisphere stratospheric ozone depletion (Thompson and Solomon 2002)."***

References:

Baldwin, M. P. and Dunkerton, T. J.: Stratospheric harbingers of anomalous weather regimes, Science, 294, 581–584, doi:10.1126/science.1063315, 2001.

Black, R. X., Mcdaniel. B. A., Robinson, W. A.: Stratosphere Troposphere Coupling during Spring Onset. J. Climate, 19, 4891-4901, 2005.

Black, R. X. and Mcdaniel, B. A.: SubMonthly polar vortex variability and stratosphere-troposphere coupling in the Arctic. J. Climate, 22, 5886-5901, 2009.

Black, R. X., Mcdaniel, B. A.: The Dynamics of Northern Hemisphere Stratospheric Final Warming Events. Journal of the Atmospheric Sciences, 64, 2932-2946, 2006.

Thompson, D. W. J. and Solomon, S.: Interpretation of recent Southern Hemisphere climate change, Science, 296, 895–899, doi:10.1126/science.1069270, 2002.

17. Lines 236–240: This statement is not consistent with the figures. Figures 4–6 show a barotropic circulation response (same sign throughout the depth of the troposphere), with an anomalous cyclone over western North America at all levels (Fig. 6).

18. Lines 248–250: How so? I don't understand the dynamical basis for this statement.

Response: We thank the reviewer for the two comments. We apologize for the incorrect statement here. In the revised manuscript, we have rewritten the paragraph in lines 231–250 as follows (see lines 199–232 in the revised manuscript):

"Figure 3 shows the correlation coefficients between March ASO anomalies and April zonal wind variations at 200, 500, and 850 hPa, respectively. The spatial distribution of significant correlation coefficients over the North Pacific exhibits a tripolar mode with a zonal distribution at 200 and 500 hPa; i.e. a positive correlation in the high and low latitudes in the North Pacific and a negative correlation in mid-latitudes. This implies that the increase in ASO can result in enhanced westerlies in the high and low latitudes of the North Pacific but weakened westerlies in the mid-latitudes, corresponding to the weakened Aleutian Low in April, and vice versa for the decrease in ASO. The Aleutian Low acts as a bridge connecting variations in ASO and circulation anomalies over the North Pacific (Xie et al., 2017a). At 850 hPa, the anomalous circulation signal in the low latitudes of the North Pacific has weakened

and disappeared. It is evident that the anomalous changes in the zonal wind over the North Pacific can extend westward to East Asia. Xie et al. (2018) identified the effect of spring ASO changes on spring precipitation in China. Note that the weakened westerlies in the mid-latitudes and the enhanced westerlies at low latitudes can also extend eastward to the western United States. This kind of circulation anomaly corresponds to two barotropic structures; i.e., an anomalous anticyclone in the Northeast Pacific and a cyclone in the southwestern United States at 500 hPa and 200 hPa. Coincidentally, the northwestern United States is located to the north of the intersection of the anticyclone and cyclone, corresponding to convergence of the airflow at high levels, which may lead to downwelling in the northwestern United States, and vice versa for negative March ASO anomalies.

To further validate our inference regarding the response of the circulation in the western United States to ASO changes, we analyze the differences between April horizontal wind anomalies during positive and negative March ASO anomaly events at 200, 500, and 850 hPa (Fig. 4). As in the increased ASO case, the difference shows an anomalous anticyclone in the Northeast Pacific and an anomalous cyclone in the southwestern United States. This kind of circulation anomaly over the southwestern United States enhances cold and dry airflow from the North American continent to the North Pacific, reducing the water vapor concentration in the air over the western United States and possibly reducing April precipitation in the northwestern United States. In addition, the northwestern United States is located to the north of the intersection of the anticyclone and cyclone, suggesting downwelling flow in the region.”

19. Lines 254, 258, 365: Reanalyses cannot adequately resolve convective activity. The *anomalous downwelling here is associated with synoptic-scale processes (see positive geopotential heights in northeast Pacific in Fig. 5). The pattern in Fig. 7a should closely correspond to sea-level pressure anomalies (a surface high in the northwestern United States and a surface low in the southwestern United States).*

Response: We thank the reviewer for this comment. The term "convective activity" used here may not be appropriate. We have used "downwelling" instead of "convective activity" in the revised paper.

Figure R12 shows the differences in composite April sea-level pressure anomalies between positive and negative ASO anomaly events for 1984–2016. The result agrees with the reviewer's speculation; i.e., a surface high in the northwestern United States and a surface low in the southwestern United States.

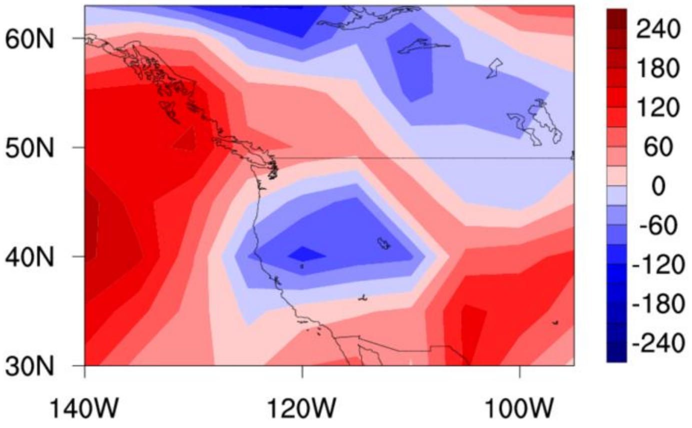


Figure R12. Differences in composite April sea-level pressure anomalies between positive and negative ASO anomaly events for 1984–2016. Before performing the analysis, the seasonal cycle and linear trend were removed from the original dataset. The ASO anomaly events are selected from Table 2 in the manuscript. The SLP (Pa) dataset is from the UK Met Office Hadley Centre.

20. Line 282: It doesn't look like opposite to me … just shifted a little further to the north in the model than in the observations (which, of course, would make a difference for regional impacts as the authors nicely state on the subsequent lines).

Response: Revised. Thanks.

21. Line 301: The SST pattern looks a lot like the Pacific Decadal Oscillation (PDO) or the North Pacific Mode (Hartmann 2015). How well correlated is the time series of the "Victoria Mode" with these modes?

Response: Thanks for the comment. Please see the Table R4.

Table R4. Correlation coefficients among the time series of April VM, April PDO, and April Nino 3.4 indices for 1984–2016.

Time series	PDO	ENSO
VM	-0.18	0.09

22. All figures: I think it's unnecessary to show both the correlations and composite differences (Figs. 1 and 3, left and right columns of Fig. 4-5), as they basically convey identical information.

Response: Thanks for this comment. Only the correlation results remain in the revised manuscript.

23. Figures 1 and 3: It's difficult to interpret these patterns with so much of the map left blank. I would recommend showing the correlation coefficients for the entire map, and stippling those regions that are statistically significant.

Response: Modified, thanks. See following Fig. R13 (this is Figure 1 in the manuscript). Figure 3 in the revised manuscript has been deleted.

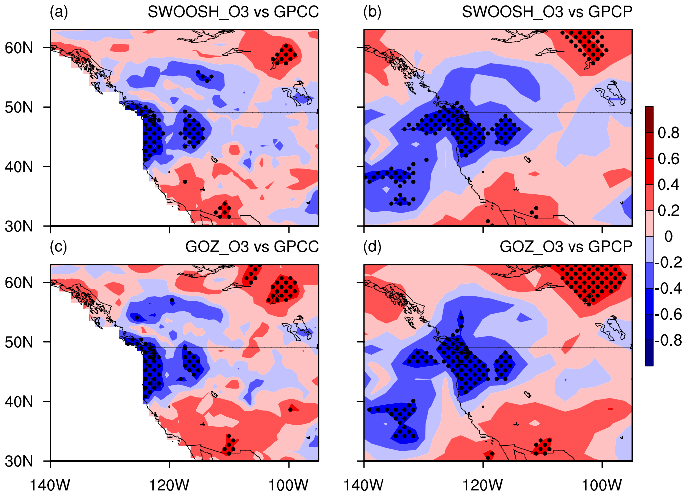


Figure R13. Correlation coefficients between March ASO and April precipitation variations

calculated from SWOOSH (a, b) and GOZCARDS (c, d) ozone, and GPCC (a, c) and GPCP (b, d) rainfall for the period 1984–2016. Dots denote significance at the 95% confidence level, according to Student's t-test. The long-term linear trend and seasonal cycle in all variables were removed before the correlation analysis.

24. Figure 2: What are the dashed black lines? A measure of statistical significance?

Response: This point is right, thanks. The dashed blacked lines refer to the correlation coefficient that is significance at 95% confidence level. In the revised paper, we added it in the caption of Fig. 2.

25. Figures 4–5: Is it necessary to show both geopotential heights and zonal wind? Both figures convey exactly the same information (via geostrophic balance).

Response: Deleted Figure 5. Thanks.

26. Figure 7: It would be good to clarify that blue is upward motion and red is downward motion.

Response: Clarified it in the caption of Figure 7. Thanks.

27. Figure 12: Because the model has prescribed SSTs, how do you know the model SSTs associated with ASO anomalies? Are these some version of the observed SST anomalies as they don't look exactly like those in Fig. 10?

Response: We thank the reviewer for this comment. The SST anomalies used to force the model (Fig. 12; that is Fig. 9 in the revised manuscript) are composite SST anomalies for negative and positive ASO anomaly events. The mechanism by which ASO influences the North Pacific SST is discussed in the responses to points 6.1 and 6.2. The pattern in Fig. 12 (Fig. 9 in the revised manuscript) is not exactly the same as that in Fig. 10 (Fig. 8 in the revised manuscript), which may reflect the fact that the results in Fig. 12 (Fig. 9 in the revised manuscript) were obtained from composite analysis whereas those in Fig. 10 (Fig. 8 in the revised manuscript) were from correlation analysis.

Typos:

1. *Line 96: central of China -> central China*
2. *Line 134: regarding -> regarded*
3. *Line 147: is at -> are at*
4. *Lines 173, 354: Washington and Oregon states -> Washington and Oregon*
5. *Line 176: the Fig. 1 -> Fig. 1*
6. *Line 259: enhances -> weakens*
7. *Table 1, R4–R7: a SST anomalies -> SST anomalies*

Response: All revised. Thanks.