An Estimate of the Relative Contributions of Sea Surface Temperature Variations in Various Regions to Stratospheric Change

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ABSTRACT

This study investigates the effects of global and regional sea surface temperature (SST) warming from the Industrial Revolution to the present on the stratosphere using a climate model, and estimates the relative contributions of SST warming in different regions. The observed global SST warming is found to cause colder and stronger stratospheric zonal circulations in the high latitudes of both hemispheres, and a colder lower stratosphere in the tropics and ozone depletion. This occurs because the warming in the tropical Atlantic and in the north Indian Ocean and North Pacific strongly cool the stratosphere in the southern and northern high latitudes, respectively. The cooling in the lower stratosphere at lower and midlatitudes is mainly caused by SST warming in the tropical Pacific and north Indian Ocean. The changes in stratospheric temperature are related to changes in circulation and ozone. In addition, we investigate the effects on the stratosphere of ideal 1-K uniform warming of SST in different oceans and compare these effects with those caused by the realistic SST warming. The observed global SST warming and 1-K uniform global SST warming have opposite effects on the high-latitude stratosphere in both hemispheres: 1-K uniform global SST warming results in warmer and weaker stratospheric zonal circulations and a corresponding increase in ozone. This is because the 1-K uniform increase in SST in the tropical Pacific causes extremely strong warming and weakening stratospheric zonal circulations. The contribution of a 1-K uniform increase of SST in the tropical Pacific to stratospheric temperature, circulation, and ozone anomalies overwhelms that of a 1-K uniform increase of SST in other regions.

1. Introduction

Earth’s climate is changing as a result of increasing greenhouse gases (GHGs) in the atmosphere. The increased GHGs give rise to an overall tropospheric warming but a stratospheric cooling, hence leading to changes in the thermal structure of the stratosphere from tropics to poles. These changes in the thermal structure have important implications for stratospheric circulation, temperature, and chemical composition (e.g., ozone) due to changes, among other things, in the intensity of wave activity and the strength of the Brewer–Dobson (BD) circulation (e.g., Holton et al. 1995; Zhang et al. 2016, 2018; Zhao et al. 2019; He et al. 2020), and further have a downward implication for tropospheric climate change (Baldwin and Dunkerton 2001). One of primary consequences of greenhouse effect is the warming of global sea surface temperature (SST). It is well known that signals propagating from the troposphere, forced by changes in SST, strongly modulate stratospheric temperature, circulation, and chemical composition (e.g., Yulaeva and Wallace 1994; Free and Seidel 2009; Randel et al. 2009; Xie et al. 2016; Zhang et al. 2015, 2019).

The effects of SST anomalies in different regions on the stratosphere are different. In the tropical eastern Pacific, El Niño–Southern Oscillation (ENSO) is the
dominant oscillatory mode of the atmosphere–ocean system, and its impacts on the stratosphere have been investigated in detail through numerous observational analyses and modeling experiments. The tropical lower-stratospheric temperature response to El Niño is an anomalous cooling, opposite in sign to the tropospheric warming (e.g., Yulaeva and Wallace 1994; Free and Seidel 2009; Randel et al. 2009; Zhou and Zhang 2011; Scherlin-Pirsch et al. 2012; Wang et al. 2016, 2019; Zhou et al. 2018a). ENSO influences the mid- and high-latitude stratosphere by causing anomalous propagation and dissipation of long-wavelength Rossby waves in midlatitude, which modulates zonal wind in the mid- and high latitudes and the polar vortex (e.g., Brönnimann et al. 2004; Sassi et al. 2004; Manzini et al. 2006; Taguchi and Hartmann 2006; García-Herrera et al. 2006; Camp and Tung 2007; Marsh and Garcia 2007; Cagnazzo and Manzini 2009; Cagnazzo et al. 2009; Calvo et al. 2010; Xie et al. 2012, 2014; Zhang et al. 2015). For example, enhanced BD circulation related to El Niño events causes more ozone transported from the lower latitudes to high latitudes (Brönnimann et al. 2004, 2006; Cagnazzo et al. 2009). Hood et al. (2010), using a multiple linear regression, confirmed that there exists significant ENSO-like interannual variability in the ozone of the lower and middle stratosphere. Randel and Thompson (2011) further suggested that ENSO can be considered as a main factor to control interannual variations of stratospheric ozone.

In the tropical western Pacific, Zhou et al. (2018b) showed that the Indo-Pacific warm pool (IPWP) tends to cool the tropical lower stratosphere, with a node in the lower stratospheric temperature anomaly pattern located near the tropopause. There are also coherent temperature and circulation anomalies at higher latitudes in the stratosphere during either the warming or cooling of IPWP. In addition, the tropical western Pacific SST drives warming trends in the Arctic and Antarctic stratosphere since 1979 (Hu and Fu 2009; Hu and Pan 2009; Lin et al. 2012; Hu et al. 2014).

Hu and Pan (2009), Jadin et al. (2010), Hu et al. (2018), and Li et al. (2018) reported that the upward propagation of the tropospheric planetary waves into the stratosphere are modulated by the SST anomalies over the North Pacific. Hurwitz et al. (2011) found that the anomalous cold stratospheric polar vortex in March 2011 was caused by the SST anomalies over the North Pacific rather than the ENSO or the quasi-biennial oscillation (QBO). Hurwitz et al. (2012) further showed that the negative SST anomalies over the North Pacific often intensify the Aleutian low and the western Pacific (WP) teleconnection pattern, which may affect the stratospheric polar vortex (Wallace and Gutzler 1981; Nishii et al. 2010). Wang et al. (2016) found that positive sea level pressure anomalies over the North Pacific during a negative Pacific decadal oscillation phase suppress vertical wave propagation into the stratosphere, which leads to strengthened polar vortex and in turn slows the BD circulation. Hu and Guan (2018) suggested the different relationship between the North Pacific SST and stratospheric Arctic vortex on subdecadal and decadal time scales.

The tropical Indian Ocean is one of the areas where anthropogenic influences are easily detected, as an evidently monotonic SST increase against a background of moderate decadal variability (Knutson et al. 1999). It has been found that this Indian Ocean warming induces a strengthened northern polar vortex and a positive Northern Hemisphere annular mode trend in boreal winter (Hoerling et al. 2001, 2004; Manganello 2008; Li et al. 2010; Fletcher and Kushner 2011), while the response of the southern polar vortex in austral summer is opposite (Li and Chen 2014). Fletcher and Kushner (2011), using model simulation, proposed a possible mechanism by which Rossby waves induced by warming in tropical Indian Ocean interfere destructively with the climatological stationary wave. Yet as noted in Fletcher and Kushner (2013), the wave response to Indian Ocean warming depends on the details of model.

Li et al. (2007), Sutton and Hodson (2007), and Wang et al. (2008) pointed out that the low efficiency of the tropical Atlantic forcing in exciting atmospheric teleconnection has resulted in the insignificant stratospheric responses to tropical Atlantic forcing. Later, Rao and Ren (2018) provided evidence that tropical Atlantic SST forcing does indeed have significant effects on the northern winter stratosphere, but these effects vary from early to late winter in a way that explains the overall insignificant effect when the seasonal average is considered. For the North Atlantic Ocean, the multidecadal variability of stratospheric circulation is found to be associated with the Atlantic multidecadal oscillation (Manzini et al. 2018; Omrani et al. 2014, 2016). For example, Hu et al. (2019) suggested a significant decadal linkage between the North Atlantic SSTs and stratospheric Arctic vortex.

Since the Industrial Revolution, in addition to doubled GHG concentrations, global SST has increased between 60°S and 60°N (Fig. 1). It is well known that both doubled GHGs concentrations and global SST warming have important impacts on climate
FIG. 1. (a) Sea surface temperature (SST; K) differences (1990–2010 minus 1900–20). (b)–(i) SST differences in the North Pacific (NP), tropical Pacific (TP), South Pacific (SP), north Indian Ocean (NI), south Indian Ocean (SI), North Atlantic (NA), tropical Atlantic (TA), and South Atlantic (SA), respectively. The monthly SST data are from 1° × 1° HadISST1 of the Met Office Hadley Centre for the period 1870–2018 (Rayner et al. 2003). The label in the upper right corner matches the experiment.
change in the stratosphere. Figure 2 shows the changes in stratospheric temperature, zonal circulation, and ozone forced by doubled GHGs concentrations and global SST warming from the Industrial Revolution to the present. It is found that the stratospheric temperature is decreased and zonal circulation is strengthening in the high latitudes of both hemispheres. However, the stratospheric ozone is only decreased in the lower and middle latitudes but is increased in the poles, which may be related to less active ozone loss due to stratospheric cooling caused by doubled GHGs concentrations (Wang et al. 2014). A question arises as to which extent the observed increase in SST from the Industrial Revolution to the present has influenced the stratosphere. In addition, as mentioned above, the impacts of SST on the stratosphere show spatial dependence. The relative contributions of SST in various regions to stratospheric variations also remain unclear. We first estimate the effect of the observed SST warming between 60°S and 60°N from 1900 to 2000 (Fig. 1a) on the stratospheric temperature, circulation, and ozone using a climate model. Then, we divide the global ocean into eight regions: North Pacific (NP; Fig. 1b), tropical Pacific (TP; Fig. 1c), South Pacific (SP; Fig. 1d), north Indian Ocean (NI; Fig. 1e), south Indian Ocean (SI; Fig. 1f), North Atlantic (NA; Fig. 1g), tropical Atlantic (TA; Fig. 1h), and South Atlantic (SA; Fig. 1i). The various characteristics and relative contributions of the observed SST increase in these oceans to the stratosphere are evaluated. Note that since this study focuses on the estimation of the relative contributions of SST variations in regions to the stratosphere, we did not investigate in details the mechanisms responsible for the effects of SST anomalies on the stratosphere in each of these key ocean regions. The mechanisms by which regional SST anomalies affect stratospheric anomalies are based on previous studies (see below). The remainder of this paper is organized as follows. Section 2 describes the simulation and our methods. In section 3, we show results for the different effects on the stratosphere of SST warming from 1900 to 2000 in several regions, and the relative contributions of SST warming in these regions are analyzed. The sensitivity of the stratospheric response to a 1-K temperature increase in different oceans is investigated in section 4. Finally, we discuss the results and draw conclusions in section 5.

2. Model and simulations

The Whole Atmosphere Community Climate Model, version 4 (WACCM4) is a part of the Community Earth System Model (CESM), version 1.0.6, from the National Center for Atmospheric Research (Hurrell et al. 2013). The WACCM4 used in this paper includes atmosphere, data ocean (run as a prescribed component, simply reading in SST data from observed data file), land, and sea ice (Holland et al. 2012) and its physics are based on Community Atmospheric Model version 4 (CAM4; Neale et al. 2013). It uses a finite-volume dynamic core covering a geometric altitude from the ground to approximately 145 km (5.1 × 10^-6 hPa) and 66 levels with vertical resolution of 1.1–1.4 km in the tropical tropopause layer and the lower stratosphere (located below a height of 30 km). The simulations presented in this paper are performed at a resolution of 1.9° × 2.5°, with interactive tropospheric and stratospheric chemistry. More information on WACCM is provided in Marsh et al. (2013).

Two groups of experiments are performed in this study. Eleven experiments in group 1 (R1–R11) are
performed to estimate the influence of observed increase of global SST from 1900 to 2000 on stratosphere and the contributions of increased SST in different regions to stratospheric variations. The experiments are described in Table 1. Nine experiments in group 2 (E1–E9) are performed to investigate the sensitivity of stratosphere responses to the same magnitude of SST increase in different regions. The experiments are described in Table 2. All the experiments are each run for 43 years, with the first 3 years excluded as a spinup period. The remaining 40 years are used for the analysis, and model climatologies are obtained from this period.

3. Effects and relative contributions of observed SST warming in different oceans on the stratosphere

Figures 3a, 3e and 3i show the simulated stratospheric temperature, circulation, and ozone changes forced by the observed global SST increase (Fig. 1a), from the Industrial Revolution to the present and between 60°S and 60°N, using the WACCM4 model. Note that the changes, anomalies, or differences in all figures of the paper are all zonal mean results. In the north and south polar regions, stratospheric temperature decreases by more than 1 K (Fig. 3a), circulation is enhanced by ≈2 ms⁻¹ (Fig. 3e), and ozone in some areas decreases by more than 1 ppmv (Fig. 3i) because of global SST increases. These changes correspond to deviations relative to climatological averages of ~1% in temperature (Fig. 3b), ~20% in zonal wind at the North and South Poles (Fig. 3f), and ~4% in ozone (Fig. 3j). In the tropics, the lower-stratospheric temperature decreases by 1 K (~0.4%; Figs. 3a,b) and is associated with decreased tropical lower-stratospheric ozone (ozone decreases by >10%; Figs. 3i,j). These results are generally in agreement with those of Kodama et al. (2007) and Xie et al. (2008).

Comparing the trends of stratospheric temperature, zonal circulation, and ozone caused by global warming (Fig. 2) with those only associated with global SST warming (Figs. 3a,e,i), some differences are found among these trends. Opposing stratospheric temperature anomalies at midlatitudes of the Southern Hemisphere (Figs. 2a and 3a) are found for the two scenarios. Opposing stratospheric zonal circulation anomalies in the Southern Hemisphere (Figs. 2b and 3e) are also found. The significant decrease of stratospheric ozone in the Northern Hemisphere in the global warming scenario (Fig. 2c) is not found in the global SST warming scenario (Fig. 3i). With these exceptions, the trends in Figs. 3a, 3e, and 3i are similar to those shown in Fig. 2. This suggests that the stratospheric temperature, zonal circulation, and ozone trends caused by SST warming contribute significantly to the overall trends of the past 100 years.

Figures 3a, 3e, and 3i show the total effect of the observed global SST increase from the Industrial Revolution

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
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<tbody>
<tr>
<td>R1</td>
<td>Control run. The 12-month seasonal cycle of SST and sea ice data is averaged over the period 1900–2000 from the Met Office Hadley Centre for Climate Prediction and Research (Rayner et al. 2003). Monthly mean climatologies of surface emissions used in the model are obtained from the A1B emissions scenario developed by the Intergovernmental Panel on Climate Change (IPCC), averaged over the period 1900–2000. A fixed solar constant and volcanic aerosols from the Stratospheric Chemistry–Climate Model Validation (CMV) REF-B2 scenario recommendations are applied.</td>
</tr>
<tr>
<td>R2</td>
<td>As in R1, but with SST and sea ice data averaged over the period 1900–2010, and surface emissions averaged over the period 1990–2010.</td>
</tr>
<tr>
<td>R3</td>
<td>As in R1, but with observed global SST increase between 60°S and 60°N in the 12-month SST forcing. To prevent discontinuities in SST forcing at the boundaries, SST anomalies at the boundary are added to the three grid points closest to the boundary with weights of 0.75, 0.50, and 0.25, respectively, moving away from the boundary. The applied global SST anomalies are as shown in Fig. 1a.</td>
</tr>
<tr>
<td>R4</td>
<td>As in R3, but with observed North Pacific SST increase used in the 12-month SST forcing. The applied SST increase is as shown in Fig. 1b.</td>
</tr>
<tr>
<td>R5</td>
<td>As in R3, but with observed tropical Pacific SST increase used in the 12-month SST forcing. The applied SST increase is as shown in Fig. 1c.</td>
</tr>
<tr>
<td>R6</td>
<td>As in R3, but with observed South Pacific SST increase used in the 12-month SST forcing. The applied SST increase is as shown in Fig. 1d.</td>
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<tr>
<td>R7</td>
<td>As in R3, but with observed north Indian Ocean SST increase used in the 12-month SST forcing. The applied SST increase is as shown in Fig. 1e.</td>
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<tr>
<td>R8</td>
<td>As in R3, but with observed south Indian Ocean SST increase used in the 12-month SST forcing. The applied SST increase is as shown in Fig. 1f.</td>
</tr>
<tr>
<td>R9</td>
<td>As in R3, but with observed North Atlantic SST increase used in the 12-month SST forcing. The applied SST increase is as shown in Fig. 1g.</td>
</tr>
<tr>
<td>R10</td>
<td>As in R3, but with observed tropical Atlantic SST increase used in the 12-month SST forcing. The applied SST increase is as shown in Fig. 1h.</td>
</tr>
<tr>
<td>R11</td>
<td>As in R3, but with observed South Atlantic SST increase used in the 12-month SST forcing. The applied SST increase is as shown in Fig. 1i.</td>
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Table 2. Descriptions of experiments E1–E9. All 9 experiments were run for 43 years, with the first 3 years excluded as model spinup and the remaining 40 years used for the analysis.

<table>
<thead>
<tr>
<th>Experiment</th>
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<tbody>
<tr>
<td>E1</td>
<td>As in R3, but with a uniform 1-K increase of global SST between 60°S and 60°N used in the 12-month SST forcing.</td>
</tr>
<tr>
<td>E2</td>
<td>As in E1, but with a uniform 1-K increase of North Pacific SST used in the 12-month SST forcing. The modified region is that shown in Fig. 1b.</td>
</tr>
<tr>
<td>E3</td>
<td>As in E1, but with a uniform 1-K increase of tropical Pacific SST used in the 12-month SST forcing. The modified region is that shown in Fig. 1c.</td>
</tr>
<tr>
<td>E4</td>
<td>As in E1, but with a uniform 1-K increase of South Pacific SST used in the 12-month SST forcing. The modified region is that shown in Fig. 1d.</td>
</tr>
<tr>
<td>E5</td>
<td>As in E1, but with a uniform 1-K increase of north Indian Ocean SST used in the 12-month SST forcing. The modified region is that shown in Fig. 1e.</td>
</tr>
<tr>
<td>E6</td>
<td>As in E1, but with a uniform 1-K increase of south Indian Ocean SST used in the 12-month SST forcing. The modified region is that shown in Fig. 1f.</td>
</tr>
<tr>
<td>E7</td>
<td>As in E1, but with a uniform 1-K increase of North Atlantic SST used in the 12-month SST forcing. The modified region is that shown in Fig. 1g.</td>
</tr>
<tr>
<td>E8</td>
<td>As in E1, but with a uniform 1-K increase of tropical Atlantic SST used in the 12-month SST forcing. The modified region is that shown in Fig. 1h.</td>
</tr>
<tr>
<td>E9</td>
<td>As in E1, but with a uniform 1-K increase of South Atlantic SST used in the 12-month SST forcing. The modified region is that shown in Fig. 1i.</td>
</tr>
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</table>

Figure 4 shows the stratospheric temperature, circulation, and ozone anomalies forced by the observed North Pacific, tropical Pacific, and South Pacific SST warming (Figs. 1b–d). Consistent with previous studies (Hurwitz et al. 2012; Woo et al. 2015), we find that North Pacific SST warming forces lower temperature and stronger wind in the Arctic stratosphere (Figs. 4a,d). Higher North Pacific SST tends to weaken the Aleutian low, subsequently weakening the upward propagation of the wavenumber-1 planetary wave flux, and further strengthening stratospheric zonal circulation. Hu et al. (2018) reported a positive trend in Arctic stratospheric zonal wind intensity during 1998–2016 that is partly driven by warming of the SST over the central North Pacific. Note that the Antarctic stratospheric zonal wind and temperature are also significantly enhanced and cooled (Figs. 4a,d). Thus, the SST warming in the North Pacific causes ozone depletion (Fig. 4g). Tropical Pacific SST anomalies are known to have significant impacts on the tropical and high-latitude stratosphere. The tropical Pacific SST warming causes warmer and weaker Arctic and Antarctic stratospheric zonal circulations (Figs. 4b,e) and correspondingly increased stratospheric ozone in both high latitudes (Fig. 4h). Tropical eastern Pacific warming increases the upward propagation of wave activity in the stratosphere in the Northern Hemisphere midlatitudes, which suggests a strengthening of BD circulation in the Northern Hemisphere. Consequently, the northern polar vortex is weakened and warmed. On average, the tropical eastern Pacific is warming, although the signals of SST warming in some regions are not significant (Fig. 1c). Tropical western Pacific warming excites teleconnections, similar to the Pacific–North America pattern in the Northern Hemisphere and the Rossby wave train in the Southern Hemisphere, which affects climatological waves at mid- to high latitudes, intensifying the upward propagation of planetary waves into the stratosphere and, in turn, affecting the polar vortex. The warmer and weaker Arctic stratospheric polar vortex may be related to SST warming in the tropical eastern Pacific (Calvo et al. 2004, 2010; Manzini et al. 2006; Garfinkel and Hartmann 2007, 2008; Cagnazzo et al. 2009; Free and Seidel 2009; Randel et al. 2009; Xie et al. 2012, 2018a), but the Antarctic stratospheric zonal wind anomalies are thought to be associated with SST warming in the western Pacific (Xie et al. 2018b; Zhou et al. 2018b). The tropical Pacific SST warming reduces lower-stratospheric temperature since the enhanced tropical upwelling results in adiabatic cooling and ozone reduction in the lower stratosphere (Figs. 4b,h). The impacts of South Pacific SST warming on the northern stratosphere are relatively weak, whereas they can cause a cooling in the Antarctic stratosphere (Figs. 4c,f,i).
Figure 5 shows the stratospheric temperature, circulation, and ozone anomalies in response to observed north and south Indian Ocean SST warming (Figs. 1e,f). A warming north Indian Ocean produces a colder and stronger Arctic stratospheric zonal circulation, but a warmer and weaker Antarctic stratospheric zonal circulation (Figs. 5a,c). This corresponds to decreased stratospheric ozone in the northern high latitudes and...
increased ozone in the southern high latitudes (Fig. 5e). Many previous studies have pointed out that Indian Ocean warming induces a strengthened zonal wind and lower temperature in the Arctic stratosphere (Hoerling et al. 2001, 2004; Manganello 2008; Li et al. 2010; Fletcher and Kushner 2011), whereas the Antarctic stratospheric zonal wind has the opposite response (Li and Chen 2014). The direct impact of the diabatic heating associated with the tropical rainfall, induced by Indian Ocean warming, does not account for the response in the extratropics. Instead, the forced stationary wave anomalies and transient eddies are key to the formation of anomaly structures of stratospheric circulation. By contrast, the influence of an increase in south Indian Ocean SST on the stratosphere (Figs. 5b,d,f) is much weaker than that of an increase in north Indian Ocean SST (Figs. 5a,c,e); that is, there is a higher temperature and weaker Arctic stratospheric zonal circulation, and lower temperature and stronger Antarctic stratospheric zonal circulation (Figs. 5b,d) associated with increased stratospheric ozone in northern high latitudes and decreased ozone in southern high latitudes (Fig. 5f).

Figure 6 shows the stratospheric temperature, circulation, and ozone anomalies caused by the observed North Atlantic, tropical Atlantic, and South Atlantic SST warming (Figs. 1g–i). Previous studies have found that North Atlantic warming induces wave-induced stratospheric vortex weakening, strong stratosphere–troposphere coupling, and high-latitude tropospheric warming in the Northern Hemisphere (Omrani et al. 2014, 2016). Consistent with the results of these studies, we find a higher temperature and weaker stratospheric Arctic stratospheric zonal wind, but a lower temperature and stronger Antarctic stratospheric zonal wind (Figs. 6a,d). Note that the north of the North Pacific has cooled (or not changed) over the last 100 years (Fig. 1a). This suggests that the forced stratospheric anomalies (Figs. 6a,d) are more likely to be caused by subtropical Atlantic warming. North Atlantic Ocean warming seems to have a weak impact on stratospheric ozone (Fig. 6g).
increase in tropical Atlantic SST has a strong influence on the stratosphere. Like North Atlantic warming, tropical Atlantic warming also causes a higher temperature and weaker Arctic stratospheric zonal circulation and a lower temperature and stronger Antarctic stratospheric zonal circulation (Figs. 6b,e). This leads to positive stratospheric ozone anomalies in the northern high latitudes and negative anomalies in the southern high latitudes (Fig. 6h). An interesting feature of this system is that the stratospheric anomalies in the Southern Hemisphere are larger than those in the Northern Hemisphere. Previous studies reported rather weak winter-mean stratospheric responses to tropical Atlantic warming (Li et al. 2007; Sutton and Hodson 2007; Wang et al. 2008); however, Rao and Ren (2018) found that the stratospheric Arctic stratospheric polar vortex is anomalously weaker and warmer in November–December and in April–May during warm tropical Atlantic years. Tropical Atlantic warming produces a south–north dipole in geopotential heights, much like the North Atlantic Oscillation (NAO), which influences the upward propagation of planetary waves into the stratosphere. The NAO-like linear response occurs when the tropical Atlantic SST warming induces transient-eddy forcing at the exit of the Atlantic jet. The structure of the background absolute vorticity in this region is such that this transient-eddy forcing induces a nearly north–south dipole in anomalous geopotential heights. An increase in South Atlantic SST causes a lower temperature and stronger Antarctic stratospheric zonal wind and decreased ozone (Figs. 6c,f,i), but has a relatively weak impact on the Arctic stratosphere.

In addition, we calculate the magnitudes of temperature, circulation, and ozone anomalies averaged in the lower and middle stratosphere and in the high-latitude stratosphere caused by the observed SST warming in eight regions (Figs. 1b–i). Results shown in Fig. 7 provide a clearer estimation of the relative contributions of SST increase in different regions to the changes in stratospheric temperature, circulation, and ozone from the Industrial Revolution to recent times.

For the stratospheric temperature changes in southern high latitude (Fig. 7a), only warming in the tropical Pacific and north Indian Ocean makes positive contributions, and these contributions are noticeable. Warming in the tropical Atlantic makes the largest negative contribution, whereas warming in the North and South Atlantic makes substantial negative contributions. In the lower and middle latitudes (Fig. 7b), the cooling is mainly caused by SST warming in the tropical Pacific and north Indian Ocean. For temperature changes in northern high latitudes (Fig. 7c), warming in the tropical Atlantic makes the largest negative contribution, whereas warming in the North and South Atlantic makes substantial negative contributions. In the lower and middle latitudes (Fig. 7b), the cooling is mainly caused by SST warming in the tropical Pacific and north Indian Ocean.
Indian Ocean greatly weakens the circulation but increases ozone in the Antarctic stratosphere, and warming in the tropical Atlantic strongly enhances the circulation but decreases ozone. Warming in the North and South Atlantic substantially strengthens circulation and reduces ozone, whereas warming in the North and South Pacific only has a small effect on the Antarctic stratospheric zonal circulation and ozone. The units for temperature, zonal wind, and ozone anomalies are K, m s\(^{-1}\), and ppmv.

Indian Ocean greatly weakens the circulation but increases ozone in the Antarctic stratosphere, and warming in the tropical Atlantic strongly enhances the circulation but decreases ozone. Warming in the North and South Atlantic substantially strengthens circulation and reduces ozone, whereas warming in the North and South Pacific only has a small effect on the Antarctic stratospheric zonal circulation and ozone. Figures 7e and 7h show that the SST warming in the tropical Pacific and north Indian Ocean are the main factors reducing the lower-stratospheric zonal wind and ozone in the lower and midlatitudes. However, warming of the tropical Atlantic has the strongest effect on the lower- and midlatitude stratospheric circulation and ozone. Figures 7f and 7i show that the strongest enhancement of the Arctic stratospheric zonal circulation and the maximum reduction of ozone are caused by warming of the north Indian Ocean. Warming of the North Pacific and tropical Pacific makes important contributions to the strengthening and weakening of the Arctic stratospheric zonal wind, respectively. In the northern polar regions, the positive effect of tropical Atlantic warming on ozone changes is significant.

4. Sensitivity of the stratospheric response to ocean warming

The above results show the effects on stratospheric change of observed SST increase from the Industrial Revolution to recent times (Fig. 1a) in eight regions.
Note that the magnitude of the SST increase differs among oceans. Even over a single area, the increase in SST is not uniform. SST anomalies in different oceans may affect the stratosphere through a range of mechanisms, resulting in inconsistent relative contributions to the stratosphere (Fig. 7). Nevertheless, these different relative contributions may still be partly related to the different magnitudes of SST increase in the various regions. To further confirm the sensitivity of stratosphere to the SSTs in different regions, we investigate the effects of a 1-K uniform increase in SST in all oceans on the stratosphere. Note that we consider the same areas as shown in Fig. 1.

Figure 8a, 8e, and 8i show the simulated stratospheric temperature, circulation, and ozone changes in the WACCM4 model forced by global SST (60°S–60°N) uniformly increasing by 1 K. A comparison with Figs. 3a, 3e, and 3i shows that these two kinds of global SST warming have opposite effects on the high-latitude stratosphere in both hemispheres: the observed global SST warming (Fig. 1a) causes lower temperature and stronger stratospheric zonal winds and ozone depletion in the lower stratosphere in both hemispheres (Figs. 3a,e,i), but a 1-K uniform warming results in higher temperature and weaker stratospheric zonal circulations and corresponding increases in ozone, except for the ozone reductions in the Antarctic lower stratosphere (Figs. 8a,e,i). However, both types of SST warming lead to similar results in the lower- and midlatitude stratosphere: the lower temperature and a decrease of ozone in the tropical lower stratosphere, and higher midlatitude stratospheric zonal wind. In the northern and southern polar regions, the stratospheric temperature increases by much more than 1 K (Fig. 8a), circulation weakens by 1 m s⁻¹ (Fig. 8e), and ozone increases by much more than 1 ppmv (Fig. 8i) because of the 1-K increase in global SST. This increase corresponds to changes relative to climatological averages of more than ~1% in temperature (Fig. 8b), a decrease of ~25% in zonal wind (Fig. 8f), and an increase of more than ~6% in ozone (Fig. 8j). In the tropics, the middle- to lower-stratospheric temperature decreases by much more than 1 K (a decrease of more than 1%; Figs. 8a,b), and is associated with decreased ozone in the lower stratosphere (ozone decreases by much more than 10%; Figs. 8i,j). The stratospheric circulation at midlatitudes is enhanced by more than 25% (Fig. 8f).

Next, we investigate the independent impact of 1-K uniform increases in SST in different regions on the stratosphere. Again, before investigating the individual impacts, the combined effects of SST 1-K uniform warming in different regions of the stratosphere are compared with the effect of global SST 1-K uniform
warming (Figs. 8a,e,i) to see whether the effects are approximately equal. Figures 8c, 8g, and 8k show the linear sum of temperature, zonal circulation, and ozone anomalies caused by uniform 1-K SST warming in these different regions (Figs. 1b–i). In general, the patterns in Figs. 8c, 8g, and 8k agree with those in Figs. 8a, 8e, and 8i. This is further confirmed by Figs. 8d, 8h, and 8l, which show the differences between Figs. 8a, 8e, and 8i and Figs. 8c, 8g, and 8k. Note that the differences shown in Figs. 8d, 8h, and 8l are larger than those in Figs. 3d, 3h, and 3l, suggesting that the nonlinear interactions among ocean regions in their effects on the atmosphere are amplified by the uniform 1-K SST increase.

Figure 9 shows the stratospheric temperature, circulation, and ozone anomalies forced by 1-K uniform increases in SST in the North Pacific, tropical Pacific, and South Pacific. The North Pacific SST increase forces lower temperature and stronger Arctic and Antarctic stratospheric zonal circulations and correspondingly greater ozone depletion (Figs. 9a,d,g). The effect of a 1-K uniform increase in North Pacific SST on the Antarctic stratospheric zonal wind is stronger than that of observed increase in SST, whereas the effect on the Arctic stratospheric zonal circulation is weaker than that of the observed increase in SST (Figs. 9a,d,g and 9a,d,g). A 1-K uniform increase in tropical Pacific SST causes extremely strong weakening of the Arctic and Antarctic stratospheric zonal winds (Figs. 9b,e), and correspondingly increased stratospheric ozone in both high latitudes (Fig. 9h), whereas it causes very strong cooling and ozone depletion in the tropical lower stratosphere (Figs. 9b,h). The magnitudes of temperature, circulation, and ozone anomalies caused by a 1-K uniform increase in SST in tropical Pacific SST are much larger than those caused by the observed increase in SST (Figs. 4b,e,h). The impact of 1-K uniform SST warming in the South Pacific (Figs. 9c,i) on the high-latitude stratosphere in the Northern Hemisphere is relatively weak, like that of the observed SST warming (Figs. 4c,i). However, its impact on the Southern Hemisphere is strong, unlike the effect of the observed SST warming.

Figure 10 shows the stratospheric temperature, circulation, and ozone anomalies response to 1-K uniform increases in SST in the north and south Indian Ocean. The patterns of the anomalies (Fig. 10) agree with those caused by the observed SST warming (Fig. 5), although the magnitudes of the anomalies caused by the 1-K uniform increase in SST (Fig. 10) are larger than those caused by the observed SST warming (Fig. 5).

Figure 11 shows the stratospheric temperature, circulation, and ozone anomalies caused by 1-K uniform increases in SST in the North Atlantic, tropical Atlantic, and South Atlantic. Uniform warming in the North Atlantic causes a higher temperature and weaker Antarctic stratospheric zonal circulation but a lower temperature and stronger Arctic stratospheric zonal circulation (Figs. 11a,d). This is opposite to the effect of the observed warming in the North Atlantic (Figs. 6a,d).
The North Atlantic has cooled (or not changed) over the past 100 years, as mentioned above. The uniform 1-K increase in SST in the North Atlantic may thus lead to the opposite stratospheric signals shown in Figs. 6a,d and 11a,d. North Atlantic Ocean warming appears to have a weak impact on stratospheric ozone (Fig. 11g). The influence of a 1-K uniform increase in SST in the tropical Atlantic on the stratosphere has a similar pattern to that of the observed increase in SST (Figs. 11b,e,h and 6b,e,h), although the magnitudes of the anomalies associated with the uniform 1-K warming are greater than those for the observed warming. This difference in the effects of the 1-K warming relative to the observed SST is seen more clearly in the South Atlantic (Figs. 11c,f,i and 6c,f,i): the observed increase has practically no effect on the stratosphere (Figs. 6c,f,i), whereas a 1-K uniform increase in SST in the tropical Pacific and north Indian Ocean has strong positive contributions to stratospheric temperature (Fig. 12a), whereas in lower and middle latitudes stratospheric cooling is caused mainly by the 1-K uniform increase in SST in the tropical Pacific and north Indian Ocean (Fig. 12b). Note that in the northern high latitudes, the tropical Pacific has the greatest effect on stratospheric temperature, circulation, and ozone changes (Figs. 12c,f,i).

In summary, the abovementioned analysis results show that the observed global SST warming (Fig. 1a) causes a colder stratosphere and stronger stratospheric zonal winds, and ozone depletion in most regions of the high latitudes of both hemispheres (Figs. 3a,e,i), whereas a 1-K uniform global warming results in higher temperature and weaker stratospheric zonal winds and a corresponding ozone increase (Figs. 8a,e,i). This is because the effect on the stratosphere of a 1-K uniform SST warming in the tropical Pacific (Figs. 9b,e,h) is far stronger than that of the observed SST warming.

![Fig. 10. (a) Temperature, (c) zonal wind, and (e) ozone differences between E5 and R1. (b) Temperature, (d) zonal wind, and (f) ozone differences between E6 and R1.](image-url)
in addition, the warming polar stratosphere due to a uniform 1-K warming in the north Indian Ocean (Figs. 10a,c,e) also offsets the stratospheric cooling caused by other oceans, compared to the observed north Indian Ocean warming (Figs. 5a,c,e).

5. Conclusions and discussion

Global SST has been increasing since the Industrial Revolution, and has important impacts on the climate in the stratosphere. The extent of this influence is of considerable scientific interest. Using the WACCM4 model, this study investigated the effects of observed global and regional SST warming from the Industrial Revolution to the present on stratospheric temperature, circulation, and ozone changes, and estimated the relative impact on the stratosphere of SST warming in different regions by time-slice experiments. It is found that the warming in the tropical Atlantic greatly decreases stratospheric temperature in the southern high latitudes, whereas warming in the north Indian Ocean and North Pacific greatly decreases the stratospheric temperature in northern high latitudes. The cooling in the lower- and midlatitude lower stratosphere is caused mainly by SST warming in the tropical Pacific and north Indian Ocean. In summary, observed global SST warming leads to colder and stronger stratospheric zonal winds in the high latitudes, a colder tropical lower stratosphere, and correspondingly decreased ozone. This study also investigates the effects on the stratosphere of a 1-K uniform increase in SST in all oceans. The 1-K uniform warming results in warmer and weaker stratospheric zonal winds and a corresponding ozone increase in the high latitudes, which means that these two kinds of global SST warming have opposite effects on the high-latitude stratosphere in both hemispheres. Our research has shown that this is because the 1-K uniform increase in SST in the tropical Pacific causes very strong weakening of the Arctic and Antarctic stratospheric zonal winds, and its strength overwhelms the effects on the stratosphere caused by SST warming in other regions.

Note that although Figs. 7 and 12 show the contributions of SST warming in each region to stratospheric changes, we do not make quantitative comparisons of the contributions in our results and discussion. The magnitudes of the anomalies in Figs. 3c, 3g, and 3k and 8c, 8g, and 8k are not exactly the same as those in Figs. 3a, 3e, and 3i and 8a, 8e and 8i, suggesting a nonlinear interaction between oceans in their effect on the stratosphere. This nonlinear interaction may affect the accuracy of the quantitative contribution. Thus, the qualitative rather than quantitative results of this study may be more insightful. Although there are some differences between the magnitudes of anomalies in Figs. 3c, 3g and 3k and 8c, 8g and 8k and those in Figs. 3a, 3e and 3i and 8a, 8e and 8i, they do not affect the main conclusions of this study. In addition, this work analyzes results from a single chemistry–climate model (CCM), without quantification of the sensitivity of these results to the physical and chemical...
schemes of the model. However, we do not make quantitative comparisons of our results with observations. The main conclusions of this study, which are purely qualitative, are not expected to be significantly affected by using a single CCM. In addition, using a single CCM reduces the systematic errors among different models.

Until recently, much interest has been focused on the effects of SST anomalies in the tropics and in the Northern Hemisphere on stratospheric changes. This work has found that the effects of SST anomalies in the South Pacific, south Indian Ocean, and South Atlantic are also important. A key reason why previous studies have overlooked the effects of SST anomalies in these oceans is that the SST in these oceans has not increased significantly since the Industrial Revolution (Figs. 1d, f, i). In the future, if the SST in these areas also increases substantially (e.g., as in the 1-K uniform SST warming experiments in this study), their effects on the stratosphere cannot be ignored, as they are even stronger than those caused by SST warming in other oceans. The influences of SST anomalies in South Pacific, south Indian Ocean, and South Atlantic on stratosphere are also worth study and discussion in the future.

There are some unresolved questions in this study. The most important is that there is no one-to-one

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**Fig. 12.** (a) Temperature anomalies averaged in the region 60°–90°S and 70–30 hPa. Temperature anomalies from Fig. 8a (GLO), Fig. 8c (SGLO), Fig. 9a (NP), Fig. 9b (TP), Fig. 9c (SP), Fig. 10a (NI), Fig. 10b (SI), Fig. 11a (NA), Fig. 11b (TA), and Fig. 11c (SA). GLO indicates the response of the stratosphere to global SST perturbations and SGLO indicates the linear sum of the responses to regional SST forcings. (b), (c), (d) As in (a), but averaged in the region 50°–70°S and 70–30 hPa and averaged in the region 60°–90°N and 70–30 hPa, respectively. (e) Zonal wind anomalies averaged in the region 50°–70°S and 50–10 hPa. Zonal wind anomalies from Fig. 8e (GLO), Fig. 8g (SGLO), Fig. 9d (NP), Fig. 9e (TP), Fig. 9f (SP), Fig. 10c (NI), Fig. 10d (SI), Fig. 11d (NA), Fig. 11e (TA), and Fig. 11f (SA). (e), (f) As in (d), but averaged in the region 50°–70°N and 30–70 hPa and averaged in the region 50°–70°S and 50–10 hPa, respectively. (g) Ozone anomalies averaged in the region 60°–90°S and 70–30 hPa. Ozone anomalies from Fig. 8i (GLO), Fig. 8k (SGLO), Fig. 9g (NP), Fig. 9h (SP), Fig. 10c (NI), Fig. 10d (SI), Fig. 11g (NA), Fig. 11h (TA), and Fig. 11i (SA). (h), (i) As in (g), but averaged in the region 50°–70°N and 70–30 hPa and averaged in the region 60°–90°N and 30–70 hPa, respectively. The units for temperature, zonal wind, and ozone anomalies are K, m s⁻¹, and ppmv.
comparison of the mechanisms by which each ocean’s warming affects the stratosphere. The mechanism may be different for each ocean. In addition, there are some details of the mechanisms worth analyzing. For example, tropical Atlantic warming causes a higher temperature and weaker Arctic stratospheric zonal circulation and lower temperature and stronger Antarctic stratospheric zonal circulation, but the stratospheric anomalies in the Southern Hemisphere are larger than those in the Northern Hemisphere (Figs. 6b,e,h). The effect of a 1-K uniform increase in SST in the North Pacific on the Arctic stratospheric zonal circulation is weaker than that of the observed increase in SST (Figs. 9a,d,g and 4a,d,g). Uniform warming in the North Atlantic causes a warmer and weaker Antarctic stratospheric zonal circulation but a lower temperature and stronger Arctic stratospheric zonal circulation (Figs. 11a,d), which is opposite of the observed warming in the North Atlantic on the stratosphere (Figs. 6a,d). These differences may be related to the uniformity of SST increase. The 1-K increase is uniform while the observed increase is nonuniform. The patterns of SST anomalies of the two kinds of SST increase are different. An increase of nonuniformity will lead to SST gradients in a region, which are an important factor affecting the atmosphere (Hu et al. 2014). This is not the case with a uniform increase. In addition, this study only investigates the effects of SST anomalies on the atmosphere, but does not consider the impact of sea–air interactions on the results. In the Indian Ocean, for example, the observed SST warming trend is partially due to decreasing cloud fractions (e.g., Copsey et al. 2006). Many previous studies (He and Soden 2015, 2016a,b; Fletcher and Cassou 2015; Fletcher and Minokhin 2015) have demonstrated the necessity of considering sea–air interactions in climate change studies, rather than solely considering the effects of SST on the atmosphere, as is done in this study. However, the abovementioned issues are beyond the scope of this work, and will be performed in future studies.

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