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Journal
Annales Geophysicae, 25(9)

ISSN
1432-0576

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Publication Date
2007-10-02

DOI
10.5194/angeo-25-1929-2007

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Ann. Geophys., 25, 1929–1933, 2007
www.ann-geophys.net/25/1929/2007/
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Annales Geophysicae

Changes in the in-phase relationship between the Indian and subsequent Australian summer monsoons during the past five decades

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Received: 13 June 2007 – Revised: 28 July 2007 – Accepted: 10 August 2007 – Published: 2 October 2007

Abstract. This study examines the decadal changes in the in-phase relationship between Indian summer monsoon and the subsequent Australian summer monsoon using observational data from 1950–2005. The in-phase relationship is the tendency for a strong Indian summer monsoon to be followed by a strong Australian summer monsoon and vice versa. It is found that the in-phase relationship was weak during the late 1950s and early 1960s, strengthened to a maximum in the early 1970s just before the 1976/77 Pacific climate shift, then declined until the late 1990s. Pacific SST anomalies are noticed to have strong persistence from boreal to austral summer, providing the memory to connect the Indian and subsequent Australian summer monsoon. The simultaneous correlation between the Pacific SST anomalies and the Indian summer monsoon is always strong. It is the weakening and strengthening of the simultaneous correlation between the Australian summer monsoon and the Pacific SST anomalies that contributes to the decadal variations of the in-phase monsoon relation. This study suggests that the interaction between the Australian monsoon and the Pacific Ocean is crucial to tropical climate variability and has experienced significant changes over the past five decades.

Keywords. Meteorology and atmospheric dynamics (General circulation; Ocean-atmosphere interactions) – Oceanography: general (Climate and interannual variability)

1 Introduction

An interesting phenomenon in the Indian-Australian monsoon system is the tendency for a strong Indian summer monsoon to be followed by a strong Australian summer monsoon and vice versa (e.g. Hung et al., 2004, and the reference therein). Yu et al. (2003) used a coupled atmosphere-ocean general circulation model (CGCM) to examine the relative importance of the Pacific and Indian Oceans to this in-phase transition. They showed that the in-phase monsoon events occur more often in CGCM experiments that include an interactive Pacific Ocean, but less frequently in the experiment that includes an interactive Indian Ocean. They concluded that it is the sea surface temperature (SST) anomalies in the tropical Pacific that provide the needed memory during the transition season of these two monsoons to establish their in-phase relationship. One possible way for the in-phase monsoon relationship to be established (illustrated in Fig. 1) is to have highly persistent SST anomalies in the tropical Pacific which last from boreal summer (JJA) to austral summer (DJF) (process [1] in Fig. 1) and which have similar (i.e., same signs) and significant influences on the Indian monsoon in boreal summer (process [2]) and Australian monsoon in austral summer (process [3]). These conditions are known to be present during El Niño-Southern Oscillation (ENSO) events. Since many studies have suggested that ENSO experiences decadal changes in its properties (e.g. Gu and Philander, 1995; Wang, 1995) and its relationships with the Indian monsoon (Kumar et al., 1999; Kinter et al., 2002) and Australian monsoon (Power et al., 1999), it is reasonable to suspect that the in-phase relationship between the Indian and succeeding Australian summer monsoon may have also undergone decadal changes. These changes, if they exist, offer an opportunity to examine the validity of the mechanism hypothesized in Fig. 1 for the in-phase monsoon relationship. For this purpose, we analyze observational data from 1950–2005 in this study to examine the decadal changes in the in-phase monsoon relationship, the Pacific SST persistence, and their correlations with the two summer monsoons.

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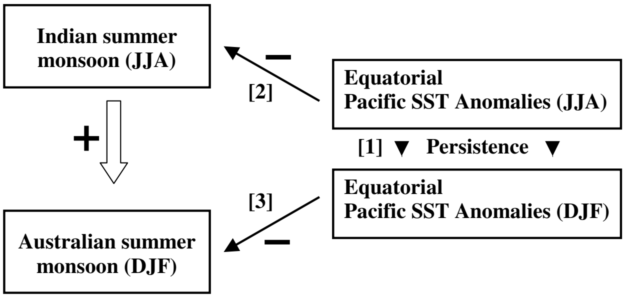

Fig. 1. A hypothetical mechanism for the in-phase relationship between the Indian and subsequent Australian summer monsoons. The "–" sign stands for a negative correlation and the "+" for a positive correlation.

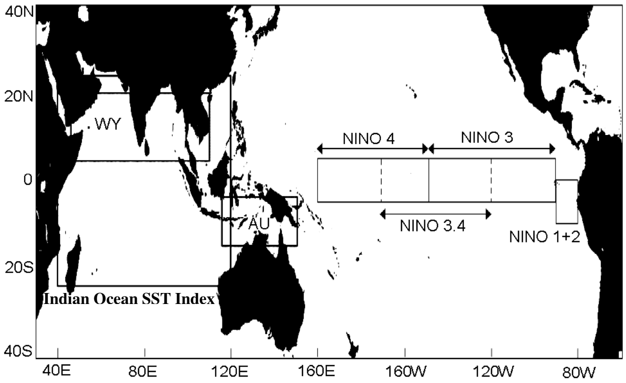

Fig. 2. The areas where the four Pacific SST Indices (NINO1+2, NINO3, NINO3.4, and NINO4), the Indian summer monsoon index (WY), the Australian summer monsoon index (AU), and the Indian Ocean SST index are defined and averaged. See text for the exact longitudinal and latitudinal ranges of each area.

2 Indices and data

This study examines the correlations among two monsoon circulation indices, four Pacific SST indices, and one Indian Ocean SST index. Figure 2 displays the areas where these indices are defined and calculated. The circulation index suggested by Webster and Yang (1992) (hereafter WY monsoon index) is used to represent the strength of Indian monsoon. This index is defined as the vertical shear of zonal wind between 850 hPa and 200 hPa averaged over the area of 5°–20° N and 40°–110° E. Following Hung and Yanai (2004), a broad-scale circulation index (AU monsoon index) was used to represent the strength of the Australian monsoon. This index is defined as the 850 hPa zonal wind averaged over the area of 2.5°–15° S and 110°–150° E. Monthly SST anomalies averaged over the NINO4 (160° E–150° W, 5° S–5° N), NINO3.4 (170°–120° W, 5° N–5° S), NINO3 (150° W–90° W, 5° N–5° S), and NINO1+2 (90° W–80° W, 0°–10° S) regions were used to represent ENSO SST anomalies in the central-to-eastern Pacific. The above indices were calculated from the NECP/NCAR Reanalysis (Kalnay et al., 1996) over the period 1950–2005. Anomalies were calculated using a base period of 1950–2005. The analyses presented here were performed without de-trending the data. We have repeated the analyses with the de-trended data and found little effect on the results.

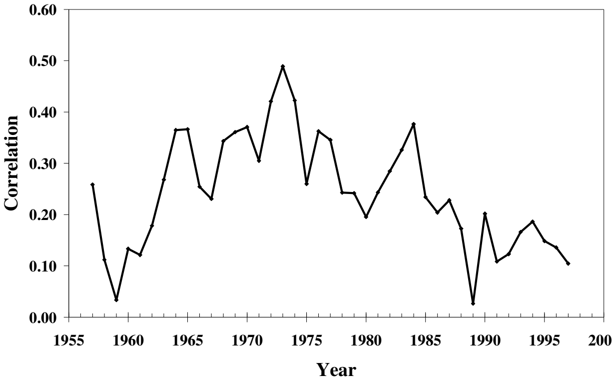

Fig. 3. The correlation coefficients between the WY monsoon index (JJA) and AU monsoon index (DJF) obtained from a sliding correlation analysis with a 15-year window.

3 Results

A 15-year sliding window was used to calculate the correlation between the boreal-summer WY monsoon index and the austral-summer AU monsoon index. We repeated the calculation with a 10-year and 20-year window and found the results similar. Figure 3 shows the decadal changes in the in-phase relationship between the Indian and succeeding Australian summer monsoon. It shows that the in-phase relationship was weak in the late 1950s, strengthened over the next decade and peaked in the early 1970s before the well-known 1976/77 Pacific climate shift. The in-phase relationship then weakened until the mid 1990s. We next examined the decadal changes in the three processes at work in the in-phase mechanism hypothesized in Fig. 1. The upper four curves in Fig. 4 show the decadal changes in the persistence of Pacific SST anomalies from boreal to austral summer. As a measure of the seasonal persistence, a 15-year sliding correlation analysis was used to calculate the correlation between JJA SST anomalies and DJF SST anomalies. The figure shows that SST anomalies in all four NINO regions maintained high persistence throughout the analysis period, except in the far eastern Pacific (NINO1+2) where the SST persistence dropped significantly from the mid 1970s to the early 1990s before returning to its previous strength. Our results are consistent with Yu and Kao (2007) who found the SST persistence barrier in the NINO1+2 region shifted from boreal spring to late summer during 1978–1988. They linked this barrier shift to changes of mean thermocline depth along

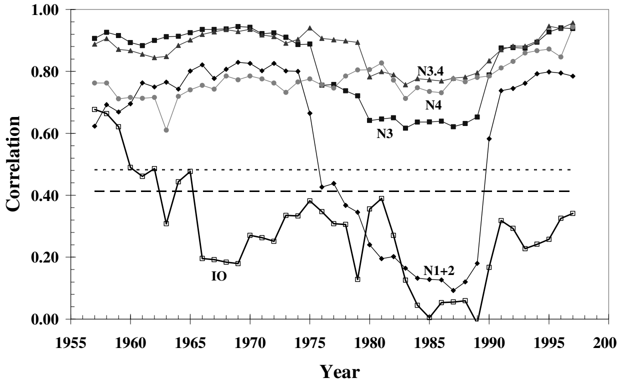

Fig. 4. Correlation coefficients between Pacific SST anomalies in boreal summer (JJA) and in austral summer (DJF) over the NINO4 (circles), NINO3.4 (triangle), NINO3 (square), and NINO1+2 (diamond) regions. Also shown is the correlation coefficient calculated for a tropical Indian Ocean SST index (see text) (hollow square). The dashed lines indicate the 90% (long-dashed) and 95% (short-dashed) significance levels.

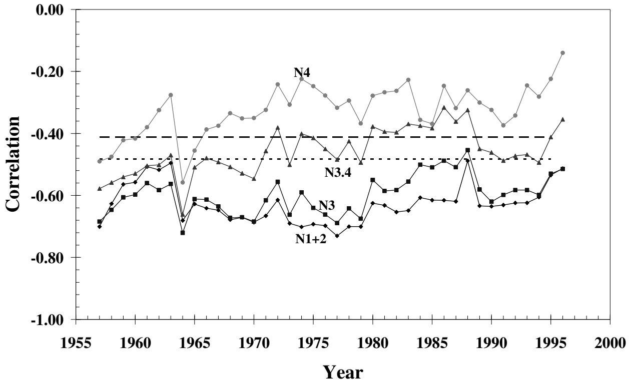

Fig. 5. Same as Fig. 4 but for the simultaneous correlation coefficients between the WY monsoon index (JJA) and the four NINO SST indices (JJA).

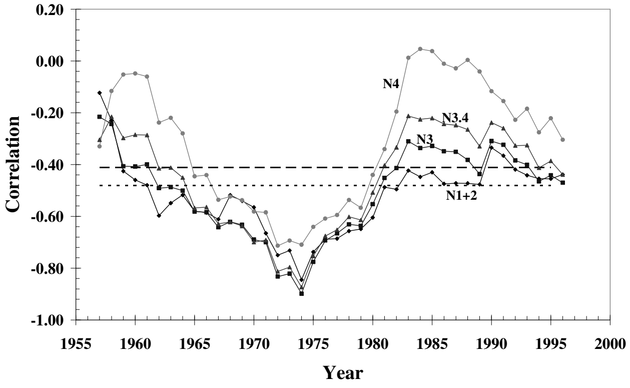

Fig. 6. Same as Fig. 4 but for the simultaneous correlation coefficients between the AU monsoon index (DJF) and the four NINO SST indices (DJF).

the equatorial Pacific. Figure 4 indicates that during the past five decades there were always SST anomalies in the central-to-eastern Pacific that can last from boreal to austral summer to link the strength of monsoon in these two seasons.

We next examined the changes in the relationships between Pacific SST anomalies and the two summer monsoons. Figure 5 shows the decadal changes in the simultaneous correlation between the WY monsoon index and the four NINO SST indices during boreal summer. The figure shows that the well-known negative simultaneous correlation between the Indian summer monsoon and Pacific SST anomalies (e.g. Rasmusson and Carpenter, 1983) exists throughout the analysis period. The monsoon has significant correlations with SST anomalies in the eastern Pacific (NINO1+2 and NINO3 regions) but not with the central Pacific (NINO3.4 and NINO4 regions). The correlations between summer WY index and NINO3 and NINO1+2 SST anomalies were strong and remained nearly constant throughout the past five decades. Therefore, the weakening of the in-phase monsoon relationship shown in Fig. 3 cannot be attributed to the changes in the simultaneous relationship between the boreal-summer Indian monsoon and Pacific SST anomalies either.

Figure 6 shows the decadal changes in the simultaneous correlations between the AU monsoon index and the four NINO SST indices during austral summer. It shows mostly negative correlations throughout the analysis period, which reflects the well-known fact that Australian monsoon is typically weakened (strengthened) during warm (cold) ENSO events (McBride and Nicholls, 1983). As in Fig. 5, the negative correlation is stronger with SST anomalies in the eastern Pacific (NINO1+2 and NINO3 regions). Unlike Fig. 5, there are large decadal changes in the correlation between the Australian summer monsoon and Pacific SST anomalies. The correlation was insignificant during 1957–1965. The correlation became significant from 1965 and peaked in the mid 1970s. This is consistent with a peak in the positive correlation between Australian monsoon rainfall and the Southern Oscillation Index (SOI) observed by Power et al. (1999). From the mid 1970s until the early 1980s this correlation weakened but remained significant. After the early 1980s the correlation between the Australian monsoon and Pacific SST anomalies became insignificant. Changes in the simultaneous correlation between the Australian summer monsoon and Pacific SST anomalies are similar and consistent with the changes seen in the in-phase relationship between the Indian and succeeding Australian summer monsoon (Fig. 3) except that the signs are reversed. When the correlation between the Australian monsoon and Pacific SST anomalies was weak (strong) the in-phase monsoon relationship was also weak (strong).

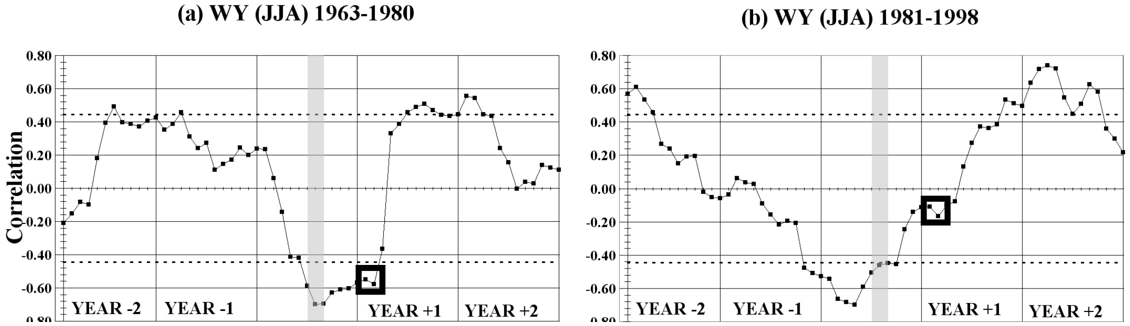

Fig. 7. The lead/lag correlation between WY monsoon index (JJA) and NINO 3 index for the periods of **(a)** 1963–1980 and **(b)** 1981–1998. Dotted lines indicate 95% significance. Shadings indicate the Indian summer monsoon season (JJA).

Several studies have argued that Indian Ocean SST anomalies are important in establishing the in-phase monsoon correlation. Joseph et al. (1991) suggested that tropical Indian Ocean SST anomalies induced by the Indian summer monsoon affect the strength of Australian summer monsoon by controlling the seasonal transition of the equatorial trough. The in-phase monsoon relation can be established as a result. To examine this mechanism, we repeated the SST persistence analyses of Figs. 4 with a tropical Indian Ocean SST index (SST averaged over 24° S–24° N and 40° E–120° E) but found very weak persistence for this Indian Ocean SST index. We include in Fig. 4 the correlation coefficient between the JJA and DJF values of the Indian Ocean SST index obtained from the 15-year sliding correlation analysis. It is obvious that the correlation is insignificant throughout most of the analysis period. This supports the suggestion of Yu et al. (2003) that the Indian summer monsoon forces Indian Ocean SST anomalies into transition after the monsoon season thus reducing the amplitude and persistence of these anomalies.

It is important to note that the weakening of the ENSO-Indian monsoon relation reported by earlier studies (e.g. Kinter et al., 2002) refers to the correlation between the Indian summer monsoon and the following-winter Pacific SST anomalies, not the simultaneous correlation examined in this study (Fig. 5). Thus, our results do not contradict those studies. Figure 7 shows the lead/lag correlation between the boreal-summer WY monsoon index and NINO3 SST anomalies for the periods of 1963–1980 and 1981–1998. These two periods were chosen to represent strong and weak, respectively, in-phase relationships between the Indian and succeeding Australian summer monsoon. From this figure, we can see that the lag correlation between the Indian summer monsoon and the following-winter Pacific SST anomalies is about -0.6 during 1963–1980 but less than -0.2 and thereby insignificant during 1981–1998 (indicated by hollow squares in Fig. 7). Those values are close to those reported by Kinter et al. (2002) for the periods before and after 1976. However, from Fig. 7, it is evident that the weakening of this lag correlation is related to the fact that the lead/lag ENSO-Indian monsoon relation changed from a quasi-biennial cycle during 1963–1980 to a longer one (close to 4 years) during 1981–1998. Large simultaneous correlations between the Indian summer monsoon and Pacific SST anomalies can still be found in 1981–1998. According to Meehl and Ablaster (2002), a strong connection between the Australian summer monsoon and the Pacific SSTs is necessary to switch the phase of the tropical biennial oscillation. Since the correlation between the Australian summer monsoon and Pacific SST anomalies weakened after 1980 (cf. Fig. 6), tropical biennial variability also likely weakened. This may explain why the ENSO-Indian summer monsoon relations shown in 1981–1998 (Fig. 7b) were less biennial.

4 Conclusions and discussions

We examined in this study the changes in the correlations between tropical Pacific SST, Indian summer monsoon, and Australian summer monsoon during the past five decades (1950–2005). It is found that: (1) SST anomalies in the central-to-eastern Pacific always had high persistence from boreal to austral summer; (2) the Pacific SST anomalies in the boreal summer maintained significant negative correlations with variations in the strength of the Indian summer monsoon; but (3) the simultaneous negative correlation between Pacific SST anomalies and Australian summer monsoon strength changed from decade to decade; and (4) these changes are consistent with the changes in the in-phase relationship between the Indian and succeeding Australian summer monsoon. Our results indicate that the changes in the in-phase monsoon correlation over the past five decades are related to the changes in the correlation of Pacific SSTs with the Australian summer monsoon. These results support our hypothesis that the in-phase monsoon relation results from persistent Pacific SST anomalies and their influences on the two summer monsoons. The results presented in this study suggest that the interaction between the Australian monsoon and the Pacific Ocean SST is crucial to tropical climate variability and has experienced significant changes over the past five decades. Identifying the cause of these changes is beyond the scope of this short report but is clearly important to our understanding of tropical decadal variability and ENSO periodicity.

Acknowledgements. The authors thank two anonymous reviewers for their useful comments which have improved this paper. M. A. Janiga is supported by the NSF grant ATM-0453495 and the UCI Earth System Science REU Program. J.-Y. Yu is supported by NSF grant ATM-0638432. Data analyses were performed at University of California, Irvine's Earth System Modeling Facility.

Topical Editor F. D'Andrea thanks two anonymous referees for their help in evaluating this paper.

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