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The Relationship between Lower Stratospheric Ozone in the Southern High Latitude and Sea Surface Temperature in the East Asia Marginal Seas

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Abstract

Using satellite observations, reanalysis data, and model simulations, this study investigates the effect of sea surface temperatures (SST) on interannual variations of lower stratospheric ozone in the southern high latitude. It is found that the SST variations across the East Asian marginal seas (5 °S–35 °N, 100 °E–140 °E) rather than the tropical eastern Pacific Ocean, where ENSO occurs, have the most significant correlation with the southern high latitude lower stratospheric ozone changes. Further analysis reveals that planetary waves originating over the marginal seas can be propagated to southern middle to high latitudes via two teleconnection pathways in summer and one pathway in autumn. The anomalous propagation and dissipation of ultra-long Rossby waves in the stratosphere strengthen/cool (weaken/warm) the southern polar vortex which produces more (less) active chlorine and enhances (suppresses) ozone depletion in the southern high latitude stratosphere on one hand, and impedes (favors) the transport of ozone from the southern middle latitude stratosphere to high latitude on the other. The model simulations also reveal that approximately 17% of the decreasing trend in the southern high latitude lower stratospheric ozone observed over the past five decades can be attributed to the increasing trend in SST over the East Asian marginal seas.

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1. Introduction

Ozone variations over recent decades exhibit not only a strong decreasing trend, forced by changes in ozone-depleting substances superimposed on a changing climate, but also interannual variability influenced by various external and internal climate forcings (e.g. Manney et al. 1994; Müller et al., 1994, 2005; Weiss et al., 2001; Hadjinicolaou et al., 2002; Tian and Chipperfield, 2005; Austin et al., 2006, 2010; Eyring et al., 2010; Liu et al., 2011, 2013; Douglass et al., 2014). Ozone variations can change the amount of harmful solar ultraviolet rays reaching the Earth's surface (Kerr and McElroy, 1993) and even influence climate (Forster and Shine, 1997; Thompson et al., 2011; Li et al., 2016; Xie et al., 2016). Therefore, clarifying the processes that are responsible for ozone variability is crucial for understanding how global climate interacts with ozone variations (Austin et al., 2006; Hess and Lamarque, 2007; Frossard et al., 2013; Rieder et al., 2013). Many previous studies have analyzed the ozone variability caused by external processes such as volcanic aerosols (e.g. Hofmann and Oltmans, 1993; Rozanov et al., 2002; Dhomse et al., 2015) and the solar cycle (e.g. Chandra and McPeters, 1994; Rozanov et al., 2005; Dhomse et al., 2016) and these studies showed that volcanic aerosols and solar variations can result in considerable short- and long-term variations in ozone levels. Ozone variations can also be caused by changes in the surface climate (Zhang et al., 2014). Other studies have reported the effects of internal climate variability on ozone, including El Niño–Southern Oscillation (ENSO; Ziemke and Chandra, 1999; Cagnazzo et al., 2009; Randel et al., 2009; Xie et al., 2014a, 2014b; Zhang et al., 2015a, 2015b), Madden–Julian Oscillation (MJO; Fujiwara et al., 1998; Tian et al., 2007; Liu et al., 2009; Weare, 2010; Li et al., 2012), Arctic Oscillation (AO) or North Atlantic Oscillation (NAO; Schnadt and Dameris, 2003; Lamarque and Hess, 2004; Creilson et al., 2005;

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Steinbrecht et al., 2011), and Quasi-Biennial Oscillation (QBO; Bowman, 1989; Tung and Yang, 1994; Dhomse, 2006; Li and Tung, 2014). These studies indicate that ozone over different regions shows different variability due to the location-specific nature of the processes that influence this variability.

The stratospheric ozone hole (Farman et al., 1985) over the Antarctic has been shown to have an important impact on the Southern Hemisphere climate (Shindell and Schmidt, 2004; Son et al., 2008, 2009, 2010, Perlwitz et al., 2008; Feldstein, 2011, Kang et al., 2011, Polvani et al., 2011; Thompson et al., 2011; Cagnazzo et al., 2013; Keeble et al., 2014; Previdi and Polvani, 2014). Although the principal mechanisms responsible for the formation of the ozone hole are well understood (e.g., Solomon, 1990, 1999; Ravishankara et al., 1994, 2009), the factors or processes that generate interannual variations in ozone levels in the southern high latitude stratosphere remain under debate. Among various factors, the QBO has been reported to have a significant impact on the interannual variations of the Antarctic ozone (Garcia and Solomon, 1987; Lait et al., 1989; Mancini et al., 1991; Gray and Ruth, 1993; Bodeker and Scourfield, 1995; Shindell et al., 1997a). The September to March levels of ozone over the Antarctic is also marginally correlated with the wintertime mean eddy heat flux (Weber et al., 2003). Heat transport induced by upward propagating planetary waves warms the polar vortex (Schoeberl and Hartmann, 1991), which reduces the occurrence of polar stratospheric clouds (PSCs), a key prerequisite for the heterogeneous chemistry that depletes Antarctic ozone. Subsequent efforts to understand Antarctic ozone variations during individual years have considered planetary wave activity, which account for much of the interannual variations of ozone levels over the Northern Hemisphere (Hadjinicolaou et al., 1997; Fusco and Salby, 1999; Salby and Callaghan, 2004, 2007a, 2007b; Hadjinicolaou and Pyle,

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2004). Studies based on measurements (Bodeker and Scourfield, 1995), modeling (Shindell et al., 1997a, 1997b), and reanalysis data (Huck et al., 2005) have shown that interannual differences in the severity of Antarctic ozone depletion are anti-correlated with Southern Hemisphere planetary wave activity. However, the source of the planetary wave activity that modulates interannual variability in southern high latitude stratospheric ozone is still not well understood.

Variations in tropical sea surface temperatures (SST) associated with El Niño-Southern Oscillation (ENSO), are an important factor in the modulation of the planetary wave activity in the Northern Hemisphere that affects the interannual variability of temperature and ozone levels in the northern polar stratosphere (Sassi et al., 2004; Manzini et al., 2006; Calvo et al., 2004, 2009; Cagnazzo et al., 2009; Hu and Pan, 2009; Hurwitz et al., 2011a, b; Ren et al., 2010; Zubiaurre and Calvo, 2012; Xie et al., 2012; Yao et al., 2015). The long-term trend in tropical SST also has corresponding to the trend of temperature in the southern polar stratosphere (Grassi et al., 2005, 2006; Hu and Fu, 2009; Li et al., 2010; Clem et al., 2016). Although ENSO is reported to cause circulation and temperature anomalies in the southern high latitude stratosphere, the interannual variability of the southern polar vortex and ozone levels over the past three decades cannot be explained by ENSO variations alone (Angell, 1988, 1990; Hurwitz et al., 2011a, 2011b; Lin et al., 2012; Wilson et al., 2014; Evtushevsky et al., 2015; Yu et al., 2015; Yang et al., 2015; Welhouse et al., 2016).

Over recent decades, SST in the East Asian marginal seas has followed an increasing trend with strong interannual variations (Zheng et al., 2014). Zhao et al. (2015, 2016) pointed out that Rossby waves generated by variations in the SST of the South China Sea can cross the equator and be propagated towards to southern middle to high latitudes. It is likely that the Rossby waves generated by SST changes in the

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vicinity of the East Asian marginal seas can cross the equator to the Southern Hemisphere and regulate ozone levels in the southern high latitude stratosphere via their influence on the southern stratospheric circulation. Therefore, it is worthwhile to examine the potential connections between SST variations over the East Asian marginal seas and southern high latitude lower stratospheric ozone variations. The remainder of the paper is organized as follows. The data, method and model used are introduced and briefly described in section 2. Section 3 analyzes the connection between the East Asian marginal seas and southern high latitude lower stratospheric ozone. Section 4 presents and discusses the simulations of the connection. Finally, the results are summarized and conclusions drawn in section 5.

2. Data, Model, and Methods

The ozone data used in this study is obtained from the NASA Modern Era Retrospective Analysis for Research and Applications (MERRA) dataset version 2 (Rienecker et al., 2011) and TOMCAT/SLIMCAT 3-D model simulations (Chipperfield, 2006). The MERRA2 data uses 42 pressure levels from the surface up to 0.1 hPa. The vertical resolution of MERRA2 is ~1–2 km in the UTLS and 2–4 km in the middle and upper stratosphere. MERRA2 is assimilated by 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 data compares well with satellite ozone observations (Rieder et al., 2014; Zhang et al., 2015b) and shows a better representation of the QBO and stratospheric ozone compared to MERRA1 (Coy et al., 2016). In the present study, the ozone data from a

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3D offline chemical transport model, SLIMCAT (Feng et al., 2007, 2011), is also used. The simulation performed in this study is driven by horizontal winds and temperatures from meteorological analyses of the ERA-Interim data provided by European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al., 2011). The vertical advection in the model is calculated from the divergence of the horizontal mass flux (Chipperfield, 2006), and chemical tracers are advected by the conservation of second-order moments (Prather, 1986). Figure 1 shows the ozone variations over the region 200–50 hPa and 60–90°S, where the variability and depletion of ozone concentration is most pronounced in the Southern Hemisphere in the past five decades (Austin and Wilson, 2006; Solomon 1990, 1999; Ravishankara et al., 1994, 2009), from the two datasets. The ozone variations from MERRA2 are in good agreement with those from SLIMCAT (Fig. 1a), and the difference between the two kinds of ozone data is small (Fig. 1b).

SST data is obtained from HadISST dataset compiled by the UK Met Office Hadley Centre for Climate Prediction and Research (Rayner et al., 2003). Geopotential height, zonal wind, and temperature data are obtained from the ECMWF ERA-Interim dataset.

We also use version 4 of the Whole Atmosphere Community Climate Model (WACCM4) in this study since WACCM has been shown to simulate well the stratospheric circulation, temperature and ozone variations (Garcia et al. 2007). WACCM4 is part of the Community Earth System Model (CESM) framework developed by the National Center for Atmospheric Research (NCAR). WACCM4 uses a finite-volume dynamical core, with 66 vertical levels extending from the ground to 4.5×10^{-6} hPa (145 km geometric altitude), and a vertical resolution of 1.1–1.4 km in the tropical tropopause layer and the lower stratosphere (below a height of 30 km).

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The simulations presented in this paper are performed at a horizontal resolution of 1.9° × 2.5° and with interactive chemistry (Garcia et al., 2007). More details regarding WACCM4 are provided in Marsh et al. (2013).

We calculate 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} is determined using 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 two sampled time series, X and Y, respectively, at time lag j.

We use the formulae given by Andrews et al. (1987) to calculate the quasi-geostrophic 2D Eliassen–Palm (E–P) flux. The meridional (F_y) and vertical (F_z) components of the E–P flux, and the E–P flux divergence D_F, are expressed as:

$$F_y = -\rho_0 a \cos\varphi \overline{u'v'}$$

$$F_z = -\rho_0 a \cos\varphi \frac{Rf}{HN^2}\overline{v'T'}$$

$$D_F = \frac{\nabla \cdot F}{\rho_0 a \cos\varphi} = \frac{\partial(\mathrm{F}_y \cos\varphi)/a\cos\varphi\partial\varphi + \partial F_z/\partial z}{\rho_0 a \cos\varphi},$$

where ρ_0 is the air density, a is the radius of the Earth, R is the gas constant, f is the Coriolis parameter, H is the atmospheric scale height (7 km), u and v are the zonal and meridional wind components, respectively, and T is the temperature; the overbar denotes the zonal mean, and the prime symbol denotes departures from the zonal mean.

3. The connection between the East Asian marginal seas and southern high latitude lower stratospheric ozone

Figure 2a shows the correlation coefficients between SST and southern high latitude lower stratospheric ozone variations between 1979 and 2015 using ozone data from the MERRA2 dataset and SST from HadISST dataset. Ozone data from SLIMCAT simulations was further used to confirm the correlation coefficients (Fig. 2b). The regions of significant correlation are generally different for the two ozone datasets except for the East Asian marginal seas; i.e., 5 °S–35 °N, 100 °E–140 °E, where the most significant correlations between Antarctic stratospheric ozone variations and SST are seen in both datasets. Figure 2 implies an interannual connection between SST in the East Asian marginal seas and southern high latitude lower stratospheric ozone variations. Figure 2 also reveals that SST variations associated with ENSO are not the main factor controlling the interannual variability of southern high latitude lower stratospheric ozone.

Through the interannual connection in Fig. 2 possibly caused by the influence of lower latitude SST on the south high latitude stratosphere, south high latitude stratospheric ozone has also been shown to affect tropical climate (Son et al., 2008; Kang et al., 2011; Thompson et al., 2011). Thus, it is first necessary to confirm the causality of this connection. To investigate the SST variations across the marginal seas of East Asia, we first define an SST index over the region with the most significant correlations in Fig. 2, i.e., the ST_MSEA index. This index is a time series that represents SST variations across the marginal seas of East Asia (Figure 3a). It is calculated by averaging the SST variations in the region from 5 °S–35 °N at 100 °E–140 °E, and then removing the seasonal cycle and linear trend. Fig. 3b and c show the composite warm and cold SST anomalies for the events that occurred in the marginal seas of East Asia between 1979 and 2015 (see Table 1).

The ST_MSEA index and southern high latitude lower stratospheric ozone variations show a significant simultaneous correlation (Fig. 4). This implies that SST variations in the marginal seas of East Asia have an impact on southern high latitude lower stratospheric ozone, since there is a lag of several months associated with the effect of southern high latitude lower stratospheric ozone on the tropical climate (Son et al., 2008; Kang et al., 2011; Thompson et al., 2011).

It is well known that the SST changes in the eastern Pacific, the Indo-Pacific warm pool, and the Atlantic can significantly influence the northern polar stratosphere (Calvo et al., 2004, 2009; Hoerling et al., 2001, 2004; Cagnazzo et al., 2009; Hu and Fu, 2009; Hu and Pan, 2009; Li et al., 2010; Hurwitz et al., 2011a, b; Lin et al., 2012; Zubiaurre and Calvo, 2012; Xie et al., 2012; Li and Chen, 2014). SST variations in some regions can excite Rossby wave trains and those waves can propagate into northern middle and high latitude stratosphere (Gettelman et al., 2001; Sassi et al., 2004; Manzini et al., 2006; García-Herrera et al., 2006; Taguchi and Hartmann, 2006; Garfinkel and Hartmann, 2007, 2008; Free and Seidel, 2009). The mechanism that allows SST variations in the East Asian marginal seas to affect the southern high latitude stratosphere is also possibly related to tropospheric wave propagation from northern lower latitude to southern middle and high latitudes.

Figure 5 shows the ray paths of waves generated by the SST anomalies over the region 5°S–35°N, 100°E–140°E, at 300 hPa in four seasons. The wavenumbers along these rays are between 1 and 5. 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 is described in detail by Li et al. (2015) and Zhao et al. (2015). We found that the Rossby waves generated by SST anomalies in the marginal seas of East Asia could indeed propagate to the middle to high latitudes of the Southern Hemisphere in summer and autumn (Fig. 5b and c), but not in spring and winter (Fig. 5a and d) because the Rossby waves motivated by the low-latitude SST anomalies move mostly northwards in spring and winter. Meanwhile, we must note that the propagating paths of those waves in summer and autumn are different (Fig. 5b and c). In summer, the first path of rays originates over the marginal seas of East Asia, crosses the Indian Ocean to arrive over tropical Africa or even South America, and then reflects equatorward to the middle to high latitudes of the Southern Hemisphere. The second path of rays originates over the marginal seas of East Asia reflects directly into the southern Indian Ocean and reaches the Southern Hemisphere. In autumn, the first path disappears, and only the rays that follow the second path reach the Southern Hemisphere. In addition, the ray stops at about 60 °S, which possibly implies an upward propagation of the wave at this location.

The correlation coefficients between the ST_MSEA index and 300-hPa geopotential height variations from the ERA-Interim reanalysis across the four seasons are shown in Figure 6. The positive and negative centers of correlation coefficients represent the teleconnection patterns. The teleconnection patterns in summer and autumn (Fig. 6b and c) are in good agreement with the ray paths (Fig. 5b and c). In summer, two clear wave train paths appear over the marginal seas of East Asia with one moving westwards to South America and reflecting to the middle to high latitudes of the Southern Hemisphere, and the second reflecting directly into the Southern Hemisphere (Fig. 6b). In autumn, the first path is very distinct (Fig. 6c), i.e., the negative correlation coefficient over the Indian Ocean is small, which suggests that most of the waves do not propagate westwards. The second path also remains evident. These two teleconnection pathways of the wave trains in summer and autumn (Figs. 5 and 6) are discussed in detail by Zhao et al., (2016), who refer to them as the North Australia–Southern Hemisphere and South Africa–Southern Hemisphere pathways, respectively. In spring and winter, the above two teleconnection patterns don't exist (Fig. 6a and d).

Figure 7a shows the correlation coefficients between the ST_MSEA index and stratospheric ozone variations, which indicate that warm (cold) SST anomalies over the East Asian marginal seas are associated with a decrease (increase) in southern high latitude lower stratospheric ozone. Bodeker and Scourfield (1995), Shindell et al. (1997a, 1997b), and Huck et al. (2005) have shown that interannual differences in the severity of southern high latitude lower stratospheric ozone depletion are related to Southern Hemisphere planetary wave activity. All of the above analysis illustrates that the SST anomalies over the marginal seas of East Asia are a possible main source of this planetary wave activity.

Figure 7b shows that ST_MSEA is positively correlated with zonal wind around 60 °S, where is the boundary of the southern polar vortex in summer and autumn, while Figs. 7c indicate that ST_MSEA is negatively correlated with temperature. The correlations shown in Figs 3, 5, 6, and 7 can be used to establish a hypothesis of chemical process for the connection between SST variations over the marginal seas of East Asia and southern high latitude lower stratospheric ozone as follows: 1. The warm (cold) SST anomalies over the marginal seas (Fig. 3) depress (enhance) planetary wave activity in the middle to high latitudes of the Southern Hemisphere (Figs 5 and 6). 2. The anomalous propagation of planetary waves into the stratosphere and dissipation of ultra-long Rossby waves in the stratosphere strengthen/cool (weaken/warm) the southern polar vortex (Fig. 7b and c). 3. A cooler (warmer) polar vortex allows more (less) PSCs and active chlorine to form. 4. Consequently, southern high latitude lower stratospheric ozone decreases (increases) (Fig. 7a).

However, it needs to point out that Antarctic polar vortex temperature is deeply below the threshold for heterogeneous chemistry, so that a warming (cooling) in the center of Antarctic polar vortex will have very little impact on Antarctic ozone by affecting heterogeneous chemistry (Tilmes et al. 2006; Kirner et al. 2015). It seems to challenge the above hypothesis.

Fig. 7c shows that the center of the correlation confidences locates near 60°S. It means that the center of stratospheric temperature changes caused by SST changes in the East Asia Marginal Seas locates near 60°S but not near 90°S. Temperature change near 60°S maybe more effectively affects southern high latitude lower stratospheric ozone than that near 90°S since the background temperature in the lower stratosphere near 60°S would be higher than that near 90°S. The chemical process maybe has a certain contribution on the southern high latitude lower stratospheric ozone changes caused by SST changes in the East Asia Marginal Seas.

We also found that the SST changes in the East Asia Marginal Seas are positively correlated with southern high latitude stratospheric meridional wind (Fig. 7d), suggesting a stronger (weaker) zonal circulation (Fig. 7b) related to the SST changes impeding (promoting) transport of ozone from the middle latitude stratosphere to high latitude stratosphere. Note that this correlation is the strongest in autumn but not in summer when the south polar vortex is too stable that doesn't allow ozone rich air into the vortex. Fig. 7d implies a dynamical contribution on the southern high latitude lower stratospheric ozone changes caused by SST changes in the East Asia Marginal Seas.

It is noteworthy that warm (cold) SST anomalies are generally thought to increase (suppress) planetary wave activity via strengthening (weakening) convection (Xie et al., 2008; Shu et al., 2010; Hu et al., 2014). However, this study shows that warm (cold) SST anomalies over the marginal seas of East Asia suppress (increase) planetary wave activity. This may be the warm (cold) SST anomalies over the marginal seas in summer and autumn are equal to weaken (enhance) sea–land contrast along the coastline of East Asia. This results in weaker (stronger) convection, which suppresses (increases) planetary wave activity.

4. Simulating the effect of SST changes in the marginal seas of East Asia on southern high latitude lower stratospheric ozone

We performed three time-slice simulations with WACCM4 to validate the mechanism described in Section3. The monthly mean climatologies of surface emissions used in the model were obtained from the A1B emissions scenario developed by the Intergovernmental Panel on Climate Change (IPCC), and averaged over the period 1979–2015. QBO signals with a 28-month fixed cycle are included in WACCM4 as an external forcing for zonal wind. The SST forcing used in the first time-slice experiment (S1, the control experiment) was the 12-month climatology cycle averaged over the period 1979–2015 and based on the HadISST dataset. S2 was a sensitivity experiment and was the same as S1 except that warm anomalies (as in Fig. 3b) were added to the SST in the marginal seas of East Asia (5°S–35°N and 100–140°E). The third experiment, S3, was the same as S2, but with cold SST anomalies (as in Fig. 3c). Detailed descriptions of experiments S1–S3 are provided in Table 2.

Figure 8 first shows the southern high latitude lower stratospheric ozone anomalies forced by warm and cold SST anomalies over the marginal seas of East Asia. It can be seen that the warm SST anomalies indeed cause ozone decrease in the southern high latitude lower stratosphere (Fig. 8a) and cold SST anomalies results in ozone increase (Fig. 8b). The simulations support the results shown from the statistical analysis in Section 3.

Figure 9 shows the E–P flux vectors and divergence anomalies in the stratosphere caused by SST anomalies over the marginal seas of East Asia. Analysis of changes in the E–P flux (Eliassen and Palm 1961; Andrews et al. 1987) is often used as a diagnostic for planetary wave propagation from the troposphere to the stratosphere (Edmon et al., 1980). During periods of warm (cold) SST over the marginal seas of East Asia, a decrease (increase) in upward wave flux entering the stratosphere accompanied by stronger (weaker) convergence of the E–P flux in the stratosphere at middle to high latitudes of the Southern Hemispheres (ca. 60°S) is evident (Fig. 9a and c). The anomalous wave flux entering the stratosphere around 60°S confirms the result in Fig. 5, which shows that the wave rays terminate at about 60°S.

Many previous studies have demonstrated a strongly negative correlation between upward propagating wave activity and the intensity of the stratospheric polar vortex, with an anomalously negative and positive upward wave flux alongside a stronger and weaker polar vortex, respectively (Christiansen 2001; Polvani and Waugh 2004; Li and Lau 2013). During periods of warm (cold) SST over the marginal seas of East Asia, the anomalous downward (upward) E–P flux, and larger (smaller) E–P flux divergence at middle to high latitudes (ca. 60°S) in the Southern Hemisphere (Fig. 9a and c), imply suppressed (active) wave activity in the stratosphere, which induces a strengthened (weakened) circulation at southern polar vortex edge (Fig. 9b and d). Finally, the cold (warm) polar vortex (Fig. 10a and c) allows more (less)

PSCs/active chlorine (Fig. 10b and d) to form. This is one process through which SST variations over the marginal seas of East Asia causes southern high latitude lower stratospheric ozone changes. The other process is that the strengthened (weakened) southern polar vortex impedes (promotes) air exchange between middle and high latitude stratosphere (Figure 11), and further decreases (increases) southern high latitude lower stratospheric ozone levels.

As a result of human activity, the amount of Antarctic stratospheric ozone has decreased remarkably over recent decades (Solomon 1990, 1999; Ravishankara et al., 1994, 2009). At the same time, SST over the marginal seas of East Asia has followed an increasing trend, but superimposed on strong interannual variations (Zheng et al., 2014). Figure 12 shows the correlation coefficients between southern high latitude lower stratospheric ozone and SST in which the SST and southern high latitude lower stratospheric ozone variations have not been detrended as that in Fig. 2. Comparing Fig. 12 with Fig. 2, we can see that the negative correlation coefficients over the marginal seas of East Asia become larger in Fig. 12, implying a contribution of warmer SST in the marginal seas of East Asia to decline trend of southern high latitude lower stratospheric ozone.

We used ensemble transient experiments to estimate the contribution of SST variations in the marginal seas of East Asia to southern high latitude lower stratospheric ozone changes. The transient experiments incorporated the following natural and anthropogenic external forcings for the period 1955–2005: observed SST from the HadISST dataset, surface emissions from the IPCC A1B emissions scenario, spectrally resolved solar variability (Lean et al., 2005), volcanic aerosols (from the Stratospheric Processes and their Role in Climate (SPARC) Chemistry–Climate Model Validation (CCMVal) REF-B2 scenario recommendations), and nudged QBO (the time series in CESM is determined from the observed climatology). The first transient experiment, T1, was the historical experiment covering the period 1955–2005 (Marsh et al., 2013). The second transient experiment, T2, was the same as T1 except that the SST in the marginal seas of East Asia (5 °S–35 °N and 100–140 °E) for the period 1955–2005 was replaced by the 12-month cycle of climatology averaged over the same period. This means that in T2, the SST over the marginal seas of East Asia had only a seasonal cycle, but no trend and no interannual variability. T3 was the same as T2, but used a slightly different initial condition as an ensemble experiment. Detailed descriptions of runs T1–T3 are provided in Table 3.

Figure 13a and b shows the southern high latitude lower stratospheric ozone variations over the period 1955–2005 from T1 and the ensemble experiments ((T2+T3)/2). The southern high latitude lower stratospheric ozone variations caused by the SST variability over the marginal seas of East Asia can be obtained by subtracting simulated ozone in the ensemble experiments ((T2+T3)/2)) from the ozone in T1 (Fig. 13c). There are evident differences in southern high latitude lower stratospheric ozone variations between T1 and the ensemble experiments ((T2+T3)/2)). This illustrates that the SST variability over the marginal seas of East Asia (Fig. 13d) does have a significant effect on southern high latitude lower stratospheric ozone over the past five decades (Fig. 13c). The correlation coefficient between the two lines in Fig. 13c and d is 0.29 which is significant at 99% confident level. A further analysis reveals that the linear trend of ozone variations over the region 200–50 hPa and 60–90 °S from T1 (Trend1, Fig. 3a) is $-1.2 \times e^{-3}$ ppmv/month, and from (T1 – (T2+T3)/2) (Trend2, Fig. 3c) is $-0.204 \times e^{-3}$ ppmv/month. See Table 4. It implies that the increasing linear trend in SST over the marginal seas of East Asia can contribute approximately 17% of the declining trend in southern high latitude lower stratospheric ozone from 1955–2005 (Trend2 / Trend1 × 100%).

5. Conclusions and Summary

In this study, the connection between SST and the southern high latitude lower stratospheric ozone variations at the interannual time scale is examined. We found that SST over the marginal seas of East Asia can significantly modulate the interannual variability of southern high latitude lower stratospheric ozone and the processes involved in this modulation are related to anomalous planetary wave activity induced by SST variations over the marginal seas of East Asia. The planetary waves originating from the marginal seas can propagate to the middle and high latitudes of the Southern Hemisphere in summer and autumn via the North Australia–Southern Hemisphere and South Africa–Southern Hemisphere pathways. The anomalous propagation and dissipation of ultra-long Rossby waves in the stratosphere strengthens/cools (weakens/warms) the southern polar vortex, which allows more (less) active chlorine to form and deplete more (less) ozone on one hand. On the other hand, a stronger (weaker) polar vortex impedes (promotes) the transport of middle latitude ozone to high latitudes and further decreases (increases) southern high latitude lower stratospheric ozone. The above results and analysis are based on observations but are also supported by time-slice experiments conducted using the CESM.

Our transient model simulations further demonstrated that SST variations over the marginal seas of East Asia not only modulate the interannual variability of southern high latitude lower stratospheric ozone, but also contribute to southern high latitude lower stratospheric ozone trend over the past five decades. Our analysis reveals that the trend of increasing SST over the marginal seas of East Asia may have contributed approximately 17% to the decreasing trend of southern high latitude lower stratospheric ozone over the past five decades.

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Table 1. Warm and cold SST events in the marginal seas of East Asia from 1979 to 2015 analyzed in this paper using the ST_MSEA index (Fig. 3a).

Warm Events*	Cold Events*
JUN1983–NOV1983	SEP1979–MAY1980
MAY1987–NOV1988	OCT1981–NOV1982
NOV1997–MAR2000	MAY1985–MAY1986
MAR2002–AUG2003	AUG1992–MAY1993
AUG2008–FEB2009	JUL2004–DEC2004
MAY2010–NOV2010	FEB2011–SEP2011
	MAY2012–APR2012
	NOV2014–SEP2015

*Following the definition of ENSO events (Trenberth 1997), we propose a threshold of ±0.15, which is equal to the standard deviation of the ST_MSEA series, as the indicator of warm and cold events.

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Table 2. Experiments S1–S3.

Experiments[*1]	Descriptions
S1	Time-slice run using case F_2000_WACCM in CESM. The SST is the 12-month cycle climatology mean for the period 1979–2015 based on HadISST dataset (Rayner et al., 2003); the monthly mean climatologies of surface emissions used in the model are obtained from the A1B emissions scenario developed by the IPCC, averaged over the period 1979–2015. QBO phase signals with a 28-month fixed cycle are included in WACCM4 as an external forcing for zonal wind.
S2	Same as S1, except that the SST in the marginal seas of East Asia (5 °S–35 °N and 100–140 °E) adds warm SST anomalies (as Fig. 3b).
S3	Same as S1, except that the SST in the marginal seas of East Asia (5 °S–35 °N and 100–140 °E) adds cold SST anomalies (as Fig. 3c).

[*1]Each experiment is run for 53 years, with the first 3 years excluded as a spin-up period. The remaining 50 years are used for the analysis.

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Table 3. Experiments T1–T3.

Experiments[*1]	Descriptions
T1	Transient run using case F_1955-2005_WACCM_CN in CESM. SST forcing based on HadISST dataset, surface emissions are obtained from the A1B emissions scenario developed by the IPCC, spectrally resolved solar variability (Lean et al., 2005), volcanic aerosols (from the SPARC CCMVal REF-B2 scenario recommendations), nudged QBO (the time series in CESM is determined from the observed climatology).
T2	Same as T1, except that the SST in the marginal seas of East Asia (5 °S–35 °N and 100–140 °E) between 1955 and 2005 is replaced by the 12 months cycle of climatology averaged for the period 1955–2005.
T3	Same as T2, but with slightly different initial condition[*2]

[*1]Integration period is 1955–2005 for T1–T3.

[*2]The parameter <pertlim> is used to produce different initial conditions in the CESM model, which produces an initial temperature perturbation. The magnitude was about e^{-14}.

Table 4. Linear trends of ozone variations over the region 200–50 hPa and 60–90 °S from experiments with (T1) and without SST (T2 +T3) variations in the East Asia Marginal Seas (T1–3 see Table 3).

Experiments	Values
Linear trend of ozone variations over the region 200–50 hPa and 60–90 °S from T1 (Trend1)	$-1.2 \times e^{-3}$ ppmv/month
Linear trend of ozone variations over the region 200–50 hPa and 60–90 °S from (T1 – (T2+T3)/2) (Trend2)	$-0.204 \times e^{-3}$ ppmv/month

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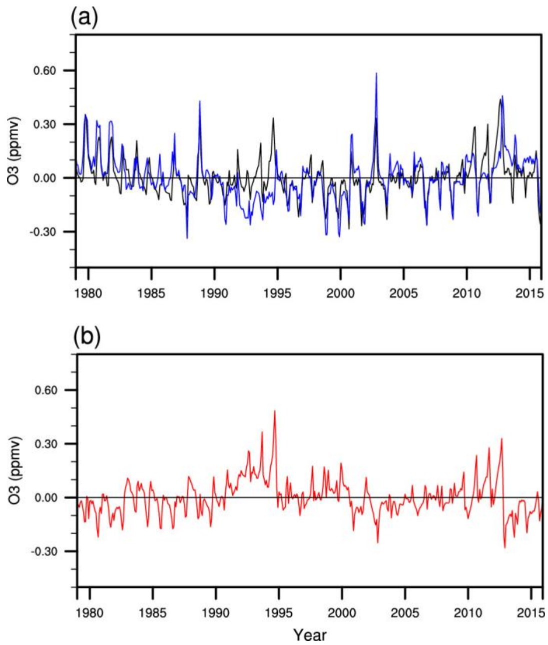

Figure 1. (a) Time series of southern high latitude lower stratospheric ozone variations averaged over the region 60–90 °S at 200–50 hPa from the MERRA2 (black line), and SLIMCAT monthly ozone (blue line) datasets. (b) The difference between MERRA2 and SLIMCAT ozone.

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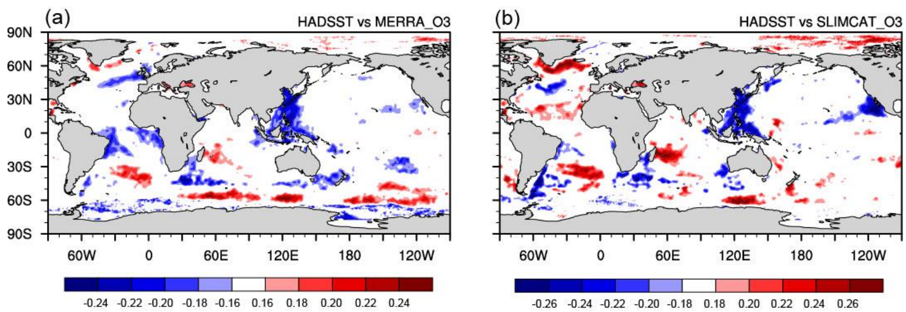

Figure 2. Correlation coefficients between southern high latitude lower stratospheric ozone variations and SST (from HadISST) between 1979 and 2015. Southern high latitude lower stratospheric ozone variations are averaged over the region 60–90°S at 200–50 hPa. (a) Ozone from MERRA2. (b) Ozone from SLIMCAT. Only the significant correlations are colored; statistical significance was calculated using the two-tailed Student's *t*-test and the N^{eff} of DOF (see section 2). The seasonal cycles and linear trends were removed prior to calculating the correlation coefficients.

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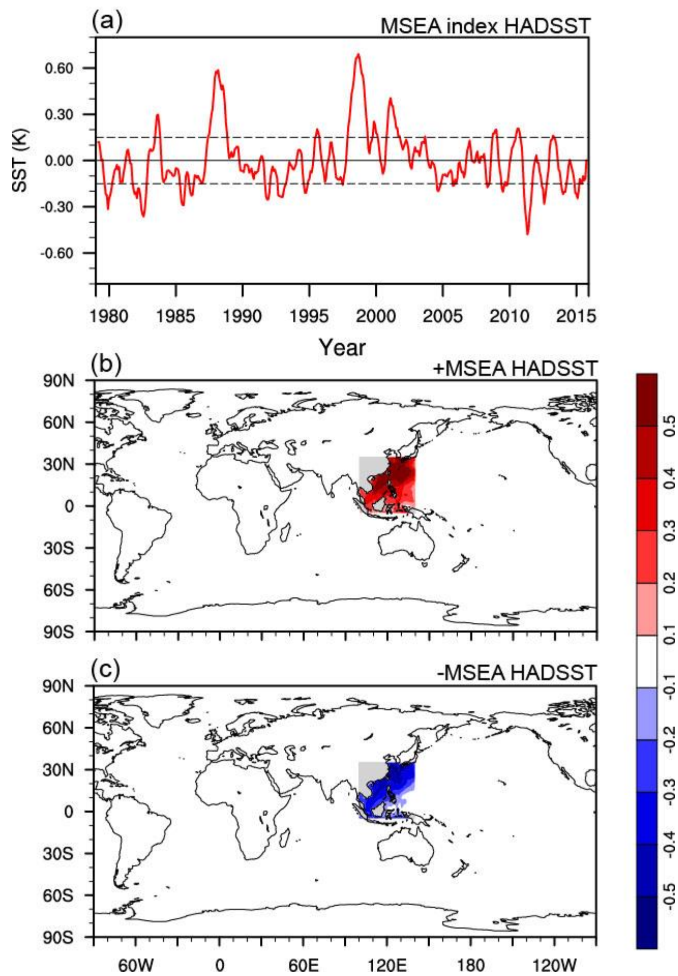

Figure 3. (a) SST variations in the marginal seas of East Asia defined using the ST_MSEA index that was calculated by averaging SST over the region from 5°S–35°N at 100°E–140°E (from HadISST), and then removing the seasonal cycle and linear trend. The dashed lines indicate the thresholds for definition of warm and cold events. (b) and (c) show the composite warm and cold SST anomalies, respectively, for the events listed in Table 1.

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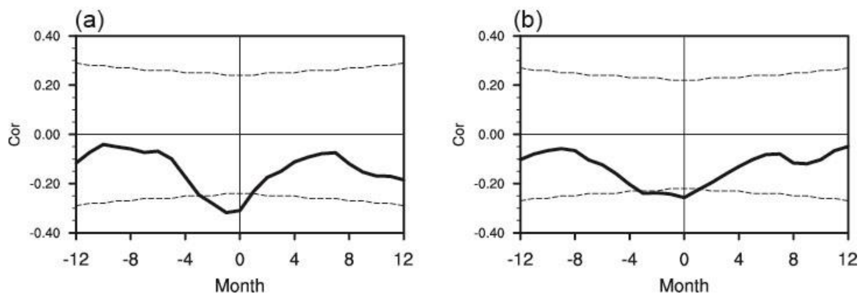

Figure 4. Lead–lag correlations between the ST_MSEA index and southern high latitude lower stratospheric ozone variations between 1979 and 2015; Southern high latitude lower stratospheric ozone variations are averaged over the region 60–90°S at 200–50 hPa from the (a) MERRA2 and (b) SLIMCAT datasets. Negative months on the *x*-axis refer to ST_MSEA leading southern high latitude lower stratospheric ozone variations, and positive months refer to the southern high latitude lower stratospheric ozone variations leading ST_MSEA. Dotted lines indicate the 90% confidence level; lead–lag correlations exceeding the dotted lines are statistically significant. The statistical significance of the lead–lag correlation between two auto-correlated time series was calculated using the two-tailed Student's *t*-test and the N^{eff} of DOF (see section 2).

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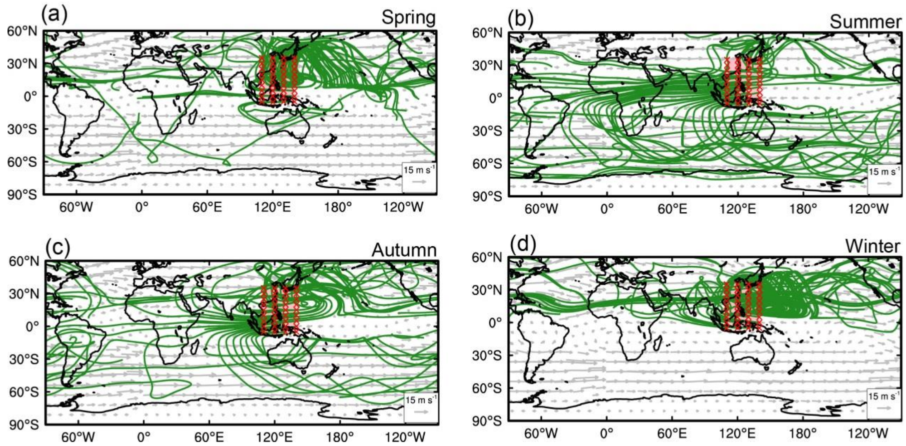

Figure 5. Ray paths (green lines) at 300 hPa in (a) spring, (b) summer, (c) autumn, and (d) winter. Red points denote wave sources in the marginal seas of East Asia (5°S–35°N, 100°E–140°E). The wavenumbers along these rays are in the range 1–5. The grey vectors indicate climatological flows.

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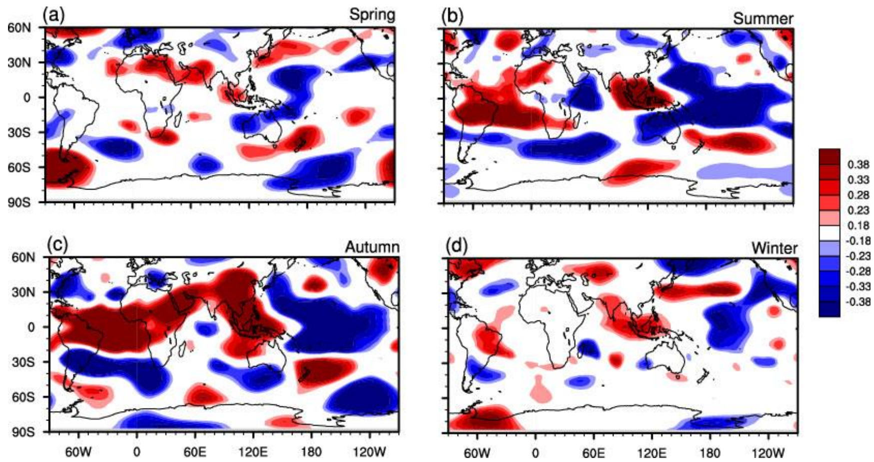

Figure 6. Correlation coefficients between the ST_MSEA index and 300-hPa geopotential height from the ERA-Interim reanalysis in (a) spring, (b) summer, (c) autumn, and (d) winter between 1979 and 2015. Only significant correlations are colored. The seasonal cycles and linear trends were removed before calculating the correlation coefficients.

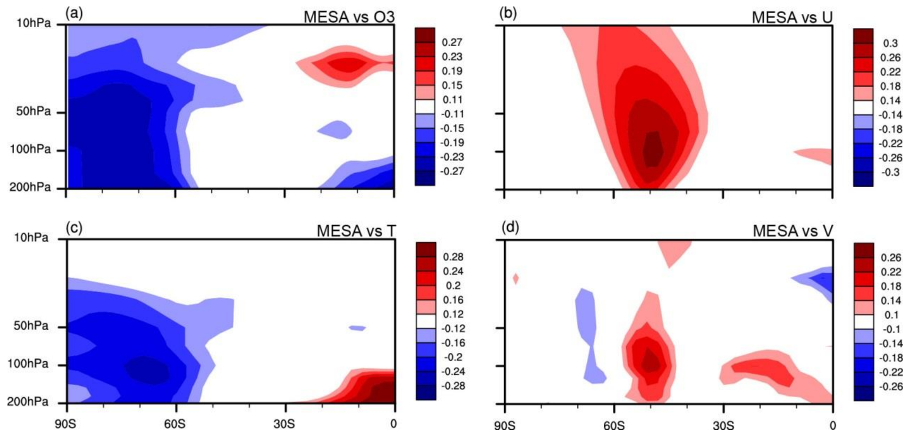

Figure 7. Correlation coefficients between ST_MSEA and (a) zonally averaged ozone, (b) zonal wind, (c) temperature, and (d) meridional wind. Wind and temperature from ERA-Interim reanalysis data; ozone from MERRA2. Only significant correlations are colored. The seasonal cycles and linear trends were removed before calculating the correlation coefficients.

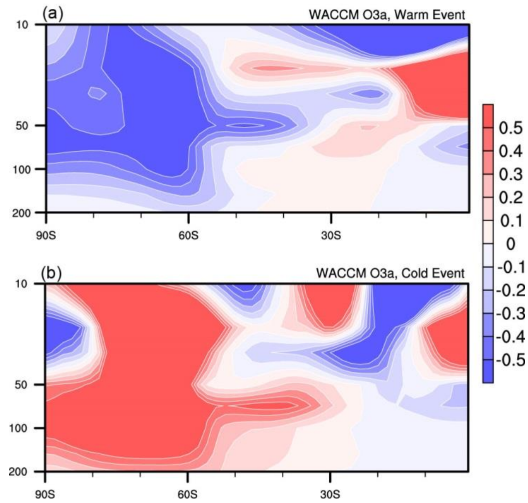

Figure 8. Zonal mean differences in ozone (ppmv) between WACCM simulations (a) S2 and S1, and (b) S3 and S1.

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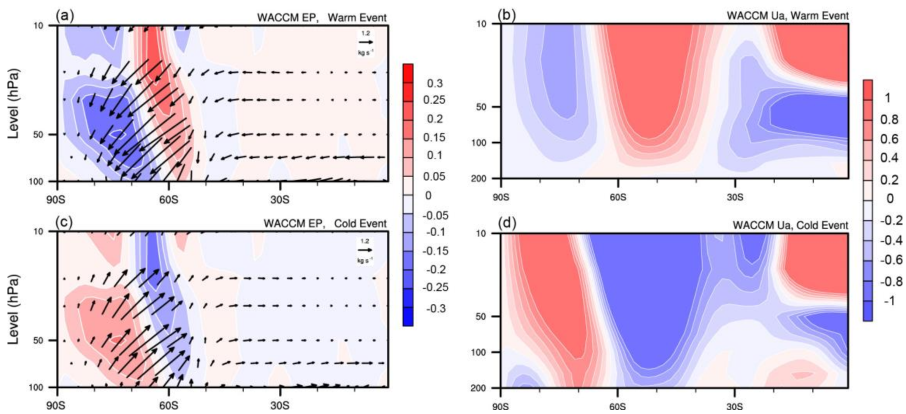

Figure 9. Differences in E–P flux vectors (black arrows) and divergence (color shading) between (a) S2 and S1, and (c) S3 and S1. Units for the horizontal and vertical vector directions are 10^7 and 10^5 kg s^{-1}, respectively. (b) and (d), as (a) and (c), but for zonal wind (m s^{-1}).

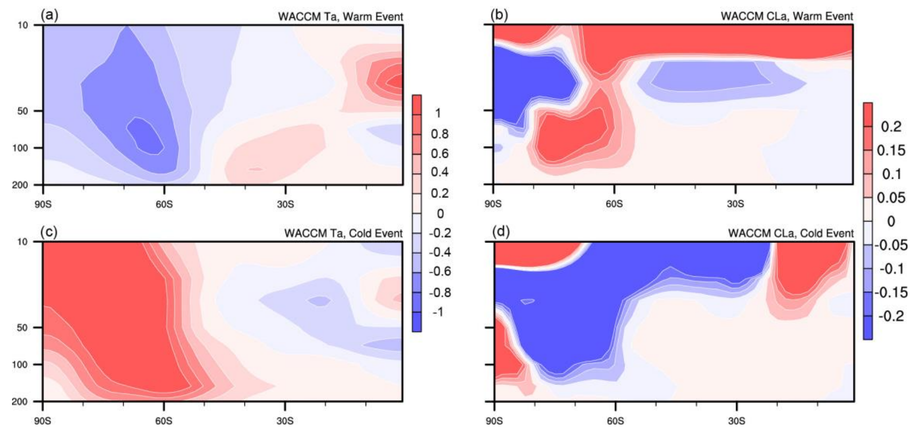

Figure 10. Zonal mean difference in temperature (K) between (a) S2 and S1, and (c) S3 and S1. (b) and (d), as (a) and (c), but for active chlorine (ppbv).

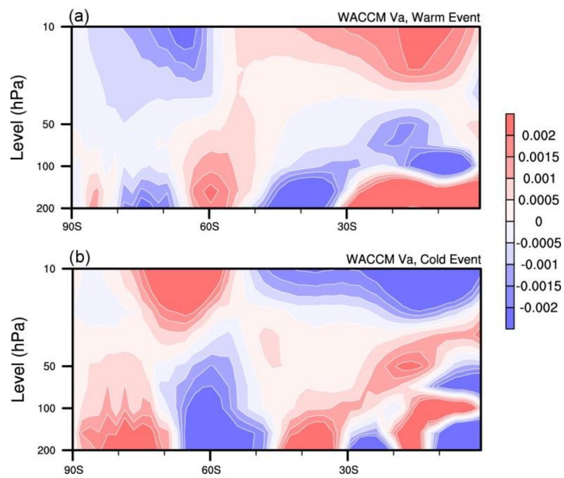

Figure 11. Zonal mean difference in meridional wind (m s^{-1}) between (a) S2 and S1, and (b) S3 and S1.

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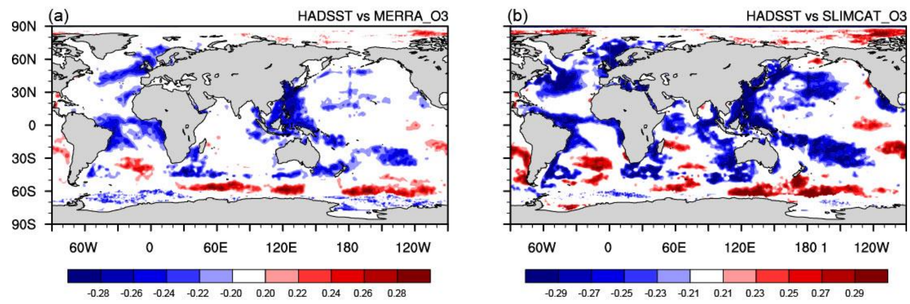

Figure 12. As Fig. 2, but with only the seasonal cycle removed before calculating the correlation coefficients.

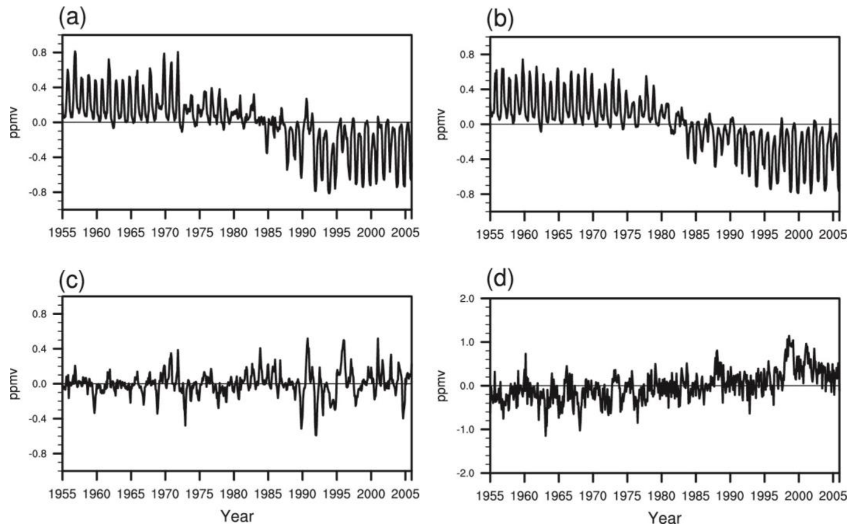

Figure 13. The southern high latitude lower stratospheric ozone variations averaged over the region 60–90°S at 200–50 hPa from T1 (a) and (T2+T3)/2 (b). (c) The difference in southern high latitude lower stratospheric ozone variations between T1 and (T2+T3)/2. (d) SST variations (×–1) in the marginal seas of East Asia (5°S–35°N, 100°E–140°E) based on the HadISST data. All values are removed the seasonal cycle.