Projections of the Tropical Atlantic Vertical Wind Shear and Its Relationship with ENSO in SP-CCSM4

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ABSTRACT

The vertical wind shear over the tropical Atlantic Ocean and its relationship with ENSO are analyzed in the superparameterized Community Climate System Model, version 4 (SP-CCSM4) and in the conventional CCSM4. The climatology of vertical wind shear over the tropical Atlantic and the ENSO–shear relationship are well simulated in the control runs of SP-CCSM4 and CCSM4. However, because of different representations of cloud processes, in a warmer climate such as the representative concentration pathway 8.5 (RCP8.5) scenario, SP-CCSM4 projects increased mean westerlies at 200 hPa during July through October (JASO), whereas CCSM4 projects decreased mean westerlies at 200 hPa over the equatorial Atlantic. The different changes in the upper-level wind further contribute to different projection of JASO mean vertical wind shear over the equatorial Atlantic. In the RCP8.5 scenario, when excluding the linear trend, projection of the ENSO–shear relationships by SP-CCSM4 retains similar features as in the observed current climate, whereas the ENSO–shear relationship projected by CCSM4 indicates an increase in the vertical wind shear dominating the tropical Atlantic during El Niño events. The difference in projection of ENSO–shear relationship is, to a certain extent, related to the different response of the tropical Atlantic SST to ENSO. Analysis of the climate change projection of Walker circulation, cloud cover, and convective activity illustrates that super-parameterization simulates a stronger suppression of African convection than the conventional parameterization of moist processes. The weak convective activity diminishes the divergent wind associated with the vertical motion, which contributes to increased westerlies projected in SP-CCSM4.

1. Introduction

Vertical wind shear, defined as the magnitude of wind vector difference between 850 and 200 hPa \( |V_{850} - V_{200}| \) has been of interest because of its close relationship with hurricane development (Gray 1984; DeMaria 1996). In warmer climate scenarios, numerical results of the models from phase 3 of the Coupled Model Intercomparison Project (CMIP3) project a robust intensification of vertical wind shear over the north tropical Atlantic Ocean (Vecchi and Soden 2007). The projections of warmer climate also show a weakening of the Pacific Walker circulation (Vecchi and Soden 2007; Tokinaga et al. 2012), which further contributes to the increase of vertical wind shear over the tropical Atlantic (Vecchi and Soden 2007).

Although the sea surface temperature (SST) gradient along the equator drives the Walker circulation, its distinguishing characteristic is the rising of warm air and deep convection over the warm waters in the western Pacific Ocean and the descending of colder and dry air over the central and eastern Pacific (Bjerknes 1969). The subsidence in the Walker circulation branch located over the eastern tropical Pacific is partially compensated by rising motions over the Amazon, which is further connected with the Atlantic Walker circulation (Wang 2002, 2005). Observational and numerical studies indicate that moist convection is also a forcing of the Walker circulation (Cornejo-Garrido and Stone 1977; Frenkel et al. 2013).

In most of the CMIP3/CMIP5 models, the moist atmospheric convection is simulated by conventional
parameterization with or without stochastic forcing (Arakawa 2004; Neelin et al. 2008). The superparameterization (Grabowski 2001, 2004; Khairoutdinov and Randall 2001) of moist convection provides a different framework of representing cloud processes (Randall et al. 2003). This approach improves the simulation of ENSO (Stan et al. 2010), captures the observed seasonal and intraseasonal variability of the tropical atmosphere (DeMott et al. 2011, 2013), and simulates a realistic distribution of the North Atlantic hurricane statistics (Stan and Xu 2014; Kooperman et al. 2014). Hence, the first objective of this study is to explore whether the projections of vertical wind shear in the representative concentration pathway 8.5 (RCP8.5) scenario are sensitive to the superparameterization of cloud process. In this paper we will compare simulations produced by a model with parameterized representation of convection and its superparameterized version.

The variability of vertical wind shear over the tropical Atlantic also has been proved to have a strong connection with ENSO (Goldenberg and Shapiro 1996), with a warm (cold) ENSO event being associated with strong (weak) vertical wind shear over the western tropical Atlantic from July to October (Zhu et al. 2012). The mechanism of interaction is provided by the Pacific Walker circulation, which acts as an atmospheric bridge between the Pacific SST and the tropical Atlantic atmosphere (Klein et al. 1999; Wang 2005). During the warm phase of ENSO, a warm eastern tropical Pacific SST anomaly triggers anomalous convection over the eastern tropical Pacific and further slows down the Pacific Walker circulation (Wang and Fiedler 2006). This disrupts the ascending branches of the Atlantic Walker cell and the upper-level overturning flow. Therefore, a weakening of the Pacific Walker circulation during El Niño events is accompanied by a westerly anomalous flow at 200 hPa over the tropical Atlantic (Klein et al. 1999). As a result, the vertical wind shear increases over the western tropical Atlantic during warm ENSO events (Zhu et al. 2012). Considering the close relationship between ENSO and tropical Atlantic vertical wind shear, the second objective of this paper is to investigate how the ENSO–shear relationship is projected in a warmer climate by a different parameterization of cloud processes.

The paper is organized as follows: section 2 describes the datasets and models, and section 3 evaluates the mean state of vertical wind shear and its relationship with ENSO, as well as the mean state of the Walker circulation in control runs and observations. The change of vertical wind shear and its relationship with ENSO in the RCP8.5 climate scenario are compared between the superparameterized model and conventional model in section 4. In section 5, physical processes, which contribute to differences in projections of vertical wind shear between two models, are discussed. Finally, conclusions are summarized in section 6.

2. Datasets and models

The European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) from 1979 to 2012 (Dee et al. 2011), with a spectral T255 horizontal resolution and 37 vertical levels, is used to evaluate the atmospheric variables simulated by the numerical models. The Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) dataset is used from 1979 to 2012 as observed SST (Rayner et al. 2003). The horizontal resolution of the HadISST dataset is 1° longitude by 1° latitude. The observation of cloud amount is obtained from the International Satellite Cloud Climatology Project (ISCCP) from January 1984 to December 2006. The season in which we are interested is July–October (JASO), which is the peak of Atlantic hurricane season.

The numerical models used in this study are the superparameterized Community Climate System Model, version 4 (SP-CCSM4; Stan and Xu 2014), and the Community Climate System Model, version 4 (CCSM4; Gent et al. 2011), which have different cloud process representations. In SP-CCSM4, cloud processes are simulated by an ensemble of 2D cloud-resolving models (CRMs) embedded in each grid column of the atmospheric model. The CRMs and their coupling to the dynamics are described in Khairoutdinov and Randall (2001) and Grabowski (2001). In CCSM4, cloud processes are represented by the conventional parameterization schemes described by Neale et al. (2013).

The horizontal resolution of all simulations is 0.9° × 1.25° for the atmospheric model and 1° × 1° for the ocean model. Two types of simulations will be analyzed: a control experiment with fixed atmospheric CO2 concentration and a climate change scenario. The fixed forcing experiment, initialized in January 2000 with external forcing characteristic of year 2000, is used as the control run for the CCSM4 model. The simulation branches out from the CCSM4 twentieth-century run and spans 50 years. The control run for the SP-CCSM4 model is initialized in January 2005, with initial condition taken from the same CCSM4 twentieth-century run, and forced with constant forcing (characteristic of year 2000) for 100 years. The first 50 years of the SP-CCSM4 control simulations are considered as spin-up time, and only the last 50 years are used in the model evaluation and comparison analysis.
The climate change experiments follow the RCP8.5 mitigation scenario (Moss et al. 2010), which has an extreme increase of the external forcing, such as the concentration of atmospheric CO₂ reaching 1000 ppm at year 2100 (Meinshausen et al. 2011). The RCP8.5 experiment with the SP-CCSM4 model consists of three ensemble members, which are integrated from January 2005 to December 2100 and are initialized like the control simulation. CCSM4 has six ensemble members available for the RCP8.5 experiments from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). However, to make a fair comparison, in this study, we use only three ensemble members for CCSM4, which share the same initial conditions with the RCP8.5 simulations produced by SP-CCSM4.

3. Simulated vertical wind shear and tropical Atlantic circulations

Before analyzing the projected change of vertical wind shear in the RCP8.5 scenario, the climatology of vertical wind shear and the ENSO–shear relationship in control runs are compared between SP-CCSM4 and CCSM4, as well as against observations, the ERA-Interim.

a. Climatological vertical wind shear

Figure 1 shows the JASO mean vertical wind shear (Fig. 1a) and the JASO mean zonal wind at 200 hPa in the ERA-Interim (Fig. 1b). In observations, the JASO mean vertical wind shear is lower than 10 m s⁻¹ over the Amazon basin and western tropical Atlantic and is higher than 10 m s⁻¹ over western Africa and the Gulf of Guinea. These results are consistent with the JASO climatology of the vertical wind shear in the National Centers for Environmental Prediction (NCEP) reanalysis and the 40-yr ECMWF Re-Analysis (ERA-40) (figure not shown). The zonal wind component at 200 hPa could alter the ENSO–shear relationship and contributes more to the variation of tropical Atlantic vertical wind shear than the zonal wind at 850 hPa (Zhu et al. 2012). The meridional winds at both levels are about 10 times weaker than the zonal winds (Vecchi and Soden 2007). Hence, in addition to the analysis of vertical wind shear, we further analyze the zonal wind at 200 hPa to evaluate the models’ ability to simulate the observed patterns in the large-scale circulation.

Compared to observations, over the western tropical Atlantic, the JASO mean vertical wind shear is overestimated in both SP-CCSM4 (Fig. 1c) and CCSM4 (Fig. 1e), and the error is likely to be related to tropical SST biases present in numerical simulations (Zhu et al. 2012). In addition, this overestimated vertical wind shear over the western tropical Atlantic is accompanied by larger-than-observed westerlies at 200 hPa in numerical models (Figs. 1d,f). Over the western Atlantic and Amazon, easterlies prevail in observations (Fig. 1b), but westerlies prevail in SP-CCSM4 (Fig. 1d) and CCSM4 (Fig. 1f).

In observations, the eastern Atlantic is dominated by easterlies (Fig. 1b), which are related to the tropical easterly jet at 200 hPa and the African easterly jet at 600 hPa. Compared to observations, the pattern of easterlies in SP-CCSM4 over the eastern tropical Atlantic is consistent with the reanalysis but with a relatively stronger magnitude (Fig. 1d). As a result, over the eastern tropical Atlantic, the vertical wind shear simulated in SP-CCSM4 (Fig. 1c) is stronger than that in observations (Fig. 1a). However, the prevailing easterlies at 200 hPa simulated in CCSM4 are retreated eastward and are weaker-than-observed easterlies (Fig. 1f). In general, the control runs in both SP-CCSM4 and CCSM4 capture the large-scale features of the JASO mean vertical wind shear and zonal wind at 200 hPa.

b. Walker circulation

The Walker circulation, which refers to the east–west circulation over the tropics, acts as an atmospheric bridge between ENSO and the tropical Atlantic atmosphere (Klein et al. 1999; Wang 2005). As this zonal circulation plays an important role in the ENSO–shear relationship, the Walker circulations over the tropical Atlantic simulated in SP-CCSM4 and CCSM4 are analyzed. To evaluate the zonal circulation in the Walker cell, the wind is decomposed into two components: the rotational component related to Earth’s rotation and the divergent component associated with the overturning circulation. Hence, the divergent component of wind together with the vertical velocity can be used to represent the Walker circulation.

Figure 2a shows the climatology of JASO mean Walker circulation averaged between 10°S and 10°N (dashed rectangle in Fig. 2b) for the ERA-Interim. In observations, the Amazon and western Africa regions are dominated by upward motion, indicating convergence at the two sides of the tropical Atlantic basin (Fig. 2a). These ascending motions are accompanied by a large cloud fraction over the Amazon region and over western Africa (Fig. 2b). Moreover, the ascent over these convectively active regions is partially compensated by the subsidence dominating the equatorial Atlantic from 40°W to 0° (Fig. 2a), which is marked by less cloud cover along the equator (Fig. 2b).

Compared to observations, SP-CCSM4 simulates a weaker upward motion over the Amazon basin between 80° and 40°W (Fig. 2c); consequently, the model underestimates the cloud amount over the Amazon region (Fig. 2d).
Over western Africa, the climatology of JASO cloud amount is well simulated in SP-CCSM4 (Fig. 2d). However, SP-CCSM4 overestimates the upward motion over the eastern equatorial Atlantic, especially between 20°W and the Greenwich meridian (Fig. 2c). Hence, over the eastern equatorial Atlantic, a region dominated by downward motion in observations (Fig. 2a), SP-CCSM4 simulates more cloud cover than in the observation (Fig. 2d). The biases in SP-CCSM4 noted here are consistent with the underestimation of precipitation over the western Atlantic and overestimated precipitation over the eastern Atlantic reported by Stan and Xu (2014).

Similar to the SP-CCSM4 simulation, the Amazon convection is underestimated as well in CCSM4, with weaker upward motion (Fig. 2e) and underestimated cloud amount (Fig. 2f). But different from SP-CCSM4, CCSM4 underestimates the upward motion (Fig. 2e) and the cloud amount (Fig. 2f) over western Africa. The weak African and Amazon convection we notice here is consistent with the underestimation of precipitation in the CCSM4 simulations (Gent et al. 2011). However, comparing to SP-CCSM4, the downward motion over the central equatorial Pacific is well simulated in CCSM4 (Fig. 2e), and the cloud cover along the equator in CCSM4 is closer to observations (Fig. 2f).

With underestimated Amazon convection but overestimated convection over the eastern equatorial Atlantic, the climatological divergent wind at 200 hPa shows...
stronger westward wind in SP-CCSM4 than in observations (Fig. 2d). This overestimated westward divergent wind in SP-CCSM4 contributes to a higher-than-observed climatological zonal wind at 200 hPa (Fig. 1d), which further yields to a stronger climatological vertical wind shear over the eastern equatorial Atlantic (Fig. 1c). However, both SP-CCSM4 and CCSM4 underestimate the Amazon convection, particularly between 60° and 40°W. Hence, the stronger eastward divergent winds simulated in SP-CCSM4 (Fig. 2d) and CCSM4 (Fig. 2f) could explain the overestimated westerlies at 200 hPa over South America (Figs. 1d,f).

c. ENSO–shear relationship

Figure 3a shows the regression of JASO mean vertical wind shear onto the Niño-3.4 index. In observations, warm ENSO events are accompanied by increased (anomalously positive) vertical wind shear over the western tropical Atlantic and decreased (anomalously negative) vertical wind shear over the eastern equatorial Atlantic (Fig. 3a). During El Niño events, the Pacific Walker circulation becomes weaker and further triggers westerly anomalies at the upper levels over the tropical Atlantic (Fig. 3b). Hence, during El Niño (La Niña) events, the vertical wind shear increases (decreases) over the western
tropical Atlantic, where westerlies prevail at 200 hPa, and decreases (increases) over the eastern tropical Atlantic, where easterlies dominate (Zhu et al. 2012).

In both control runs for SP-CCSM4 and CCSM4, the ENSO–shear relationships show realistic patterns, with red color indicating a significant increase of JASO mean vertical wind shear during El Niño events (Figs. 3c,e). In SP-CCSM4, a 1°C warming of SST over the Niño-3.4 region (5°S–5°N, 170°–120°W) is accompanied by about a 1.5-m s⁻¹ increase of wind shear over the western tropical Atlantic and a 1.5-m s⁻¹ decrease in the wind shear over the eastern equatorial Atlantic (Fig. 3c). The spatial pattern of the ENSO–shear relationship in CCSM4 (Fig. 3e) is similar to SP-CCSM4 and observations. In addition, the observed anomalous westerlies at 200 hPa during ENSO events (Fig. 3b) are well simulated in both SP-CCSM4 (Fig. 3d) and CCSM4 (Fig. 3f).

However, in CCSM4, the region with reduced shear during El Niño events over the eastern tropical Atlantic is confined eastward to about 40°W (Fig. 3c). This is due to weaker easterlies simulated in CCSM4 over this region (Fig. 1f). With the same anomalous westerlies during the El Niño events, the shear increases over the region with prevailing westerlies and decreases over the region with prevailing easterlies. In CCSM4, the westward mean flow at the upper levels only extends to 40°W (Fig. 1f). Hence, the zero line for the ENSO–shear relationship in the CCSM4 only reaches to 40°W (Fig. 3e). This superposition of the mean and anomalous flow further verifies that the mean flow plays
an important role in modulating the ENSO–shear relationship.

The comparison between control runs and observations indicates that both the superparameterized CCSM4 and the conventional CCSM4 give reasonable simulation of the climatological JASO mean vertical wind shear, Walker circulation, cloud cover over the tropical Atlantic, and the ENSO–shear relationship. Both models overestimate the vertical wind shear, which is related to overestimated westerlies over the tropical Atlantic. Furthermore, both models underestimate the Amazon convection, which is related to the equatorial zonal wind stress bias (Richter and Xie 2008). However, the overestimated convection over the eastern equatorial Atlantic in SP-CCSM4 yields to a stronger westward divergent wind at 200 hPa, which further leads to stronger easterlies than observations.

4. Projected change of vertical wind shear and ENSO–shear relationship in RCP8.5

a. Projected change of vertical wind shear

In the projections from 18 models of global warming for the IPCC Fourth Assessment Report (AR4), Vecchi and Soden (2007) found that there is a robust increase in the vertical wind shear over the region 13°–25°N, 90°–40°W, which is called the shear enhancement region (SER, shown as rectangles in Fig. 4). In the RCP8.5 scenario, both SP-CCSM4 and CCSM4 show increased JASO mean vertical wind shear over the SER (red color inside the rectangles in Figs. 4a,b). SP-CCSM4 projects an increase in the JASO mean vertical wind shear over the western tropical Atlantic warm pool and a decrease over the eastern equatorial Atlantic (Fig. 4a). In contrast, the projected vertical wind shear in CCSM4 is dominated by a decreasing trend over the equatorial Atlantic between 10°S and 10°N (Fig. 4b).

The differences in the change of vertical wind shear between SP-CCSM4 (Fig. 4a) and CCSM4 (Fig. 4b) are closely related to the different response of zonal wind at 200 hPa to external forcing simulated by SP-CCSM4 (Fig. 4c) and CCSM4 (Fig. 4d). In SP-CCSM4, increased anomalous westerlies dominate the whole tropical Atlantic under global warming, extending all the way from the western tropical Atlantic to the eastern equatorial Atlantic (Fig. 4c). Hence, over the western tropical Atlantic, where the westerly jet prevails (Fig. 1b), the vertical wind shear also increases (Fig. 4a). Over the eastern equatorial Atlantic, where the easterly jet prevails (Fig. 1b), the vertical wind shear decreases (Fig. 4a).

Similar to the superparameterized model, CCSM4 also projects an increase of zonal wind at 200 hPa over the SER in the global warming scenario (Fig. 4d). Consequently,
over the SER, CCSM4 projects an increase in the vertical wind shear in the RCP8.5 scenario as well (Fig. 4b). However, CCSM4 projects increased easterlies over the equatorial Atlantic between 8°S and 8°N (Fig. 4d), which is not consistent with the SP-CCSM4 projection. As a result, based on the superposition of mean flow and anomalous flow, the projected vertical wind shear in CCSM4 exhibits a decreasing trend over the equatorial Atlantic (Fig. 4b).

b. Projection of ENSO–shear relationship

The influence of ENSO on tropical Atlantic vertical wind shear is further investigated in the global warming scenario in this section. Note that the effect of global warming results in the warming of SST and changing of wind, which could be considered as responses of climate to external forcing on the centennial time scale. However, the relationships between ENSO and atmospheric variables are interactive on time scales shorter than a century. Hence, we investigate the influence of ENSO on the vertical wind shear in the RCP8.5 scenario with the long-term trend excluded.

In the RCP8.5 scenario, SP-CCSM4 does not project changes of the relationship between ENSO and tropical Atlantic wind shear (Fig. 5a). Similar to the control simulation, in a warmer climate, the El Niño events are accompanied by enhanced westerlies at 200 hPa over the whole tropical Atlantic (Fig. 5c). As a result, the western tropical Atlantic experiences an increased vertical wind shear, whereas a decreased vertical wind shear prevails over the eastern tropical Atlantic (Fig. 5a).

Results from CCSM4 suggest a similar pattern of the ENSO–shear relationship but with different centers of action in the climate change scenario (Fig. 5b). While the relationship between ENSO and zonal wind at 200 hPa indicates similar westerly anomalies in CCSM4 (Fig. 5d), the ENSO–shear relationship in CCSM4 shows that almost the entire tropical Atlantic Ocean is dominated by increased vertical wind shear during El Niño events (Fig. 5b). This is, to some extent, related to weaker climatological easterlies simulated in CCSM4. In the RCP8.5 simulation, the detrended climatology of zonal flow at the upper levels is dominated by westerlies all over the tropical Atlantic (not shown). Hence, the reduced vertical wind shear during the El Niño events (negative ENSO–shear relationship) retreats from the eastern tropical Atlantic (Fig. 2b) to western Africa (Fig. 5b). In addition to the weaker climatological easterlies, the magnitude of westerly anomalies associated with ENSO projected in CCSM4 is stronger than that in SP-CCSM4 over the northern tropical Atlantic, especially over the region 8°–20°N, 65°–20°W, which is

![Fig. 5. The regression coefficients of vertical wind shear (V_{850} - V_{200}) with the Niño-3.4 index in RCP8.5 for (a) SP-CCSM4 and (b) CCSM4. The regression coefficients of zonal wind at 200 hPa with the Niño-3.4 index in RCP8.5 for (c) SP-CCSM4 and (d) CCSM4. Shading denotes the 0.05 significance level.](image-url)
referred to as the main development region (MDR; Zhu et al. 2012).

One possible explanation for the difference in anomalous westerlies during El Niño events could be the different Atlantic SST responses to ENSO projected by the two models. Figure 6 shows the response of tropical Atlantic SST to ENSO in SP-CCSM4 (Fig. 6a) and CCSM4 (Fig. 6b) in the RCP8.5 experiment. While the ENSO pattern over the tropical Pacific is similar between them, the response of tropical Atlantic SST to ENSO is different. During El Niño events, SP-CCSM4 projects significant warm SST anomalies over the northern tropical Atlantic and cold SST anomalies over the southeast equatorial Atlantic, although the cold SST anomalies do not pass the 0.05 significance level (Fig. 6a). CCSM4 projects a different pattern in which the tropical Atlantic SST cools significantly during warm ENSO episodes from the Atlantic warm pool to the southeastern equatorial Atlantic (Fig. 6b).

During El Niño events, SP-CCSM4 projects a significant warmer SST anomaly over the northern tropical Atlantic than the conventional CCSM4 (Fig. 6). The warm SST anomaly in the northern tropical Atlantic could cause an anomalous upper-level anticyclonic circulation, which further contributes to the reduction in the vertical wind shear over the tropical Atlantic (Wang et al. 2007; Smirnov and Vimont 2011). The anomalous anticyclonic circulation simulated by SP-CCSM4 may also trigger anomalous easterlies over the MDR, which reduce the westerly anomalies caused by the warm ENSO events. The westerly anomalies during El Niño events projected in CCSM4 could further contribute to a dominating pattern of increased vertical wind shear all over the tropical Atlantic.

It is worth noting that the linear trend caused by the strong external forcing could dominate the ENSO–shear relationship. Figure 7 shows the regression analysis of the data without removing the linear trend for the vertical wind shear, zonal wind, and Niño-3.4 index in SP-CCSM4 and CCSM4. In SP-CCSM4, the trend does not show a strong impact on the spatial pattern of the ENSO–shear relationship (cf. Figs. 5a and 7a) and the relationship between ENSO and the 200-hPa zonal wind (U200) (cf. Figs. 5c and 7c). Conversely, in CCSM4, the influences of ENSO on the vertical wind shear and zonal wind at 200 hPa show some regional sensitivity to the linear trend. Over the equatorial Atlantic between 10°S and 5°N, CCSM4 projects a decrease of the vertical wind shear during El Niño events, when linear trends are included (Fig. 7b). This negative ENSO–shear relationship is accompanied by a negative ENSO–U200 relationship, which indicates increased easterlies between 10°S and 5°N during El Niño events (Fig. 7d). Over the western Atlantic warm pool, especially over the SER, the ENSO–shear relationship is not affected by the trend, and consists of increased vertical wind shear during El Niño events (Fig. 7b). Such a comparison of ENSO–shear relationship with and without trend demonstrates that long-term linear response of variables to external forcing could alter interactions on shorter time scale.

5. Discussion

It was established in the previous analysis that SP-CCSM4 and CCSM4 project different changes in the zonal wind at upper levels and consequently project different changes in vertical wind shear between 10°N and 10°S. Furthermore, because of the different projected changes of vertical wind shear, the projected ENSO–shear relationships with and without trend show different patterns in SP-CCSM4 and CCSM4. Hence, in this section, the physical processes that contribute to the differences between the two models are analyzed.

At first, changes in the Walker circulation between 10°N and 10°S are analyzed in the RCP8.5 experiment (Fig. 8). Under the global warming scenario, both
SP-CCSM4 (Fig. 8a) and CCSM4 (Fig. 8b) project a weakening of the Pacific Walker circulation, accompanied by enhanced convection over the eastern tropical Pacific. Similar to the results from the warming scenarios of IPCC AR4 (Vecchi and Soden 2007), the weakening of the Pacific Walker circulation in the RCP8.5 scenario will cause anomalous westerlies over the tropical Atlantic and, further, an increase in the vertical wind shear over the western tropical Atlantic.

In addition, the increased upward motion over the eastern tropical Pacific in the RCP8.5 scenario is accompanied by increased subsidence over the tropical Atlantic in both SP-CCSM4 (Fig. 8a) and CCSM4 (Fig. 8c). Over the Amazon region between 80° and 60°W, both SP-CCSM4 and CCSM4 project a strong reduction of the upward motion. As a result, over the Amazon basin between 80° and 60°W, both SP-CCSM4 and CCSM4 project a strong reduction of the upward motion. A result, over the Amazon basin between 80° and 60°W, both SP-CCSM4 (red line in Fig. 9a) and CCSM4 (blue line in Fig. 9a) project a strong reduction of the cloud cover, despite the spike along the 80°W where coastal air–sea interactions may dominate. However, it is interesting to notice the region of enhanced upward motion below 600 hPa in both SP-CCSM4 and CCSM4. The small cloud coverage and strong ascending motions suggest that in this region the balance in the upward branch of the Walker circulation is dominated by adiabatic expansion, whereas diabatic processes are weak.

The subsidence over western Africa projected by SP-CCSM4 (Fig. 8a) is much stronger than in the CCSM4 projection (Fig. 8b). This result, combined with the climate projection of cloud cover in Fig. 9, suggests that convective activity response to the greenhouse forcing influences the zonal flow in the upper troposphere over western Africa, between 20°W and the Greenwich meridian. While SP-CCSM4 (red line in Fig. 9a) projects a decrease in the cloud cover, CCSM4 (blue line in Fig. 9a) projects an increase of cloud amount under warmer conditions.

Cloud cover influences the solar radiation reaching the surface. In SP-CCSM4, the reduction of cloud cover between 20°W and 0° increases the surface downwelling shortwave radiation (red line in Fig. 9b). A warmer surface increases the atmospheric stability, which does not favor the development of convection. In CCSM4 the increased cloud cover over western Africa (Fig. 9a) reduces the surface downwelling shortwave radiation between 20°W and 0° and thus cools the surface. The warm air over the cold surface favors the development of shallow cumulus clouds. In the SP-CCSM4, the deep convective activity over western Africa between 20°W and 0° seems to be strongly inhibited by the global warming. In CCSM4, the response of convection to global warming tends to be a decrease in deep convection and increase in shallow convection over western Africa.

This hypothesis is tested in Fig. 10, which shows the trend in the deep convective activity simulated by the
models. The fraction of days within the JASO season with the precipitation rate larger than 2 mm day\(^{-1}\) is used as a proxy for deep convection. During the JASO season, the percentage of convective days is about 70% over western Africa and shows a similar pattern in both SP-CCSM4 and CCSM4 (not shown). Consistent with the reduced upward motion over the equatorial Atlantic (Fig. 8), both models show a reduction of convective days despite the spike along 80°W (Fig. 10). However, because of different responses of diabatic heating to external forcing, SP-CCSM4 projects a stronger reduction of convective days over western Africa (red line in Fig. 10) than CCSM4 does (blue line in Fig. 10).

Hence, the strong reduction of African convection in SP-CCSM4 (Figs. 9, 10) results in “enhanced westerly” divergent wind at the upper levels over the equatorial Atlantic (Fig. 8a) and a decrease in the easterly zonal wind (Fig. 4c). Because of a different diabatic heating profile simulated by the conventional cloud parameterization scheme, CCSM4 projects a weaker suppression of the African convection (Figs. 9, 10), which further contributes to “enhanced easterly” divergent wind at the upper levels (Fig. 8b) and an increase in the easterly zonal wind (Fig. 4d).

The difference in the projection of African convection is due to a different response to global warming of cloud representations in the two models. In the superparameterization approach, the heating profile in each subgrid is more accurately calculated, which further gives different upward motion from the one conventional scheme given (Stan et al. 2010). In the conventional parameterization, convection is driven by the energy of large-scale circulation (Arakawa and Schubert 1974), whereas the superparameterization operates on spatial

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**Fig. 8.** The trend of JASO mean Walker circulation by averaging the divergent wind and vertical velocity between 10°S and 10°N in RCP8.5 for (a) SP-CCSM4 and (b) CCSM4. Shading represents the trend of vertical velocity (10\(^{-2}\) Pa s\(^{-1}\) century\(^{-1}\), positive upward). Streamlines represent the trend of vertical velocity (10\(^{-2}\) Pa s\(^{-1}\) century\(^{-1}\)) and zonal divergent wind (m s\(^{-1}\) century\(^{-1}\)).
scales close to the native scales of observed cloud processes (Khairoutdinov and Randall 2001).

6. Conclusions

This paper evaluates the simulation of vertical wind shear over the tropical Atlantic region and its relationship with ENSO and the Atlantic Walker circulation in a model with conventional representation of cloud processes (CCSM4) and its superparameterized version (SP-CCSM4). Simulations in control runs, as well as projections in the RCP8.5 scenario with anthropogenic changes in the atmospheric concentration of greenhouse gases, are compared between the two models.

The climatology of the JASO mean vertical wind shear is generally captured by both models in control runs, with a realistic spatial pattern but overestimated magnitude. The overestimated vertical wind shear over the western equatorial Atlantic is related to the stronger-than-observed westerlies at the upper levels. This is a common bias of coupled models, and the comparison in this study suggests that representation of cloud processes is unlikely to have a direct impact on the simulation of the upper-level flow over this region.

As a bridge between the Atlantic and Pacific basins, the Walker circulation is further analyzed in observations and the control runs in SP-CCSM4 and CCSM4. In observations, there are two convection centers at the two sides of the tropical Atlantic, with one center being located over the Amazon basin while the other resides over western Africa. The upward motions, associated with the Amazon convection and the western Africa convection, are partially offset by the subsidence over the central equatorial Atlantic. Both SP-CCSM4 and CCSM4 underestimate the upward motion over the Amazon and northeast Brazil. However, SP-CCSM4 overestimates the upward motion over the eastern equatorial Atlantic, whereas CCSM4 underestimates the upward motion over western Africa and the eastern equatorial Atlantic. As a result, SP-CCSM4 simulates a stronger westward divergent wind at 200 hPa than CCSM4 does, which further contributes to stronger climatological easterlies at 200 hPa simulated in SP-CCSM4. The different convective activity over western Africa between SP-CCSM4 and CCSM4 indicates that African convection is sensitive to the cloud parameterization.

Furthermore, the ENSO–shear relationships in the control run are also well simulated by both SP-CCSM4 and CCSM4. Consistent with observations and theoretical explanations, during El Niño events anomalous westerlies occur at upper levels over the tropical Atlantic resulting from changes of the Walker circulation. Consequently, under the superposition of mean flow and anomalous flow, the western tropical Atlantic is dominated by increased vertical wind shear, whereas the eastern equatorial Atlantic is dominated by decreased vertical wind shear.

Although the control runs in both models show similar simulations of the tropical Atlantic shear and zonal wind, the changes of vertical wind shear and zonal wind
at 200 hPa projected in the RCP8.5 scenario are different over the equatorial Atlantic between SP-CCSM4 and CCSM4. The model with superparameterization representation of cloud processes projects increased westerlies at 200 hPa, which further contribute to an increased vertical wind shear over the western tropical Atlantic and a decreased shear over the eastern tropical Atlantic. In contrast, the model with conventional representation of cloud processes projects increased easterlies at 200 hPa over the equatorial Atlantic between 10°S and 10°N. As a result, with decreased westerlies at the upper levels projected in CCSM4, the vertical wind shear decreases over the equatorial Atlantic.

In addition, the projection of the ENSO–shear relationship is compared between SP-CCSM4 and CCSM4. Although the ENSO–shear relationships simulated in control runs are similar in both SP-CCSM4 and CCSM4, the projected ENSO–shear relationships are different between the two models. When excluding the long-term linear trend, the ENSO–shear relationship and the ENSO–U200 relationship projected in SP-CCSM4 are similar to those in the control run and observations. However, different from the control run and observations, the projected ENSO–shear relationship in CCSM4 without the long-term trend indicates increased vertical wind shear during El Niño events all over the whole tropical Atlantic, with decreased vertical wind shear confined to the African continent.

The difference in projected ENSO–shear relationship between the two models is related to differences in anomalous westerlies at the upper levels. The climatology of easterly flow at 200 hPa simulated in CCSM4 is weaker and retreated eastward relative to the zonal extension of the easterly flow in SP-CCSM4. Moreover, the projected westerly anomalies due to ENSO are stronger in CCSM4 than those in SP-CCSM4. The differences in projected westerly anomalies between the two models could be related to different responses of tropical Atlantic SST to ENSO. In the RCP8.5 scenario, the model with super-parameterization of cloud processes projects warm SST anomalies dominating the tropical Atlantic during El Niño events, which may cause an anomalous anticyclonic circulation and further contribute to weaker anomalous westerlies at the upper levels. However, the model with conventional parameterization projects cold SST anomalies during El Niño events dominating the tropical Atlantic. As a result, because of anomalous cyclonic circulation at the upper levels caused by the local Atlantic SST anomaly, the westerly anomalies due to ENSO could be strengthened in CCSM4.

In addition, it is interesting to notice that, to a certain extent, the long-term trends could mask out the interaction on a shorter time scale, such as the interannual variability. In SP-CCSM4, the projection of the ENSO–shear relationships with and without the linear trend retains similar features as in observations. However, when including the linear trend, the ENSO–shear relationship projected by CCSM4 indicates decreased vertical wind shear over the equatorial Atlantic. The difference in the vertical shear could explain why CCSM4 projects a change in the ENSO–shear relationship in the warmer climate when the trend is not removed, whereas SP-CCSM4 retains a similar pattern with and without the linear trend.

As for the change of vertical wind shear in a warmer climate, the trend of vertical wind shear indicates a robust increase of vertical wind shear over the SER in both models. However, because of different projections of zonal wind at 200 hPa, the projections of vertical wind shear over the equatorial Atlantic are different between SP-CCSM4 and CCSM4. A further discussion on convective activity over western Africa between the two models helps explain the difference in the projection of zonal wind in the RCP8.5 scenario. Under the global warming scenario, compared to the CCSM4 projections, the reduction of African convection is stronger in SP-CCSM4, with stronger suppression of ascending motion, reduced cloud cover, and increased surface downwelling shortwave radiation over western Africa. The strong suppression of convection over western Africa yields to an enhanced eastward divergence wind at 200 hPa in SP-CCSM4. Conversely, CCSM4 projects an increase of the cloud cover over western Africa, which reduces the surface downwelling solar radiation. Surprisingly, the increase in cloud cover is accompanied by a weakening of the upward motion in the ascending branch of the Walker circulation located over western Africa. The weaker ascent slows down the westward divergent wind at 200 hPa, which contributes to the increased easterly flow in CCSM4 in the RCP8.5 scenario.

The comparison between SP-CCSM4 and CCSM4 shows large differences in the convection over western Africa, which is considered to be a hotspot in climate change (Diffenbaugh and Giorgi 2012). This implies that convection at the two sides of the tropical Atlantic is critical for the variability of the tropical Atlantic climate in a warmer climate. For example, the model with the stronger (weaker) projection of suppression of the western African convection tends to project increased (decreased) westerlies at the upper levels, which further contribute to increased (decreased) vertical wind shear dominating the equatorial Atlantic. This may explain, to a certain extent, the lack of a robust agreement among the IPCC AR4 models on the change of shear over the equatorial Atlantic projected in a warmer climate (Vecchi and Soden 2007).
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