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THE INTERANNUAL VARIABILITY IN THE TROPICAL INDIAN OCEAN AND ITS DECADAL MODULATION

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1. INTRODUCTION

The mechanism of the interannual variability in the tropical Indian Ocean is a major issue in tropical climate research. Examining ocean-atmosphere analyses for the past 40 years, Huang and Kinter (2000, 2001) showed that equatorial oceanic dynamics and *in situ* air-sea interaction play an important role in forming the basin-wide pattern of the interannual fluctuation in the tropical Indian Ocean. On the other hand, they also found that this Indian Ocean fluctuation is closely connected to the El Niño/Southern Oscillation (ENSO) in the tropical Pacific. Considering the Indian Ocean and its overlaying atmosphere as a coupled system, both the internal dynamics of the Indian Ocean and the external ENSO forcing are important for its oscillation.

Further analysis showed that a modulation of the Indian Ocean oscillation occurred on a multi-decadal time scale, with the dominant oscillating period of the upper ocean heat content changing from around two years to four years in late 1970s. It is consistent with Clark et al.'s (2000) finding that a change in the equatorial sea surface temperature (SST) variability occurred in Indian Ocean around 1976. At present, it is not clear what caused this change. Is it due to a change of mean state within the Indian Ocean as a part of a global climate transition? Or did the change of the ENSO cycle, which also underwent a frequency shift in late 1970s, caused a different external forcing to the Indian Ocean? We examine the ocean-atmosphere processes in these different periods.

2. DATA AND METHOD

In this study, we analyzed SST and the upper ocean heat content (HC). The latter is a crucial indicator of the dynamical displacement of the thermocline and oceanic wave propagation. Both quantities are derived from 41-year (1958-1998) ocean data assimilation (ODA) at COLA, using a 3-D variational scheme (Derber and Rosati, 1989, Huang et al., 1999). We have also analyzed the atmospheric fields from the NCEP re-analyses for the same period. The CPC precipitation data available for a relatively shorter period (1979-1998) have also been used in the analysis.

Considering the significant change of the Indian Ocean variability around 1976, we analyzed the data for the two periods, 1958-1976 and 1976-1998 separately. Moreover, to examine the characteristics of the interannual variability in the different ocean basins and their interaction, we conducted extended empirical orthogonal function (EXEOF) analysis for the seasonally averaged anomalies respectively for each variable in the Indian, the Pacific, and the Indo-Pacific domains. The seasonal average filters out month-to-month fluctuations that are not of our concern for this study. The EXEOF is performed with lags up to eight seasons (two years), surpassing the life span of a typical anomalous event in the Indian Ocean as well as an El Niño episode.

3. RESULTS

Our analyses show significantly different characteristics of the interannual variability for these two periods in the tropical Indian Ocean and its interactions with the Pacific. They are summarized as follows.

For 1976-1998, oscillatory patterns are identified by the two leading EXEOF modes of the HC anomalies in each ocean basin as well as in the indo-Pacific domain. In each case, the two modes explain comparable amount of variances and have similar temporal-spatial structure except a quadrantal lag between each other. Although derived separately, the principal components of these EXEOF modes all demonstrate a dominant period around four years and are highly correlated among each other. For instance, the correlation coefficient between the principal components of the 1st EXEOF modes from the Pacific and Indian Ocean alone cases is 0.63.

The temporal-spatial structure of the tropical Pacific oscillation shows the typical ENSO cycle, with the accumulation of, say, the warm HC anomalies in the west due to the off-equatorial westward propagation from central Pacific, followed by an eastward propagation along the equator and the warming up in the eastern ocean. On the other hand, the evolution of the HC anomalies within the Indian Ocean, as depicted from the Indian Ocean alone case, shows the accumulation of warm anomalies in the eastern equatorial Indian Ocean, which then slowly propagate westward in both south and north of the equator. During the propagating process, the HC anomalies are enhanced, especially in the south, which also persisted in the western Indian Ocean for a relatively longer period.

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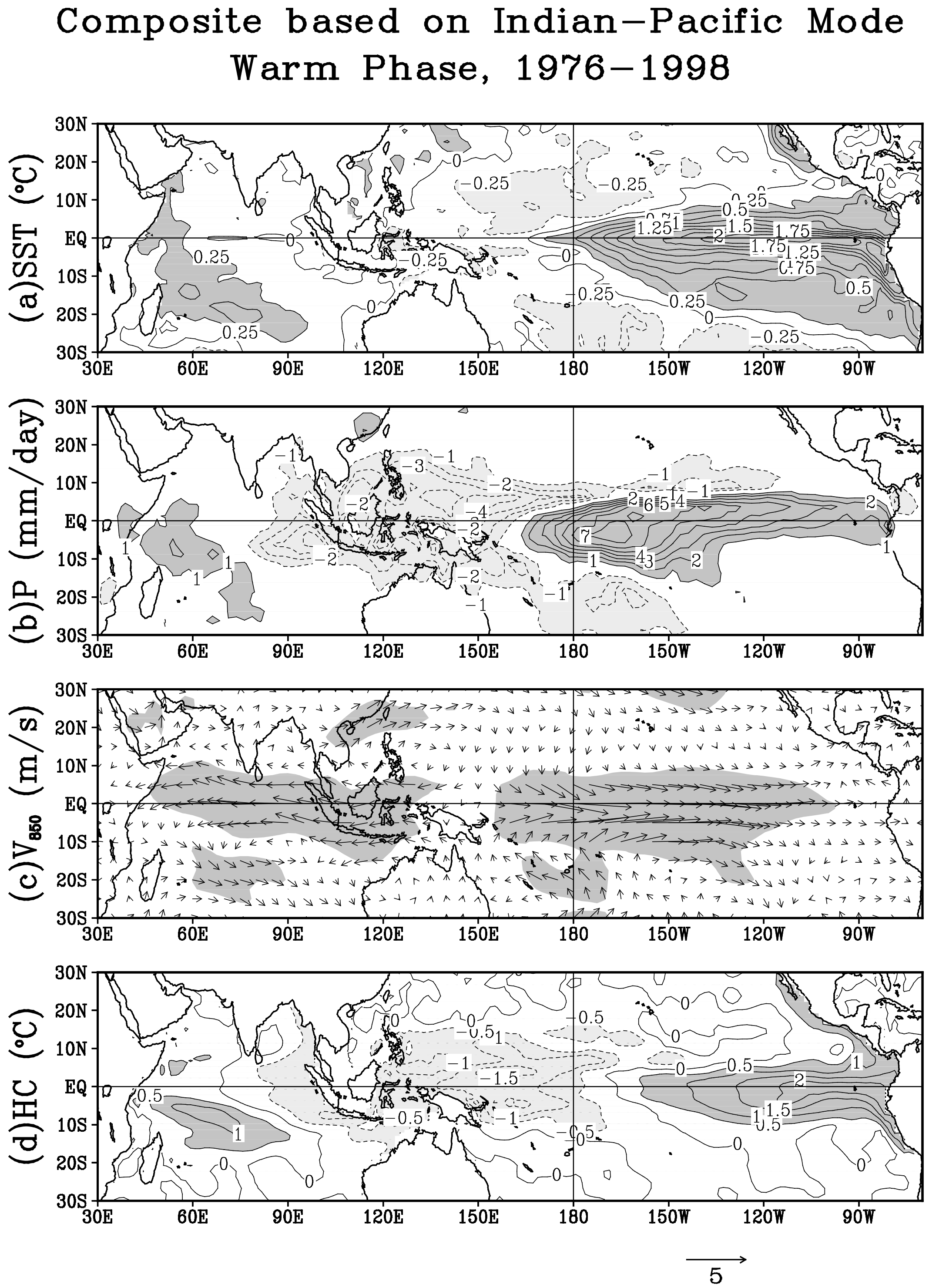

Figure 1 The warm phase in the eastern Pacific and the western Indian Oceans within a mean life cycle of the interannual HC evolution during 1976-1998 for the Indo-Pacific domain. Panel a is for SST with regions greater than 0.25°C darkly shaded and less than -0.25°C lightly shaded. Panel b is for precipitation with regions greater than 0.25°C darkly shaded and less than -0.25°C lightly shaded. Panel c for 850hPa winds with speed higher than 1m/s shaded. Panel d for HC with regions greater than 0.5°C darkly shaded and less than -0.5°C lightly shaded. Details of the composite procedure can be seen from Huang and Kinter (2001).

The most striking aspect of this variability is the quasi-simultaneity of the anomalous HC developments in these two ocean basins, which is best exhibited in the EXEOF modes from the Indo-Pacific domain. The HC anomalies are accumulated in the western Pacific and the eastern Indian Ocean simultaneously and they reach the eastern Pacific and the western Indian Ocean at nearly the same time. Figure 1 shows the composite of the HC, SST, precipitation, and 850hPa wind anomalies at the phase of warm eastern Pacific and the western Indian Oceans during an Indo-Pacific cycle, which exhibits its basic physics at work.

Associated with the Pacific SST anomalies (Fig. 1a), the anomalous rainfall pattern at this stage shows a shift of the convection from far-western Pacific to the central Pacific (Fig.1b). The shift of the convection center and the corresponding atmospheric heating sources produce an anomalous Walker Circulation with branches in both the Pacific with equatorial westerly winds and Indian Ocean with equatorial easterly winds (Fig.1c). It was these equatorial wind anomalies that affect the HC propagation in both ocean basins (Fig.1d), which in turn enhance the SST anomalies (Fig.1a). It should be pointed out that there is an increased convection near the western equatorial Indian Ocean, which further enhances the equatorial wind anomalies over the Indian Ocean. In this sense, what happened in the equatorial Indian Ocean "mirrored" the Pacific ENSO. The positive feedback will be terminated by the negative HC anomalies, which is accumulated in the far-western Pacific and the eastern Indian Ocean at this stage (Fig.1d).

During 1958-1976, however, the situation is somewhat different. The EXEOF mode from Indo-Pacific domain showed a spatial-temporal evolution that is dominated by the Pacific ENSO cycle, similar to the one from Pacific alone case, while the signals in the Indian basin are weak. The frequency of the ENSO cycle in this period is somewhat shorter, at around two to three years, which has been noticed by previous studies (e.g., Wang and Wang 1996). On the other hand, the Indian Ocean oscillation, derived from the leading EXEOF modes for the Indian Ocean alone, showed an oscillating frequency that is different from ENSO, with a nearly biennial period. The correlation coefficient between the leading principal components of the Indian and the Pacific EXEOF mode (0.45) are not as high as for the period of 1976-1998.

The temporal-spatial structure of the Indian Ocean mode was still characterized by anomalous HC propagations in the equatorial ocean somewhat similar to the one described for 1976-1998 period. The main difference is that the time of persistence of the HC anomalies in the southern western Indian Ocean was shorter, which seems to be the main reason of the higher oscillating frequency. A composite analysis based on the mean life cycle of the HC development showed that there was still a certain phase relationship between the Indian Ocean oscillation and ENSO. However, the mean amplitude of the ENSO signals in these composites is not large, suggesting that the link is relatively weak. On the other hand, measured by the 200hPa velocity potential, the regional east-west shift of the convections within the Indian Ocean seemed more active and was responsible for the fluctuation of the equatorial zonal winds.

In summary, the shift of the tropical convection in the warm pool region can affect the interannual variability in both the Pacific and the Indian Oceans through generating anomalous Walker circulation over both oceans, which in turn change the oceanic thermocline structure and SST. On the other hand, the shift of the convection is largely controlled by SST anomalies in both oceans. During the period of 1976-1998, the variability in the Indo-Pacific domain was dominated by the ENSO cycle, while the Indian Ocean mainly responded to this external forcing. This may explain the quite in-phase evolution between these two oceans during this period. However, it is not yet clear whether the active involvement of the tropical Indian Ocean affected the nature of ENSO, which may account for its lower frequency at this period. On the other hand, although the ENSO forcing may still not be totally ignored over the Indian Ocean, it seemed weaker during 1958-1976. The interannual variability there was mainly influenced by the regional ocean-atmosphere-land coupling. That may be why a different frequency of oscillation emerged, which could be the eigen-frequency of this regional coupled system.

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