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Key Points:

- AGCM simulations forced with uniform and structured SST warming are compared
- The atmospheric circulation is insensitive to the pattern of SST warming
- Coupling and radiative forcing are more important than pattern of SST change

Supporting Information:

- Readme
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6
- Figure S7
- Figure S8
- supporting information

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The robustness of the atmospheric circulation and precipitation response to future anthropogenic surface warming

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Abstract The impact of long-term sea surface temperature (SST) change on the atmospheric circulation is studied by comparing atmospheric general circulation model (AGCM) simulations forced with a spatially uniform SST increase and a structured SST increase. The structured SST increase is calculated from the response of an ensemble of coupled ocean-atmosphere models to increased CO_2. Most of the impact of SST pattern change is confined to equatorial Indo-Pacific. However, the circulation change under the two types of SST forcing is similar over the rest of the tropics and almost identical in the extratropics, indicating that the pattern of future SST change has overall little impact on the response of the atmospheric circulation and, in turn, on the resulting changes in precipitation. The tropical similarity is argued to result from energetic constraints that weaken the atmospheric circulation, whereas the extratropical similarity likely results from the insensitivity of Rossby Wave generation to the changes in near-equatorial upper level divergence. A comparison of the AGCM simulations with those from externally forced coupled ocean-atmosphere models suggest that ocean coupling or the direct effect of radiative forcing has a larger impact on the projected changes in circulation and precipitation than the pattern of SST change over most regions.

1. Introduction

Several recent studies have examined the spatial variations in long-term sea surface temperature (SST) change simulated by coupled climate models, especially in the tropics [e.g., *Collins and CMIP Modeling Groups*, 2005; *DiNezio et al.,* 2009; *Xie et al.,* 2010]. The response of tropical Pacific SST to global warming is often described as "El Niño-like" [e.g., *Yu and Boer,* 2002; *Collins and CMIP Modeling Groups*, 2005], although more recent studies argued that it could also be described as "equatorial warming" because the meridional SST gradient is more robust in climate models than the zonal SST gradient [*Liu et al.*, 2005; *DiNezio et al.,* 2009; *Xie et al.,* 2010]. Changes in the tropical Atlantic SST are also characterized by enhanced equatorial warming, whereas changes in the tropical Indian SST show a dipole pattern [*Xie et al.,* 2010; *Zheng et al.*, 2013], with enhanced warming over the West Indian Ocean (Figure 1, left).

The response of the tropical SST pattern to increasing CO_2 is important because of its potential impact on global climate through atmospheric teleconnections. Studies using both simplified and complex atmospheric general circulation models (AGCMs) suggested that localized changes in tropical SST alter the upper level divergence and generate Rossby Waves, which modify extratropical circulation as they propagate poleward [e.g., *Sardeshmukh and Hoskins,* 1988; *Ting and Sardeshmukh,* 1993; *Schneider et al.,* 2003]. These studies have helped understand the response of extratropical circulation to El Niño. Under global warming, both the pattern and the spatial mean of tropical SST change. *Yin and Battisti* [2001] showed that changes in the tropical SST pattern are much more important than changes in the tropical mean SST for simulating the extratropical circulation of the Last Glacial Maximum. However, *Lu et al.* [2008] showed that the response of the zonal mean circulation to global warming is somewhat opposite to that of El Niño forcing, despite an "El Niño-like" SST response in the tropical Pacific. This suggests that the impact of SST pattern change resulting from global warming should be different than that resulting from natural variability.

Previous studies have shown that large discrepancies exist between the historical tropical SST pattern changes of the past few decades in observations and model simulations and suggested that these discrepancies may add large uncertainties to our understanding of future circulation change [e.g., *Liu et al.*, 2005; *Xie et al.,* 2010; *Shin and Sardeshmukh,* 2011]. For example, *Shin and Sardeshmukh* [2011, SS11 thereafter] showed that the warming pattern of tropical oceans is the key to simulating the circulation trend of the second half of the twentieth

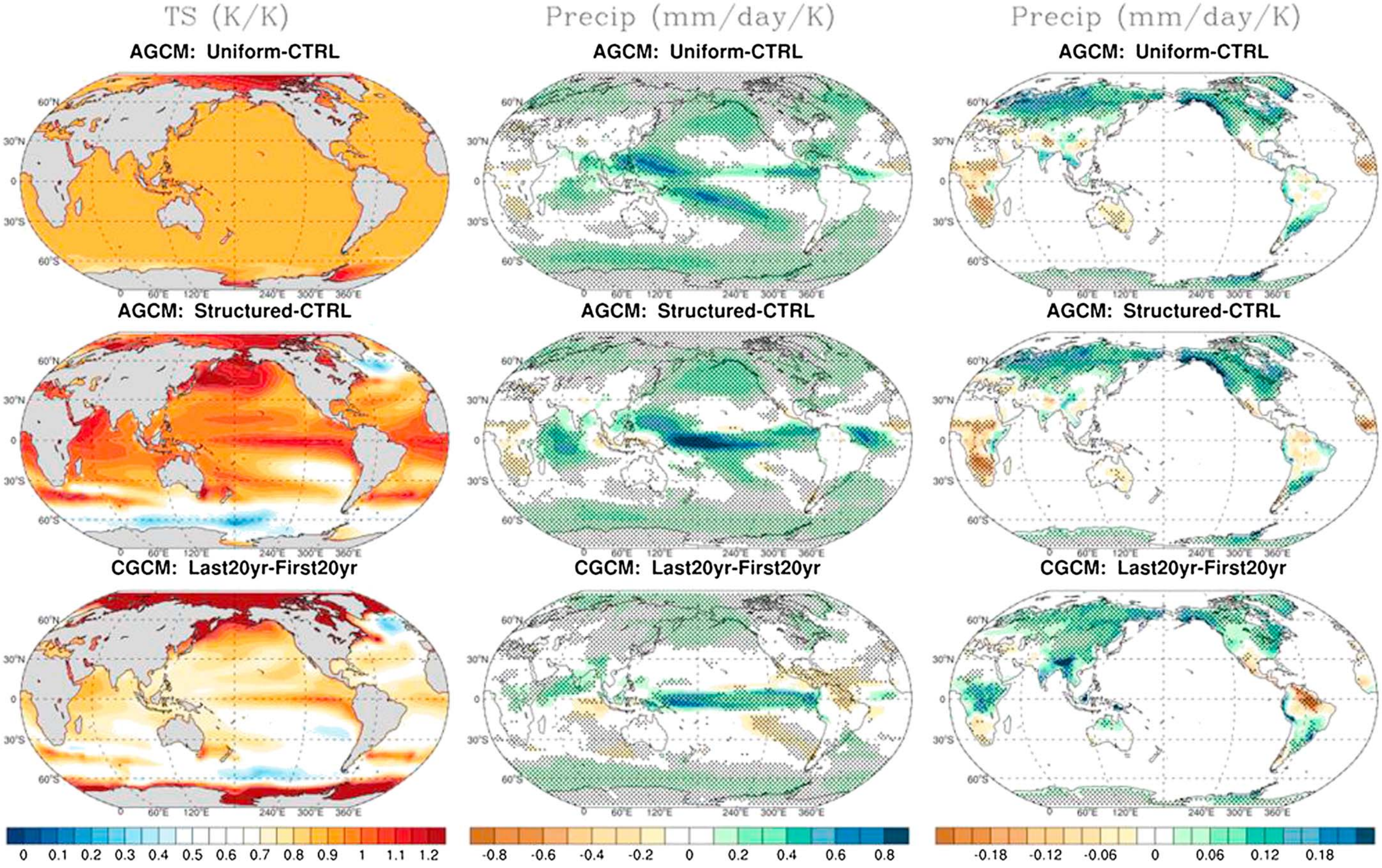

Figure 1. Ensemble mean changes in annual mean (left) surface temperature, (middle) precipitation, and (right) land precipitation for the uniform AGCM - CTRL (top), structured AGCM - CTRL (middle), and last 20 years–first 20 years from the CGCMs (bottom). All fields are normalized by the change in global mean surface temperature before ensemble averaging. Areas where at least six (out of seven) models agree on the sign of changes are stippled.

century over the landmasses around the North Atlantic Ocean (their Figure 7). However, according to *Deser et al.* [2012], climate changes on multidecadal time scales are dominated by internal variability. Therefore, the role of the tropical ocean warming pattern is expected to change as the signature of global warming becomes large enough to rise above the internal variability. *Ma et al.* [2012] and *Ma and Xie* [2013] found approximately equal importance of tropical mean warming and tropical warming pattern to the atmospheric circulation changes over tropical oceans, although most of their results were based on experiments that had a global mean warming less than or equal to 2 K. The purpose of the present study is to understand the circulation response to the pattern of SST change as a result of increased CO_2 instead of internal variability. We will achieve this by imposing a large warming signal (a 4 K global mean SST increase), which is significantly larger than the amplitude of any known internal variability.

We investigate the impact of the pattern of future SST change on atmospheric circulation by comparing AGCM simulations forced with a uniform SST increase and a structured SST increase using the pattern expected from future increases in CO_2. Although the use of AGCM is convenient, it is not a perfect representation of the real climate because of the lack of coupling with an underlying ocean [e.g., *Barsugli and Battisti,* 1998; *Wu et al.,* 2006; *Kumar et al.,* 2008]. This is particularly true in regions where the SST variation is caused by, instead of causing, the variation of atmospheric circulation. These regions include the Indian Ocean and most of the extratropics [e.g., *Deser and Timlin,* 1997; *Wu et al.,* 2006]. These previous studies focused on the effect of coupling on the simulation of natural climate variability; the effect of coupling on long-term climate change is largely unknown, so we also compare the AGCM simulations with simulations from the fully coupled ocean-atmosphere models (CGCMs) forced with increasing CO_2.

The AGCM simulations that we use for this study do not include the direct radiative effect of increasing CO_2, which was recently found important for tropical circulation change [*Bony et al.*, 2013]. Specifically, the increase of CO_2 slows down the tropical circulation without changes in surface temperature. However, it is unknown how the direct radiative effect works in the extratropics and how important it is compared to changes in SST pattern. This study provides insight on this matter by comparing AGCM simulations forced with SST only with CGCM simulations forced with increasing CO_2.

2. Model Simulation and Data

We analyze AGCM and CGCM simulations that were performed as part of the Coupled Model Intercomparison Project, phase 5 (CMIP5). The AGCM simulations are (1) the control simulation (CTRL), which was run from year 1979 to year 2008 forced with observed monthly mean SST and sea ice concentration; (2) the uniform SST increase simulation (uniform AGCM), which is the same as CTRL except adding a uniform +4 K SST anomaly; and (3) the structured SST increase simulation (structured AGCM), which is the same as CTRL except adding the SST anomalies as the composite of the SST responses taken from the "1pctCO2" coupled model CMIP3 experiments at the time of CO_2 quadrupling. The characteristics of the SST anomalies in the structured AGCM are described in section 1.

To study how well the AGCM simulations reproduce the externally forced coupled simulations, we also analyze the "1pctCO2" simulation from CGCMs. The CGCMs contain the same atmospheric components and use the same resolution as the AGCMs. It is important to note that while the AGCM simulations used for this study account for changes in surface temperature, unlike the CGCM simulations, they do not include the direct radiative effect of increasing CO_2 on the tropical circulation change [e.g., *Bony et al.*, 2013]. Therefore, differences between the structured AGCM and CGCM simulations may result from a lack of coupling to the ocean and/or direct radiative forcing to the circulation. Additional experiments that are not available from the CMIP5 model archive would be required to isolate these two effects. Changes in tropical and midlatitude SST are very similar between the AGCM and CGCM simulations (Figure 1, left and Figure S1 in the supporting information), although the AGCM simulations show a reduced polar amplification due to a lack of sea ice reduction. We assume the difference in polar surface temperature to be a minor contributor to the difference in circulation response based on previous studies, which showed that SST changes are much more important in the tropics than higher latitudes [e.g., *Schneider et al.*, 2003; *Schubert et al.*, 2004; *Deser and Phillips*, 2009].

Seven CGCMs and their AGCM counterparts are used, namely CanESM2/CanAM4, CCSM4, CNRM-CM5, HadGEM2-ES/HadGEM2-A, MIROC5, MPI-ESM-MR, and MRI-CGCM3. All models were run with one realization except CCSM4, from which we only take the first realization. Details about the model simulations can be found at http://cmip-pcmdi.llnl.gov/cmip5/getting_started_CMIP5_experiment.html. Model data and description can be found at http://pcmdi3.llnl.gov/esgcet/home.htm.

Circulation changes due to uniform (structured) SST increase are defined as the climatological difference between the uniform (structured) AGCM and CTRL, whereas changes in the CGCM simulation are defined as the difference between years 121 to 140 (last 20 years of the "1pctCO2" simulation available in the CMIP5 archive) and years 1 to 20. The circulation changes are normalized by each model's global mean surface temperature change and then averaged across models to yield a multimodel ensemble mean, in order to avoid dominance by models with large climate sensitivity. We present our results based on annual mean, but our main conclusions do not depend on the season. Results for DJF and JJA are provided in the supporting information.

3. Results

Our main result is that the atmospheric circulation is very insensitive to the pattern of future SST change, except over the equatorial Pacific, which is dominated by enhanced surface warming (Figure 1, left). The effect of enhanced equatorial warming is most pronounced in tropical ocean precipitation change because the largest precipitation change occurs at the equator (Figure 1, middle). This is consistent with previous studies [*Xie et al.*, 2010; *Ma et al.*, 2012; *Ma and Xie*, 2013]. It is important to note that the plots for ensemble mean precipitation change (Figure 1, middle) may overestimate the impact of SST pattern change because of larger intermodel discrepancy in the non-SST-related precipitation change than the SST-related precipitation change in the AGCM simulations. As shown in Table 1, the precipitation—SST correlation is positive but small

Table 1. Ensemble Mean Spatial Correlation Between the Uniform AGCM Response, Structured AGCM Response, and CGCM Response for Global, Tropics (30°S to 30°N), Extratropics (Poleward of 30°S and 30°N), and Each Tropical Basin

	Land Precipitation		SLP		Omega500		Precipitation Versus SST		Precipitation	Omega500
	Uniform Versus Structured	Structured Versus CGCM	Uniform Versus Structured	Structured Versus CGCM	Uniform Versus Structured	Structured Versus CGCM		Structured	Uniform Versus Structured	Uniform Versus Structured
Global	0.81	0.37	0.94	0.80	0.79	0.56	Pacific	0.14	0.48	0.62
Tropics	0.74	0.25	0.72	0.56	0.75	0.55	Atlantic	0.28	0.68	0.76
Extratropics	0.90	0.70	0.96	0.82	0.89	0.57	Indian	-0.04	0.58	0.74

in the tropics and negative in the extratropics, indicating that changes in SST pattern could be important in certain tropical regions but insignificant at a global scale. Compared to oceanic precipitation, land precipitation (Figure 1, right), and other atmospheric variables are even more insensitive to the pattern of future SST change. Table 1 shows the ensemble mean spatial correlation of uniform AGCM, structured AGCM, and CGCM response for land precipitation, sea level pressure (SLP), and 500 hPa vertical pressure velocity (ω500). The response of the atmospheric circulation to the uniform and structured SST increase is very similar in the tropics and almost identical in the extratropics, indicating the insensitivity of atmospheric circulation response to the pattern of SST change. However, the circulation response is less similar between the AGCM and CGCM simulations, suggesting a greater role for coupling compared to the impact of SST pattern change. These results are also robust in every individual model. (In Figures 1, 2, and 4, areas where at least six models agree on the sign of change are stippled.)

To compare with the work of SS11, which showed a large sensitivity of regional land precipitation to the observed pattern of SST change in the second half of the twentieth century (their Figure 7), we examine the global pattern of land precipitation changes in the uniform and structured simulations (Figure 1, right). Note that the mean tropical SST increase in our simulations (4 K) is about 9 times as large as that of SS11 (0.43 K). Contrary to SS11, the global pattern of precipitation over land is very insensitive to the pattern of SST change under increased CO_2. This suggests that either the response of the circulation becomes less sensitive to the pattern of SST change as the magnitude of the mean warming increases, or that pattern of warming used in SS11—the observed warming from the second half of the twentieth century—is more strongly influenced by internal variability rather than increasing CO_2. It further implies that the circulation responds differently to these two types of surface temperature changes, being more sensitive to the pattern of the response for internal variability compared to increased CO_2.

3.1. Tropics

The annual mean ω500 responses ($\delta\omega$500) to uniform and structured SST increase are dominated by their common features (Figure 2, left). The forcing from both types of SST change reduces convection at the major climatological convective regions, namely, south central Africa, Indonesia, and the Amazon rainforest. Also common in the two $\delta\omega$500 is the anomalous convection at the northern flank of convective regions and southeast Pacific. These common features, to the first order, are consistent with a weakening of the mean atmospheric circulation [e.g., *Held and Soden,* 2006; *Vecchi and Soden,* 2007]. This weakening is a robust feature of all climate models and reflects the disparity between the rate at which water vapor and precipitation increase in a warming climate. Atmospheric moisture increases by about 7% per degree warming, whereas precipitation only increases at about 2% per degree warming, due to constraints imposed by the rate of atmospheric radiative cooling [*Allen and Ingram,* 2002; *Stephens and Ellis,* 2008]. This means the upward mass flux, should weaken by about 5% per degree warming. This argument does not rely on the pattern of SST change but simply the mean warming.

As shown in Figure 2, $\delta\omega$500 (shading) in the tropics generally opposes the pattern of climatological ω500 (contour), consistent with a uniform weakening of the mean circulation. In the tropics this pattern of weakening has been attributed to the mean advection of the increased static stability [*Ma et al.,* 2012]. However, noticeable differences between the pattern of change and climatology do exist, especially outside of the tropics. The scatter plot shows generally a linear relationship between $\delta\omega$500 and climatological ω500 in the

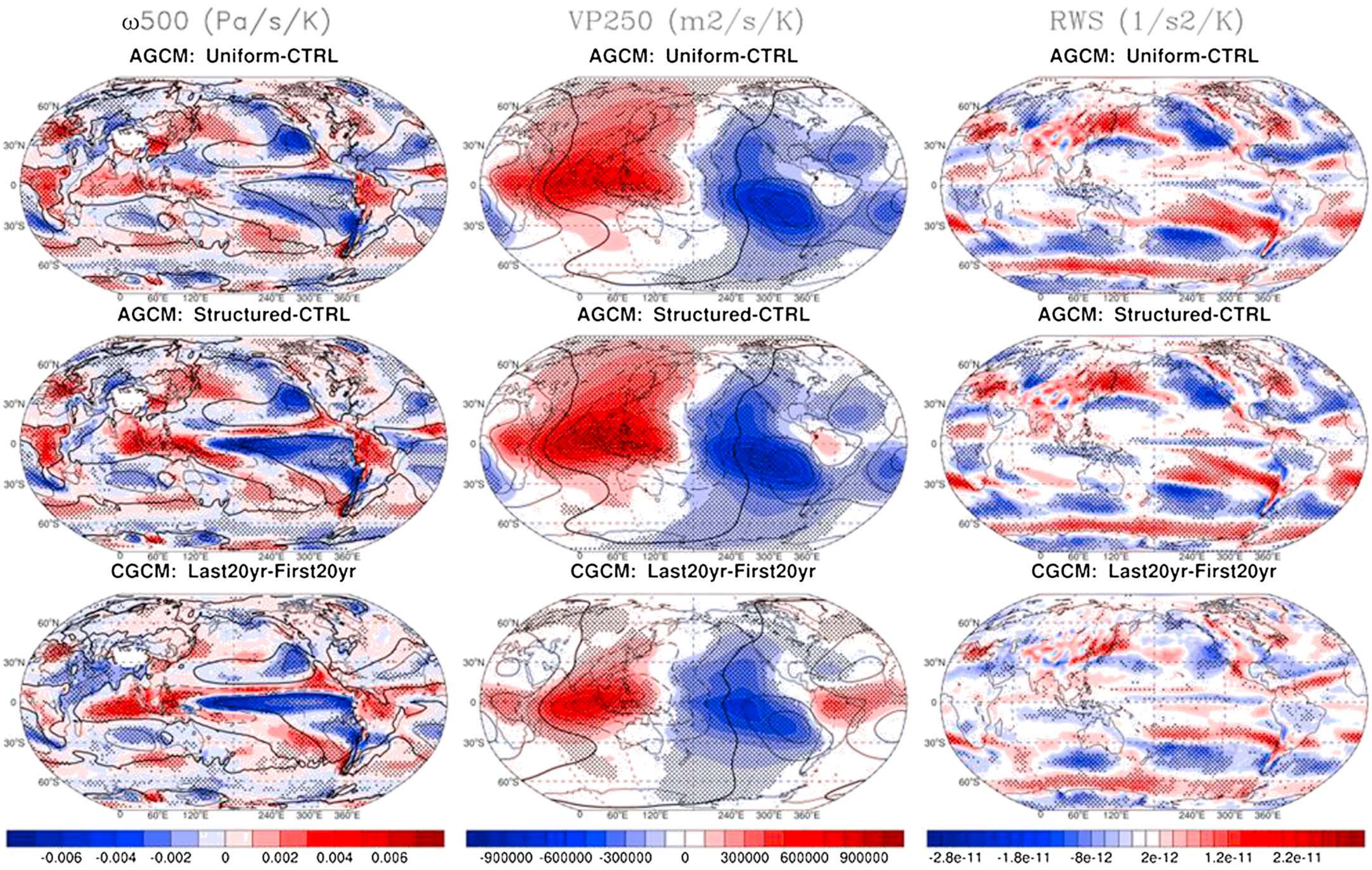

Figure 2. Same as Figure 1, except for (left) ω500, (middle) 250 mb velocity potential, and (right) RWS. The contours in Figures 2, left and 2, middle represent the climatological ω500 and 250 mb velocity potential, respectively; contour interval is 0.03 Pa/s and 2×10^6 m^2/s. The zero contours are thickened. Dashed lines are for negative values.

tropics (Figure 3, left), although outliers for the structured and CGCM simulations are noted over the equatorial Pacific, where anomalous surface warming increases local convection [*Xie et al.,* 2010]. The spatial correlation between climatological ω500 and δω500 is −0.43 and −0.48 for uniform AGCM and structured AGCM, respectively (Figure 3). Note that the spatial correlation between uniform and structured δω500 is 0.77. Therefore, part of the common features of tropical circulation change is likely caused by mechanisms other than the global energetic constraints, such as changes in moisture and temperature advection and changes in convection height [*Chou and Neelin,* 2004; *Chou et al.*, 2009].

The differences in δω500 between structured AGCM and uniform AGCM are mostly confined at the equatorial oceans, including anomalous equatorial convection over the Pacific and Atlantic Ocean, anomalous subsidence over south Pacific and a dipole pattern over the Indian Ocean. These differences reflect the local changes in SST pattern (Figure 1, left), with warmer (colder) surface associated with anomalous convection (subsidence), consistent with *Xie et al.* [2010]. The spatial correlation of δω500 between uniform and structured AGCM for each tropical basin (Table 1) shows that the impact of SST pattern change is the largest over the tropical Pacific Ocean and smallest over the tropical Atlantic Ocean. The δω500 correlation is 0.67 for the entire tropical ocean, which is larger than the precipitation correlation (0.55), a result expected from the cancelation between the slowing down of tropical circulation and the increase in moisture [*Chadwick et al.*, 2013]. The spatial correlation is higher for tropical land (0.87 for δω500 and 0.76 for precipitation change) than tropical ocean, indicating that the impact of SST pattern change does not extend much to land.

We further examine the effect of SST pattern change on large-scale overturning circulation by looking at changes in the Walker circulation and Hadley circulation. A weakening of the Walker circulation, represented by 250 mb velocity potential, is evident in both the uniform and structured simulations (Figure 2, middle). The Walker circulation weakens by about 5% per degree warming, consistent with the results of *Held and Soden* [2006].

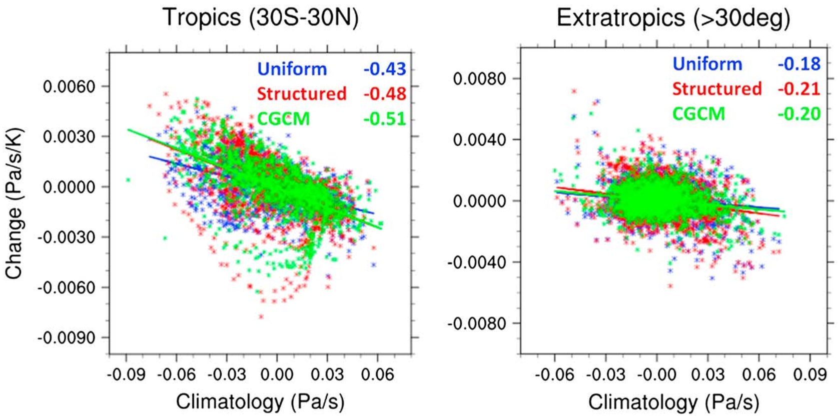

Figure 3. Scatter plot of ensemble mean δω500 versus the climatological ω500 for (left) 30°S–30°N and poleward of (right) 30°. Blue, red, and green are for the uniform AGCM, structured AGCM, and CGCM simulations, respectively. The numbers at the top right corner of each plot is the spatial correlation of δω500 and climatological ω500.

Changes in SST pattern have little effect on the pattern or amplitude of velocity potential change. The velocity potential change has a spatial correlation of 0.97 between the uniform and structured simulations and is about 15% larger in the structured simulations. This is consistent with the results of *Ma and Xie* [2013]. On the other hand, changes in the Hadley circulation are very different at the equator between the uniform and structured simulations (Figure 4). The ensemble mean Hadley circulation from the uniform simulations does not show much robust change due to intermodel inconsistency, except an increase of tropopause in the deep tropics, which has also been found in other studies [e.g., *Holzer and Boer,* 2001; *Santer et al.,* 2003]. However, changes in Hadley circulation from the structured simulations feature a strengthening at the center of the Southern Cell and at the south side of the Northern Cell and a weakening at the north side of the Southern Cell. The total effect of SST pattern change is to shift the convective center toward the equator. This is robust for all the models and consistent with previous studies [*Ma et al.,* 2012; *Ma and Xie,* 2013].

To study the importance of atmosphere-ocean coupling and direct radiative forcing on the circulation response, we examine δω500 from the CGCM experiments (Figure 2, left bottom). Similar to the AGCM simulations, the changes in the tropical atmospheric circulation from the CGCMs generally oppose the mean circulation,

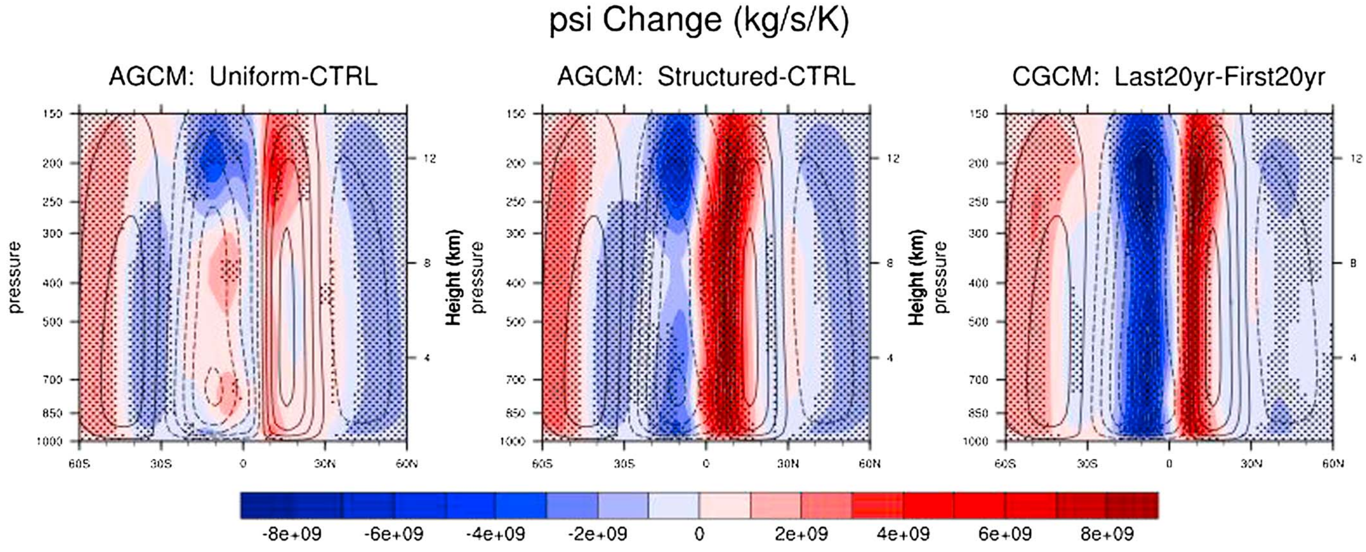

Figure 4. Ensemble mean changes (shading) in annual mean zonal mean stream for the (left) uniform AGCM-CTRL, (middle) structured AGCM-CTRL, and (right) last 20 years-first 20 years from the CGCMs. Changes are normalized by the change in global mean surface temperature before ensemble averaging. The contours represent the climatological annual mean stream function; contour interval is 3×10^{10} kg/s. The zero contours are thickened. Dashed lines are for negative values. Areas where at least six (out of seven) models agree on the sign of changes are stippled.

with anomalous subsidence in the convective regions and anomalous convection at the subsiding branch. However, noticeable regional discrepancies exist between the structured AGCM and CGCM simulations, despite the similarity in the pattern of their tropical SST change (Figure 1, left). The largest discrepancies can be seen over South Indian Ocean, where air-sea interaction plays a crucial role in simulating monsoon climate [e.g., *Wu and Kirtman,* 2005; *Wu et al.,* 2006], although *Chen et al.* [2013] suggested that atmospheric noise may also be playing a role. The discrepancies over central Africa is most likely caused by difference in direct radiative forcing. Specifically, the reduced convection is counteracted by radiatively induced convection, consistent with the pattern of precipitation change shown in *Bony et al.* [2013]. The CGCM simulations also show 51% less weakening of the Walker circulation compared to the structured simulations (Figure 2, middle). This is contrary to what could be expected from the direct radiative forcing alone, which should result in more weakening [*Bony et al.,* 2013]. Therefore, air-sea coupling might also be important for changes in Walker circulation. Further studies are needed to determine the individual effect of coupling and direct radiative forcing. In general, there are larger discrepancies (i.e., lower spatial correlation, Table 1) between the CGCM and structured AGCM simulation than between the two AGCM simulations, suggesting that the effect of coupling and direct radiative forcing is more important than the pattern of SST change.

3.2. Extratropics

As shown in Table 1, changes in the annual mean extratropical circulation are almost identical between the uniform and structured AGCM simulations, but less similar between the AGCM and CGCM simulations. Changes in extratropical SLP and stream function in both AGCM and coupled simulations feature a deepening of the Aleutian Low, a positive shift in the North Atlantic Oscillation and a positive shift in the Southern Annular Mode (Figure S8 in the supporting information). These common features of SLP changes have also been found in observations and other model simulations of climate trends of the past half century [e.g., *Schneider et al.,* 2003; *Deser and Phillips*, 2009]. The robustness of SLP change from the CGCM simulations (indicated by the stippled area, Figure S8 in the supporting information) suggests that these changes should be a result of global warming instead of natural variability.

As shown in Figure 3 (right), outside of the tropics, the changes in circulation are not simply a weakening of the mean circulation, suggesting that other mechanisms are responsible for the similarity in the extratropical circulation change between the two AGCM simulations. We hypothesize that the extratropical similarity may reflect the insensitivity of Rossby Wave generation to the pattern of SST changes in the tropics. Previous AGCM studies have shown that extratropical circulation is insensitive to local SST changes but are mostly influenced by tropical SST changes [e.g., *Schneider et al.,* 2003; *Schubert et al.,* 2004; *Deser and Phillips*, 2009]. The mechanism by which tropical SST variations influence extratropical circulation is through the poleward dispersion of Rossby Waves forced by tropical upper level divergence [e.g., *Sardeshmukh and Hoskins,* 1988; *Ting and Sardeshmukh,* 1993; *Schneider et al.,* 2003].

The similarity of extratropical circulation change is further explored by comparing the Rossby Wave generation in the uniform and structured AGCM simulations. Following *Sardeshmukh and Hoskins* [1988], the nonlinear, frictionless Rossby Wave equation at upper troposphere can be written as

$$\frac{\partial \varsigma}{\partial t} + V_\psi \bullet \nabla \varsigma = -\varsigma \bullet D - V_\chi \bullet \nabla \varsigma. \tag{1}$$

Here V_ψ and V_χ are the rotational wind and divergent wind, respectively. ς is the absolute vorticity. D is the divergence. The right-hand side of (1) is generally considered as the Rossby Wave Source (RWS), which is often used to quantitatively define the origin of Rossby Waves [e.g., *Jin and Hoskins,* 1995; *Kirtman et al.,* 2001]. The change in RWS in response to global warming can be written as

$$\text{RWS}' = \left(-\varsigma \bullet D - V_\chi \bullet \nabla \varsigma\right)', \tag{2}$$

which is dominated by $-\varsigma \bullet D'$. for both AGCM and CGCM simulations (figures not shown). Therefore, changes in upper level divergence are what essentially drive changes in RWS.

$$\text{RWS}' \approx -\varsigma \bullet D'. \tag{3}$$

Changes in 200 hPa divergence field (not shown) generally follow $\delta\omega500$, with divergence (convergence) generated where $\delta\omega500$ is negative (positive). Overall, the 200 hPa divergence response is very similar in the uniform and structured AGCM simulations. Most differences between the uniform and structured AGCM simulations are near the equator.

According to (3), there must be large enough local absolute vorticity to cause RWS change. Near the equator, the planetary vorticity is close to zero and the relative vorticity is small because of weak wind shear. Therefore, very little RWS change is generated at the equator, despite large local divergence change (Figure 2, right). The difference in the divergence change due to uniform and structured SST increase, which is mostly near the equator, is not efficiently transformed into a change in RWS. As a result, changes in RWS in the uniform and structured AGCM simulations are almost identical, with an ensemble mean global spatial correlation of 0.89. The insensitivity of the Rossby Wave generation to the pattern of SST change in the tropics is evident by comparing the pattern of RWS changes in the uniform and structured AGCM simulations (Figure 2, right). Compared to the AGCM simulations, the magnitude of the ensemble mean RWS change in the coupled simulation is smaller. Overall, there is much larger discrepancy in RWS change between the AGCM and coupled simulations than between the two AGCM simulations. The ensemble mean global spatial correlation between the structured AGCM and CGCM simulation is 0.58.

4. Summaries and Discussion

We have shown that the atmospheric circulation is insensitive to SST pattern change by comparing AGCM simulations forced by uniform and structured SST increase. The structured SST increase is calculated from the response of an ensemble of coupled ocean-atmosphere models to increased CO_2. It features equatorial warming in the Pacific and Atlantic Oceans and a dipole pattern in the Indian Ocean as well as a polar amplification in the northern high latitudes. All seven AGCMs show that the response of atmospheric circulation to uniform and structured SST increase is very similar, with ensemble mean spatial correlation of about 0.75 in the tropics and 0.9 in the extratropics. This indicates a less significant impact of the SST pattern change compared to the global mean warming. In the tropics, the effect of SST pattern change is mostly confined at the equator, where enhanced warming increases convection. This “warmer-get-wetter” effect was shown in previous studies [e.g., *Xie et al.,* 2010] and is important with regard to changes in regional precipitation and equatorial Hadley circulation. In comparison, our results show that overall, change in SST pattern is not the dominant factor of tropical precipitation and circulation change; its impact does not extend much beyond the equatorial oceans. It has even less impact in the extratropics. Overall, the tropical circulation change is determined by a weakening of the mean circulation. The mechanism by which tropical SST variations influence extratropical circulation is likely through the generation of Rossby Waves, which can be approximately quantified as the product of upper level divergence change and absolute vorticity. The upper level divergence change is very similar in the uniform and structured AGCM simulations. The difference in divergence change caused by changes in SST pattern is mostly at the equator where the absolute vorticity is small and therefore cannot be efficiently transformed into RWS.

Previous studies have suggested an important role of SST pattern change in determining regional climate change in the second half of the twentieth century [e.g., *Shin and Sardeshmukh,* 2011]. The present study shows that such dependence is not present in model projections of future climate change due to increasing CO_2. Results from the CMIP5 data suggest that the atmospheric circulation is insensitive to the pattern of future SST change. This insensitivity supports the recent findings of *Deser et al.* [2012] that regional climate changes on multidecadal time scales are dominated by internal variability rather than increasing CO_2. Based on the results in this paper, most of the future circulation change is a result of global mean warming instead of the pattern of SST change and we should have high confidence in the pattern of future circulation change without full knowledge of the pattern of SST change.

Although it makes little difference to change the structure of SST increase in AGCM simulations, it makes a much bigger impact whether the effect of air-sea coupling and direct radiative forcing is added. We have investigated the role of air-sea coupling and direct radiative forcing by comparing AGCM simulations forced with SST increase only and CGCM simulations forced with increasing CO_2. Results show noticeable discrepancies between the circulation response in the structured AGCM and CGCM simulations, despite that they have the same atmospheric components and similar SST pattern change in the tropics and midlatitudes. The largest differences exist over tropical Indian Ocean, central Africa, and most of the extratropics. This suggests the importance of ocean coupling or radiative forcing in simulating the circulation changes in these regions. Further studies are needed to determine the individual effect of coupling and direct radiative forcing.

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