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Fei Xie¹, Jianping Li^{1,2,8}, Jiankai Zhang³, Wenshou Tian³, Yongyun Hu⁴, Sen Zhao^{5,6}, Cheng Sun¹, Ruiqing Ding⁷, Juan Feng¹ and Yun Yang¹¹ College of Global Change and Earth System Science, Beijing Normal University, Beijing, People's Republic of China² Laboratory for Regional Oceanography and Numerical Modeling, Qingdao National Laboratory for Marine Science and Technology, Qingdao, People's Republic of China³ College of Atmospheric Sciences, Lanzhou University, Lanzhou, People's Republic of China⁴ Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing, People's Republic of China⁵ Key Laboratory of Meteorological Disaster of Ministry of Education, and College of Atmospheric Science, Nanjing University of Information Science and Technology, Nanjing, People's Republic of China⁶ School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, HI, United States of America⁷ State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, People's Republic of China⁸ Author to whom any correspondence should be addressed.E-mail: ljp@bnu.edu.cn**Keywords:** Arctic stratospheric ozone (ASO), North Pacific SST, North Pacific Oscillation (NPO), Victoria ModeSupplementary material for this article is available [online](#)**Abstract**

Recently, observations and simulations have shown that Arctic stratospheric ozone (ASO) variations affect the middle–high latitude tropospheric climate in the Northern Hemisphere. In particular, a connection from the ASO to El Niño–Southern Oscillation (ENSO) has been reported. However, no detailed study has been made of a key process in the connection, the influence of ASO on the North Pacific sea surface temperature (SST) and its underlying mechanism. Using observations, reanalysis and simulations, it is found that the ASO changes in March have the strongest connection with North Pacific SST variations in April. This implies a leading effect of ASO on North Pacific SST. The stratospheric circulation anomalies caused by March ASO changes can rapidly extend to the lower troposphere in the region 60°–90°N, 180°–120°W. Nevertheless, a theoretical analysis indicates that circulation anomalies from the region 60°–90°N, 180°–120°W in the lower troposphere would take about a month to propagate horizontally to the North Pacific middle latitudes (30°–60°N, 180°–120°W).

1. Introduction

The stratospheric circulation influences the chemical composition of the stratosphere, and anomalies in stratospheric circulation may also propagate downward to affect tropospheric weather and climate (Baldwin and Dunkerton 2001, Black 2002, Graf and Walter 2005, Scaife *et al* 2005, Sigmond *et al* 2008, Cagnazzo and Manzini 2009, Ineson and Scaife 2009, Gerber *et al* 2010, Reichler *et al* 2012, Ivy *et al* 2014, Karpechko *et al* 2014, Kidston *et al* 2015, Zhang *et al* 2016). Stratospheric ozone is vital to protecting life on the Earth, as it absorbs harmful solar ultraviolet radiation (Lubin and Jensen 2002, Chipperfield *et al* 2015), and is also

essential to the control of the stratospheric circulation via atmospheric radiative heating (Haigh 1994, Ramaswamy *et al* 1996, Forster and Shine 1997).

A strong trend and a large variability in stratospheric ozone, which are associated with chemical and dynamical processes, respectively, mainly occur at high latitudes in both hemispheres. In the Southern Hemisphere, Antarctic stratospheric ozone has significantly decreased from the industrial revolution to the early 21st century as a consequence of anthropogenic emissions of ozone-depleting substances (Solomon 1990, 1999, Ravishankara *et al* 1994, 2009). Recent studies have found that the Antarctic ozone hole can influence the tropospheric climate in the Southern Hemisphere

(Son *et al* 2008, 2010, Feldstein 2011, Kang *et al* 2011, Thompson *et al* 2011, Gerber and Son 2014, Waugh *et al* 2015); for example, rainfall, and sea surface temperature (SST).

Variability in Arctic stratospheric ozone (ASO) differs from that in Antarctic stratospheric ozone. On one hand, the Antarctic stratospheric ozone loss from 1950 to 2000 has been much larger than that of ASO (WMO 2011), as the winter/spring Antarctic polar vortex is much colder and stronger than the Arctic polar vortex. Accordingly, the effect of ASO loss on Northern Hemisphere surface climate may be less evident (e.g. Thompson and Solomon 2005). On the other hand, the amplitude of the year-to-year variability in ASO in the past several decades is at least as large as, or even larger than, that in the Antarctic (Randel 1988, Manney *et al* 2011, 2016), owing to frequent 'sudden warming' events in the high latitude Northern Hemisphere (Charlton and Polvani 2007). Given the noticeable difference in variability between ASO and Antarctic stratospheric ozone, their influences on the tropospheric climate may also be significantly different and merit further investigation. The impact of ASO interannual variations on Northern Hemisphere climate is one such example.

To investigate the possible surface impacts associated with extreme Northern Hemisphere ozone anomalies, Karpechko *et al* (2014) and Cheung *et al* (2014) used the ECHAM5 atmospheric circulation model and the UK Met Office operational weather forecasting system, respectively. They concluded that stratospheric ozone changes alone did not appear to have a significant effect on surface conditions on the synoptic scale. However, on the climatic scale, ASO variations caused anomalies of Northern Hemisphere mid–high latitude tropospheric circulation and sea level pressure (SLP). Smith and Polvani (2014) found significant influence of ASO on tropospheric circulation and the surface temperature and precipitation patterns using ensemble simulations. More interestingly, these impacts have very clear regional patterns. Subsequently, Calvo *et al* (2015) used a comprehensive stratosphere-resolving atmospheric model coupled with ocean, sea ice, and land components, and interactive stratospheric ozone chemistry to explore the impacts of large springtime ozone anomalies in the Arctic stratosphere on the troposphere and surface. They found that extremely small changes in ASO can produce large and robust anomalies in tropospheric wind, temperature, and precipitation in April and May over large parts of the Northern Hemisphere. More recently, Ivy *et al* (2017) presented observational evidence for linkages between extreme ASO anomalies in March and Northern Hemisphere tropospheric climate in spring (March–April), suggesting that March stratospheric ozone is a useful indicator of spring averaged (March–April) tropospheric climate in specific regions of the Northern Hemisphere.

Using statistical analysis and simulations, Xie *et al* (2016) established a possible connection from the ASO to the El Niño–Southern Oscillation (ENSO) by combining two steps: a high-latitude stratosphere-to-troposphere pathway and an extratropical-to-tropical climate teleconnection. This implies that the ASO radiative anomalies influence the North Pacific Oscillation (NPO), and then the anomalous NPO and induced Victoria Mode anomalies (Bond *et al* 2003, Ding *et al* 2015) link to the North Pacific circulation that in turn influences ENSO. Garfinkel (2017) pointed out that the mechanism for ASO modulation of ENSO still deserves thorough analysis; for example, Xie *et al* (2016) reported a statistical relation between the ASO and North Pacific SST about one month later, which was also shown by Ivy *et al* (2017). Many questions arise here. In which month does the ASO have the strongest connection with North Pacific SST? How long does it take for the anomaly in the polar stratosphere to influence subtropical SSTs, and what is the pathway for this influence? The goal of the present study is to answer these questions. Note that the mechanism for downward propagation of the stratospheric signal to the North Pacific is not discussed in detail here, as it is still under investigation (e.g. Garfinkel *et al* 2013, Kidston *et al* 2015).

2. Data and method

The ozone data used in this study are obtained from the NASA Modern Era Retrospective Analysis for Research and Applications (MERRA) dataset version 2 (Rienecker *et al* 2011). MERRA2 (longitude \times latitude resolution: $0.5^\circ \times 0.5^\circ$) uses 72 pressure levels from the surface up to 0.1 hPa (Molod *et al* 2015). The vertical resolution of MERRA2 is $\sim 1\text{--}2$ km in the upper troposphere and lower stratosphere (UTLS) and $2\text{--}4$ km in the middle and upper stratosphere. MERRA2 is produced using the Goddard Earth Observing System Model, Version 5 (GEOS-5) with ozone from the Solar Backscattered Ultra Violet (SBUV) radiometers from October 1978 to October 2004, and thereafter from the Ozone Monitoring Instrument (OMI) and AURA Microwave Limb Sounder (MLS) (Bosilovich *et al* 2015). The MERRA2 reanalysis ozone compares well with satellite ozone observations (Wargan *et al* 2017) and shows a better representation of the QBO and stratospheric ozone than MERRA1 (Coy *et al* 2016).

Black lines in figure S1 in the supplementary information available at stacks.iop.org/ERL/12/114023/mmedia show the ASO anomaly variations from 1979–2015 in each month over a region limited to approximately $60^\circ\text{N}\text{--}90^\circ\text{N}$ and $150\text{--}50$ hPa, the region where the variability and depletion of ozone concentration is most pronounced in the Northern Hemisphere (Manney *et al* 2011). The monthly anomaly of ozone concentration (after removing the climatological mean

Table 1. The ASO decrease and increase events.

Decrease events	Increase events
1990	1989
1993	1999
1996	2001
1997	2009
2000	2010
2011	

seasonal cycle and linear trend), averaged over this region, is defined as the ASO index (Xie *et al* 2016). Data from the Stratospheric Water and OzOne Satellite Homogenized (SWOOSH) ozone satellite (Davis *et al* 2016) and the Global Ozone Chemistry and Related trace gas Data Records for the Stratosphere (GOZCARDS) project (Froidevaux *et al* 2015) are compared with the MERRA2 ozone (figure S1). The zonal mean SWOOSH dataset is a merged record of stratospheric ozone and water vapor measurements taken by a number of limb sounding and solar occultation satellites (SAGE-II/III, UARS HALOE, UARS MLS, and Aura MLS instruments). Its meridional resolution is 2.5° and it has 31 pressure levels from 300 to 1 hPa. The zonal mean satellite-based GOZCARDS dataset (1979–2012) is produced from high quality data from past missions (e.g. SAGE, HALOE data) as well as ongoing missions (ACE-FTS and Aura MLS). Its meridional resolution is 10° with 25 pressure levels from the surface up to 0.1 hPa. The ASO variations from MERRA2 are in good agreement with those from SWOOSH data and GOZCARDS data (figure S1), particularly in spring, which is the focus of this study. However, there are many missing values in the SWOOSH data and GOZCARDS data, so the following analysis uses MERRA2 ozone data.

The SST and SLP data were obtained from the UK Met Office Hadley Centre for Climate Prediction and Research SST (HadSST) and SLP (HadSLP) field datasets, respectively. Geopotential height, zonal wind, and temperature data were obtained from ERA-Interim and NCEP2.

A threshold of ± 0.2 ppmv, which is equal to the standard deviation of the ASO series, is applied to the time series in figure S1 to identify ASO decrease and increase events. We use composite analysis to check the changes of circulation during ASO decrease and increase events in March during the period from 1979 to 2015. The selected events are listed in table 1.

We calculated the statistical significance of the correlation between two auto-correlated time series using the two-tailed Student's *t*-test and the effective number (N^{eff}) of degrees of freedom (DOF) (Bretherton *et al* 1999). For this study, N^{eff} was determined by the following approximation (Li *et al* 2012):

$$\frac{1}{N^{\text{eff}}} \approx \frac{1}{N} + \frac{2}{N} \sum_{j=1}^N \frac{N-j}{N} \rho_{XX}(j) \rho_{YY}(j),$$

where N is the sample size, and ρ_{XX} and ρ_{YY} are the autocorrelations of the two sampled time series, X and Y , respectively, at time lag j .

3. Propagation of Arctic stratospheric circulation anomalies to the North Pacific

Figure 1 shows the correlation coefficients between ASO and SST in each month. A meridional tripole structure is found in spring which is referred to as the Victoria Mode SST anomaly pattern over the North Pacific (Bond *et al* 2003, Ding *et al* 2015). The Victoria Mode is similar to the North Pacific Gyre Oscillation (Di Lorenzo *et al* 2008). The strongest SST anomaly pattern occurs in March (figure 1(c)), implying that the strongest connection between ASO and Victoria Mode SST anomalies is in March. This result also suggests that the connection between ASO and ENSO found in Xie *et al* (2016) is mainly caused by spring ASO changes. Note that we can also see significant correlation coefficients in winter. However, these correlation coefficients are more likely caused by North Pacific SST affecting ASO (Jadin *et al* 2010, Hurwitz *et al* 2012, Garfinkel *et al* 2015, Kren *et al* 2015, Woo *et al* 2015).

In March, sunlight reaches the north polar stratosphere. A decrease (increase) in ASO will lead to less (more) warming of the north polar vortex such that the ASO variations are positively correlated with north polar stratospheric temperature (figure 2(a)). The cooler (warmer) north polar stratosphere strengthens (weakens) the temperature gradient from the tropics to the North Pole. According to the thermal wind relationship, this situation results in a stronger (weaker) polar vortex such that the ASO variations are negatively correlated with north polar stratospheric circulation changes (figure 2(b)). An obvious feature of figure 2(b) is that the north polar stratospheric circulation anomalies extend to the north polar troposphere, even to the surface. Another feature is a wave train signal in the troposphere from the North Pole to northern lower latitudes.

Figure 2(c) shows the connection between ASO and zonal wind at 850 hPa in March. High correlation coefficients are found in the region 60°–90°N, 180°–120°W, which possibly corresponds to the main pathway for Arctic stratospheric circulation anomalies caused by the ASO changes to reach the Arctic surface. The zonal wind anomalies follow a wave train from the North Pole to the northern North Pacific, and then to the central North Pacific (figure 2(c)). The circulation anomalies over the North Pacific correspond to SLP changes (figure 2(d)), which have also been noted in Calvo *et al* 2015 and Ivy *et al* 2017. The SLP changes show a dipole structure resembling the North Pacific Oscillation (NPO, Walker and Bliss 1932, Rogers 1981). As reported by Alexander *et al* (2010) and Yu and Kim (2011), anomalous surface winds associated with the NPO can force a tripole-like pattern of the

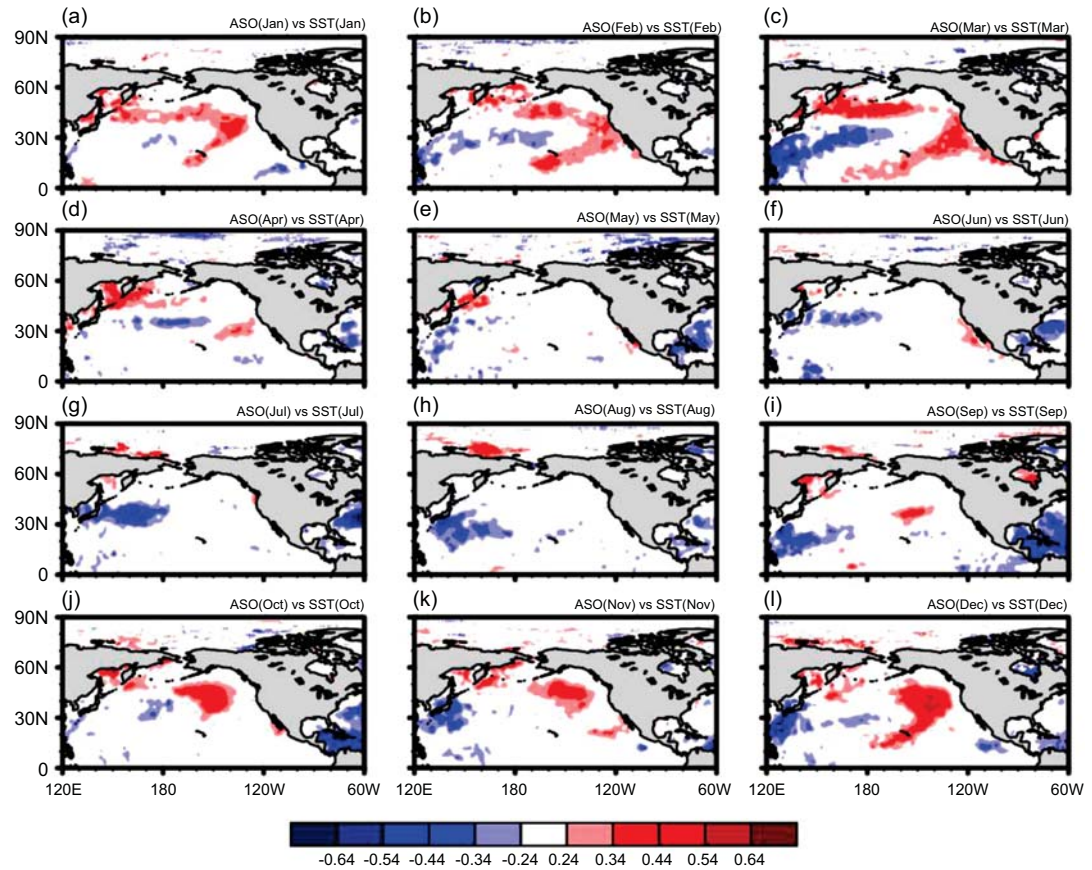


Figure 1. Correlation coefficient between $-ASO$ and SST in each month. The ASO data are from MERRA2 and SST from HadSST for 1979–2015. Only regions above the 95% confidence level are colored; statistical significance was calculated using the two-tailed Student’s t -test and the N^{eff} of DOF (section 2). Seasonal cycles and linear trends were removed prior to calculating the correlation coefficients.

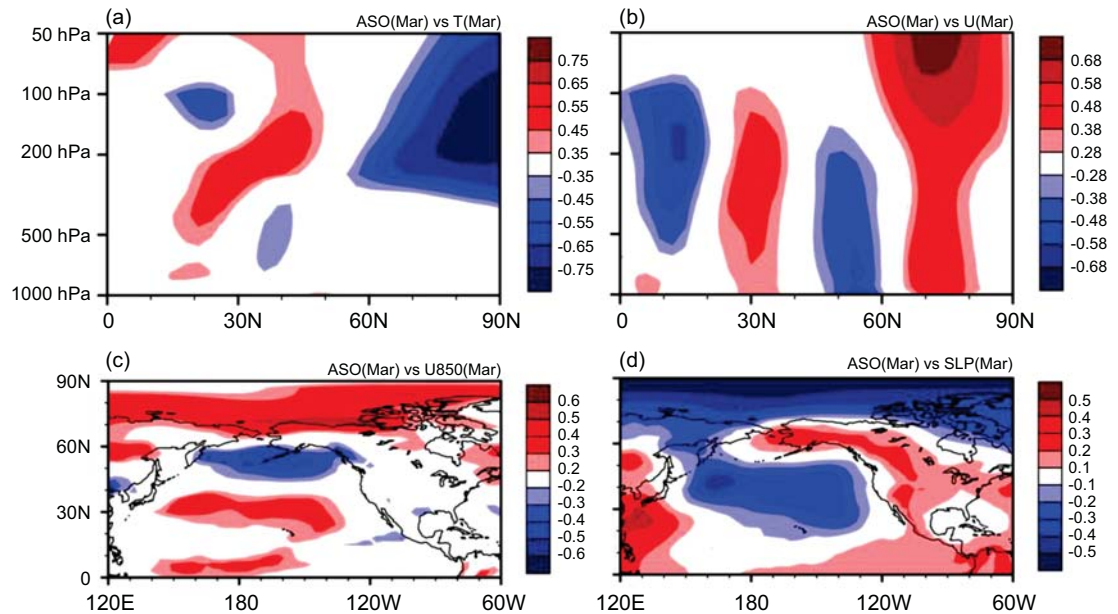
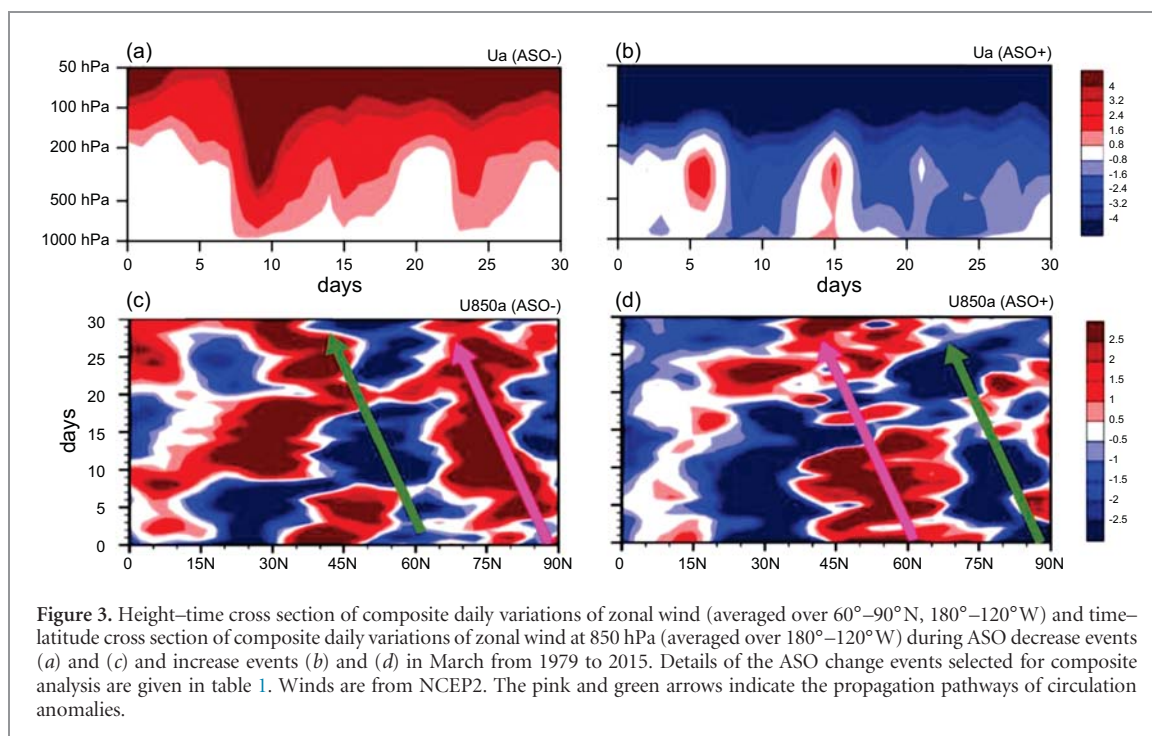


Figure 2. Correlation coefficients in March for 1979–2015 between $-ASO$ and (a) temperature (averaged over $120^{\circ}E$ – $120^{\circ}W$), (b) zonal wind (averaged over $120^{\circ}E$ – $120^{\circ}W$), (c) zonal wind at 850 hPa and (d) SLP. Only regions above the 95% confidence level are colored. The ASO data are from MERRA2, temperature and wind from ERA-Interim, and SLP from HadSLP.

surface heat flux anomalies in the North Pacific, which in turn induces a tripole SST anomaly pattern of the Victoria Mode in the North Pacific from 20° – $60^{\circ}N$ (figure 1(c)). Figure 2 implies the possibility of a

signal caused by ASO changes propagating to the North Pacific.

Figure 2 depicts the processes that the stratospheric circulation anomalies caused by ASO changes



extending to the Arctic surface and then horizontally to the central North Pacific. We used composite analysis to understand these processes in more detail, by showing the composite changes of circulation on a daily time scale during ASO decrease and increase events (figure 3). Several studies have presented evidence suggesting that variability in the stratospheric polar vortex has a substantial impact on the circulation of the troposphere (e.g. Baldwin and Dunkerton 2001, Scaife *et al* 2005, Hitchcock and Simpson 2014) by the downward control principle (Haynes *et al* 1991) or by tropospheric eddy momentum feedback (Kushner and Polvani 2004, Song and Robinson 2004, Kidston *et al* 2015). Figures 3(a) and (b) indicate that the composite Arctic stratospheric circulation anomalies during ASO anomaly events would propagate downward to the lower troposphere in a few days. The anomalies reaching the troposphere continue to propagate meridionally towards the northern lower and middle latitudes along the 180°–120°W longitude zone (figures 3(c) and (d)). This southward propagation takes about one month. This phenomenon can be seen in both the ASO decrease and increase events (figures 3(a), (c) and (b), (d)).

Previous studies have pointed out the downward influence of stratosphere final warmings (SFW) on the surface climate (Black and McDaniel 2007, Ayarguenza *et al* 2009, and Hardiman *et al* 2011). Thus, one might hypothesize that some of the downward influences related to ASO change may be due to changes of SFW. However such a hypothesis is not totally correct: it is found that the SFW is more likely to occur in May (not in March) during both the ASO decrease and increase events (figure S2 in supplementary information). It means that the time of SFW occurrence

is not significantly affected by the ASO anomalies events.

To study in more detail the horizontal propagation of circulation anomalies, the ray paths of waves at 850 hPa generated by the disturbed circulation over the region 60°–90°N and 180°–120°W in March and April are shown in figure 4. 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). We found that the Rossby waves generated by the disturbed circulation over the north polar lower troposphere mainly propagate southward to the central North Pacific after about a month in March and April (they propagate to the northern North Pacific in about 15 d). The wave ray paths are in good agreement with the composite analysis in figure 3.

Figures 2, 3 and 4 imply that ASO changes take at least a month to influence North Pacific circulation and SST. Motivated by this finding, we recalculated the correlation coefficients between ASO changes in March and circulation anomalies over the North Pacific in April (figure 5). As expected, the correlation coefficients between March ASO and April zonal wind anomalies (figures 5(a) and (b)) are larger than between March ASO and March zonal wind anomalies (figures 2(b) and (c)). In addition, the correlation coefficients between March ASO and April SLP anomalies over the North Pacific are also more significant than those between March ASO and March SLP anomalies (figures 5(c) and 2(d)). The delayed effect of ASO on North Pacific circulation implies the delayed effect of ASO on North Pacific SST. Figure 6 is the same as figure 1, but with

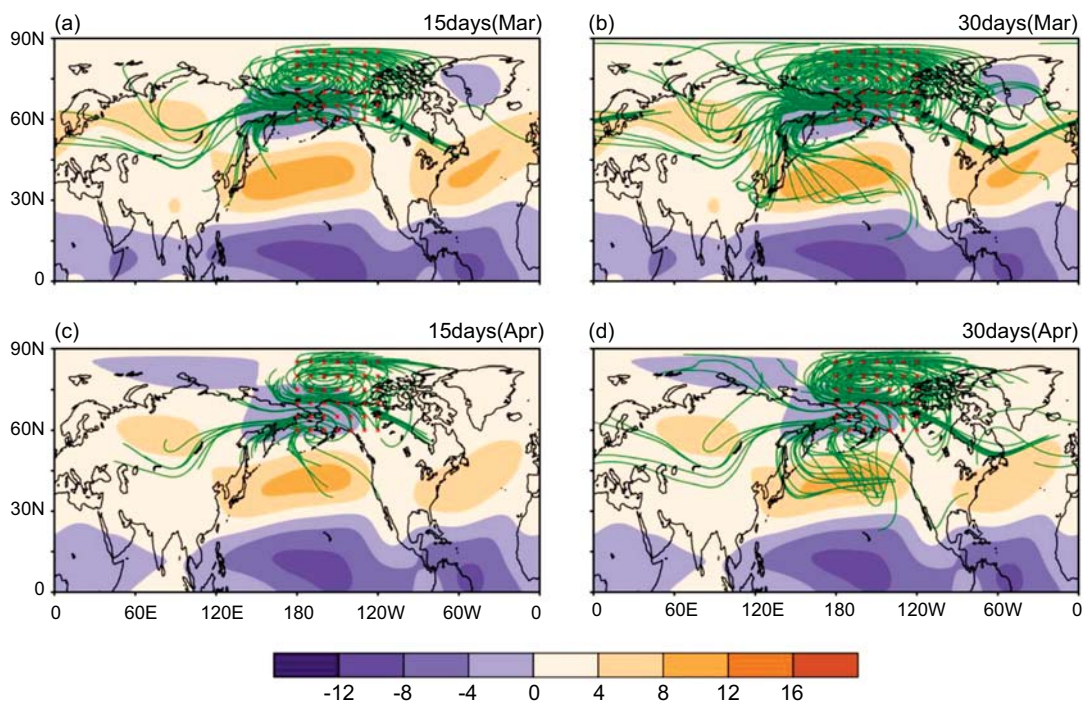


Figure 4. Ray paths (green lines) at 850 hPa in March and April after the circulation was perturbed for 15 days (a) and (c) and 30 days (b) and (d). Red dots denote wave sources in the region 60°–90°N, 180°–120°W. The wavenumbers along these rays are in the range 1–3. Color shading indicates the climatological flow.

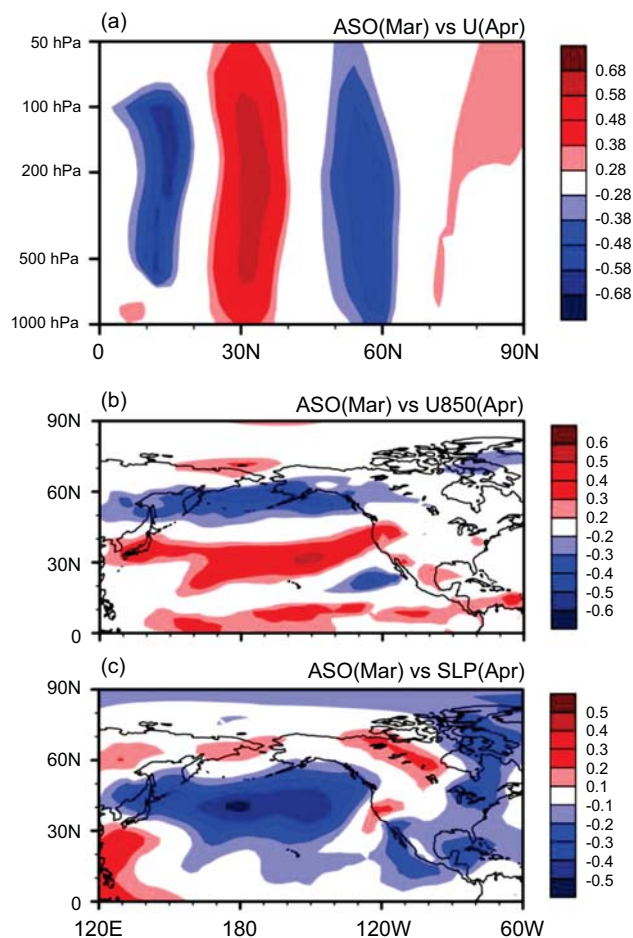


Figure 5. The correlation coefficients between $-ASO$ in March and (a) zonal wind (averaged over 120°E–120°W), (b) zonal wind at 850 hPa, and (c) SLP in April for 1979–2015. Only regions above the 95% confidence level are colored. The ASO data are from MERRA, wind from ERA-Interim, and SLP from HadSLP.

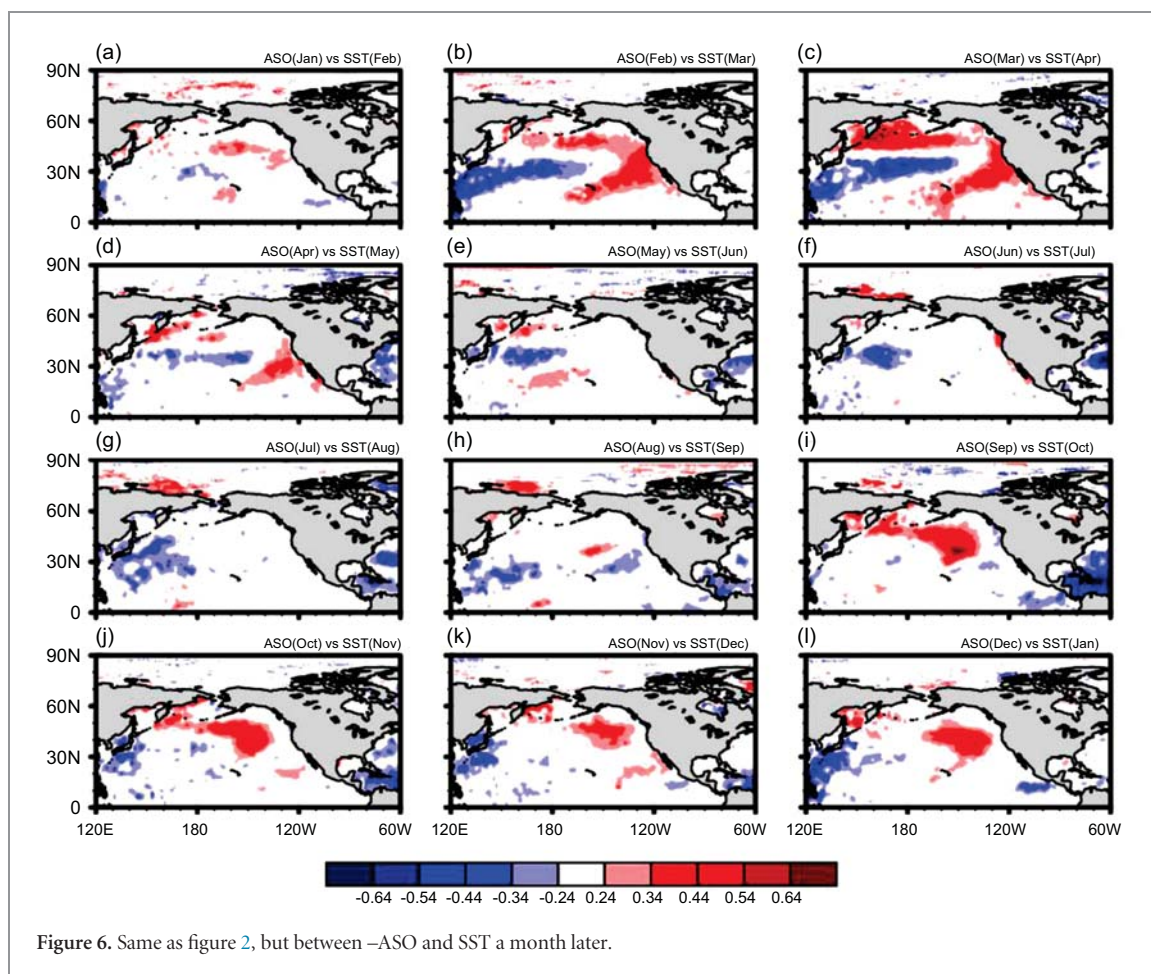


Figure 6. Same as figure 2, but between $-ASO$ and SST a month later.

ASO leading SST by a month. It is very clear that the correlation coefficients between March ASO changes and April North Pacific SST anomalies (figure 6(c)) are larger than those between March ASO changes and March North Pacific SST anomalies (figure 1(c)).

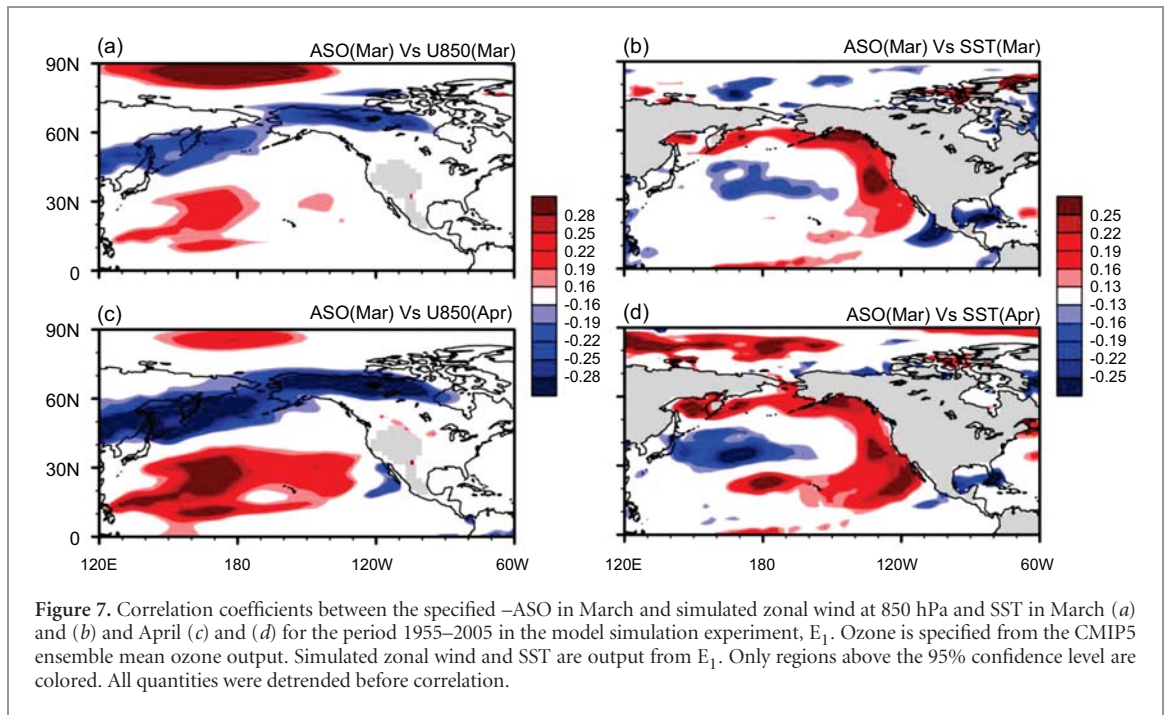
Why do the ASO changes in March have the most significant impact on North Pacific SST? We suggest three possible reasons. First, previous studies have pointed out that the North Pacific jet is more sensitive to external forcing in spring than in winter due to stronger eddy feedbacks (Garfinkel and Hartmann 2011, Mcgraw and Barnes 2016). Second, the Arctic is still experiencing polar night in February. The circulation anomalies caused by ASO radiative forcing may not be strong enough to influence the troposphere (Calvo *et al* 2015, Ivy *et al* 2017). Third, from figures 2(c) and (d) we can see that the North Pacific circulation and SLP anomalies are located in the Aleutian low area of the central and northern North Pacific. The negative correlation coefficients in the region $50^{\circ}N-60^{\circ}N$, $180^{\circ}W-120^{\circ}W$ and the positive correlation coefficients in the region $30^{\circ}-40^{\circ}N$, $180^{\circ}-120^{\circ}W$ in figure 2(c) are associated with the northern and southern branch flows of the Aleutian low, respectively. The Aleutian low may act as a bridge connecting circulation anomalies over the North Pole and over the North Pacific. We can see that the Aleutian low in April is much weaker than in March (figure S3 in supplementary information).

These three conditions may result in the ASO changes in March having the most significant impact on North Pacific SST.

4. Simulated lead of ASO on North Pacific SST

To further confirm the leading effect of ASO on North Pacific SST, we used the National Center for Atmospheric Research's Community Earth System Model (CESM) version 1.0.6 to simulate this process. CESM 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, we used the Whole Atmosphere Community Climate Model (WACCM), version 4 (Marsh *et al* 2013). WACCM4 is a climate model that has detailed middle-atmosphere chemistry and a finite volume dynamical core, and it extends from the surface to approximately 140 km. For our study, we disabled the interactive chemistry. WACCM4 has 66 vertical levels, with a vertical resolution of about 1 km in the tropical tropopause and lower stratosphere layers. Our simulations used a horizontal resolution of $1.9^{\circ} \times 2.5^{\circ}$ (latitude \times longitude) for the atmosphere, and approximately the same for the ocean.

The transient experiment (E_1) 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. E_1 is a historical simulation covering the period 1955–2005. All the forcing data used in this study are available from the CESM model input data repository.

The experiment E_1 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 (figure 7). The circulation and VM-like pattern SST anomalies that appear over the North Pacific in April (figures 7(c) and (d)) are evidently larger than in March (figures 7(a) and (b)). This simulated result is similar to the observations. Note that the ozone forcing is specified in the simulation; therefore, the relationship between ASO and SST could only be caused by North Pacific SST anomalies related to the ASO changes.

5. Conclusions and discussion

The North Pacific SST anomalies are well known to significantly influence the Northern Hemisphere middle–high latitude climate. Thus, it is important to

understand the factors that affect North Pacific SST. This study investigates the effect of ASO changes on North Pacific SST and the processes by which the stratospheric circulation anomalies caused by ASO changes propagate to the North Pacific, induce North Pacific Oscillation (NPO) anomalies, and then force North Pacific SST anomalies. Using observations, reanalysis data, statistical methods and simulations, it is found that the stratospheric circulation anomalies caused by March ASO changes rapidly extend all the way to the lower troposphere in the region $60^{\circ}N$ – $90^{\circ}N$, $180^{\circ}W$ – $120^{\circ}W$; however, the circulation anomalies from this region take about 30 days to propagate to the North Pacific middle latitudes ($30^{\circ}N$ – $60^{\circ}N$, $180^{\circ}W$ – $120^{\circ}W$). The horizontal transport of circulation anomalies is confirmed by wave ray tracing. This implies a leading effect of ASO on North Pacific SST. That is, the ASO changes in March have the strongest connection with North Pacific SST variations in April, not March.

This study still leaves a question unanswered. We found that the ASO changes lead North Pacific SST by about a month. It is known that North Pacific SST variations lead ENSO by about 12 months (Ding *et al* 2015). This cannot explain the 20 month lead of ASO changes on ENSO found by Xie *et al* (2016). One possible reason is that the North Pacific SST anomaly forced by the ASO is initially stored beneath the surface and is then re-entrained into the mixed layer when it deepens again in the following winter (Alexander *et al* 1999, Zhao and Li 2012, Garfinkel 2017). The winter-to-winter persistence of North Pacific SST would influence the ENSO. This process takes about 20 months, and is the subject of our next study.

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