Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
3 July 2017

REVISED
27 September 2017

ACCEPTED FOR PUBLICATION
29 September 2017

PUBLISHED
7 November 2017

LETTER

Variations in North Pacific sea surface temperature caused by Arctic stratospheric ozone anomalies

Fei Xie[1], Jianping Li[1,2,8], Jiankai Zhang[3], Wenshou Tian[3], Yongyun Hu[4], Sen Zhao[5,6], Cheng Sun[1], Ruiqing Ding[7], Juan Feng[1] and Yun Yang[1]

1 College of Global Change and Earth System Science, Beijing Normal University, Beijing, People's Republic of China
2 Laboratory for Regional Oceanography and Numerical Modeling, Qingdao National Laboratory for Marine Science and Technology, Qingdao, People's Republic of China
3 College of Atmospheric Sciences, Lanzhou University, Lanzhou, People's Republic of China
4 Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing, People's Republic of China
5 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 China
6 School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, HI, United States of America
7 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 China
8 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 Mode

Supplementary 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 × latitude resolution: 0.5° × 0.5°) uses 72 pressure levels from the surface up to 0.1 hPa (Molod *et al* 2015). The vertical resolution of MERRA2 is ∼1–2 km in the upper troposphere and lower stratosphere (UTLS) and 2–4 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°N–90°N and 150–50 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):

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

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 *el 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

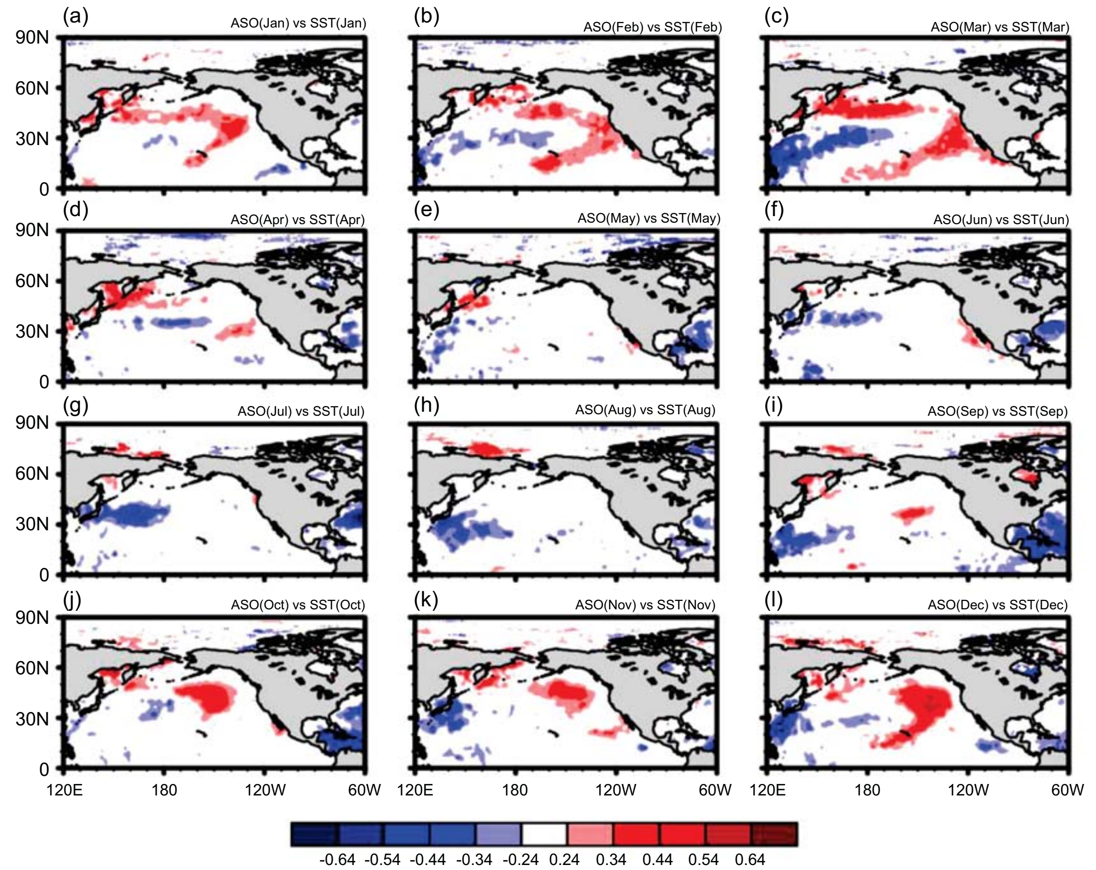

Figure 1. Correlation coefficient between –ASO and SST in each month. The ASO data are from MERRA2 and SST from HadSST for 1979–2015. Only regions above the 95% confidence level are colored; statistical significance was calculated using the two-tailed Student's *t*-test and the N^{eff} of DOF (section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

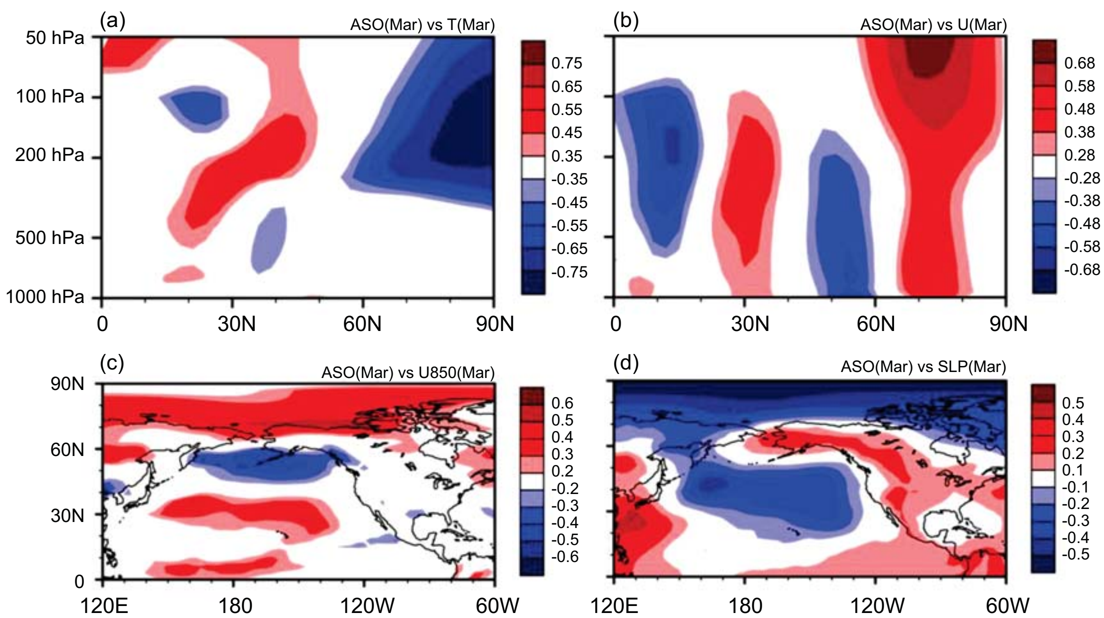

Figure 2. Correlation coefficients in March for 1979–2015 between –ASO and (*a*) temperature (averaged over 120°E–120°W), (*b*) zonal wind (averaged over 120°E–120°W), (*c*) zonal wind at 850 hPa and (*d*) SLP. Only regions above the 95% confidence level are colored. The ASO data are from MERRA2, temperature 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°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

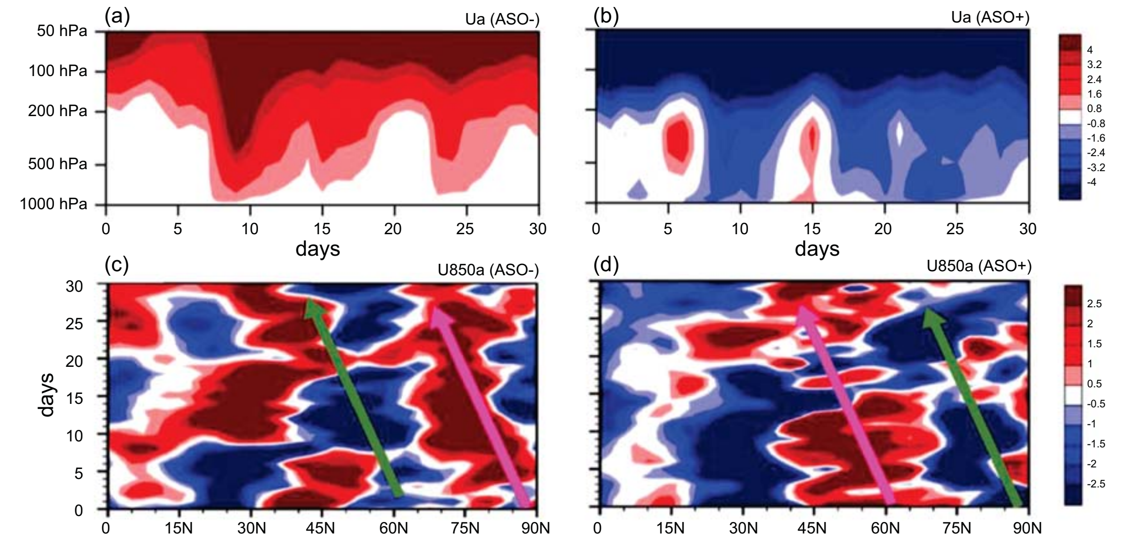

Figure 3. Height–time cross section of composite daily variations of zonal wind (averaged over 60°–90° N, 180°–120° W) and time–latitude cross section of composite daily variations of zonal wind at 850 hPa (averaged over 180°–120° W) during ASO decrease events (*a*) and (*c*) and increase events (*b*) and (*d*) in March from 1979 to 2015. Details of the ASO change events selected for composite analysis are given in table 1. Winds are from NCEP2. The pink and green arrows indicate the propagation pathways of circulation anomalies.

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

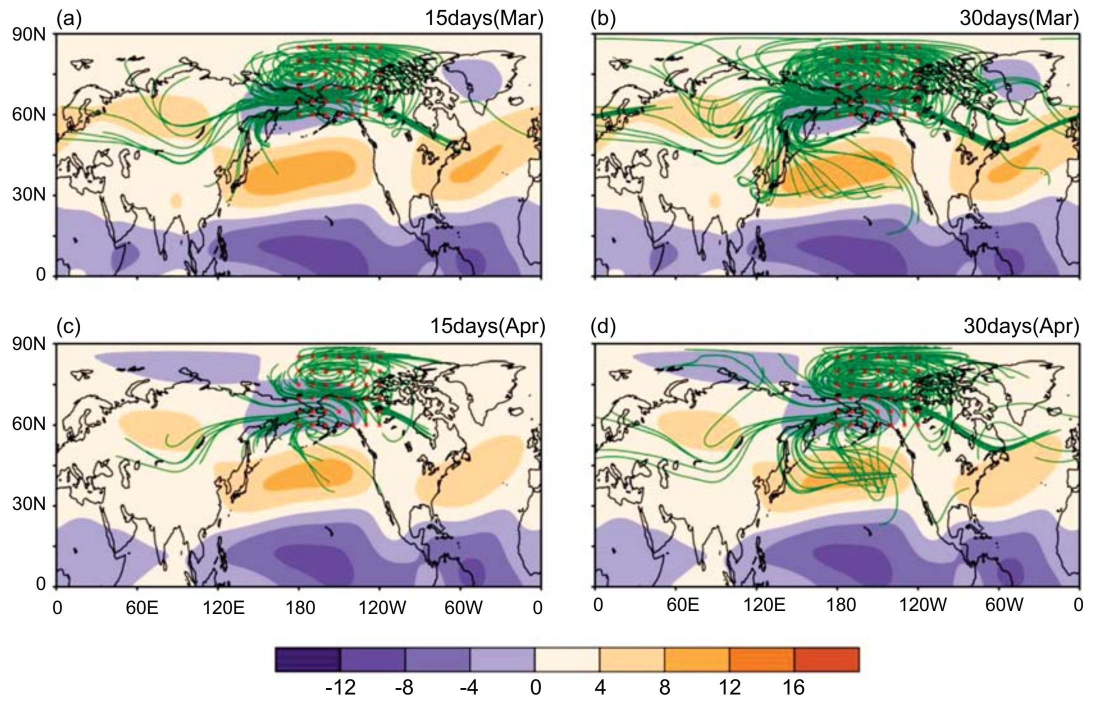

Figure 4. Ray paths (green lines) at 850 hPa in March and April after the circulation was perturbed for 15 days (*a*) and (*c*) and 30 days (*b*) and (*d*). Red dots denote wave sources in the region 60°–90°N, 180°–120°W. The wavenumbers along these rays are in the range 1–3. Color shading indicates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

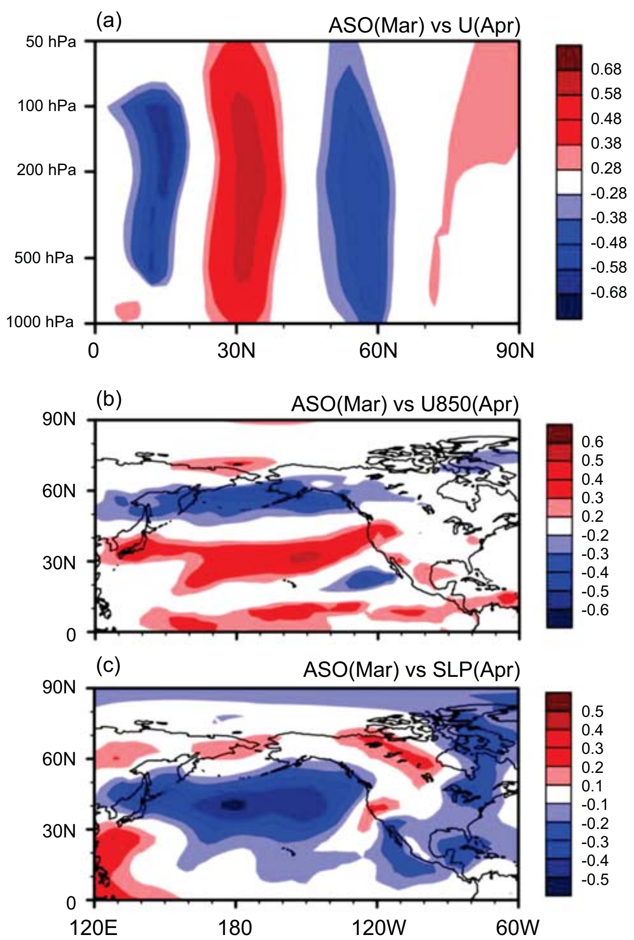

Figure 5. The correlation coefficients between –ASO in March and (*a*) zonal wind (averaged over 120°E–120°W), (*b*) zonal wind at 850 hPa, and (*c*) SLP in April for 1979–2015. Only regions above the 95% confidence level are colored. The ASO data are from MERRA, wind from ERA-Interim, and SLP from HadSLP.

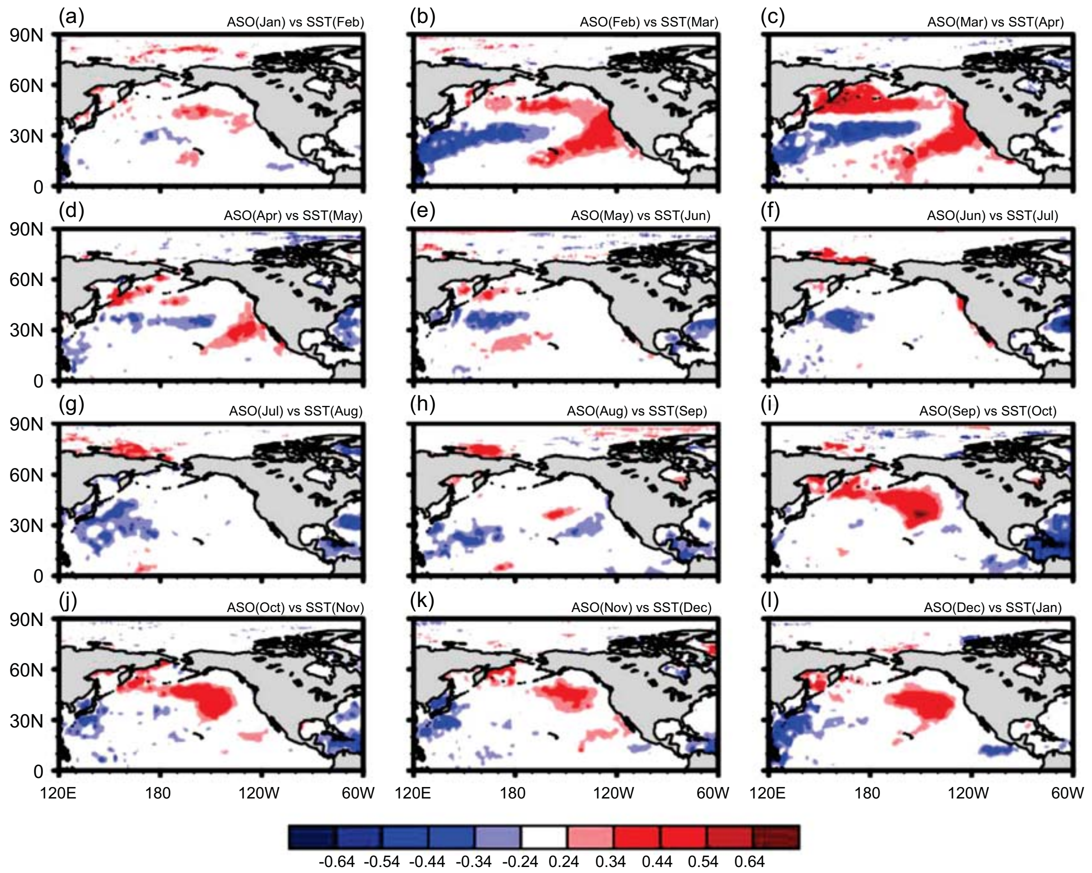

Figure 6. Same as figure 2, but between –ASO and SST a month later.

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°N–60°N, 180°W–120°W and the positive correlation coefficients in the region 30°–40°N, 180°–120°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° × 2.5° (latitude × 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

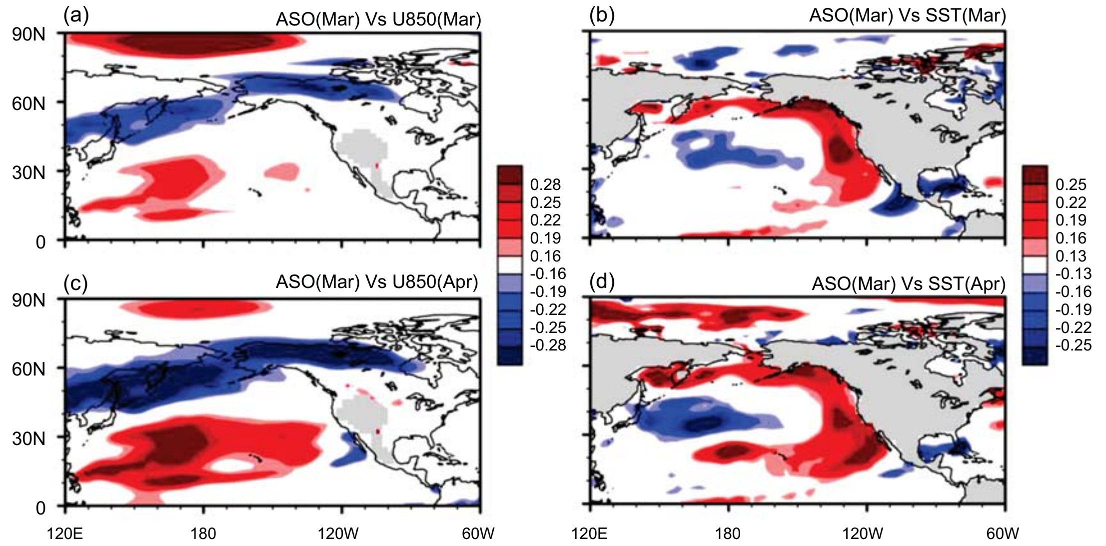

Figure 7. Correlation coefficients between the specified –ASO in March and simulated zonal wind at 850 hPa and SST in March (*a*) and (*b*) and April (*c*) and (*d*) for the period 1955–2005 in the model simulation experiment, E_1. Ozone is specified from the CMIP5 ensemble mean ozone output. Simulated zonal wind and SST are output from E_1. Only regions above the 95% confidence level are colored. All quantities were detrended before correlation.

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°N–90°N, 180°W–120°W; however, the circulation anomalies from this region take about 30 days to propagate to the North Pacific middle latitudes (30N°–60°N, 180°W–120°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.

Acknowledgments

Funding for this project was provided by the National Natural Science Foundation of China (41630421, 41375072, 41530423, and 41575039), Youth Scholars Program of Beijing Normal University. F Xie and J Zhang are supported by the Fundamental Research Funds for the Central Universities fron BNU and from LZU (lzujbky-2017-4). We acknowledge the datasets from the MERRA, Climate Prediction Center/NOAA, SWOOSH, Hadley Centre, NCEP2, RICH. We thank NCAR for providing the CESM model.

ORCID iDs

Fei Xie https://orcid.org/0000-0003-2891-3883
Jianping Li https://orcid.org/0000-0003-0625-1575
Cheng Sun https://orcid.org/0000-0003-0474-7593

References

Alexander M A, Deser C and Timlin M S 1999 The reemergence of SST anomalies in the North Pacific Ocean *J. Clim.* **12** 2419–33

Alexander M A, Vimont D J, Chang P and Scott J D 2010 The impact of extratropical atmospheric variability on ENSO: testing the seasonal footprinting mechanism using coupled model experiments *J. Clim.* **23** 2885–901

Ayarzagüena B and Serrano E 2009 Monthly characterization of the tropospheric circulation over the Euro-Atlantic area in relation with the timing of stratospheric final warmings *J. Clim.* **22** 6313–24

Baldwin M P and Dunkerton T J 2001 Stratospheric harbingers of anomalous weather regimes *Science* **294** 581–4

Black R X 2002 Stratospheric forcing of surface climate in the Arctic oscillation *J. Clim.* **15** 268–77

Black R X and Mcdaniel B A 2007 The dynamics of Northern hemisphere stratospheric final warming events *J. Atmos. Sci.* **64** 2932–46

Bond N A, Overland J E, Spillane M and Stabeno P 2003 Recent shifts in the state of the North Pacific *Geophys. Res. Lett.* **30** 2183

Bosilovich M G *et al* 2015 MERRA-2: Initial evaluation of the climate *NASA Tech. Memo. NASA/TM-2015–104606* **43** 145

Bretherton C S *et al* 1999 The effective number of spatial degrees of freedom of a time-varying field *J. Clim.* **12** 1990–2009

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

Cagnazzo C and Manzini E 2009 Impact of the stratosphere on the winter tropospheric teleconnections between ENSO and the North Atlantic and European region *J. Clim.* **22** 1223–38

Charlton A J and Polvani L M 2007 A new look at stratospheric sudden warmings. Part I. Climatology and modeling benchmarks *J. Clim.* **20** 449–69

Cheung J C H, Haigh J D and Jackson D R 2014 Impact of EOS MLS ozone data on medium-extended range ensemble forecasts *J. Geophys. Res.* **119** 9253–66

Chipperfield M P, Dhomse S S, Feng W, McKenzie R L, Velders G and Pyle J A 2015 Quantifying the ozone and ultraviolet benefits already achieved by the montreal protocol *Nat. Commun.* **6** 7233

Coy L, Wargan K, Molod A, McCarty W and Pawson S 2016 Structure and dynamics of the quasi-biennial oscillation in MERRA-2 *J. Clim.* **29** 5339–54

Davis S M *et al* 2016 The stratospheric water and ozone satellite homogenized (SWOOSH) database: a long-term database for climate studies *Earth Syst. Sci. Data Discuss* **8** 461–90

Di Lorenzo E *et al* 2008 North Pacific Gyre Oscillation links ocean climate and ecosystem change *Geophys. Res. Lett.* **35** L08607

Ding R, Li J, Tseng Y H, Sun C and Guo Y 2015 The Victoria mode in the North Pacific linking extratropical sea level pressure variations to ENSO *J. Geophys. Res.* **120** 27–45

Feldstein S B 2011 Subtropical rainfall and the Antarctic ozone hole *Science* **332** 925–6

Forster P and Shine K 1997 Radiative forcing and temperature trends from stratospheric ozone changes *J. Geophys. Res.* **102** 10841–55

Froidevaux L *et al* 2015 Global ozone chemistry and related trace gas data records for the stratosphere (GOZCARDS): methodology and sample results with a focus on HCl, H_2O, and O_3 *Atmos. Chem. Phys.* **15** 10471–507

Garfinkel C I and Hartmann D L 2011 The influence of the quasi-biennial oscillation on the troposphere in winter in a hierarchy of models. Part II: perpetual winter WACCM runs *J. Atmos. Sci.* **68** 2026–41

Garfinkel C I, Waugh D W and Gerber E P 2013 The effect of tropospheric jet latitude on coupling between the stratospheric polar vortex and the troposphere *J. Clim.* **26** 2077–95

Garfinkel C I, Hurwitz M M and Oman L D 2015 Effect of recent sea surface temperature trends on the Arctic stratospheric vortex *J. Geophys. Res.* **120** 5404–16

Garfinkel C I 2017 Might stratospheric variability lead to improved predictability of ENSO events? *Environ. Res. Lett.* **12** 031001

Gerber E P *et al* 2010 Stratosphere-troposphere coupling and annular mode variability in chemistryclimate models *J. Geophys. Res.* **115** D00M06

Gerber E P and Son S 2014 Quantifying the summertime response of the austral jet stream and hadley cell to stratospheric ozone and greenhouse gases *J. Clim.* **27** 5538–59

Graf H F and Walter K 2005 Polar vortex controls coupling of North Atlantic ocean and atmosphere *Geophy. Res. Lett.* **32** L01704

Haigh J D 1994 The role of stratospheric ozone in modulating the solar radiative forcing of climate *Nature* **370** 544–6

Hardiman S C *et al* 2011 Improved predictability of the troposphere using stratospheric final warmings *J. Geophys. Res.* **116** 597–616

Haynes P H, McIntyre M E, Shepherd T G, Marks C J and Shine K P 1991 On the downward control of extratropical diabatic circulations by eddy-induced mean zonal forces *J. Atmos. Sci.* **48** 651–78

Hitchcock P and Simpson I R 2014 The downward influence of stratospheric sudden warmings *J. Atmos. Sci.* **71** 3856–76

Hurwitz M M, Newman P A and Garfinkel C I 2012 On the influence of North Pacific sea surface temperature on the Arctic winter climate *J. Geophys. Res.* **117** D19

Ineson S and Scaife A A 2009 The role of the stratosphere in the European climate response to El Niño *Nat. Geosci.* **2** 32–6

Intergovernmental Panel on Climate Change 2001 *Climate Change, The Scientific Basis* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press)

Ivy D J, Solomon S and Thompson D W J 2014 On the identification of the downward propagation of Arctic stratospheric climate change over recent decades *J. Clim.* **27** 2789–99

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

Jadin E A, Wei K, Zyulyaeva Y A, Chen W and Wang L 2010 Stratospheric wave activity and the Pacific decadal oscillation *J. Atmos. Sol-Terr. Phy.* **72** 1163–70

Kang S M, Polvani L M, Fyfe J C and Sigmond M 2011 Impact of polar ozone depletion on subtropical precipitation *Science* **332** 951–4

Karpechko A, Yu A, Perlwitz J and Manzini E 2014 A model study of tropospheric impacts of the Arctic ozone depletion 2011 *J. Geophys. Res.* **119** 7999–8014

Kidston J, Scaife A, Hardiman S, Mitchell D, Butchart N, Baldwin M and Gray L 2015 Stratospheric influence on tropospheric jet streams, storm tracks and surface weather *Nat. Geosci.* **8** 433–40

Kren A C, Marsh D R, Smith A K and Pilewskie P 2015 Wintertime northern hemisphere response in the stratosphere to the Pacific decadal oscillation using the whole atmosphere community climate model *J. Clim.* **29** 1031–49

Kushner P J and Polvani L M 2004 Stratosphere–troposphere coupling in a relatively simple AGCM: the role of eddies *J. Clim.* **17** 629–39

Manney G L *et al* 2011 Unprecedented Arctic ozone loss in 2011 *Nature* **478** 469–75

Manney G L and Lawrence Z D 2016 The major stratospheric final warming in 2016: dispersal of vortex air and termination of Arctic chemical ozone loss *Atmos. Chem. Phys.* **16** 1–40

Marsh D R, Mills M J, Kinnison D E, Lamarque J-F, Calvo N and Polvani L M 2013 Climate change from 1850–2005 simulated in CESM1 (WACCM) *J. Clim.* **26** 7372–91

McGraw M C and Barnes E A 2016 Seasonal sensitivity of the eddy-driven jet to tropospheric heating in an idealized AGCM *J. Clim.* **29** 5223–40

Molod A, Takacs L, Suarez M and Bacmeister J 2015 Development of the GEOS-5 atmospheric general circulation model: evolution from MERRA to MERRA2 *Geosci. Model Dev.* **7** 1339–56

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

Li Y, Li J P and Feng J 2012 A Teleconnection between the reduction of rainfall in Southwest Western Australia and North China *J. Clim.* **25** 8444–61

Li Y J, Li J, Jin F-F and Zhao S 2015 Interhemispheric propagation of stationary rossby waves in a horizontally no uniform background flow *J. Atmos. Sci.* **72** 3233–56

Lubin D and Jensen E H 2002 Effects of clouds and stratospheric ozone depletion on ultraviolet radiation trends *Nature* **377** 710–3

Ramaswamy V, Schwarzkopf M D and Randel W J 1996 Fingerprint of ozone depletion in the spatial and temporal pattern of recent lower-stratospheric cooling *Nature* **382** 616–8

Randel W J 1988 The seasonal evolution of planetary waves in the Southern hemisphere stratosphere and troposphere *Q. J. R. Meteorol. Soc.* **114** 1385–409

Ravishankara A R *et al* 1994 Do hydrofluorocarbons destroy stratospheric ozone *Science* **263** 71–5

Ravishankara A R, Daniel J S and Portmann R W 2009 Nitrous oxide (N_2O): the dominant ozone-depleting substance emitted in the 21st Century *Science* **326** 123–5

Reichler T, Kim J, Manzini E and Kroger J 2012 A stratospheric connection to Atlantic climate variability *Nat. Geosci.* **5** 783–7

Rienecker M M *et al* 2011 MERRA: NASA's modern-era retrospective analysis for research and applications *J. Clim.* **24** 3624–48

Rogers J C 1981 The North Pacific Oscillation *J. Climatol.* **1** 39–57

Scaife A A, Knight J R, Vallis G K and Folland C K 2005 A stratospheric influence on the winter NAO and North Atlantic surface climate *Geophys. Res. Lett.* **32** 1–5

Sigmond M, Scinocca J F and Kushner P J 2008 Impact of the stratosphere on tropospheric climate change *Geophys. Res. Lett.* **35** L12706

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

Solomon S 1990 Antarctic ozone: progress towards a quantitative understanding *Nature* **347** 347–54

Solomon S 1999 Stratospheric ozone depletion: a review of concepts and history *Rev. Geophys.* **37** 275–316

Son S-W *et al* 2008 The impact of stratospheric ozone recovery on the Southern hemisphere westerly jet *Science* **320** 1486–9

Son S-W *et al* 2010 Impact of stratospheric ozone on Southern hemisphere circulation change: a multimodel assessment *J. Geophys. Res.* **115** D00M07

Song Y and Robinson W A 2004 Dynamical mechanisms for stratospheric influences on the troposphere *J. Atmos. Sci.* **61** 1711–25

Thompson D W J and Solomon S 2005 Recent stratospheric climate trends as evidenced in radiosonde data: global structure and tropospheric linkages *J. Clim.* **18** 4785–95

Thompson D W J *et al* 2011 Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change *Nat. Geosci.* **4** 741–9

Walker G T and Bliss E W 1932 World weather V *Mem. R. Meteorol. Soc.* **4** 53–84

Waugh D W, Garfinkel C I and Polvani L M 2015 Drivers of the recent tropical expansion in the Southern hemisphere: changing SSTs or ozone depletion *J. Clim.* **28** 6581–6

Wargan K, Labow G, Frith S, Pawson S, Livesey N and Partyka G 2017 Evaluation of the ozone fields in NASA's MERRA-2 reanalysis *J. Clim.* **30** 2961–88

World Meteorological Organization (WMO) 2011 Scientific Assessment of Ozone Depletion: 2010; Global Ozone Research and Monitoring *Project Report* No. 52. *Technical report*, Geneva, Switzerland p 516

Woo S H, Sung M K, Son S W and Kug J S 2015 Connection between weak stratospheric vortex events and the Pacific decadal oscillation *Clim. Dyn.* **45** 3481–92

Xie F *et al* 2016 A connection from Arctic stratospheric ozone to El Niño-Southern Oscillation *Environ. Res. Lett.* **11** 124026

Yu J Y and Kim S T 2011 Relationships between extratropical sea level pressure variations and the Central Pacific and Eastern Pacific types of ENSO *J. Clim.* **24** 708–20

Zhang J, Tian W S, Chipperfield M P, Xie F and Huang J 2016 Persistent shift of the Arctic polar vortex towards the Eurasian continent in recent decades *Nat. Clim. Change* **6** 1094–9

Zhao S, Li J and Li Y J 2015 Dynamics of an interhemispheric teleconnection across the critical latitude through a southerly duct during boreal winter *J. Clim.* **28** 7437–56

Zhao X and Li J 2012 Winter-to-winter recurrence and non-winter-to-winter recurrence of SST anomalies in the Central North Pacific *J. Geophys. Res.: Oceans* **117** C05027