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Short Communication

A possible mechanism for El Niño-like warming in response to the future greenhouse warming

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ABSTRACT: Using the climate change experiments generated for the Fourth Assessment of the Intergovernmental Panel on Climate Change, a possible mechanism for the El Niño-like warming in response to the greenhouse warming is suggested. From the coupled global climate model (CGCM) simulations with climate change scenario, it is found that the Bjerknes air–sea coupled process is a dominant contributor to the tropical Pacific response. However, it is revealed that most CGCMs commonly simulate the off-equatorial maximum of precipitation change. It is suggested here that the off-equatorial precipitation and the associated equatorial westerlies play a seeding role in triggering an El Niño-like warming response. Atmospheric GCM (AGCM) experiments show that even uniform sea-surface temperature (SST) warming leads to off-equatorial increase in precipitation which brings equatorial westerlies, implying that these non-uniform (off-equatorial) responses can play a seeding role for the El Niño-like warming pattern. Copyright © 2010 Royal Meteorological Society

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1. Introduction

The El Niño- Southern Oscillation (ENSO) is a predominant mode of inter-annual climate variability because of strong Bjerknes feedback (Bjerknes, 1969). There is a long-standing debate in the climate community on how the tropical Pacific will respond to increased greenhouse gases. An ENSO-like response to the increased CO_2 is expected because strong instability by Bjerknes feedback may work not only in the inter-annual time scale but also in long-term mean state change. Most of the earlier studies have indicated that, under the scenario of increasing CO_2 concentration, coupled global climate models (GCMs) show a mean El Niño-like response in the tropical Pacific, thus indicating that sea-surface temperature (SST) over the central and eastern equatorial Pacific increases more than that over western equatorial and off-equatorial Pacific, with a corresponding mean eastward shift of precipitation (e.g. Knutson and Manabe, 1995, 1998; Meehl and Washington, 1996; Cubasch *et al.*, 2001a, 2001b; Vavrus and Liu, 2002; Yu and Boer, 2002; Boer and Yu, 2003a, 2003b), although a different aspect is also reported (Liu *et al.*, 2005).

However, it is not yet physically fully understood whether the response pattern to the increased CO_2 is El Niño-like or La Niña-like (e.g. Cane *et al.*, 1997, Collins, 2005; Latif and Keenlyside, 2008). For example, Collins (2005) pointed out using the earlier 20 coupled GCMs submitted to the Coupled Model Intercomparison Project (CMIP) that a skill-weighted assessment shows no trend towards either mean El Niño-like or La Niña-like warming, indicating a large uncertainty. However, Latif and Keenlyside (2008) pointed out, using the climate models presented at the Fourth Assessment Report (AR4) by the Intergovernmental Panel on Climate Change (IPCC), that the uncertainty in the mean SST changes is still there. But this is somewhat smaller than the results obtained by Collins (2005), thus clearly indicating a preference for El Niño-like warming. From their analysis, among 16 models 13 simulate El Niño-like warming in response to global warming.

Previous studies that proposed mechanisms for El Niño-like warming have suggested that it originates primarily through the atmosphere. Based on models and theory, several studies have shown that, in response to a warming climate, the zonal overturning atmospheric circulation (walker circulation) across the tropical Pacific weakens (Betts and Ridgway, 1989; Knutson and Manabe, 1995; Held and Soden, 2006; Vecchi *et al.*, 2006). This leads to a decline of the equatorial

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Table I. Model descriptions.

Model	Resolution		Flux correction
	Atm.	Ocean	
CCCMA_CGCM3_1	T63, L32	192 × 96, L29	H, W
IAP_FGOALS1_0_q	T42, L26	360 × 180	None
MIROC_3_2_MEDRES	T42, L20	256 × 192, L33	None
CNRM_CM3	T63, L45	180 × 170, L33	None
IPSL_CM4	96 × 72, L19	180 × 170, L31	None
GFDL_CM2_0	144 × 90, L24	360 × 200, L50	None
GFDL_CM2_1	144 × 90, L24	360 × 200, L50	None
MRI_CGCM2_3_2a	T42, L30	144 × 111, L23	H, W, M

Heat, water and momentum adjustment corrections are indicated by H, W and M, respectively.

easterlies, which along with other atmospheric feedbacks (Knutson and Manabe, 1995; Meehl and Washington, 1996) results in a reduction in equatorial Pacific SST gradient.

So far, the mechanisms governing the tropical Pacific's response to increased CO_2 scenario are not clear, which need to be understood further. In this study we will demonstrate a possible mechanism for the tropical Pacific response to anthropogenic forcing. First, we analyse the IPCC-AR4 climate system model output by comparing the pre-industrial control and global warming (CO_2 doubling) runs. Then we conduct idealized experiments using an atmospheric GCM (AGCM) to illustrate a possible mechanism behind this El Niño-like response.

2. Data

We use selected eight CGCM simulations from IPCC-AR4 achieves, namely, MRI_CGCM2_3_2a, GFDL_CM2_0, GFDL_CM2_1, CCCma_CGCM3_1, CNRM_CM3, IAP_FGOALS1_0_q, IPSL_CM4 and MIROC3_2_MEDRES (denoted, respectively, as MRI, GDDL1, GFDL2, CCCM, CNRM, IAP, IPSL and MIROC) (Table I). The selection is based mainly on the length of simulations and the availability of sub-surface temperature data at the time of analysis.

We here analyse both pre-industrial (control) and CO_2 doubling ($2CO_2$) experiments. The control run simulates an unperturbed climate state with CO_2 concentration fixed at the pre-industrial level. The CO_2 doubling experiment simulates transient climate response to a 1% per year increase of CO_2 concentration. In this simulation, CO_2 concentration starts at 348 ppmv, then increases at the rate of 1% per year until it doubles (696 ppmv) in the 70th year, at which point the CO_2 concentration is held constant. The analysed period is year 1–60 (71–130) for the control (doubling) experiment. Details regarding the experiment and data can be found at https://esg.llnl.gov:8443/index.jsp. We also checked that our present results are quite consistent with those of the CO_2 quadrupling experiment.

3. Results from IPCC-AR4 data

Figure 1 shows the simulated SST changes (contours) over the Tropical Pacific domain (i.e. $2CO_2$ minus the control). We also show the relative change (shading) in SST, by removing the uniform warming (area-averaged SST) over the whole tropical Pacific domain (120°–270 °E, 20 °S–20°N), for clearly demonstrating the relative magnitude of SST warming. The multi-model ensemble (MME) mean of the uniform warming over the whole tropical Pacific domain is 1.76. As shown in Figure 1, the MME shows that tropical Pacific SST increases by about 1.5–2.1 °C in response to CO_2 doubling. Also, in the equatorial central-eastern Pacific the SST increase exceeds the tropical Pacific uniform SST change by up to 0.4 °C, so that the zonal SST gradient is weakened in the equatorial Pacific. Also, it is noted that the SST increase in the off-equatorial regions is weaker than that in the equatorial region. These features are somewhat consistent with El Niño-like warming pattern. Most of the models agree well with these ensemble mean features, indicating that they exhibit El Niño-like warming, with exceptions in CNRM and IAP which mostly show an enhanced equatorial warming, which is characterized by a stronger warming (cooling) near the equator than in the subtropical Pacific (Liu *et al.*, 2005). The El Niño-like warming emphasizes a zonal SST gradient, while the enhanced equatorial warming focuses on the latitudinal SST gradient. However, the two patterns commonly result from the anomalous equatorial westerlies, and the eastern Pacific warming is related to the deepening of the thermocline depth (Liu *et al.*, 2005 and Figure 3).

The El Niño-like SST warming is accompanied by the associated changes in precipitation and large-scale circulation. Figure 2a shows these changes in 850 hPa wind (vectors) and precipitation (shading) for the MME. This shows an overall increase in rainfall in the $2CO_2$ experiment over the tropics. However, the precipitation increase is pronounced over the equatorial central Pacific, which is dynamically consistent with the maximum SST warming in the central and eastern Pacific. The MME shows an increase of 1.5 mm/day in precipitation. This feature

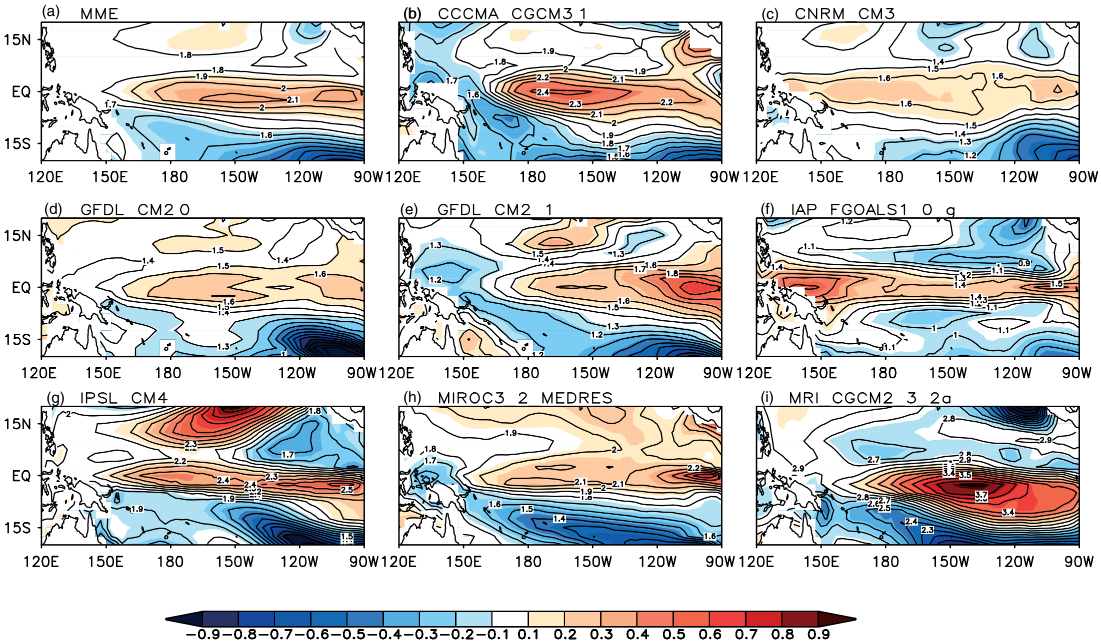

Figure 1. Difference in the SST (K) between the control and CO_2 doubling experiments produced by (a) eight-model ensemble mean and (b–i) each model. Shading indicates relative changes by removing the uniform warming averaged over the whole tropical Pacific domain (120 °E–90 °W, 20 °S–20°N). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

is clearly shown in Figure 2b, which shows the longitudinal distribution of precipitation along equator (5 °S–5°N). Though there are some exceptions (GFDL1 and IAP), most of the models show this feature consistently, indicating that the coupled Bjerknes feedback plays a dominant role in the tropical Pacific climate responses to the greenhouse gas forcing.

The enhancement of precipitation over the equatorial central Pacific can be understood as a direct response to the El Niño-like warming, which will be concentrated in the equatorial region. However, a closer look at Figure 2a reveals some interesting points. The maxima of the precipitation changes are located not at the equator but at off-equatorial regions. This is somewhat different from the typical pattern of the El Niño-related precipitation. The precipitation responses to El Niño-like SST forcing shows even negative precipitation anomalies in the off-equatorial region from the observation data (Kim *et al.*, 2008; Kug *et al.*, 2009a) and model simulation (Kim *et al.*, 2008; Kug *et al.*, 2009b). To see the meridional structure of the precipitation responses more clearly, we have plotted the latitudinal distribution (averaged along 150 °E–100 °W) of precipitation in Figure 2c. As well as the MME, the off-equatorial maximum precipitation changes are a robust feature in most of the individual models. This pattern cannot be explained by El Niño-like warming, implying that other processes contribute to the precipitation changes rather than the coupled Bjerknes feedback.

The enhanced precipitation over the central Pacific modifies atmospheric circulation in the coupled system. As shown in Figure 2a, anomalous westerlies are pronounced over the whole equatorial Pacific in the response to the CO_2 doubling. To a large extent, the equatorial westerlies can be explained by the central Pacific precipitation, which is consistent with an El Niño-like pattern. However, it is interesting to note here that the eastern Pacific westerlies, which lie on the eastern part of the increased precipitation, are still strong. Based on the typical Gill-type response, the zonal wind should be easterlies in the east of the diabatic heating due to the Kelvin wave responses. Though some observational pattern associated with El Niño suggests relatively in-phase relation between equatorial precipitation and zonal wind rather than the simple Gill-type response (Clarke, 1994), such strong westerlies over the eastern Pacific are hardly explained by the equatorial precipitation. However, it is possible that the off-equatorial maxima of the precipitation partly explain the equatorial westerlies. Based on the Gill-type solution, the off-equatorial diabatic heating can induce the equatorial westerlies by the Rossby wave responses. Because the off-equatorial maxima still exist in the eastern Pacific, it is conceived that the eastern Pacific easterlies are related to the meridional distribution of the precipitation.

The changes in the low-level atmospheric circulation will modulate the oceanic structure. In particular, the equatorial zonal slope of the thermocline is quite sensitive to the change of the equatorial zonal wind. To examine the change of oceanic structure, we analysed the heat content changes (i.e. $2CO_2$ minus the control), along the equatorial Pacific to elucidate the response of the sub-surface temperature. Heat content refers to the ocean temperature averaged from surface to 300 m depth. As shown in Figure 3a, the ensemble mean clearly shows an El Niño-like thermocline structure, deepening of thermocline in the eastern Pacific and shoaling in the western Pacific. Every model exhibits this

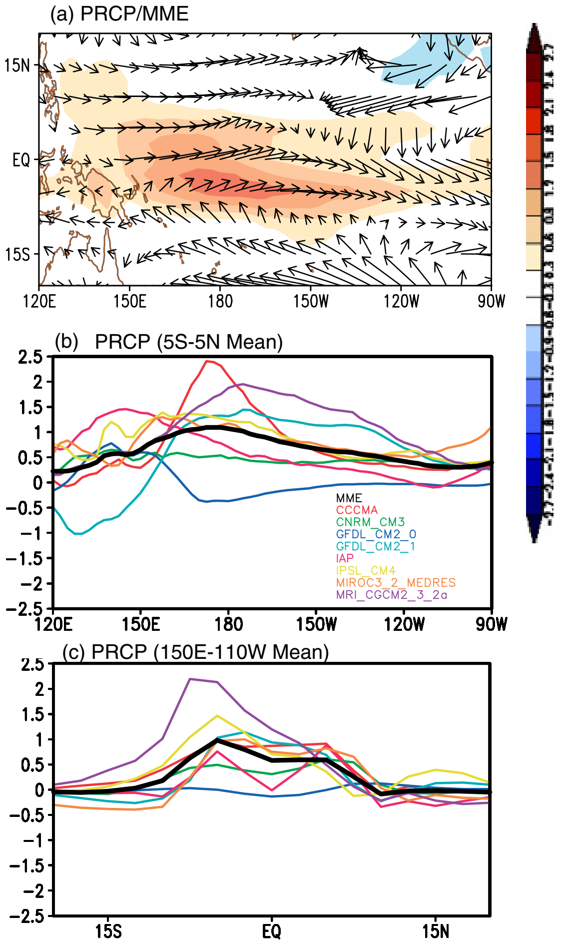

Figure 2. (a) The same as Figure 1a except for precipitation (mm/day). (b) Longitudinal distribution of the precipitation difference averaged over 5 °S–5 °N. (c) Latitudinal distribution of precipitation difference averaged over 150 °E–110 °W. Thick line indicates the eight-member ensemble mean, and coloured lines indicate individual models. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

see-saw structure consistently. It is interesting that the IAP and CNRM models, which show enhanced equatorial warming suggested by Liu *et al.* (2005) rather than the El Niño-like warming, also clearly show an El Niño-like thermocline structure, indicating that the coupled Bjerknes feedback is also at work in these models. Presumably, the western Pacific warming in these models results from other mechanisms such as surface latent heat flux and shortwave cloud feedback (Liu *et al.*, 2005).

In order to see the relation between the thermocline and SST changes, we plotted the SST changes over the eastern Pacific (Figure 3) against the slope of the equatorial heat content. The heat content is defined as the integrated oceanic temperature from surface to 300 m depth. The slope of the heat content is calculated by the difference between the heat content anomalies over the eastern Pacific (90°–150 °W, 5 °S–5°N) and the western Pacific (120°–180 °E, 5 °S–5°N). It clearly shows that, in all the models, every positive SST gradient over the eastern Pacific is accompanied by the positive slope in heat content, implying deepening of thermocline in the eastern Pacific. Also, we found that the thermocline changes are positively correlated to the SST changes, indicating that the Bjerknes feedback plays a role in the long-term climate change.

4. AGCM experiments and results

So far, we have shown that the El Niño-like response to the CO_2 induced warming is evident in most air–sea variables such as SST, wind, precipitation and thermocline. However, all these changes in atmospheric and oceanic structure are determined by a coupled process through the Bjerknes feedback and so they are dynamically linked to each other. Since all these changes are part of this feedback, it is difficult to ascertain the actual dynamic processes behind this El Niño-like response. Though there is a possibility that the strong air–sea coupled process can lead to La Niña-like response as well, it is interesting that most of the IPCC-AR4 models simulate El Niño-like warming as shown in Figure 1. This implies that there are some seeding mechanisms behind this El Niño-like warming pattern, associated with the CO_2 doubling scenario. In an earlier section, we noted that some

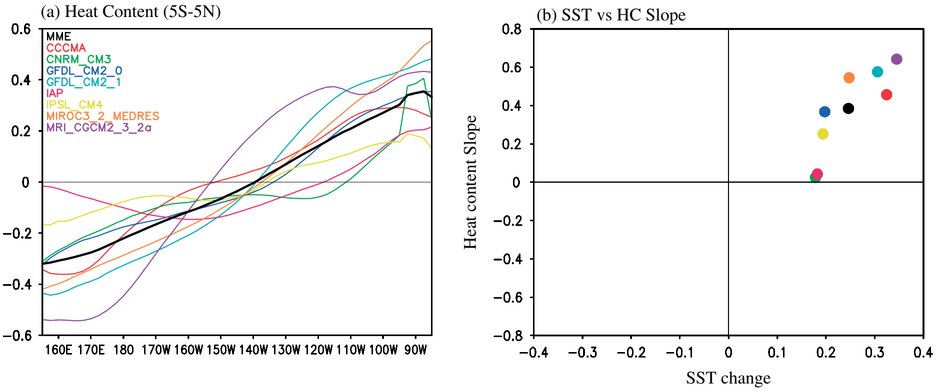

Figure 3. (a) The same as Figure 2b except for heat content (K). (b) Scatter diagram between eastern Pacific SST change (x-axis) and slope in heat content (y-axis). The eastern Pacific SST change (i.e. $2CO_2$ minus the control) refers to the SST gradient between the regions over 180°–270 °E, 5 °S–5°N and 120°–270 °E, 20 °S–20°N. The slope in heat content is the difference in heat content between eastern Pacific (90°–150 °W, 5 °S–5°N) and western Pacific (120°–180 °E, 5 °S–5°N). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

interesting features (off-equatorial precipitation maxima and eastern Pacific westerlies) are hardly explained by the Bjerknes feedback. These features may give a clue about the possible seeding mechanism to determine the direction of climate response. For understanding this seeding mechanism further, we designed an AGCM experiment, as described below.

The Seoul National University (SNU) AGCM is integrated (each simulation for 5 years) using different SST boundary conditions. The description on the SNU model is referred to in Kug *et al*. (2008). In the control simulation, denoted by CLIM, we integrated the AGCM using climatological SST, retaining the seasonal cycle. The climatological SST is derived from the period 1979 to 1999. The model is integrated for 5 years, and the last 4-year simulation is used for the analysis. In addition to the CLIM experiment, we performed one more experiment, denoted by SSTW, in which a 2 °C warming is added globally to the climatological SST boundary condition. This gives a chance to analyse the actual atmospheric response to uniform increase in SST.

Figure 4a shows the annual mean climatological precipitation and wind at 850 hPa from the CLIM experiment. Overall, the model simulates the observed precipitation pattern well, in particular the ITCZ and SPCZ. To show the atmospheric response to the uniform SST increase, we obtained the difference of the SSTW experiment from the CLIM experiment. Generally, an enhancement in precipitation is expected with SST warming, since precipitation is strongly tied to low-level moisture through the Clausius–Clapeyron equation. However, the distribution of the precipitation increase is not homogeneous in spite of the uniform SST warming. As shown in Figure 4b, it is interesting that the pattern of precipitation enhancement is quite similar to that of precipitation climatology except for the equatorial western Pacific. Namely, wet regions get wetter and dry regions drier (Held and Soden, 2006). For instance, the precipitation increases over the ITCZ and SPCZ regions.

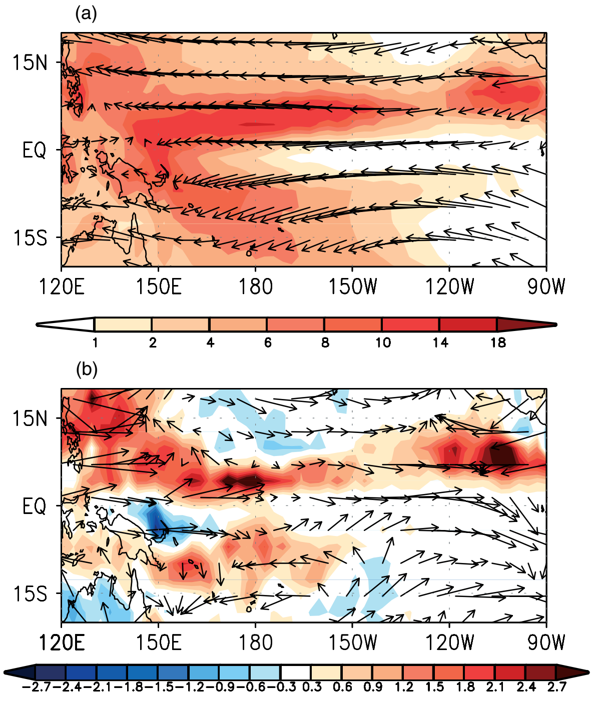

Figure 4. (a) Precipitation (shading, mm/day) and wind at 850 hPa (vector, m/s) from the CLIM experiments. (b) Differences in precipitation (shading) and wind at 850 hPa (vector) between the SSTW and CLIM experiments. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

It is interesting that precipitation increases in the off-equatorial region, but it does not change much or even decreases in the equatorial region. These changes are quite consistent with the estimates of Held and Soden (2006, see their Fig. 8). They predicted a thermodynamic component of precipitation changes using a simple formula based only on climatological distribution of the precipitation and evaporation. This indicates that the off-equatorial precipitation increases are mainly determined by the climatological mean distribution rather than an anomalous SST pattern. Corresponding to these precipitation changes, there are anomalous equatorial westerlies. Over the western Pacific, it is noted that there are anomalous westerlies along the equator even though the model simulates the dryness over that region. This is possibly because the Rossby wave responses to the off-equatorial positive precipitation anomalies overwhelm their decaying effect. It is also noted that the anomalous westerlies exist over the whole Pacific basin from the western Pacific to the eastern Pacific.

It is interesting that there are several common features between the CGCM simulations and AGCM simulation. For example, off-equatorial precipitation augmentation and equatorial westerlies are robust features in both simulations. Note that the distribution of SST anomalies is completely different except for the general SST increase. This implies that the above common features are rather an intrinsic atmospheric response to the SST warming and they play a seeding role in response to the El Niño-like warming. Once the equatorial westerlies are induced, the equatorial thermocline should be balanced, so that the thermocline in the eastern Pacific is deepened. The deepened thermocline leads to additional SST increases over the eastern Pacific, having an El Niño-like warming which is non-uniform. The warm SST, in turn, alters the equatorial precipitation and large-scale atmospheric circulation, enhancing the equatorial westerlies through Bjerkens feedback. Thus the air–sea coupled process is strongly involved in the climate responses. Finally, the El Niño-like warming pattern comes out as a robust response to the CO_2 doubling.

On the other hand, there are also notable differences between precipitation changes simulated by the multi-model CGCMs and the present AGCM. First, there is a clear difference over the equatorial Pacific. While the CGCM simulation shows an increase in precipitation, the AGCM shows either a decrease or no change in precipitation. Second, the off-equatorial precipitation changes are larger over the Southern Hemisphere in the CGCM simulations but over the Northern Hemisphere in the AGCM simulation. The two major differences can be explained by the experimental design of the AGCM. Because in the AGCM experiment a uniform warming is used, the effect of El Niño-like SST warming is excluded unlike in the CGCM simulation. The El Niño-like warming obviously induces the equatorial precipitation increase. Also, the El Niño-induced precipitation is slightly shifted to the south from the equator (Harrison and Vecchi, 1999; Kug *et al.*, 2003; Vecchi and Harrison, 2003; Vecchi, 2006). Thus, the precipitation changes in the Southern Hemisphere are enhanced in the CGCM simulations. In addition, the so-called double-ITCZ problem of most CGCMs can further enhance the precipitation changes in the Southern Hemisphere compared to those from the present AGCM simulation. Therefore, the major differences between the CGCM and AGCM simulation can be understood by the direct responses to the El Niño-like SST warming.

4. Summary and discussion

In this study, a possible mechanism for the El Niño-like warming pattern in response to the increase of the greenhouse gas concentration is suggested. From the multi-model simulations, it is shown that the major changes in atmospheric and oceanic structure are determined by a coupled process through the Bjerknes feedback and so they are dynamically linked to each other. However, we found some robust features simulated in most of the models, which are not readily explained by the simple air–sea coupled process. That is, most CGCMs simulate the off-equatorial maxima in the precipitation changes. Our AGCM experiments with uniform SST increase also simulate this off-equatorial increase in precipitation. The unique feature in both (AGCM experiments and CGCMs) reveals that this precipitation increase is rather an intrinsic atmospheric response to a general SST increase than to an El Niño-like SST warming. Further both the CGCMs and AGCM experiments show anomalous westerlies over the whole Pacific basin, extending from the western Pacific to the eastern Pacific. Therefore, these equatorial westerlies associated with the off-equatorial precipitation pattern play a seeding role by switching on the Bjerknes feedback, thus eventually leading to an El Niño-like warming response.

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