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How does a weakened Atlantic thermohaline circulation lead to an intensification of the ENSO-south Asian summer monsoon interaction?

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[1] This study investigates the change of the El Niño–Southern Oscillation (ENSO)-South Asian summer monsoon interaction in response to a weakened Atlantic thermohaline circulation (THC) by applying an additional freshwater flux into the North Atlantic. The simulated results indicate that the weakened THC leads to intensified ENSO-South Asian summer monsoon relationship and enhanced South Asian summer monsoon interannual variability. Furthermore, it is suggested that this intensification of the ENSO-monsoon relationship is likely due to the enhanced ENSO variability induced by the weakened THC. This study indicates that the low frequency fluctuation of Atlantic SSTs might have an influence on South Asian summer monsoon interannual variability and the ENSO-monsoon interaction, and suggests a nonlocal mechanism for the observed decadal-multidecadal modulation of ENSO-monsoon relationship.

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1. Introduction

[2] Coupled modeling studies [e.g., *Delworth et al.*, 1993; *Dong and Sutton*, 2002; *Vellinga and Wood*, 2002; *Timmermann et al.*, 2005; *Dahl et al.*, 2005; *Zhang and Delworth*, 2005; *Dong and Sutton*, 2007; *Timmermann et al.*, 2007] have shown that a weakened Atlantic thermohaline circulation (THC) generates substantial cooling in the North Atlantic and slightly warming in the South Atlantic, leading to a southward shift of the Atlantic intertropical convergence zone (ITCZ). The climatic impacts of weakened THC extend from the Atlantic region into the Pacific and the resulting changes of mean state in the Pacific lead to changes in El Niño–Southern Oscillation (ENSO) variability [e.g., *Dong and Sutton*, 2002, 2007; *Zhang and Delworth*, 2005; *Timmermann et al.*, 2005, 2007]. Most recent studies [*Dong and Sutton*, 2007; *Timmermann et al.*, 2007] clearly showed that a weakened THC leads to a stronger ENSO variability. On the other hand, using coupled atmosphere-ocean models, *Zhang and Delworth* [2005] and *Lu and Dong* [2008] simulated weakened South and East Asian summer monsoons in response to a weakened Atlantic THC. They argued that this effect on the monsoons is predominantly through atmosphere-ocean interactions in the tropical Pacific and Indian Ocean.

[3] Interaction between the ENSO and South Asian monsoon is one of the most dominant coupled phenomena in the climate system, and the decadal-multidecadal fluctuation of this interaction is still far from being understood. For instance, there is no consensus about the causes of the weakening of the ENSO-South Asian summer monsoon relationship since the late 1970s that were first documented by *Krishna Kumar et al.* [1999]. Recently, *Kucharski et al.* [2007] demonstrated that the tropical South Atlantic SST anomalies concurring with the ENSO may be responsible for this weakening of the relationship. This mechanism is only one of various possible causes that have been previously proposed, and a good review of them is given by *Kucharski et al.* [2007]. For instance, *Krishnan Kumar et al.* [2006] related the changing teleconnection to the spatial configuration of tropical Pacific SST anomalies.

[4] Although previous studies have shown that a weakened THC significantly enhances the ENSO variability [e.g., *Dong and Sutton*, 2007; *Timmermann et al.*, 2007] and weakens the climatological Asian summer monsoon [e.g., *Zhang and Delworth*, 2005; *Lu and Dong*, 2008], it is unknown whether a weakened THC modulates the South Asian summer monsoon interannual variability and its relationship with ENSO or not? If it does, what are the mechanisms responsible for this modulation? In this study, we attempt to answer these questions through investigating the responses to a weakened THC in a fully coupled atmosphere-ocean model.

2. Model and Experiments

[5] The model used in this study is a coupled atmosphere-ocean GCM developed at the Hadley Centre (HadCM3). The atmospheric component of HadCM3 has 19 levels with a horizontal resolution of 2.5° of latitude by 3.75° of longitude [*Pope et al.*, 2000], and the oceanic component has 20 levels with a horizontal resolution of 1.25 by 1.25° [*Gordon et al.*, 2000]. The model does not require flux corrections to maintain a stable climate. It has been shown that this model can capture the main features of circulation anomalies over the Asian summer monsoon region associated with the different ENSO phases [*Li et al.*, 2007], and simulate the internal variability of the ENSO-South Asian summer monsoon relationship that is independent of climate change [*Turner et al.*, 2007].

[6] A water-hosing experiment is conducted in which an extra freshwater flux of 1.0 Sv is applied for 100 years to

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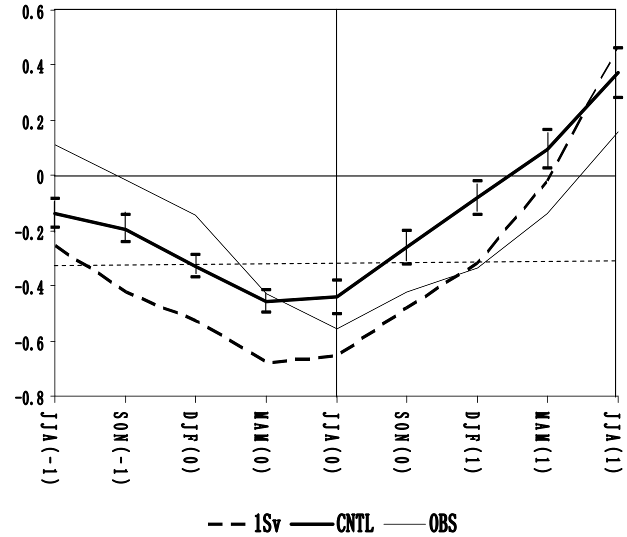

Figure 1. Lead-lag correlation coefficients between JJA-mean DMI and seasonal mean Niño 3 index in the control and water-hosing experiments, respectively. The dashed straight line represents the 99% confidence level for the simulated results. The lengths of bars indicate one standard deviation of correlation coefficients by using 100-year chunks in the 1000-year control simulation. Lead-lag correlations based on NCEP-NCAR reanalysis data and all Indian rainfall index (AIR) during 1948-2004 are shown as thin line for comparison with simulation.

the ocean surface of the North Atlantic between 50°N and 70°N. The initial condition is taken from the 1000 year control simulation of the coupled model [*Gordon et al.*, 2000]. This study analyzes the 100-yr parallel simulations of the control and water-hosing experiments. The same simulations were used by *Dong and Sutton* [2007] and *Lu and Dong* [2008] by focusing on the impacts of the weakened THC on the ENSO variability and mean Asian summer monsoon, respectively.

3. Results

[7] In this study, a dynamical monsoon index (DMI), first suggested by *Webster and Yang* [1992], is adopted to measure the intensity of the South Asian summer monsoon. Following *Turner et al.* [2005], the DMI is defined as the vertical shear of the area mean anomalous zonal wind [u(850 hPa) – u(200 hPa)] in the region (40°–110°E, 5°–20°N). Because we are focusing on the relationship between the ENSO and South Asian monsoon, we extract the signal of interannual variability by first removing 11-year running mean values before analysis. Those years in which the JJA-mean DMI falls outside half a standard deviation from the time mean have been defined as strong (positive) or weak (negative) monsoons, and used to perform composite analyses. It is worth pointing out that similar results and the same conclusion are reached using the unfiltered data.

[8] Figure 1 shows lead-lag correlation coefficients between JJA DMI and seasonal mean Niño 3 index. In the control experiment, there is a significant inverse correlation between the DMI and simultaneous Niño 3 index, which is consistent with that based on observations. Regarding the evolution of SSTs in the Niño 3 region associated with the DMI, however, HadCM3 does not well represent the timing of the teleconnection. As indicated in Figure 1 for the control experiment, the summer DMI is most strongly correlated with the Niño 3 SSTs in the preceding spring, while the simultaneous correlation is the strongest in observations. This discrepancy of the model relates to the effect of systematic model errors on the spatio-temporal evolution on El Nino, as discussed by *Turner et al.* [2005].

[9] In response to the weakened THC, the correlation between DMI and Niño 3 index increases considerably from time when ENSO is leading by two seasons to time when ENSO is lagging by a season. The simultaneous correlation coefficient increases from -0.44 in the control experiment to −0.65 in the water-hosing experiment. This increase of negative correlations is significantly larger than the correlation uncertainty estimated by using 100-year chunks in the 1000-year control simulation. These results suggest that the weakened THC leads to an intensified relationship between the ENSO and South Asian summer monsoon.

[10] Composites of 850-hPa horizontal wind and precipitation anomalies of strong minus weak South Asian summer monsoon years based on the DMI are illustrated in Figure 2. For the control simulation, the composites indicate that there are stronger southwesterlies in the lower troposphere over the Arabian Sea and the Indian subcontinent during strong monsoons relative to weak monsoons (Figure 2a), which are a well-known signature of strong South Asian monsoons [*Webster and Yang*, 1992; *Turner et al.*, 2005]. However, as Figure 2c indicates, the precipitation anomalies over the Indian continent associated with strong monsoon circulation are small in the control simulation. This implies a weak correspondence between the DMI and AIR, defined as precipitation over region (70°–90°E, 10°–20°N) for simulation, and the correlation between the JJA-mean two indices is 0.23, consistent with *Turner et al.* [2005, 2007] but much weaker than the observed (0.51). In comparison with that in the control experiment (Figure 2a), the easterly anomaly in the equatorial western and central Pacific associated with strong South Asian monsoon is much stronger in the water-hosing experiment (Figure 2b). The southwesterly anomaly to the west of India and westerly anomaly over India and the Bay of Bengal are also stronger in the water-hosing experiment than in the control experiment. Corresponding to these circulation anomalies, more significant precipitation anomalies appear in the tropical Indian Ocean and Pacific in the water-hosing experiment (Figures 2c and 2d). In the water-hosing experiment, particularly, there is a much stronger and significant positive precipitation anomaly in the Indian continent and the Bay of Bengal, which seems consistent with stronger wind anomaly around the monsoon trough over Northeast India and the head of the Bay of Bengal (Figure 2b). These results indicate that under the weakened THC monsoon variability, as measured dynamically, has significantly increased and that the DMI is more closely related to precipitation anomalies locally and in the tropical Pacific. In fact, the correlation between the DMI and AIR increases significantly to 0.62 in the water hosing experiment.

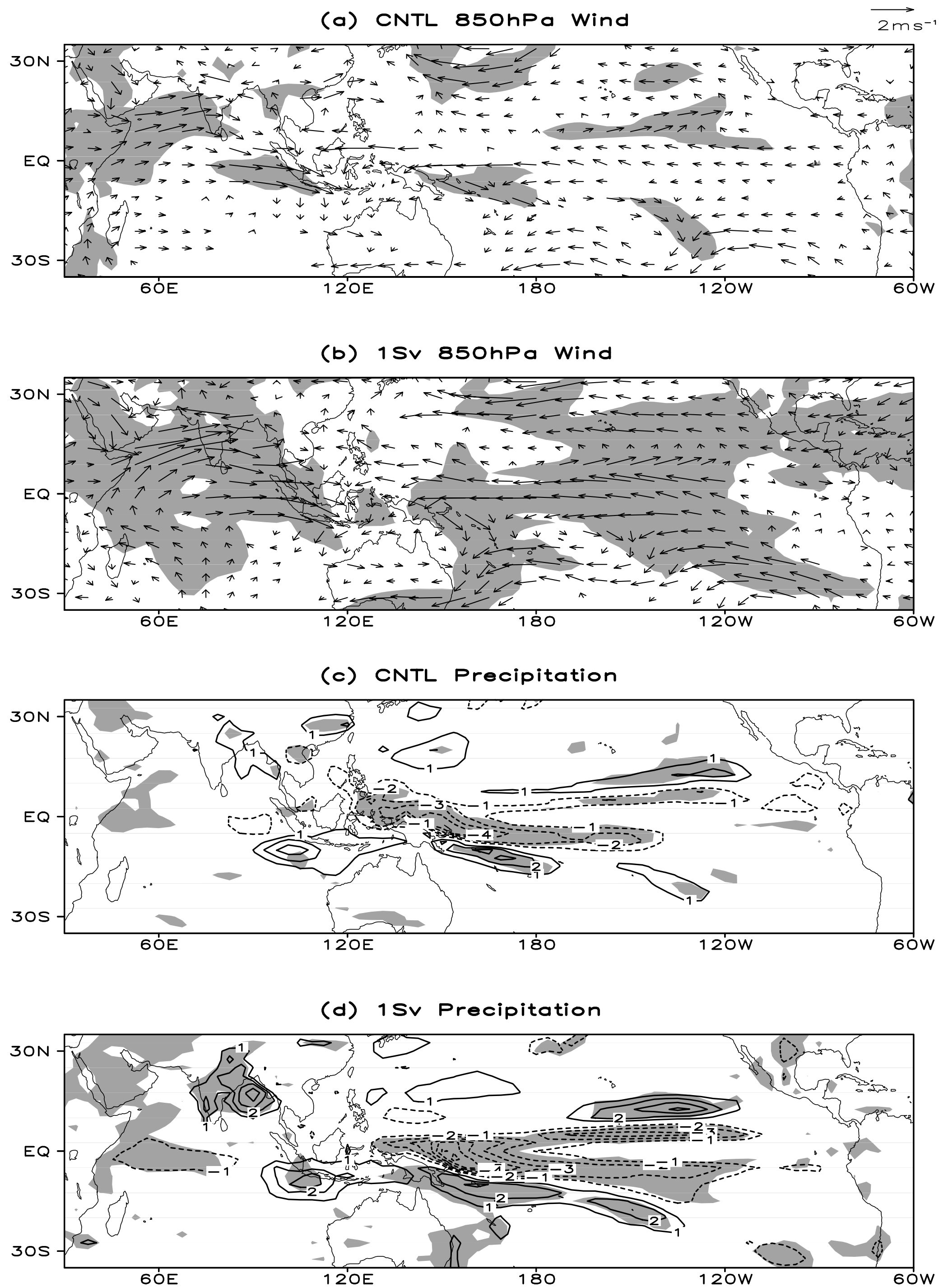

Figure 2. (a and b) Composite 850-hPa wind and (c and d) precipitation differences between strong and weak monsoons, based on the DMI, in the control and water-hosing experiments, respectively. Shading indicates the regions where anomalies are significant at 99% confidence level using t-test. For wind anomalies, shading indicates regions where either zonal or meridional components are significant.

[11] The SST anomalies associated with strong versus weak monsoons (Figure 3) further demonstrate a stronger ENSO-monsoon interaction in the water-hosing experiment. Both in the control and water-hosing experiments, the strong minus weak monsoon SST anomalies are negative in the equatorial central and eastern Pacific, consistent with the well-known negatively correlated relationship between the South Asia summer monsoon and ENSO, although it should be noted that ENSO variability in HadCM3 is too meridionally confined and extends too far into the western Pacific [e.g., *Turner et al.*, 2005, *Dong and Sutton*, 2007]. The magnitudes of these SST anomalies, including the negative SST anomalies in the Indian Ocean basin, however, are much stronger in the water-hosing experiment than

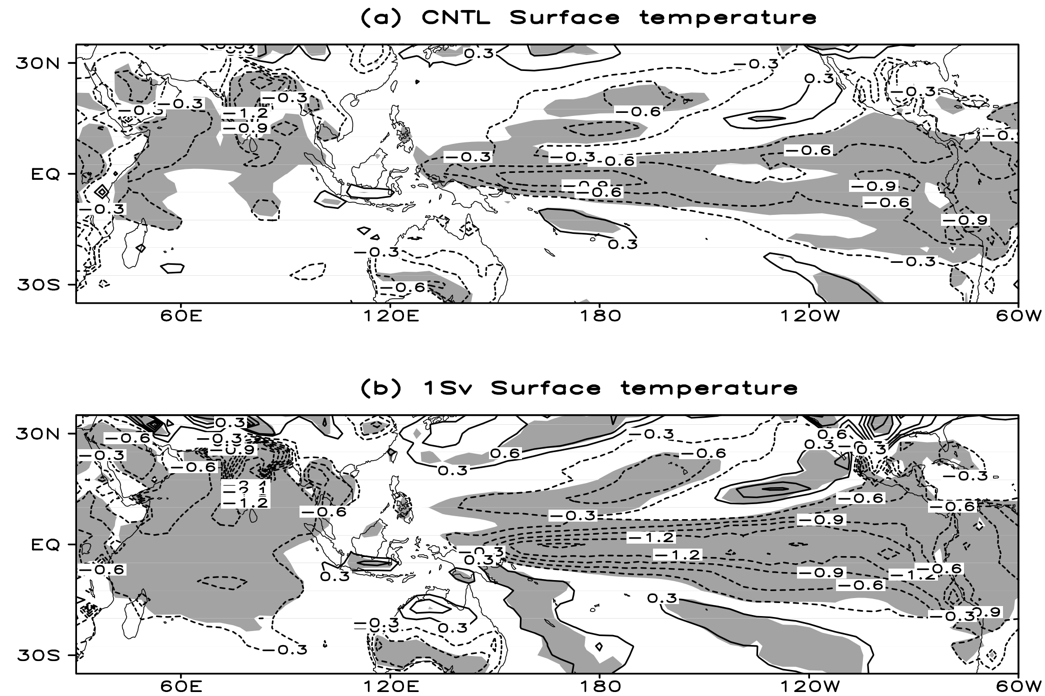

Figure 3. Same as Figures 2c and 2d, but for SST.

in the control experiment, indicating a stronger relationship between the monsoon and ENSO resulted from the weakened THC.

[12] Table 1 shows that the summer monsoon interannual variability is enhanced in response to the weakened THC. Considering that the mean summer monsoon itself is substantially suppressed by the weakened THC [*Zhang and Delworth*, 2005; *Lu and Dong*, 2008], the consequences of such a change in monsoon variability may result in particularly severe droughts in South Asia associated with El Niños. In addition, the variability in JJA-mean Niño 3 index is strengthened in the water-hosing experiment. Differences in interannual standard deviation of surface temperature between the 1Sv and control experiments (not shown) indicate that JJA-mean SSTs exhibit a greater interannual variability in the equatorial eastern Pacific in response to the weakened THC, consistent with *Dong and Sutton* [2007]. The enhancement of ENSO variability might favor a stronger monsoon-ENSO interaction. We performed a composite analysis based on strong and weak ENSO events in both the 1000-yr control and 1Sv experiments, and found that the atmospheric circulation anomalies associated with strong ENSO events exhibit larger amplitudes than those associated with weak ENSO events (not shown).

[13] *Turner et al.* [2005] illustrated a strong ENSO variability and an enhanced ENSO-monsoon interaction in a version of the model which used equatorial flux adjustments, and suggested that these changes are due to the improvement of mean state in the Indo-Pacific Oceans. The changes of climatological SSTs, 850-hPa horizontal winds and precipitation caused by the weakened THC (Figure 4) in the tropical Indian ocean and western tropical Pacific resemble those caused by the flux adjustments [*Turner et al.*, 2005, Figures 3d–3f]. This resemblance is characterized by the warmer SSTs/enhanced precipitation in the western Indian Ocean and cooler SSTs/suppressed precipitation in the eastern Indian Ocean, maritime continent and the western tropical Pacific, and by the westerly anomaly in the western Pacific and easterly anomaly in the eastern Pacific. The changes of climatological SSTs and precipitations induced by the weakened THC over central and eastern tropical Pacific (Figures 4a and 4c), however, exhibit appreciable differences to the flux corrected results [*Turner et al.*, 2005, Figures 3d and 3f]. The similarity of the mean state changes over the tropical Indian Ocean and western Pacific and differences of the changes over the central and eastern tropical Pacific between two studies imply that the mean state change over the Indian Ocean and western tropical Pacific might be more important than the eastern tropical Pacific in the change in ENSO-monsoon relationship.

4. Conclusion and Remarks

[14] A coupled atmosphere-ocean model, HadCM3, is utilized to study the changes of South Asian summer monsoon interannual variability and its interaction with ENSO in response to the weakening of the Atlantic THC by applying anomalous external freshwater forcing in the North Atlantic. The simulated results indicate that the

Table 1. Interannual Standard Deviations of the JJA-Mean DMI and Niño 3 Index in the Control and Water-Hosing Experiments[a]

	CNTL	1Sv
DMI SD	1.14	2.02
Niño 3 SD	0.87	1.27

[a]Units are in m s^{-1} for the DMI, and in °C for the Niño 3 index.

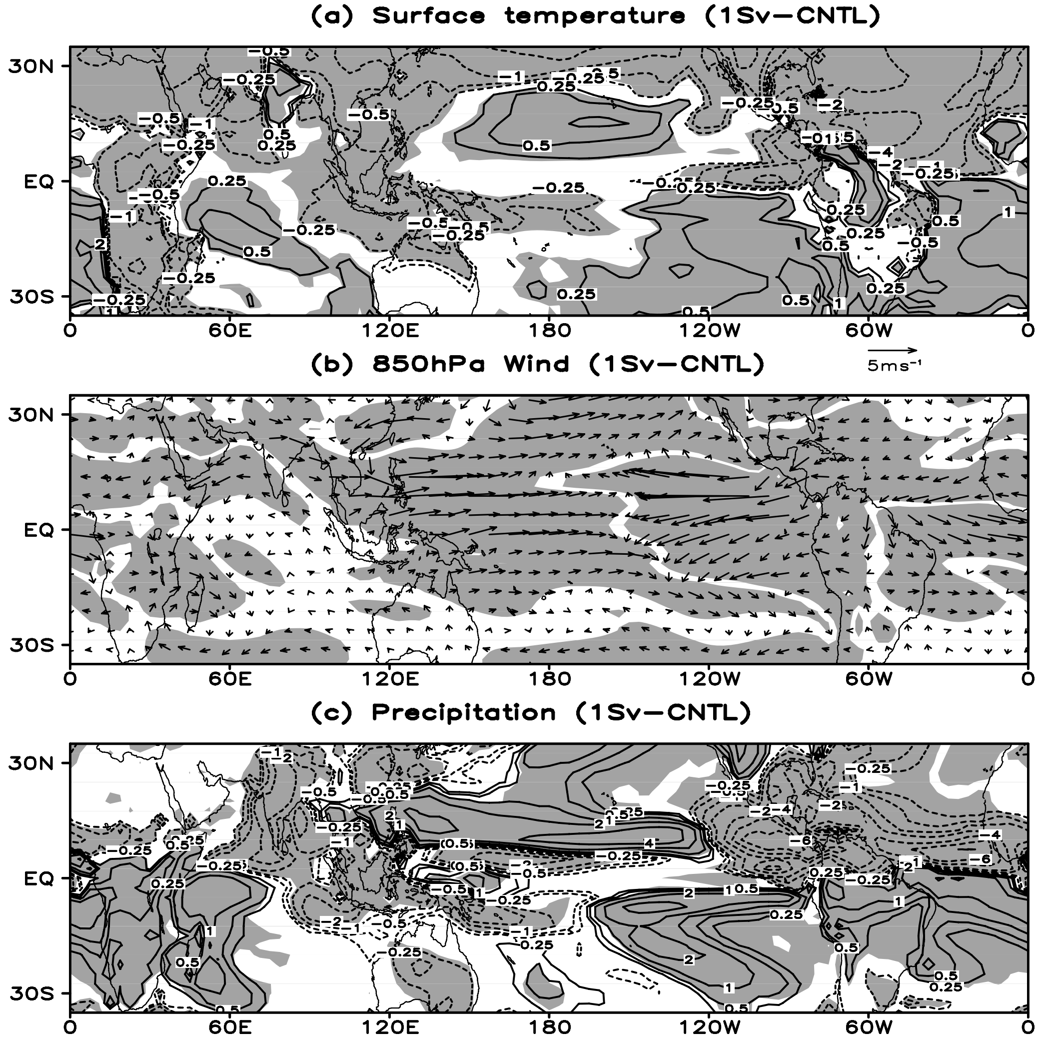

Figure 4. The climatological mean anomalies in JJA between the water-hosing and control experiments. (a) Surface temperature (°C), (b) 850-hPa wind (m s^{-1}), and (c) precipitation (mm day^{-1}). Shading indicates regions where anomalies are significant at 99% confidence level using t-test, and in (b) indicates regions where zonal wind anomalies are significant. Contours are ±0.25, ±0.5, ±1, ±2, ±4, and ±6 in Figures 4a and 4c. Adopted from *Lu and Dong* [2008], but with a focus on the tropics.

weakened THC leads to a stronger inverse ENSO-South Asian summer monsoon relationship. This intensification of the relationship is likely due to the intensified ENSO variability induced by the weakened THC. In addition, interannual variability of the South Asian summer monsoon is enhanced in the water-hosing experiment, consistent with the enhancement of ENSO variability, although the mean monsoon is weakened. The results indicate that fluctuations of the THC can mediate not only mean climate globally but also modulate the ENSO-monsoon interaction, and suggest the existence of non-local mechanisms for the decadal-multidecadal modulation of ENSO-monsoon relationship. However, there is an obvious need to be cautious to apply present results to explain the weakened ENSO-monsoon relationship since the late 1970s [*Krishna Kumar et al.*, 1999], which concurred with enhanced ENSO intensity [*Torrence and Compo*, 1998]. It has been suggested that other mechanisms [e.g., *Kucharski et al.*, 2007], rather than the change in ENSO intensity, would be responsible for the changes in ENSO-monsoon relationship in late 1970s.

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