Responses to Referees' Comments

Effects of Arctic stratospheric ozone changes on spring precipitation in the northwestern United States

(ACP-2018-414)

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Response to Referee 2

The manuscript presents a well-designed study of the effects of variability in springtime Arctic stratospheric ozone (ASO) on the tropospheric circulation over the Pacific basin, extending into the north-west United States. The authors present statistical relationships between a variety of physical climate variables and ASO in observations, finding an inverse correlation between ASO anomalies and March precipitation over the north-west United States, and then explore the causality with a number of WACCM model simulations using anomalies applied to the prescribed ozone and sea-surface temperatures used in the model. The model simulations provide convincing evidence that the combined effect of the ASO anomalies and correlated changes in sea-surface temperatures over the Pacific can reproduce the observed pattern of changes in winds and precipitation. The study is well thought out and presented and I have no serious concerns about the methodology.

The one significant missing aspect to the manuscript is the way the authors discuss ozone variability and the effects of ozone variability on dynamics as a completely independent forcing. The model simulations are convincing in that the specified ozone can be modified and the impact on the dynamics can be estimated in a one-way cause-and-effect manner. But in the real atmosphere there is a very tight coupling between dynamical modes of variability and Arctic ozone. Variability in the amount of planetary wave forcing from the troposphere has a direct connection to the strength of the Brewer-Dobson circulation and the amount of poleward ozone transport each year. And the occurrence of Sudden Stratospheric Warmings in the late winter or early spring can determine whether polar stratospheric temperatures cold enough for heterogenous chemistry on polar stratospheric clouds will occur and produce significant chemical ozone destruction in the Arctic. I think there are two important implications for the manuscript under consideration here. One is that the observation-based analysis must discuss the strong coupling between dynamical variability and ozone variability and must recognize that the correlations of certain physical variables with ozone also *reflect correlations with other aspects of dynamical variability. And second, I believe the authors cannot state that the Victoria Mode anomalies in Pacific sea-surface temperatures are caused by, as opposed to being associated with, the ASO anomalies.*

Response: We thank the reviewer for taking the time to assess the manuscript and we sincerely appreciate the reviewer's helpful comments, which have greatly improved the paper. We have revised the manuscript carefully according to the reviewer's comments and suggestions.

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 RR1 shows the correlation coefficients between the February SPV (multiplied by –1) index and April 200 hPa zonal wind and precipitation variations (Fig. RR1a and b), and between March ASO and April 200 hPa zonal wind and precipitation (Fig. RR1c 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. RR1 are similar, the ASO variations are much closer than the strength of the stratospheric polar vortex to the variations in 200 hPa zonal wind and precipitation. Fig. RR1 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.

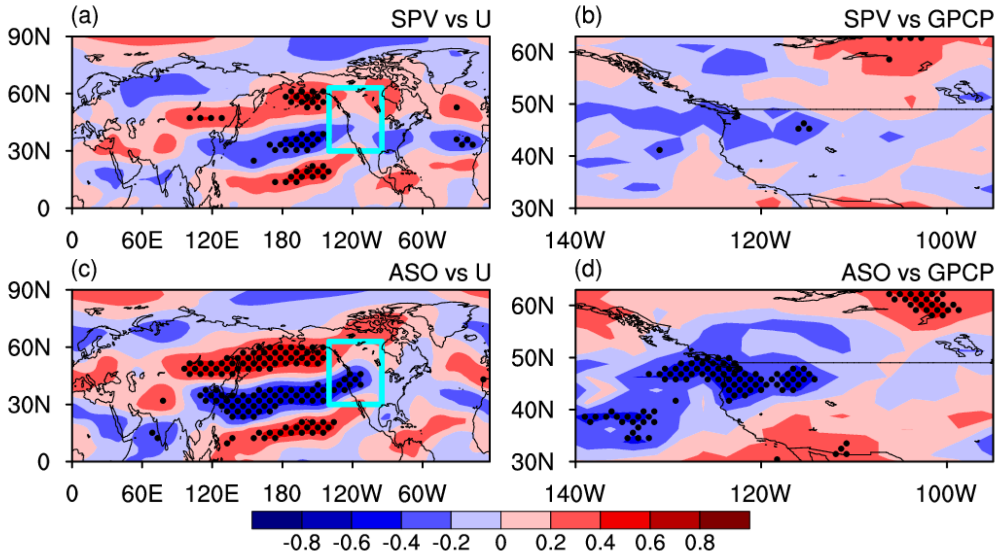


Figure RR1. (a) Correlation coefficients between the February –SPV (10^5 K m^2 kg^{-1} s^{-1}) index defined by Zhang et al. (2018) and April zonal wind variations at 200 hPa for 1984–2016. (b) Correlation coefficients between February –SPV index and April precipitation variations. (c) and (d) As for (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 is 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. RR1 and relevant discussion have been added to the discussion section in the revised manuscript. See lines 368–388.

Xie et al. (2017) explained why the ASO has a lagged impact on the circulation and sea surface temperature in the North Pacific mid–high latitudes based on observations and a fully coupled climate–ocean model. Detailed responses are given below.

References:

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.

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

As given below in the minor comments, in a few places through the manuscript the differences in the circulation between different WACCM experiments are described in very direct ways. It would be much more illustrative for the reader if these changes could be associated with changes in the position of significant climatological features, in a similar way that the Antarctic wind changes can be summarized as a pole-ward shift of the jet.

Response: Thank you for the good suggestion. We also recognize this problem. We have described those features in the Figures in a more physical and professional language. Please see the manuscript in detail.

Minor Comments:

1. Lines 15 – 18: Following my concerns about correlation and causality, the sentence 'In addition, the ASO changes cause sea surface temperature anomalies over the North Pacific that would cooperate with the ASO changes to modify the circulation anomalies *over the northwestern US.' should be softened.*

Response: Thanks to the comment. This sentence has been modified as follows:

"In addition, sea surface temperature anomalies over the North Pacific, which may be related to the ASO changes, would cooperate with the ASO changes to modify the circulation anomalies over the northwestern United States."

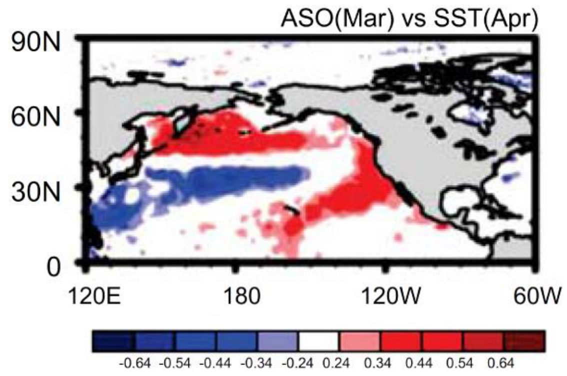
Xie et al. (2017) have recently explained why the ASO has a lagged impact on the sea surface temperature in the North Pacific mid–high latitudes (Fig. RR2). They found that the stratospheric circulation anomalies caused by ASO changes can rapidly extend to the lower troposphere in the Northern Hemisphere 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 RR3 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 RR3a 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. RR3c and d). This southward propagation takes about 1 month. This phenomenon can be seen in both the ASO decrease and increase events (Fig. RR3a/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. RR4 (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

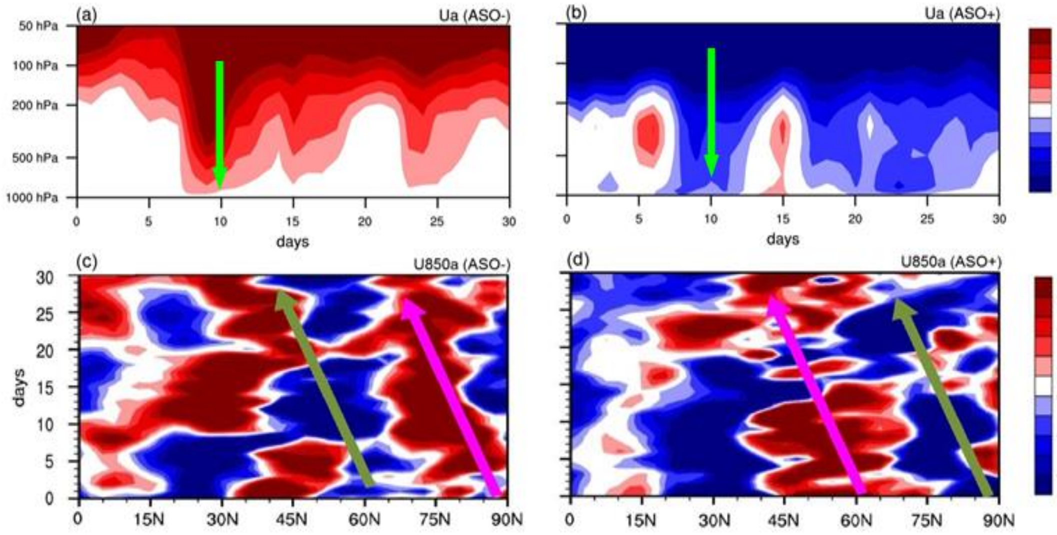
paths represent the climate teleconnections; i.e., the propagation of stationary waves in realistic flows. The calculation of the wave ray paths and application of the barotropic model are described in detail by Li et al. (2015) and Zhao et al. (2015). Xie et al. (2017) found that the Rossby waves generated 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. RR3.

Figures RR2-4 imply that ASO changes take at least 1 month to influence North Pacific circulation and SST.



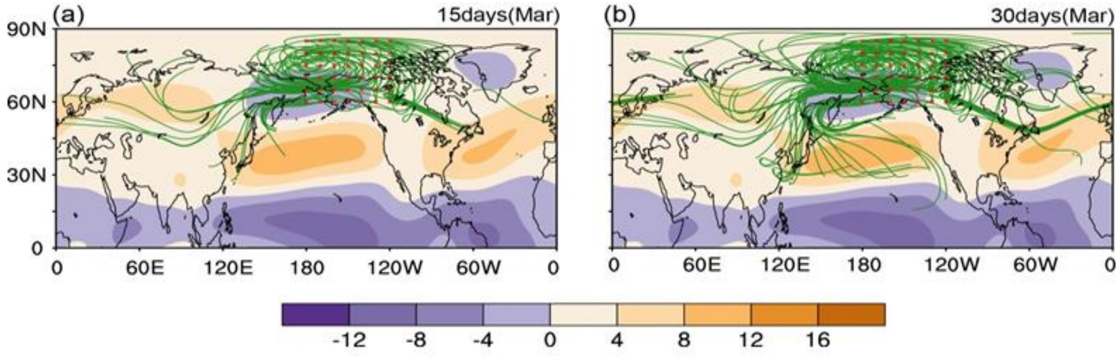
(Figure 6c in Xie et al. 2017)

Figure RR2. 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 RR3. 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 RR4. 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.

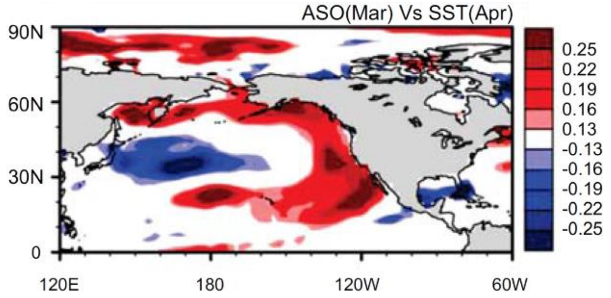
The further proof from full-couple climate-ocean model, Xie et al. (2017) used

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. RR5). The VM-like pattern SST anomalies that appear over the North Pacific in April. This simulated result is similar to the observations (Figs. RR2). 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 RR5. 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.

References:

Lean, J., Rottman, G., Harder, J. and Kopp, G.: SORCE contributions to new understanding of global change and solar variability. Sol. Phys. 230 27–53, 2005.

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.

Marsh, D. R., Mills, M. J., Kinnison, D. E., Lamarque, J. F., Calvo, N., and Polvani, L. M.: Climate Change from 1850 to 2005 Simulated in CESM1(WACCM), J. Climate, 26, 7372–7391, doi:10.1175/JCLI-D-12-00558.1, 2013.

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.

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.

2. Lines 109 – 111: As stated here, the ASO is calculated as an anomaly after removing the annual cycle and trend. I would imagine the long-term trend is predominately due to the rise in ozone depleting substances. Why was the trend removed from the calculation of ASO, as I would think the March ASO anomaly related to ozone depletion would be part of the signal you are looking for? And is the trend calculated as a single linear trend across the entire period or some measure that is related to halogen loading *in the stratosphere such as Equivalent Effective Stratospheric Chlorine (EESC)? As the period analysed is 1984 – 2015, or so, this would include both the rapid increase in EESC up to ~2000 and the plateau or slow decline since then and a single linear trend across the entire period would be a less than ideal estimate of the forced response.*

Response: We thank the reviewer for this comment. Figure RR6 shows the standardized time series of the original March ASO index (black line), the index after removal of the linear trend across the entire period (blue line), and that after removal of the EESC signal (red line). The correlation coefficients between these ASO time series are listed in Table RR1. These three ASO time series are very similar, and the correlation coefficients are all above 0.95 and significant at the 95% confidence level.

To further assess the response of April circulation variations to ASO changes with and without the linear trend and EESC signal, Figure RR7 shows the correlation coefficients between these three ASO time series and April zonal wind variations. All three March ASO indices are significantly correlated with April zonal wind variations over the North Pacific, and their patterns are similar in each case. This implies that the trend of ASO from 1984 to 2016 does not affect the main conclusions of this study.

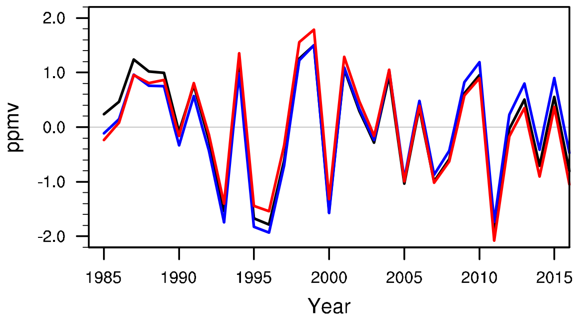


Figure RR6. ASO represented by a standardized time series of March mean ozone from SWOOSH ozone for 1984 to 2016. Black line presents the original data; blue line shows the ASO with the linear trend removed and the red line is the ASO with the EESC signal removed.

Table RR1. Correlation coefficients between the three ASO time series shown in Fig. RR6.

	ASO	**ASO (linear trend removed)**	**ASO (EESC removed)**
ASO	**1.0**	**0.97**	**0.98**
ASO (linear trend removed)	**—**	**1.0**	**0.95**
ASO (EESC removed)	**—**	**—**	**1.0**

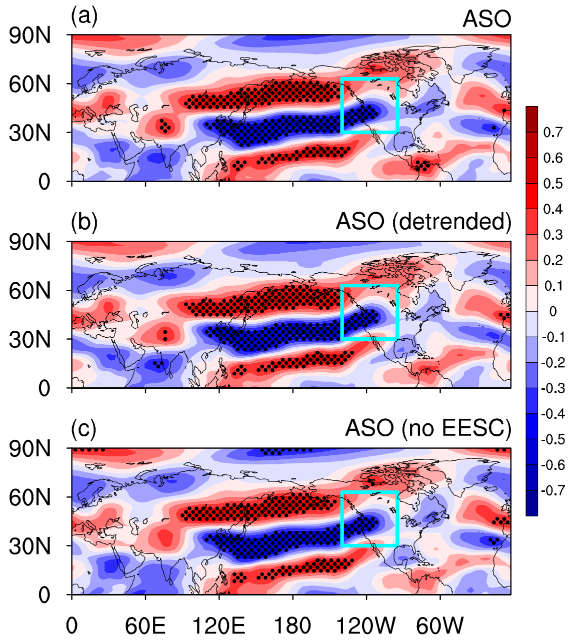


Figure RR7. (a) Correlation coefficient between the original March ASO index and April zonal wind variations (m/s, from NCEP2) from 1984 to 2016 at 200 hPa. (b) and (c) As for (a), but for the ASO index with the linear trend and EESC signal removed, respectively. Dots denote significance at the 95% confidence level, according to Student's *t*-test.

3. Line 117: 'Another set of ozone dataset is...' sounds a bit redundant. Could I suggest 'Another set of ozone data is...'

Response: Revised. Thanks.

4. Lines 149 – 151: The statement 'The model's radiation scheme uses these conditions: fixed greenhouse gas (GHG) values, averages of emissions scenario A2 of the Intergovernmental Panel on Climate Change (IPCC) (WMO, 2003) for 1980–2015.' is *difficult to interpret. Is it that the fixed GHG values that were used are the 1980-2015 average from the A2 scenario? It seems a bit clearer in the text in Table 1, but there the average is said to be over 1995-2005.*

Response: Thanks for the comment. We are sorry for the mistake. The average time is 1995-2005, which have been modified in the revised paper. Please see lines 148 – 151.

"The model's radiation scheme uses these conditions: fixed greenhouse gas (GHG) values (averages of emissions scenario A2 of the Intergovernmental Panel on Climate Change (WMO, 2003) over the period 1995–2005)."

5. Lines 212 – 214: The correlation of zonal wind anomalies with the ASO is described as: 'This implies that the increase (decrease) in ASO can result in enhanced (weakened) westerlies in the high and low latitudes of the North Pacific but weakened (enhanced) westerlies in the mid-latitudes.' The changes in southern hemisphere winds associated with ozone depletion are often described in terms of a shift of the jet that produces a dipole pattern of changes in wind. Here the authors argue that the ASO is associated with a tripole of changes in zonal wind. Do the authors have an explanation for the pattern of changes that can be related to shifts or changes in magnitude of climatological features like the Aleutian Low? And can other explanations for the changes at low latitudes, such as ENSO, be ruled out?

Response: We thank the reviewer for this comment. Weakened westerlies in the high-latitude North Pacific and enhanced westerlies in the mid-latitudes during negative ASO anomaly events may not imply a poleward shift of the westerlies during ASO depletion.

However, as discussed by Xie et al. (2017), the pattern of zonal wind anomalies associated with ASO variations is related to changes in the North Pacific Oscillation (NPO) and Aleutian Low. Figure RR8 shows the differences in composite zonal wind between positive and negative April Aleutian Low (AL) anomaly events (selected AL events refer to Table RR2). The result shows that the

pattern of zonal wind anomalies related to the AL index is similar to that related to the ASO (see Figure 3 in the revised manuscript). This may implies that the AL acts as a bridge connecting variations in ASO and circulation anomalies over the North Pacific (This is also stated by Xie et al., 2017). In other words, the weakened westerlies in the high-latitude North Pacific and enhanced westerlies in the mid-latitudes during negative ASO anomaly events imply that the AL is enhanced when ASO is depleted, but weakened when ASO increases.

Figure RR9 is the same as Fig. RR8, but for the Nino 3.4 index. The pattern of zonal wind anomalies related to ENSO differs from that related to ASO.

The above results illustrate that the pattern of zonal wind anomalies associated with ASO variations is possibly associated with changes in the AL. The relevant content has been added to the revised manuscript (lines 204–207) as follows:

"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."

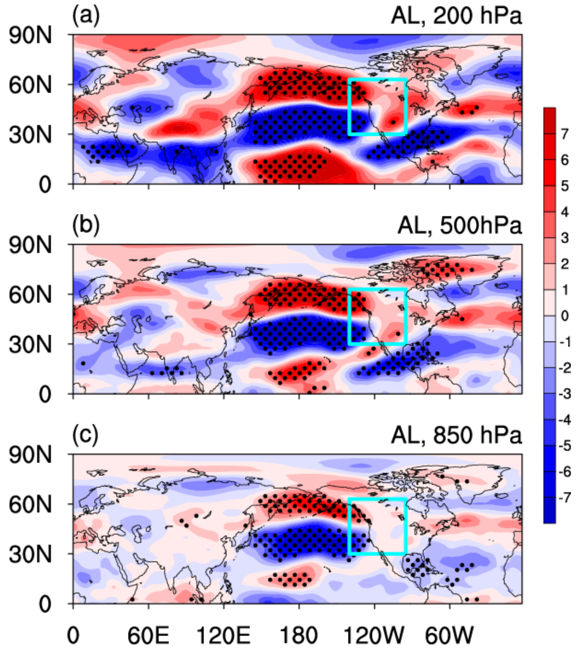


Figure RR8. Differences in composite April zonal wind (m/s) anomalies between positive and negative AL anomaly events at 200 hPa (a), 500 hPa (b), and 850 hPa (c). Dots denote

significance at the 95% confidence level, according to Student's *t*-test. Before performing the analysis, the seasonal cycle and linear trend were removed from the original datasets. AL anomaly events are selected using Table RR2.

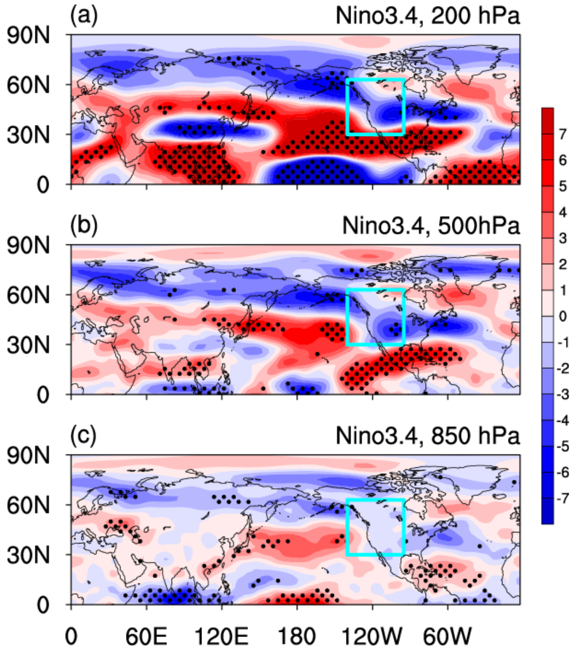


Figure RR9. Same as Fig. RR8, but for the Nino 3.4 index.

Table RR2. Positive (left column) and negative (right column) anomaly events based on the AL and Nino 3.4 indices for the period 1984–2016.

	index > 1 STD	**index < –1 STD**
AL index	**1985, 1986, 1999, 2002, 2008, 2013**	**1993, 1996, 1997, 2004, 2007, 2014, 2016**
Nino 3.4 index	**1987, 1992, 1993, 1998, 2015, 2016**	**1985, 1989, 1999, 2000, 2008, 2011**

References:

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.

6. Lines 236 – 240: 'This kind of circulation anomaly corresponds to an anomalous cyclone (anticyclone) in the western US in the middle and upper troposphere, which is likely associated with a strong low (high) pressure system in the middle and upper troposphere and a relatively weak high (low) pressure system in the lower troposphere.' I can see how this description fits with the pattern of wind changes shown in Figure 6, but that the pattern of changes shown in panel (A), for example, showing a cyclonic pattern centered over the south-western US does not necessarily mean that this is caused by the appearance of a well-defined, anomalous cyclone. While the pattern of the differences is cyclonic, it could be due to the weakening of an anticyclone? The description would have a stronger physical basis if the changes were related to changes in the strength of position of well-recognized climatological features.

7. Lines 248 -250: 'In addition, a strong low-pressure system in the middle and upper troposphere over the western US during positive ASO anomaly events (Fig. 6) suggests downwelling flow in the region.' Similar to the concerns about the interpretation of Lines 236 – 240, there is a direct link made between a pattern of changes and the appearance of a particular meteorological feature.

Response: We thank the reviewer for this comment. Figure RR10 shows the climatology of April horizontal wind vectors. The circulation over the western United States is controlled mainly by westerlies (no significant anticyclonic circulation). This means that the cyclonic anomaly in Fig. 4 of the revised manuscript is unlikely to be caused by weakening of an anticyclone.

We are also aware of the problem associated with this paragraph, and we have rewritten it as follows (please see the 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.”

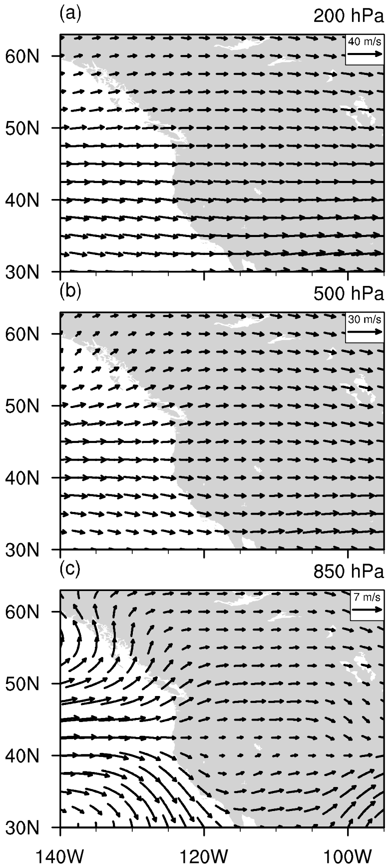


Figure RR10. Climatology (1984–2016) of April horizontal wind vectors from NCEP2 at 200 hPa (a), 500 hPa (b) and 850 hPa (c).

8. Lines 251 – 262: While I can understand how changes in vertical velocity (w) are coherent with the large-scale changes in circulation, the text in this paragraph makes a direct link between changes in w from the NCEP2 reanalysis and changes in convective precipitation. For example, at lines 253 – 255: ‘When the March ASO increases, tropospheric convective activity in the northwestern US (115°–130° W) *weakens, corresponding to anomalous downwelling.' Can a direct link between convective precipitation and changes in monthly-average vertical velocity be made? I think the authors would need to support this statement with citations to previous work. I am also some-what sceptical about the general direction of the argument, which appears to be trying to link the circulation changes to precipitation changes. Is convective precipitation an important fraction of precipitation in the north-west US in March-April? I would have thought the precipitation changes shown in Figure 1 are a much more straight-forward reflection of changes in orographic precipitation related to the decrease in wind and (presumably) moisture transport?*

Response: We thank the reviewer for this comment. There was indeed a problem with the description in this paragraph; in particular, the use of the phrase "convective activity" is inaccurate. As can be seen from the Responses to #6 and #7, the large-scale circulation caused by ASO anomalies may lead to upwelling or downwelling in the northwestern United States. Upwelling (downwelling) favors (inhibits) precipitation. This view is often expressed in papers analyzing precipitation (e.g., Kang et al., 2011). The relevant literature has been cited in the revised manuscript. In addition, Figure RR11 shows a significant negative correlation (*r* = –0.72) between vertical velocity (Pa/s) and precipitation anomalies in the northwestern United States in April. This also demonstrates that upwelling (downwelling) in the northwestern United States favors (inhibits) precipitation. This paragraph has been rewritten as follows in the revised manuscript (lines 233-244):

**"*Figure 5a shows a longitude–latitude cross-section of differences in April vertical velocity anomalies averaged over 1000–500 hPa between positive and negative March ASO anomaly events. When the March ASO increases, anomalous downwelling is found in the northwestern United States (115°–130° W). This situation may inhibit precipitation in the northwestern United States in April. Figure 5b depicts the longitude–height cross-section of differences in April vertical velocity averaged over 43°–50°N between positive and negative March ASO anomaly events, which further shows that anomalous downwelling over the United States when the*

ASO increases. Based on the above analysis, the circulation anomalies in the northwestern United States associated with positive March ASO anomalies may inhibit the formation of local precipitation in April, and vice versa for that with negative March ASO anomalies.”

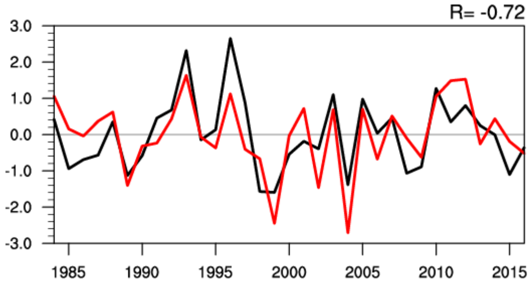


Figure RR11. Standardized time series of April precipitation and vertical velocity (Pa/s) (averaged over 1000–500 hPa) from 1984 to 2016. Both quantities are averaged over the area 43°–50°N, 115°–130°W, and the vertical velocity is multiplied by –1 for ease of comparison. The seasonal cycle and linear trend were removed from the original datasets. Precipitation is from GPCP, vertical velocity from NCEP2.

References:

Kang, S. M., Polvani, L. M., Fyfe, J. C., and Sigmond, M.: Impact of Polar Ozone Depletion on Subtropical Precipitation, Science, 332, 951–954, doi:10.1126/science.1202131, 2011.

9. Lines 267 – 268: The WACCM experiments detailed in Table 1 show that the perturbed ASO simulations vary ozone by +/- 15% between 30N and 90N. How realistic is this perturbation compared with the estimates from SWOOSH and GOZCARDS datasets? Perhaps a figure of the zonal-average difference could be included for the composite positive and negative ASO years? At high latitudes a +/-15% variability does not sound too large, perhaps even a bit small, but a +/- 15% change at 30N seems quite large.

Response: We thank the reviewer for this comment. Figure RR12 shows the composite zonal mean ozone anomalies (as a percentage) during positive and negative ASO anomalies events from the SWOOSH and GOZCARDS datasets. As noted by the reviewer, during positive (negative) ASO anomaly events the

stratospheric ozone anomalies are larger (smaller) than 15% at mid and high latitudes, but smaller (larger) than 15% at lower latitudes. In Fig. RR12, ozone changes are about 15% over most of the region 30°–90°N at 300–30 hPa. To keep the experiment simple, we have increased or decreased ozone throughout the region uniformly in the simulations. In principle, the simulation forced with composite ozone anomalies in Fig. RR12 is the best option. Since the simulated results with uniform changes in ASO are in line with observations, we will not rerun the experiments in this work. However, in future work we will use composite ozone changes as external forcing.

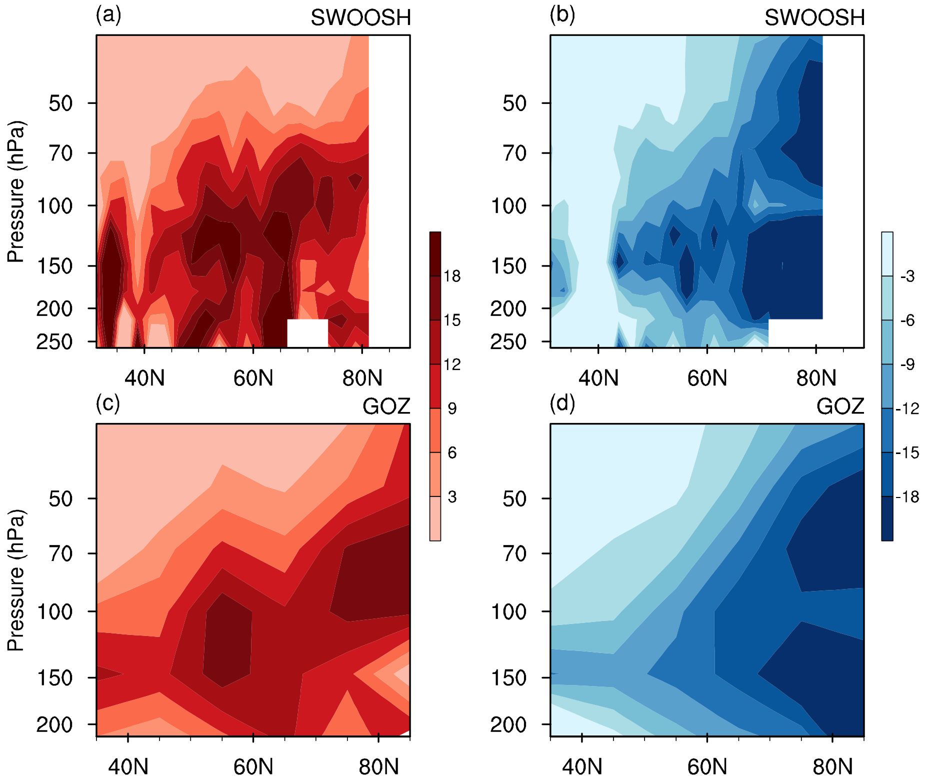
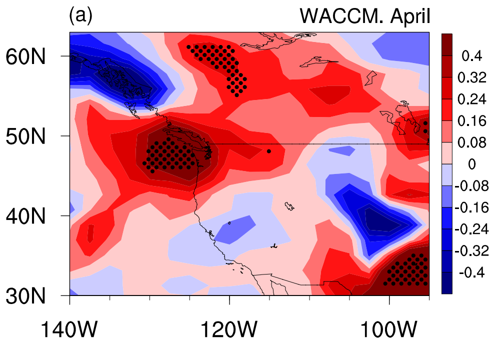


Figure RR12. Composite ozone anomaly percentage (%) during positive (a, c) and negative (b, d) ASO anomaly events, based on SWOOSH (a, b) and GOZCARDS (c, d) ozone data from 1984 to 2016. See Table 2 in the revised manuscript for the definition of ASO anomaly events.

10. Line 275: Beginning here, the results from the WACCM simulations are presented. Figures 9, 11 and 13, which show the differences between the WACCM experiments do not have any indication of the statistical significance. All of the other difference plots did have some manner of denoting statistical significance at the 90% level and these *three plots should as well.*

Response: Thanks for the comment. The statistical significance test is added for the three figures.



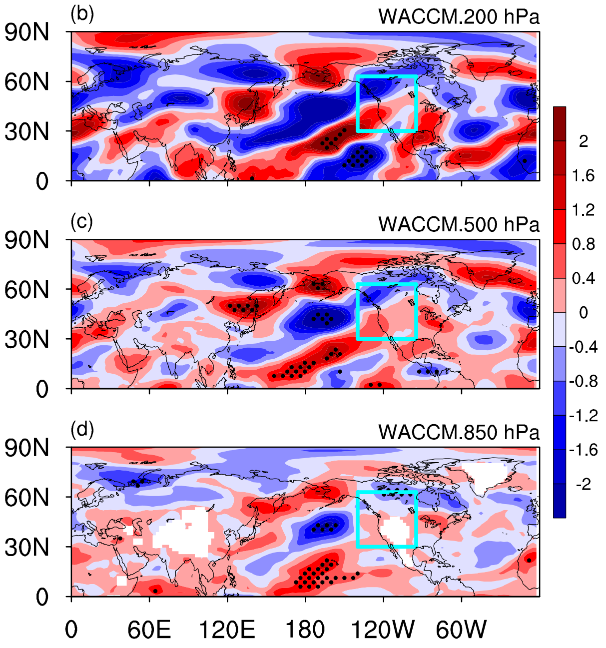
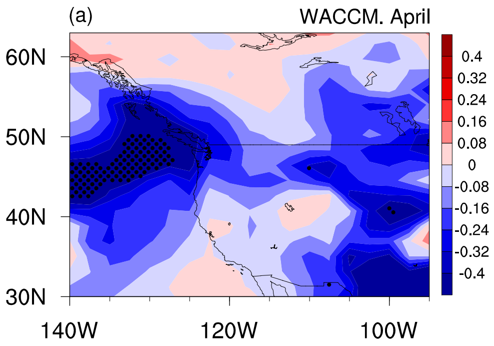


Figure RR13. Differences between experiments R3 and R2 in terms of April (a) precipitation (mm/day) and (b–d) zonal wind at 200, 500, and 850 hPa, respectively. Dots denote significance at the 95% confidence level.



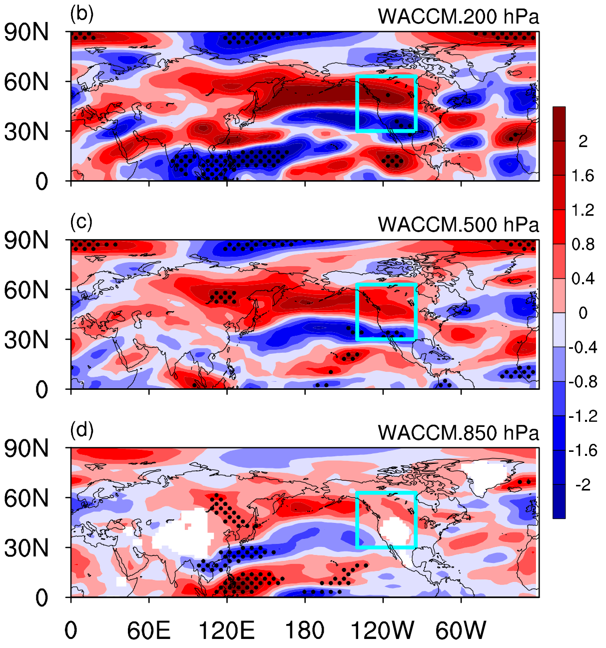
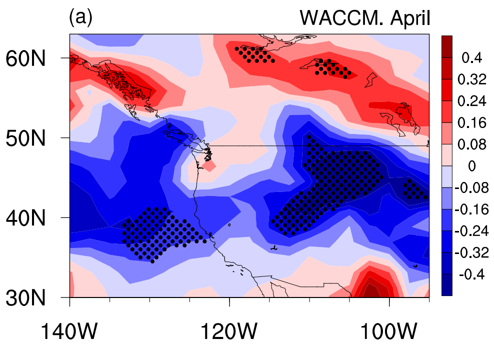


Figure RR14. Same as Fig. RR13, but for the difference between experiments R5 and R4.



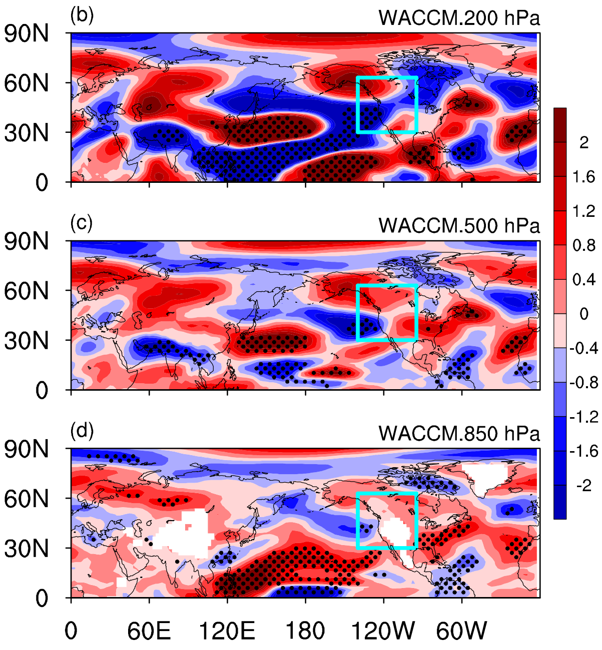


Figure RR15. Same as Fig. RR13, but for the difference between experiments R7 and R6.