J. Ocean Univ. China (Oceanic and Coastal Sea Research)
DOI 10.1007/s11802-015-2535-y
ISSN 1672-5182, 2015 14 (6): 951-956
http://www.ouc.edu.cn/xbywb/
E-mail:xbywb@ouc.edu.cn

Different Responses of Sea Surface Temperature in the North Pacific to Greenhouse Gas and Aerosol Forcing

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(Received November 17, 2013; revised January 16, 2014; accepted October 1, 2015)

Abstract The responses of Sea Surface Temperature (SST) to greenhouse gas (GHG) and anthropogenic aerosol in the North Pacific are compared based on the historical single and all-forcing simulations with Geophysical Fluid Dynamics Laboratory Climate Model version 3 (GFDL CM3). During 1860–2005, the effect of GHG forcing on the North Pacific SST is opposite to that of the aerosol forcing. Specifically, the aerosol cooling effect exceeds the GHG warming effect in the Kuroshio Extension (KE) region during 1950–2004 in the CM3 single forcing. The mid-latitude response of ocean circulation to the GHG (aerosol) forcing is to enhance (weaken) the Subtropical Gyre. Then the SST warming (cooling) lies on the zonal band of 40˚N because of the increased (reduced) KE warm advection effect in the GHG (aerosol) forcing simulations, and the cooling effect to SST will surpass the warming effect in the KE region in the historical all-forcing simulations. Besides, the positive feedback between cold SST and cloud can also strengthen the aerosol cooling effect in the KE region during boreal summer, when the mixed layer depth is shallow. In the GHG (aerosol) forcing simulations, corresponding to warming (cooling) SST in the KE region, the weakened (enhanced) Aleutian Low appears in the Northeast Pacific. Consequently, the SST responses to all-forcing in the historical simulations are similar to the responses to aerosol forcing in sign and spatial pattern, hence the aerosol effect is quite important to the SST cooling in the mid-latitude North Pacific during the past 55 years.

Key words North Pacific; sea surface temperature; response; greenhouse gas; aerosol

1 Introduction

Increasing concentrations of the greenhouse gas (GHG) in the atmosphere are believed to be the major cause of global warming (Meehl *et al.*, 2007). On the other hand, the climate influence of atmospheric aerosol is complex, including both direct radiative and indirect effects on cloud properties (Penner *et al.*, 2001). Anthropogenic aerosol effect partly offsets the GHG warming effect, and the inclusion of aerosol effect in climate model can improve the agreement between model and observation (Donner *et al.*, 2011).

The surface air temperature (SAT) response to GHG and aerosol forcing shows some resemblance to each other despite their effect is opposite (Boer and Yu, 2003) due mostly to two patterns: stronger responses over land than over ocean, and the polar amplification (Xie *et al.*, 2013). Based on the simulations with a coupled atmosphere-slab ocean general circulation model, Ming *et al.* (2011) examined the key characteristics of boreal winter extra-tropical circulation changes in response to anthropogenic aerosols. They pointed out that the circulation changes show strong zonal asymmetry, in particular, the cooling is more concentrated over the North Pacific (NP) than over the North Atlantic despite similar regional forcing. How about the Sea Surface Temperature (SST) response? Based on the climate model experiments, Xie *et al.* (2010) found that although GHG increase is nearly uniform in space, pronounced spatial variations emerge in SST response and the magnitude of spatial deviations is as large as the tropical-mean value, because the ocean dynamic role is important to SST pattern formation. Using a multi-model ensemble, Xie *et al.* (2013) first showed that globe response patterns of the SST and precipitation are remarkably similar between GHG and aerosol forcing experiments, except in the mid-latitude NP. This suggests a global ocean-atmosphere mode with spatial patterns common to radiation-induced climate change and relatively insensitive to forcing distribution, except in the NP.

Observation analysis reveals that the SST in the mid-latitude NP has decreased over the latter half of the twentieth century (Du and Xie, 2008). But in climate models, the response of SST to increased CO_2 features a warming pattern in the NP (Xie *et al.*, 2010). Why is there SST cooling in the mid-latitude NP under warming climate? Does the aerosol effect exceed the GHG effect on

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the SST in the NP? Coupled Model Intercomparison Project Phase 5 (CMIP5) Project recommended that the global mean atmospheric sulfate aerosol (SO_4) concentration had increased slowly since 1850, and accelerated in the latter half of the twentieth century. Especially, the SO_4 concentration increased sharply over Asia (70˚E–150˚E, 0˚–60˚N) since 1950s. Aerosol optical depth (AOD) over East Asia may have important impact on cloud and shortwave radiation in the western NP, which in turn, may induce SST response (Bao *et al.*, 2009).

Therefore we wish to address the following unclear questions: How about SST response to GHG and aerosol forcing in the NP during the latter half of the twentieth century, and why the spatial patterns of the SST response to GHG and aerosol forcing are different in the NP. In the present study, using the outputs from historical all-forcing and single-forcing simulations from Geophysical Fluid Dynamics Laboratory Climate Model version 3 (GFDL CM3), we investigate the aerosol cooling and GHG warming effect on the NP SST. We find that the aerosol cooling effect on SST exceeds the GHG warming effect in the Kuroshio Extension (KE) region, because of not only the ocean dynamic effect on SST, but also the positive feedback process between the cold SST and the cloud in boreal summer.

The rest of the paper is organized as follows. Section 2 briefly describes the model and simulations. Section 3 investigates the dominant mode of the SST change in the NP due to the aerosol and GHG forcing. Section 4 studies the possible physical process of the SST responses to different forcing factors. Section 5 is summary and discussion.

2 Model and Simulations

This study uses the outputs from the National Oceanic and Atmospheric Administration (NOAA) GFDL CM3 model, which is one of the primary models from GFDL contributed to the IPCC Fifth Assessment Report (AR5). The GFDL CM3 model is formulated effectively with the same ocean and sea ice components as the earlier CM2.1, and includes extensive developments made to the atmosphere and land model components (Griffies *et al.*, 2011). Especially, physically based treatments of aerosol-cloud interactions are included in GFDL CM3 as documented by Donner *et al.* (2011). The atmospheric component AM3 employs a cubed-sphere implementation of a finite-volume dynamical core with horizontal resolution of approximately 200 km. The ocean component MOM4 has a horizontal resolution of 1.0˚×1.0˚ and 50 vertical layers, 22 of which are in the upper 220 m. In the meridional direction the resolution increases toward the equator to 1/3˚ between 30˚S and 30˚N.

A number of integrations of CM3 were performed following the CMIP5 protocol (Taylor *et al.*, 2012), includeing pre-industrial control, historical ensemble of 5 members, and 4 future scenarios experiments. Detection and attribution simulations were conducted to examine the model's response to a subset of historical single forcing (GHG forcing, natural forcing, aerosol forcing, and anthropogenic forcing), each consisting of 3 runs. Historical single and all-forcing simulations employ evolution of forcing agents during 1860–2005, and each ensemble member is initialized 50 years or 100 years apart from the pre-industrial control experiment, which runs for 800 years with time-invariant radiation forcing agents fixed at 1860 values.

The outputs of GHG forcing, aerosol forcing and historical all-forcing simulations are used in the present study. The outputs are processed into long-term and ensemble means of each simulation from 3 members. The combined ensemble and time means allow for a robust signal out of natural variability presented in individual ensemble member. In CM3 aerosol forcing simulations, there are both aerosol direct and indirect effects, and their impact on SST might be different. In this paper we will discuss the total aerosol effect.

3 Dominant Modes of SST Responses to GHG and Aerosol Forcing

Previous studies indicated that the aerosol forcing peaks in the mid-latitudes Northern Hemisphere (NH) and decays to vanishing levels in the Antarctic. By contrast, GHG radiation forcing is more uniform in the meridional direction except near the poles. But the globe response patterns of the SST and precipitation are remarkably similar between GHG and aerosol experiments, except in the mid-latitude NP (Xie *et al.*, 2013).

In order to discover the specific feature of the SST evolution in the NP, we first compared the leading EOF patterns of the SST anomaly in the NP and their time series between single GHG and aerosol forcing simulations (1860–2005) (Fig.1). The SST response to increased GHG (aerosol) is warming (cooling) in the NP during 1860–2005, and features a robust rising trend that accelerates around 1960; but the GHG (aerosol) warming (cooling) time series (PC1) tendency is leveling off and looks different from each other after 1990 (Fig.1c), likely associated with the continuously increased GHG and quickly reduced aerosol after 1990. Spatial patterns of leading mode for GHG and aerosol forcing are similar to each other with the maximum anomaly center located in the KE region (Fig.1a, Fig.1b), because the ocean heat advection effect on the long-term SST change is dominant in the KE region (Kelly and Dong, 2004). Although the anomaly centers of the leading SST modes are both located in the mid-latitude NP, distinct differences between the GHG and aerosol forcing runs can be seen. The GHG forcing induces two warming centers: one is around the KE and the other is to the east of the KE (Fig.1a). However, the aerosol forcing induces only one cooling center around the KE (Fig.1b). This suggests that the ocean-atmosphere interaction processes may be different under the GHG and aerosol forcing simulations. As a result of GHG (aerosol) forcing, explained variance of the NP SST EOF leading mode is only 37.2% (27.2%) (Fig.1), but it is 97.1% (91.1%) for the globe SST EOF leading mode

(Xie *et al.*, 2013). This suggests that, in addition to the responses to external forcing, there should be other natural variations such as the Pacific Decadal Oscillation. This SST cooling trend response to aerosol forcing in the NP is similar to the observed SST trend (Du and Xie, 2008). Based on the EOF analysis, the main features of SST responses to GHG and aerosol forcing are opposite to each other, but show similar spatial pattern and robust rising trend.

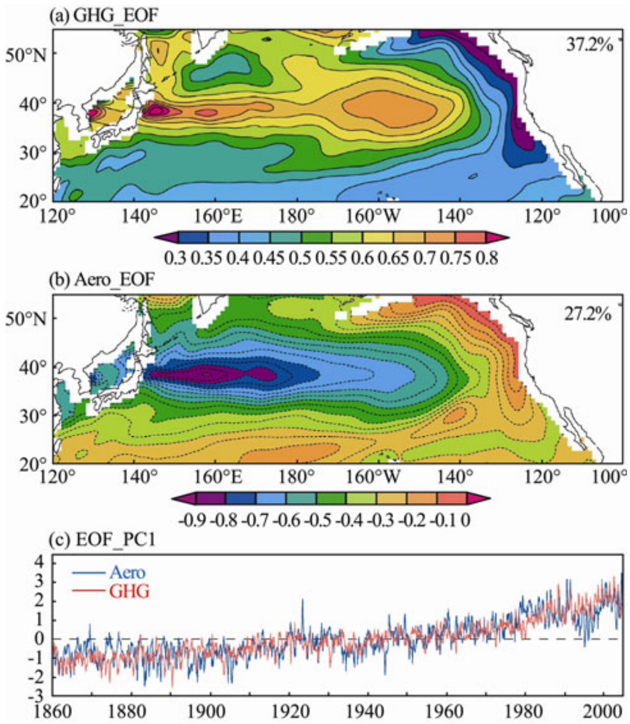

Fig.1 Leading EOF patterns of SST anomaly (unit: ℃) with explained variance noted at the upper right in the GHG (a) and aerosol (b) forcing simulations and corresponding time series (c).

4 Comparison of Responses to Different Forcing

In order to understand why there are similarities and differences between GHG and aerosol forcing patterns, and as far as possible to remove the natural variability effect, the climatology mean changes (1950–2004 minus 1860–1914) of the ensemble mean from each single forcing and historical all-forcing simulations are shown in Figs.2–5. The climatology derived from 55 years of SST can effectively eliminate the main decadal variability with 20–50 years period.

4.1 Atmosphere and Ocean Dynamic Process Responses

As response to GHG forcing, the maximum SST warming (about 1.2℃) appears north of 45˚N (Fig.2a), because the SAT is polar amplified (Fig.1b in Xie *et al.*, 2013) and the net surface heat flux is positive (atmosphere heating ocean). Besides the maximum SST warming in high latitudes, there are also other obvious warming areas, such as the KE region, where the ocean heats atmosphere (negative heat flux change) (Fig.2a). But as response to aerosol forcing, the maximum cooling (about −1.2℃) and corresponding positive net heat flux are present in the mid-latitude NP (KE region, zonal band of 40˚N) (Fig.2b). The aerosol forcing cools SST by reducing shortwave radiation (negative net heat flux anomaly) over almost all the NP except for the KE region, where the ocean gains heat from atmosphere (Fig.2b). In the historical all-forcing simulations, due to the two opposite effects on SST from the GHG and aerosol forcing, the SST change is almost zero over most of the NP except for the KE region, because net heat flux with sign reversed represents the ocean heat transport effect on SST (Xie *et al.*, 2010) and a common set of ocean-atmospheric feedback is involved in spatial pattern formation (Xie *et al.*, 2013). However, in the KE region, the aerosol cooling effect exceeds the GHG warming effect and causes a net cooling. Therefore, including the aerosol effect in the model is quite important for simulating SST as observed in the mid-latitude NP, especially in the KE region. In addition, the magnitude of surface cooling from observations is less than that from historical simulations (Wu *et al.*, 2012).

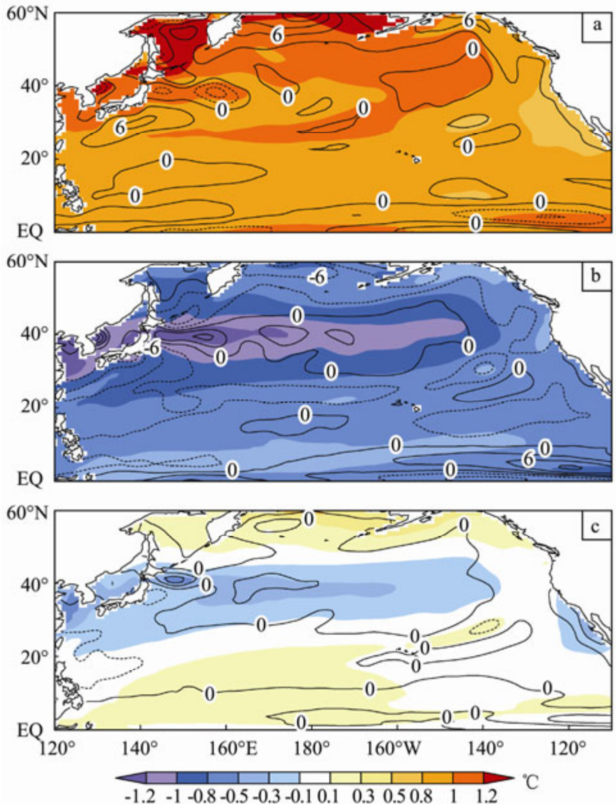

Fig.2 Climatology mean change (1950–2004 minus 1860–1914) of the SST (color; unit: ℃) and net heat flux (contour; positive downward; unit: W m^{-2}) in the North Pacific in the GHG (a), aerosol (b) and historical (c) forcing simulations.

Why did the aerosol cooling effect exceed the GHG warming effect in the KE region during the latter half of last century? We checked all the changes (1950–2004 minus 1860–1914) of the climatology mean SSH, stream function diagnosed from SSH, Sea Level Pressure (SLP) and Sea Surface Wind (SSW) in the NP from each single forcing and historical all-forcing simulations (Fig.3 left). It shows clearly that the response of ocean circulation in mid-latitude to the GHG (aerosol) forcing is to enhance (weaken) the Subtropical Gyre, especially in the KE area, and the weakened amplitude is larger than the enhanced amplitude (Fig 3a and Fig.3c). The SST warming (cooling) lies on the zonal band of 40˚N because of the increased (reduced) KE warm advection effect in the GHG (aerosol) forcing runs, and the cooling effect will surpass the warming effect in the historical all-forcing runs. Thus the increased (reduced) warm advection of the KE is an important mechanism for the SST response. Corresponding to the warming (cooling) SST anomaly in the KE region, there is weakened (enhanced) Aleutian Low in the Northeast Pacific (Fig.3b and Fig.3d). This feature about the atmospheric response to SST anomaly in the KE area has been proved in the observation analysis and via the numerical experiments of atmospheric model (Liu *et al.*, 2006; Liu *et al.*, 2007).

In the historical all-forcing runs, the changed patterns of the SSH, stream function, SLP and SSW (Fig.3e and Fig.3f) are similar to those in the aerosol forcing (Fig.3c and Fig.3d), *i.e.*, enhanced Subtropical Gyre and Aleutian Low; but their magnitudes are gentler (about 50% in aerosol run) because the aerosol effect is partly cancelled out by the GHG effect. The AOD over East Asia may have important impact on cloud and shortwave radiation over the western NP (Bao *et al.*, 2009). So we hypothesize that there is a special feedback process between SST and cloud in the aerosol forcing simulations.

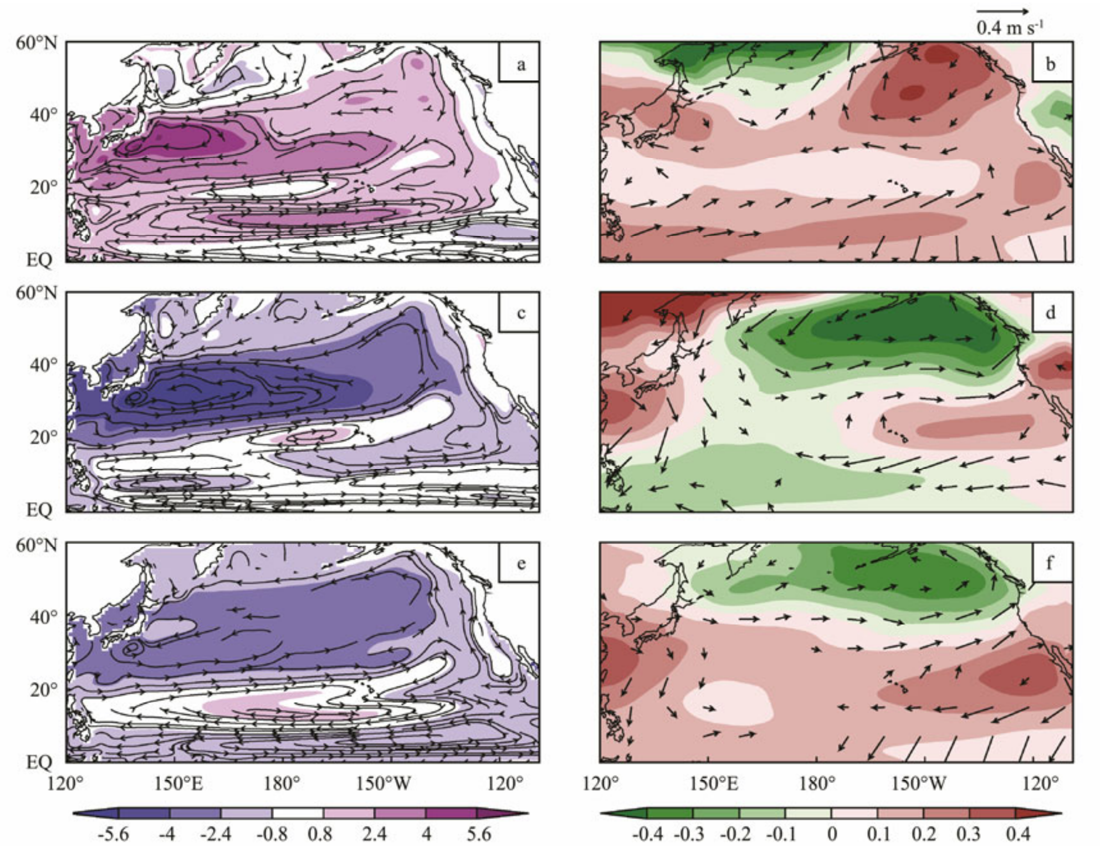

Fig.3 Climatology mean change (1950–2004 minus 1860–1914) of SSH (color; unit: cm) and stream function diagnosed from SSH (stream) in the North Pacific in the GHG (a), aerosol (c) and historical (e) forcing simulations. The (b), (d) and (f) is similar to the (a), (b) and (c) respectively but response of climatology mean SLP (color; unit: hPa) and sea surface wind (vector; unit: $m\,s^{-1}$).

4.2 Feedback Process Between SST and Cloud

In order to find out whether there is a feedback process between SST and cloud, the annual cycle change (1950–2004 minus 1860–1914) of zonal mean (140˚E–140˚W) SST and total cloud fraction in different forcing simulations are shown in Fig.4. From Fig.4b a new feedback process (SST-cloud) has been found in the aerosol forcing runs: the maximum SST change appears around 40˚N north of the maximum cloud change in boreal summer (JAS). But in the GHG forcing runs, the cloud change is almost negative north of 20˚N and the maximum SST warming center seems have no relation to the cloud change (Fig.4a).

In the aerosol forcing runs, the increased cloud fraction appears south of the cooling SST center in boreal summer. It is because the weakened Subtropical Gyre could induce SST front of KE to move southwards and the more warm and moist air will meet the KE SST front, then more cloud appears south of the KE SST front. The increased cloud fraction (about 5%) could induce less shortwave radiation (about $-12\,\mathrm{W\,m^{-2}}$) (Fig.5) and cool SST in the boreal summer when the mixed layer is the shallowest of the year, and the net heat flux change dominates the SST change. This positive feedback process between the cold SST and cloud in summer is another important mechanism to amplify the cooling role in the KE region besides the ocean dynamic effect. In the KE region, since the aerosol effect exceeds the GHG effect, the corresponding relationship between the cold SST and the increased cloud still exists in the historical all-forcing simulations (Fig.4c).

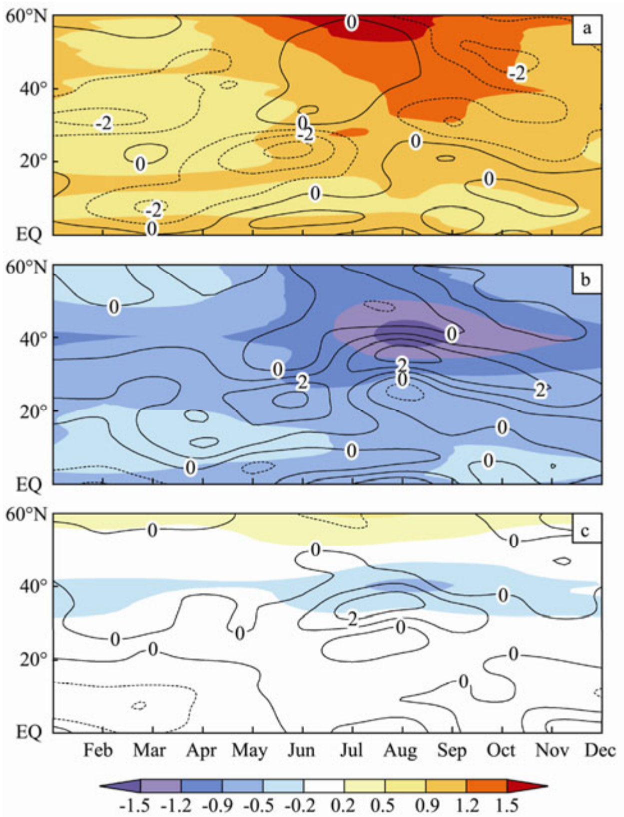

Fig.4 Annual cycle change (1950–2004 minus 1860–1914) of zonal mean (140˚E–140˚W) SST (color; unit: ℃) and cloud fraction (contour; unit: %) in the GHG (a), aerosol (b) and historical (c) forcing simulations respectively.

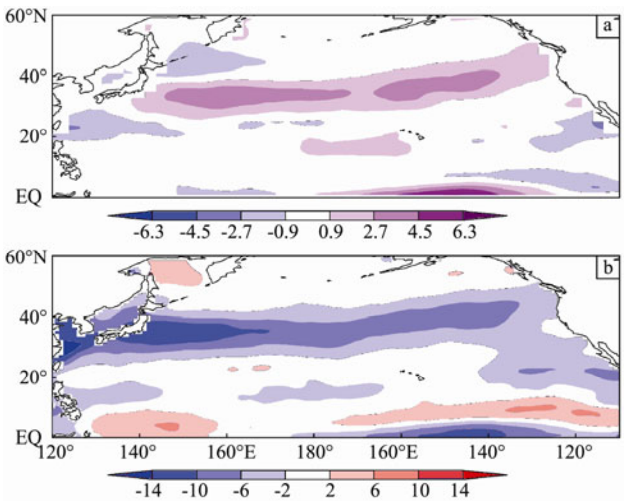

Fig.5 Summer (JAS) climatology mean change (1950–2004 minus 1860–1914) of total cloud fraction (a; unit: %) and sea surface downward short-wave radiation (b; unit: $\mathrm{W\,m^{-2}}$) in the aerosol forcing simulations.

5 Summary and Discussion

We have examined the responses of the SST in the NP to the GHG and aerosol forcing based on the outputs from single-forcing and historical all-forcing simulations of GFDL CM3. Although it is clear that there is decadal variation of SST in the NP, the leading EOF mode of SST anomaly still represents the long time persistent changes in the GHG and aerosol single forcing simulations. The NP SST warms in response to the GHG forcing, but cools in response to the aerosol forcing during 1860–2005. It is different from globe mean SST response: the NP SST responses to the GHG and aerosol forcing are distinctly different from each other.

By comparison analysis, it is found that the aerosol cooling effect is stronger than the GHG warming effect in the mid-latitude NP, and the SST shows a net cooling in response to all-forcing in history. The reduced warm advection of KE due to the weakened Subtropical Gyre under the aerosol forcing is an important mechanism for the especially strong SST cooling. In addition, the new feedback process between cold SST and cloud in south KE SST front in boreal summer is another important mechanism for SST cooling in the KE region. Although under the GHG forcing the Kuroshio recirculation also becomes stronger and the warm SST appears in the KE region, the maximum SST warming still appears north of 45˚N due to polar amplification. The different responses of ocean and atmosphere dynamic processes are the main reason for the different spatial patterns. Thus, the aerosol effect appears to be an important physical mechanism for the observed SST cooling in the NP, especially in the KE region during the past 55 years.

Aerosols in the atmosphere are of short-life duration compared with GHG. In future projection, as the emission of aerosols reduces significantly, the atmosphere aerosols will decrease subsequently. Due to the predominance of GHG forcing, the aerosol cooling effect will become quite weaker than the GHG warming effect on the NP SST, opposite to what had happened during the past 55 years. The SST in the NP ought to show warm pattern since the GHG forcing will dominate. Moreover, as a result of the decreasing aerosol cooling effect, global warming may be more serious than predicted earlier. Therefore, further climate models are necessary to better simulate the responses to significant reduction of atmospheric aerosols.

Acknowledgements

We would like to thank Prof. Shang-Ping Xie and Mr. Hai Wang for their help and comments. This work is supported by the National Basic Research Program of China (2012CB955602) and Natural Science Foundation of China (41176006 and 41221063).

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(Edited by Xie Jun)