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Changes in El Niño and La Niña teleconnections over North Pacific–America in the global warming simulations

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Abstract The change in the teleconnections of both El Niño and La Niña over the North Pacific and American regions due to a future greenhouse warming has been analyzed herein by means of diagnostics of the Intergovernmental Panel on Climate Change-Fourth Assessment Report (IPCC-AR4) coupled general circulation models (CGCMs). Among the IPCC-AR4 CGCM simulations, the composites of the eight-member multimodel ensemble are analyzed. In most CGCMs, the tropical Pacific warming due to the increase of CO_2 concentration in the atmosphere promotes the main convection centers in the equatorial Pacific associated with both El Niño and La Niña to the east. The eastward shift of the convection center causes a systematic eastward shift of not only El Niño but also La Niña teleconnection patterns over the North Pacific and America, which is demonstrated in the composite maps of 500 hPa circulation, surface temperature, and the precipitation against El Niño and La Niña, as observed in a comparison between the pre-industrial and CO_2 doubling experiments. Thus, a systematic eastward migration of convection centers in the tropical Pacific associated with both El Niño and La Niña due to a future global warming commonly causes the eastward shift of the atmospheric teleconnection patterns over the Northern Hemisphere.

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1 Introduction

Recently, the Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC) states that "warming of the climate system is unequivocal.... Most of the observed increase in globally averaged temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations." A climate warmed as a result of human activity thus becomes part of the inevitable future of our environment. Both the globally averaged air temperature and the extremes of weather and climate are expected to increase. As a driver of such extremes, the El Niño–Southern Oscillation (ENSO) is both interesting and not yet fully understood in terms of its impact on future global climate.

There is a long-standing debate in the climate community on how the tropical Pacific will respond to increased greenhouse gases (especially CO_2). An ENSO-like response to the increased CO_2 is expected because strong instability by Bjerknes feedback may work not only in interannual time scale but also in long-term mean state change. However, it is not yet physically fully understood whether the response pattern is El Niño-like or La Niña-like pattern. Most of the earlier studies mentioned that under the scenario of increasing CO_2 concentration, coupled 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 warms more than 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; Cane et al. 1997; Cubasch et al. 2001; Vavrus and Liu 2002; Yu and Boer 2002; Boer and Yu 2003a, b; Boer et al. 2004; Collins and CMIP Modeling Groups 2005). Recently, Liu et al. (2005) pointed out that major SST responses can be an enhanced equatorial warming relative to the subtropics rather than an equatorial SST gradient. As well as the changes of tropical mean climate, it is likely that the CO_2-induced global warming will modify the ENSO characteristics (e.g., Timmermann et al. 1999; Collins 2000a, b; Cubasch et al. 2001; Meehl and Teng 2007; An et al. 2008). Well-defined paleorecords indicate that El Niños were persistently weak during the warmth period of the Holocene (11–4 ka) and Medieval Warm Period (Rein et al. 2004), but overall warming in the tropical Pacific during the recent decades since the late 1970s leads an intensified ENSO amplitude as well as its impact on the global climate (An and Wang 2000; An and Jin 2000). However, multimodel experiments under the same CO_2-increasing scenario exhibit decrease in El Niño amplitude in some models, but increase or little change in others (Guilyardi 2006; Merryfield 2006). Hence, there is currently no definitive answer to what will happen to El Niño in the future. The responses of ENSO amplitude to increasing greenhouse gases in various climate system models are so diverse, but the overall increasing SST due to increasing greenhouse gases is commonly accepted (e.g., Liu et al. 2005).

The increased mean SST in the tropical Pacific alters the characteristics of ENSO (An and Jin 2000; An et al. 2006), with a consequent expected impact on short-term global climate. The precedent studies on changes in ENSO teleconnection due to global warming (e.g., Meehl et al. 2006; Muller and Roeckner 2006; An et al. 2007; Meehl and Teng 2007; Sterl et al. 2007) give more or less inconsistent results. This may be because their results are highly dependent of the amplitude changes of ENSO itself associated with the global warming (Meehl and Teng 2007; Sterl et al. 2007). The multimodel approach will be a useful way to find a systematic change of ENSO teleconnection, by reducing model-dependent problem. Therefore, we investigate changes in ENSO teleconnection due to global warming in the view of multimodel aspect, as in Meehl and Teng (2007). In particular, we focus on the northeastern Pacific and North American continent, where ENSO influences climate directly through atmospheric teleconnection (e.g., Ropelewski and Halpert 1987). Furthermore, we analyze the teleconnections of not only El Niño and but also La Niña. As mentioned in An et al. (2007), the La Niña teleconnection is not simply a mirror image of the El Niña teleconnection because of its nonlinearity in the teleconnection. Given a significant global climate impact of La Niña, it is worthy to investigate the changes in the La

Niña teleconnection. In this study, however, both El Niño and La Niña teleconnections are analyzed using eight-member multimodel ensemble.

In Section 2, the data utilized are introduced. The main results are appeared in Section 3. The summary and discussion are in Section 4.

2 Data

Both pre-industrial (control) and CO_2 doubling ($2CO_2$) experiments are analyzed. 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%/year increase of CO_2 concentration. In this simulation, CO_2 concentration starts at 348 ppmv, then increases by 1%/year until it doubles (696 ppmv) in the 70th year, at which point CO_2 concentration is held constant. Analyzed period is year 1–60 (71–130) for the control (doubling) experiment. Eight models are analyzed in this study, including CCCMA_CGCM3_1, CNRM_CM3, IPSL_CM4, GFDL_CM2_0, GFDL_CM2_1, MPI_ECHAM5, MRI_CGCM2_3_2a, and NCAR_CCSM3. Among the 16 available models for long-term simulation of both pre-industrial and CO_2 doubling experiments, we do not use several models due to too weak precipitation response (i.e., BCCR_BCM2_0, GISS_MODEL_E_R, GISS_MODEL_E_H, MIROC3_2_MEDRES, and NCAP_PCM1) and too westward precipitation response (i.e., CSIRO_mk3_0, IAP_fgoals_1_0_g and INMCM3_0) associated with ENSO, which are quite different from the observed precipitation response. In this study, we assume that the better models, particularly indicating the models which simulate reasonable atmospheric responses to the change in SST associated with ENSO in the present climate, will exhibit better simulation on the changes in the atmospheric response under global warming. It is noted that the present multimodel ensemble can be somewhat limited to represent all probable climate sensitivity under global warming, since we select only eight models based on the criteria. For example, the model group, which has too weak precipitation response to ENSO, does not show a significant change in atmospheric response between the two scenario experiments. For the El Niño and La Niña composites of eight-member multimodel ensemble, the single model composite is firstly calculated before calculation multimodel ensemble mean. In addition, the composite of each model is normalized by the standard deviations of their own Niño-3.4 SST anomalies in order to reduce the dependency of ENSO amplitude in different models. Details regarding the experiment and data are found at https://esg.llnl.gov:8443/index.jsp.
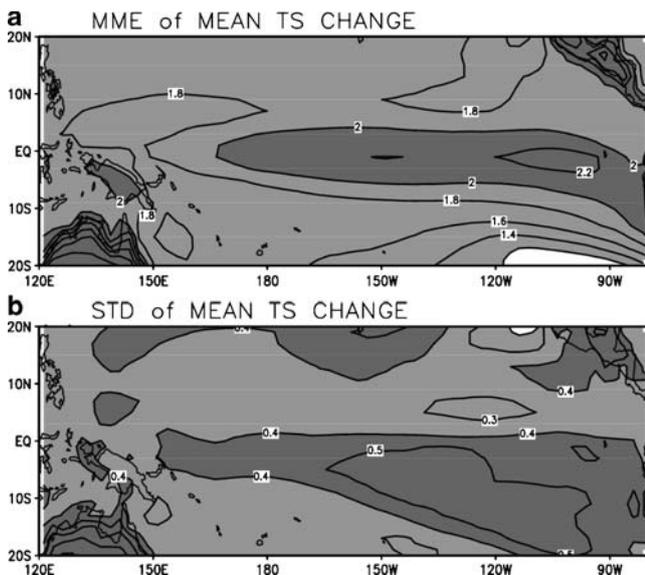
Fig. 1 a Difference in the eight-member multimodel ensemble SST between the control and CO_2 doubling experiments. b Standard deviation of SST difference

3 Results

3.1 Changes in the tropical convection

Surface warming in the tropical Pacific due to the increase of atmospheric CO_2 concentration is obtained from the multimodel ensemble surface temperature (Fig. 1). In this approach, the outputs from the eight models listed above are averaged. Figure 1a shows the difference between the ensemble-mean surface temperature from the control experiment and that from the $2CO_2$ experiment. The El Niño-like warming pattern is dominant, and overall tropical warming due to increasing greenhouse gases is larger than subtropical warming, consistent with results of Liu et al. (2005). An uncertainty range for this ensemble-mean picture is estimated from the standard deviation, which is calculated from the difference between individual SST change and their ensemble mean. As shown in Fig. 1b, the scattering range of the individual mean from the ensemble mean accounts for about 20% in the cold tongue region through about 45% in the subtropical Pacific region. Thus, the typical warming range of equatorial
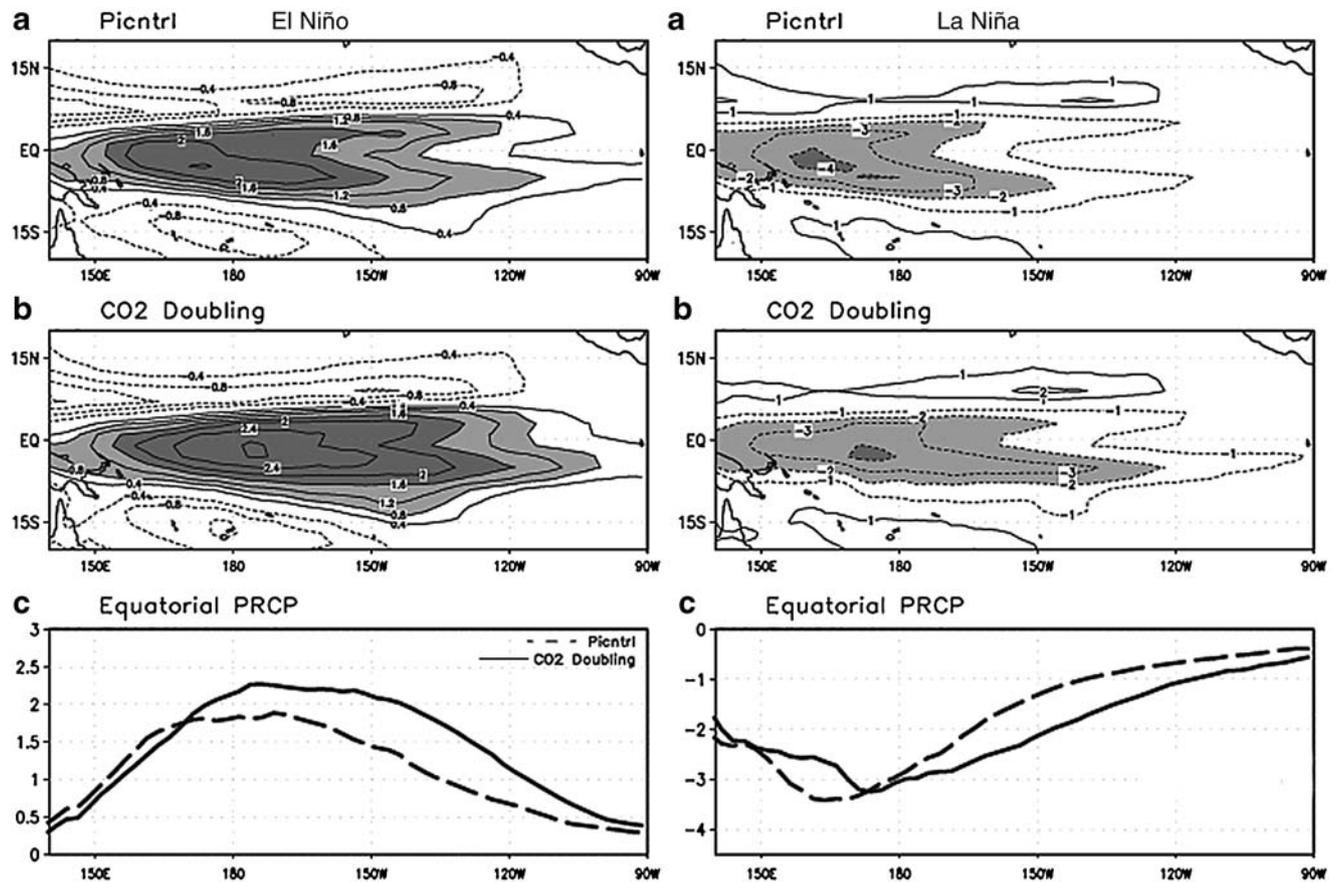
Fig. 2 a Composite map of the precipitation against Niño-3.4 index for the control experiment. b As in a but for the CO_2 doubling experiment. c Equatorial (5° S–5° N) precipitation anomalies for the control and CO_2 doubling experiment. Left and right panels refer to the El Niño and La Niña composites, respectively

eastern Pacific due to a doubled CO_2 concentration is between 1.5°C and 2.7°C.

An increase in the mean SST in the tropical Pacific can cause an eastward shift of the active convective center during El Niño events. For example, during the warm phase of the Pacific Decadal Oscillation (PDO; 1981–1995) that features a meridional extended El Niño-like SST pattern (Zhang et al. 1997), the canonical pattern of the atmospheric/oceanic variables associated with ENSO moved eastward by about 15°, as compared with the pattern that appeared during the cold phase of the PDO (1961–1975; Wang and An, 2001). As the warm pool area expands and the cold tongue temperature warms up, atmospheric response to an anomalous SST over the central to eastern Pacific can be more sensitive. For example, atmospheric convection over the cold ocean surface may not be affected by small SST change. However, as the mean SST in that region is increased, even small SST change can influence atmospheric convection. Due to this nonlinearity of atmospheric convection, the SST increases over the tropical Pacific can lead to the eastward shift of the convection pattern associated with both El Niño and La Niña.

Global warming can also lead to an eastward shift of the canonical El Niño and La Niña patterns. Figure 2 shows the composite of the precipitation averaged from December to the following February (DJF) for the control and $2CO_2$ experiments. El Niño (La Niña) events were defined as occurring when Niño-3.4 SST is greater (lower) than 1 standard deviation above the average SST. Although the simulated precipitation pattern in the control run (Fig. 2a) is slightly westward-shifted compared to the observation, which is presumably related to a common cold bias over the central Pacific in the most of current coupled GCMs, the comparison between the control experiment and $2CO_2$ experiment obviously provides a dynamically meaningful result. It is clear that anomalous precipitation is eastward-shifted in the $2CO_2$ experiment during El Niño as well as La Niña periods (Fig. 2b). The difference of anomalous precipitation patterns is statistically significant at 99% confidence level (not shown). Figure 2c more clearly shows changes in the location and amplitude of the precipitation over the equatorial region such as a pronounced increase of precipitation over the central to eastern Pacific during both El Niño and La Niña. Note that the amplitude of precipitation in the El Niño composite is increased in $2CO_2$ experiment, while that in the La Niña composite is not changed.

For each model, Fig. 3 shows changes induced by a future global warming in the intensity and longitudinal location of the precipitation center associated with ENSO. For the ensemble mean, the center of maximum precipitation in the $2CO_2$ experiment (closed circle) is

located about 8° further eastward than in the control run (open circle), as in Fig. 2. Like the ensemble mean, each model (except NCAR_CCSM3_0 and GFDL_CM2_1) similarly exhibits an eastward shift of the precipitation center by 3~25° of longitude, and in most cases, the precipitation is intensified by the greenhouse warming. This intensification is mainly associated with the El Niño rather than La Niña as shown in Fig. 2.

3.2 Changes in the teleconnections

In most cases as shown previously, increasing tropical Pacific mean SST due to greenhouse warming leads to a systematic eastward shift of the atmospheric convection associated with both El Niño and La Niña. Interestingly, the effect of greenhouse warming on the zonal location of the main atmospheric convection center is comparable with that of the El Niño–La Niña asymmetry, because the convection center during El Niño is located further east than that during La Niña (Kang and Kug 2002). According to Hoerling et al. (1997), such a zonal swing of the tropical atmospheric convection center between El Niño and La Niña causes a zonal shift of the teleconnection pattern over the North Pacific and America. In other words, atmospheric teleconnection is not symmetric with respect to ENSO (An et al. 2007), because atmospheric waves emanating from differently located tropical convective centers track different paths. In a similar manner, the zonal shift of
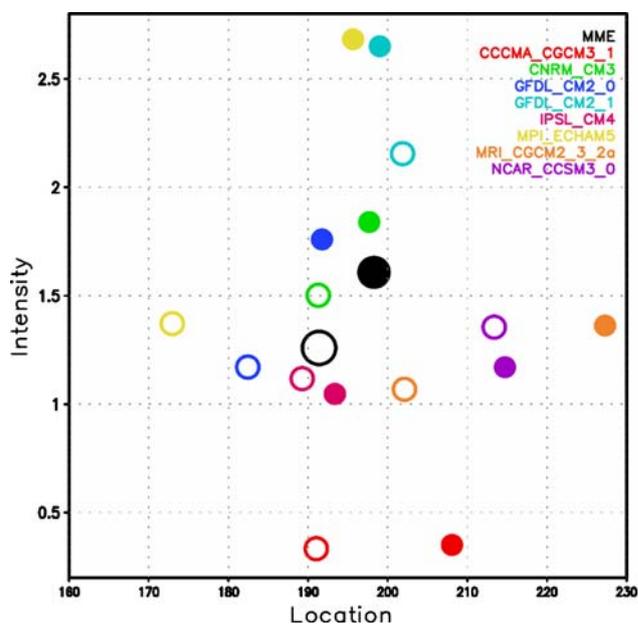
Fig. 3 Scatter plots for the intensity of the maximum precipitation vs. its longitudinal location. Intensity and location are determined based on the linear regression map of the precipitation against the Niño-3.4 index. *Open and closed dots* are obtained from the control and CO_2 doubling experiments, respectively

tropical atmospheric convection associated with the greenhouse warming may result in changes in the teleconnection pattern over the midlatitudes.

Here, we compare the impacts of both El Niño and La Niña on the North Pacific and North American continent which occurred in the pre-industrial condition and in the CO_2 doubling condition. Since the teleconnection associated with El Niño is not just a mirror image of La Niña (Hoerling et al. 1997), we separately analyze the teleconnections by El Niño and by La Niña. In order to diagnose changes in teleconnection associated with ENSO, we calculate again the eight-member multimodel ensemble mean of the composite map of the atmospheric circulation at 500 hPa. The composite maps were constructed by plotting the 500-hPa geopotential height anomalies (also surface temperature and precipitation anomalies) during DJF during the months of El Niño or La Niña events. The El Niño composite in control run shows so-called Pacific/North America pattern similar to the observed one (Fig. 4a), though overall pattern is slightly shifted to the south and west because the tropical convection anomaly is shifted to the west as shown in Fig. 2a. In the $2CO_2$ experiment, the

pattern is overall moved to the east as the tropical convection anomaly moves during both El Niño and La Niña periods. In particular, the high (low) center in the north of Canada observed in the control experiment significantly moved southeastward, reaching the coast of Canada during El Niño (La Niña) period. Another low center, located in the southern part of the North America, does not move much but it is intensified in the $2CO_2$ experiment. These features are well appeared in the difference map. All significant differences are located at the east of the action center in the control run, indicating eastward movement of atmospheric teleconnection. The statistical significance for the difference of composites is obtained by a bootstrap method.

Not only the atmospheric circulation but also the surface temperature and precipitation show similar tendencies. The overall simulated impacts of ENSO on North Pacific/America are quite similar to the observed one (e.g., Ropelewski and Halpert 1987). The cold centers in the North Pacific as well as the southern part of North America observed in the control experiment moved east by about 10° longitude. The wet center, indicated by positive
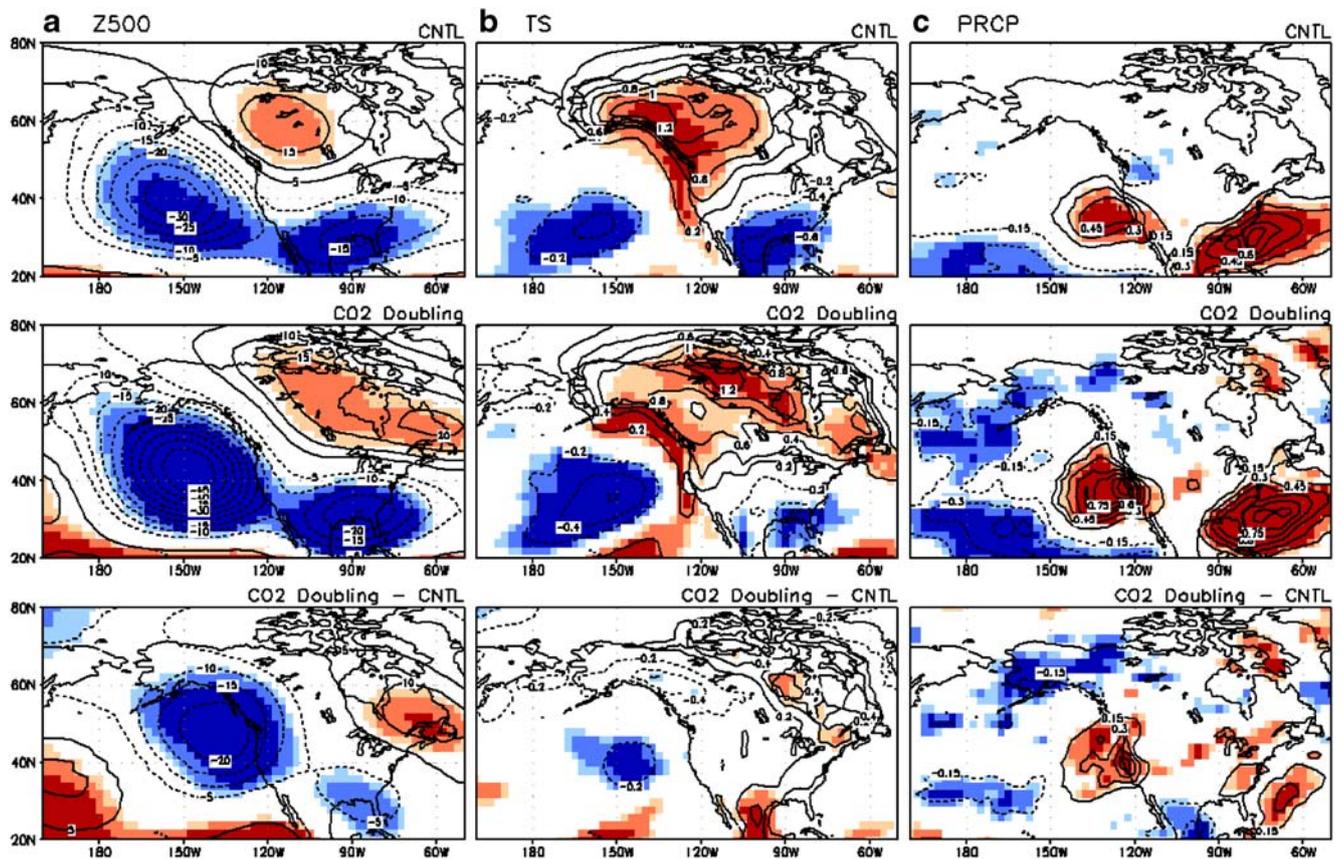
Fig. 4 a El Niño composite map of 500 hPa geopotential height for the control (*upper panel*) and CO_2 doubling (*middle panel*) experiment. **b, c** As in **a** but for the surface temperature and precipitation, respectively. *Lower panels* show the difference between control and

CO_2 doubling experiments. Units in **a**, **b**, and **c** are meters per kelvin, kelvins per kelvin, and millimeters per day per kelvin, respectively. Statistically significant areas at 90%, 95%, and 99% confidence levels are *shaded*

anomalous precipitation and located far from the western coast in the control experiment, almost touches the west coast in the $2CO_2$ experiment. Another wet center that appeared in the Atlantic Ocean in the control experiment also is slightly shifted and intensified by the CO_2 doubling. In addition, there is anomalous dry over high-latitude Pacific and the Alaska in the $2CO_2$ experiment, due to the intensified Aleutian Low.

The La Niña teleconnection is not an exact mirror image of the El Niño teleconnection because the teleconnection is nonlinear (Hoerling et al. 1997; An et al. 2007). For example, the counter parts of increases of Z500 in the central North Pacific and the east coast of North America in the difference map of El Niño composite are either disappeared in La Niña composite or located in further north. Differences are also found in the composite maps of surface temperature and precipitation. However, the La Niña composite patterns of atmospheric circulation is also systematically shift to the east as like in the El Niño composite, when comparing results of the control experiment and those of the $2CO_2$ experiment, during La Niña period (Fig. 5). In accordance with the change in atmospheric teleconnection, temperature and precipitation

anomalies in the North Pacific/America associated La Niña are also significantly changed. This systematic zonal shift of the El Niño and La Niña teleconnection patterns implies that the regional climate impact of ENSO will be changed significantly by a future global warming.

4 Summary and discussion

We investigate the change in the teleconnection of both El Niño and La Niña by comparison of the control and $2CO_2$ experiments obtained from IPCC-AR4 coupled general circulation model outputs. The eight-model ensemble mean exhibits the eastward shift of the main convection center by about 10~20° longitude as well as an intensification of the convection in the equatorial Pacific associated with El Niño (no intensification for La Niña), which is mainly due to tropical warming. The eastward shift of the main convection center causes a systematic eastward shift of both El Niño and La Niña teleconnection patterns over the North Pacific/American continent. In particular, the composite maps of 500 hPa circulation, surface temperature, and the precipitation against El Niño and La Niña demonstrates a
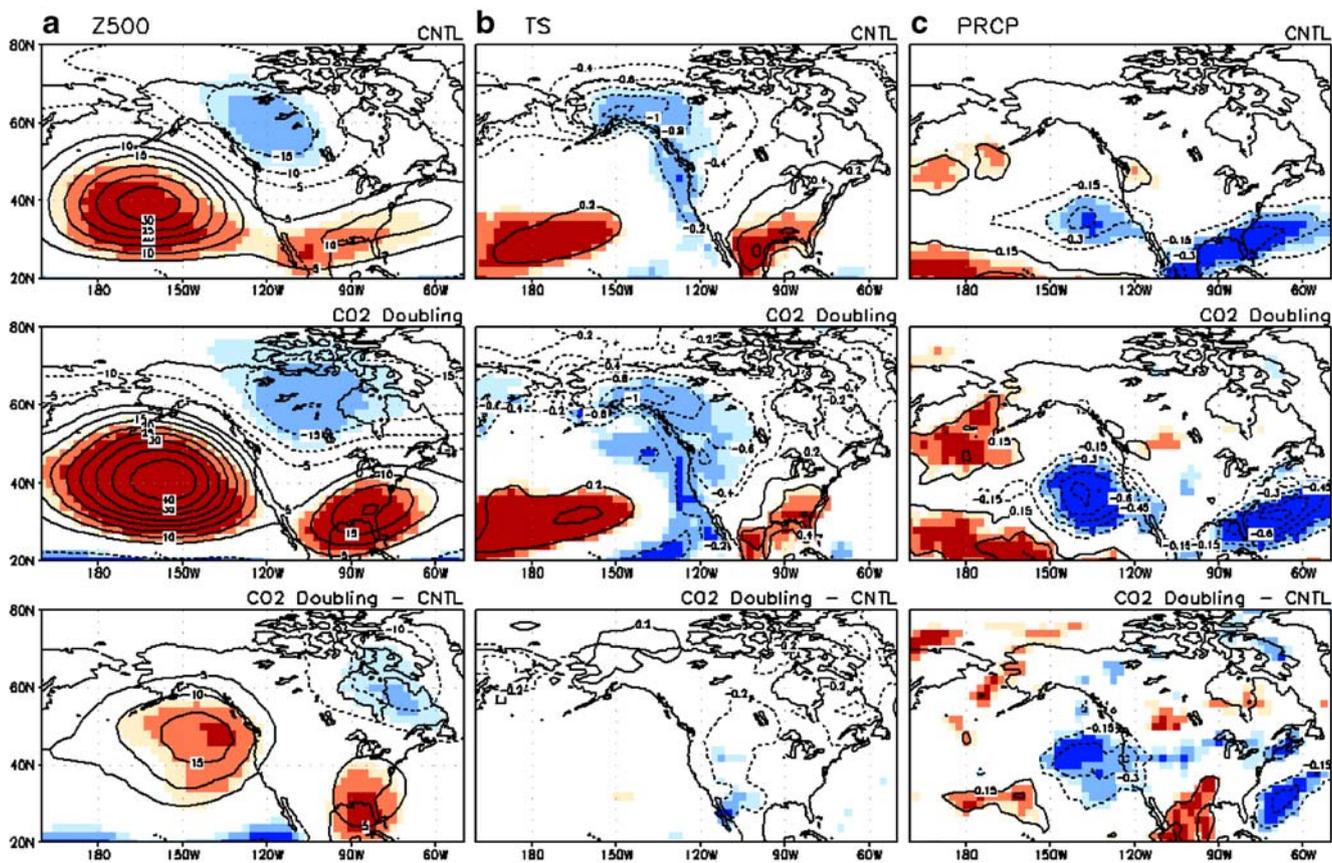
Fig. 5 As in Fig. 4 except for La Niña composite

strong possibility that the local climate impact of ENSO in a future will be different from that in the present.

As shown in Fig. 1, the multimodel ensemble shows an El Niño-like warming, meaning more increase of eastern Pacific SST than the western Pacific SST. However, it is still questionable as to whether the tropical mean climate response to the global warming is an El Niño like or not (Liu et al. 2005). One may ask whether the El Niño-like warming is critical for the eastward shift of the ENSO pattern. As discussed in Section 3, the eastward shift can be explained by the nonlinear response of the precipitation. If the mean SST is too cold, e.g., the cold tongue region, small change in SST cannot significantly alter precipitation. However, over the warm surface, small change in SST may lead to precipitation change much significantly. Therefore, the tropical Pacific warming leads to the eastward shift of the anomalous precipitation associated with ENSO. In this sense, it is clear that El Niño-like warming will enhance the eastward shift because the increase of cold tongue SST is relatively larger. However, it is expected that the future uniform warming would lead to the eastward shift of the ENSO pattern because the cold tongue SST is warmer than the current state. For example, the CNRM model simulate the eastward shift clearly in spite that the warming pattern is not El Niño like but mostly zonally uniform over the tropical Pacific. Therefore, the eastward shift of the ENSO pattern can be a robust response to the greenhouse warming irrespective of the pattern of the mean SST changes.

In this study, we showed significant differences in ENSO teleconnection pattern between the control and the greenhouse gases increasing scenario experiments. These changes are quite consistent with those in Meehl and Teng (2007), which also pointed out an eastward and southward shift of the anomalously deepened Aleutian Low. It is expected because among the eight models, used in the present study, five models are overlapped with their model selection. However, there is a remarkable difference between two results. While they argued that the anomalous Aleutian Low associated with El Niño will be weakened under global warming, our Fig. 4 clearly showed the intensified Aleutian Low anomalies, which is consistent with the intensified precipitation anomalies over the tropics as shown in Figs. 2 and 3. This difference possibly comes from the method of the multimodel ensemble. In this study, we normalized circulation anomalies of the each model based on the Niño-3.4 SST anomaly in order to avoid the dependency on ENSO magnitude. Otherwise, the models, having strong ENSO variability, have more weight for the multimodel ensemble. The amplitude change of the ENSO teleconnection is very critical issue in climate change because it has great impact on regional climate variability. Therefore, much careful examination on this problem should be taken in further study.

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