

Decadal variation of thermocline-sea surface temperature feedback in the tropical Indian Ocean and the underlying mechanisms

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Received 5 May 2021; accepted 6 August 2021

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Abstract

The thermocline-sea surface temperature (SST) feedback is the most important component of the Bjerknes feedback, which plays an important role in the development of the air-sea coupling modes of the Indian Ocean. The thermocline-SST feedback in the Indian Ocean has experienced significant decadal variations over the last 40 a. The feedback intensified in the late twentieth century and then weakened during the hiatus in global warming at the early twenty-first century. The thermocline-SST feedback is most prominent in the southeastern and southwestern Indian Ocean. Although the decadal variations of feedback are similar in these two regions, there are still differences in the underlying mechanisms. The decadal variations of feedback in the southeastern Indian Ocean are dominated by variations in the depth of the thermocline, which are modulated by equatorial zonal wind anomalies. Whereas the decadal variation of feedback in the southwestern Indian Ocean is mainly controlled by the intensity of upwelling and thermocline depth in winter and spring, respectively. The upwelling and thermocline depth are both affected by wind stress curl anomalies over the southeastern Indian Ocean, which excite anomalous Ekman pumping and influence the southwestern Indian Ocean through westward propagating Rossby waves.

Key words: Indian Ocean, thermocline-SST feedback, decadal variation, upwelling, thermocline depth

Citation: Zhang Meiqi, Sun Shuangwen, Liu Lin, Zu Yongcan, Feng Lin. 2021. Decadal variation of thermocline-sea surface temperature feedback in the tropical Indian Ocean and the underlying mechanisms. *Acta Oceanologica Sinica*, 40(11): 31–38, doi: 10.1007/s13131-021-1950-8

1 Introduction

The Bjerknes feedback is a positive feedback loop including the response of the equatorial zonal wind to the sea surface temperature (SST), the response of the thermocline to equatorial zonal winds and the response of the SST to variations in the thermocline (Bjerknes, 1969). Although the Bjerknes feedback was first used to explain air-sea interactions in the Pacific Ocean (Neelin et al., 1998; Zelle et al., 2004; Xiang et al., 2012; Zhu et al., 2015, 2021; Dong and McPhaden, 2018; Yuan et al., 2020), it has also been shown to be a key mechanism in the formation and development of the two major interannual ocean-atmosphere coupled modes in the Indian Ocean (Saji et al., 1999; Xie et al., 2010): the Indian Ocean Dipole (IOD) (Saji et al., 1999) and the Indian Ocean Basin (IOB) (Cadet, 1985) modes. Among the three components of the Bjerknes feedback, the response of the SST to variations in the thermocline, which is referred to as the thermocline-SST feedback, contributes the most to the intensity of the Bjerknes feedback (Jin et al., 2006). It is also a key process in the Bjerknes feedback influencing IOD and El Niño Southern Ocean

events (Cai et al., 2013; Ren and Jin, 2013; Ng et al., 2014, 2018; Kim et al., 2017; Zhu et al., 2021).

The strength of the thermocline-SST feedback depends on the mean state of the tropical Indian Ocean. The vertical velocity and the depth of the thermocline are the two most important factors. The subsurface temperature anomaly, which is induced by fluctuations in the thermocline depth, is transported upward by upwelling until it reaches the surface (Zelle et al., 2004). When upwelling is weak and there is a deep thermocline, the weak vertical advection cannot efficiently transfer the subsurface temperature anomaly to the surface. In addition, the response of the SST anomaly to variations in the depth of the thermocline is delayed as a result of the greater distance between the thermocline and the sea surface. The thermocline-SST feedback is therefore weakened (Zelle et al., 2004; Zhu et al., 2015). By contrast, a shallower thermocline and a greater mean vertical upwelling velocity favor a strong thermocline-SST feedback (Liu et al., 2011).

The strength of the thermocline-SST feedback has changed significantly in recent decades in response to changes in the

Foundation item: The National Natural Science Foundation of China under contract Nos 41976021, 41676020, 41876028 and 41876030; the Taishan Scholars Programs of Shandong Province under contract Nos tsqn201909165 and ts20190963; the Global Change and Air-Sea Interaction Program under contract No. GASI-04-QYQH-03.

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mean state of the oceans. For example, the climatological thermocline in the southeastern Indian Ocean has shallowed under global warming and therefore the response of the SST to the thermocline has increased. This has contributed to the increase in the frequency of the IOD in the second half of the twentieth century (Cai et al., 2013) and the emergence of an unseasonable IOD in the last 30 a (Du et al., 2013). The thermocline-SST feedback in the southwestern Indian Ocean is a key factor in the development of the IOB. The IOB and the resultant Indian Ocean capacitor effect have intensified since 1970 and will continue to intensify under global warming as the thermocline-SST feedback strengthens as a result of shallowing of the local thermocline (Xie et al., 2010; Zheng et al., 2010).

The global SST underwent rapid warming in the second half of the twentieth century. The rate of global warming then slowed and there was a hiatus in global warming in the early twenty-first century (Easterling and Wehner, 2009; Kerr, 2009; Stan et al., 2017). The trend of the depth of the thermocline in this period of hiatus is distinct from that in the period of rapid warming, when notable subsurface cooling was accompanied by a shallowing thermocline (Han et al., 2006; Trenary and Han, 2008). By contrast, abrupt subsurface warming and a deepening thermocline were detected when the surface warming of the tropical Indian Ocean stalled in the hiatus period (Lee et al., 2015; Nieves et al., 2015). Because the depth of the thermocline can greatly affect the thermocline-SST feedback, it is reasonable to hypothesize that a reversed trend in the depth of the thermocline could induce significant changes in thermocline-SST feedback in the Indian Ocean. However, the variation in the thermocline-SST feedback in this time period is not clear at the present time. We therefore analyzed the variation in the thermocline-SST feedback over the last 40 a and discuss the underlying mechanisms.

2 Data

To ensure the robustness of the results, four sea temperature datasets are used for the SST and thermocline depth calculations. The depth of the 20°C isotherm is used as a proxy for the depth of the thermocline. The four datasets are: the UK Meteorological Office Hadley Center EN 4.2.1 quality-controlled ocean temperature dataset (Good et al., 2013) from 1900 to the present day; the Simple Ocean Data Assimilation version 3.4.2 (SODA 3.4.2) reanalysis dataset from 1980 to 2019 (Carton and Giese, 2008); the Operational Ocean Reanalysis System 4 (ORAS4) reanalysis dataset from 1958 to 2016 (Balmaseda et al., 2013); and the National Centers for Environmental Prediction Global Ocean Data Assimilation System (GODAS) dataset from 1980 to 2019 (Behringer and Xue, 2004). These datasets successfully capture the reversed trend in the depth of the thermocline between the rapid warming period and hiatus period (Fig. 1). In addition, surface wind field of NCEP/NCAR Reanalysis Monthly Means dataset from 1948 to 2019 (Kalnay et al., 1996) was used to analyze the zonal wind and wind stress curl. Considering the time range of these datasets and the purpose of this study, we select the last 40 a (1980–2019; 1980–2016 for the ORAS4 dataset) to study the decadal variations in the thermocline-SST feedback.

The correlation and regression coefficient between the SST and thermocline depth are calculated based on their monthly anomalies. The thermocline depth anomalies and SST anomalies for each month are computed by subtracting the corresponding monthly climatology. The decadal variations in the correlation and regression coefficients are calculated using the four datasets and the result is consistent among all four datasets. The 20°C-isothermal depth (D20 hereafter) is used as a proxy for thermocline depth.

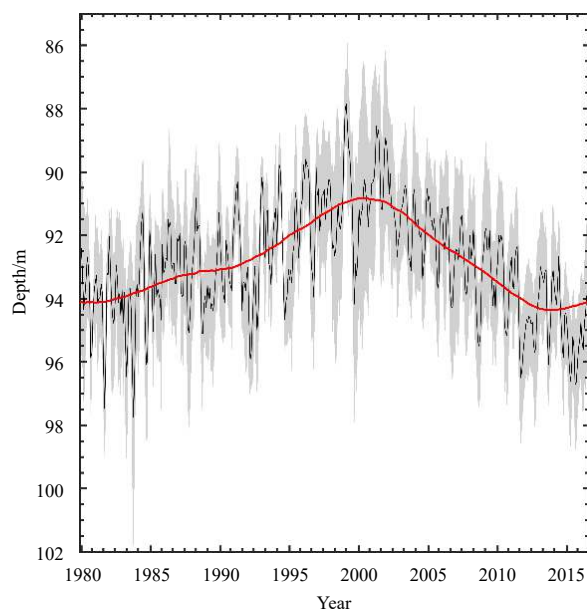


Fig. 1. Decadal variation in the depth of the thermocline in the tropical Indian Ocean (15°S–15°N, 40°–120°E). The solid black line and the gray shading are the mean and standard deviation, respectively, of the thermocline depth calculated using the GODAS, SODA 3.4.2, ORAS4 and EN 4.2.1 datasets. The solid red line is the nine-year running mean of the average thermocline depth.

3 Decadal variations in the thermocline-SST feedback

We first analyzed the seasonal variation in the correlation coefficient between the D20 anomaly and SST anomaly in the tropical Indian Ocean. Spring, summer, autumn and winter are represented by the four typical months of April, July, October and November, respectively. Figure 2 shows that the regions with the strongest positive correlation between the D20 anomaly and SST anomaly are mainly located in the southeastern and the southwestern Indian Ocean. The positive correlation in the southeastern Indian Ocean is most significant in summer and autumn, whereas that in the southwestern Indian Ocean is strongest in winter and spring. These results are consistent with previous studies (Annamalai et al., 2003). These two regions are crucial in the development of air-sea coupled phenomena in the Indian Ocean. The thermocline-SST feedback in the southwestern Indian Ocean plays a key part in the formation of the IOB and can modulate the decadal variation of the IOB and the subsequent Indian Ocean capacitor effect (Xie et al., 2010). The southeastern Indian Ocean is the region with the strongest anomalies in both the ocean and atmosphere. The thermocline-SST feedback in this region is crucial in the development and change in decadal frequency of the IOD (Cai et al., 2013). We therefore selected the southeastern Indian Ocean (0°–10°S, 90°–110°E) and the southwestern Indian Ocean (8°–14°S, 65°–80°E) for specific analysis on the interdecadal changes in the thermocline-SST feedback.

The correlation coefficient between the D20 anomaly and the SST anomaly reflects the synchronicity of their interannual variations. It is an important indicator used to measure the significance of the thermocline-SST feedback. Figures 3a and b show the 19-year sliding correlation coefficient between the D20 anomaly and the SST anomaly in the southeastern and southwestern Indian Ocean. The years in Fig. 3 denote the centers of the sliding windows (e.g., 2000 represents the correlation in the 19-year sliding window of 1991–2009). The results in Fig. 3a show that there

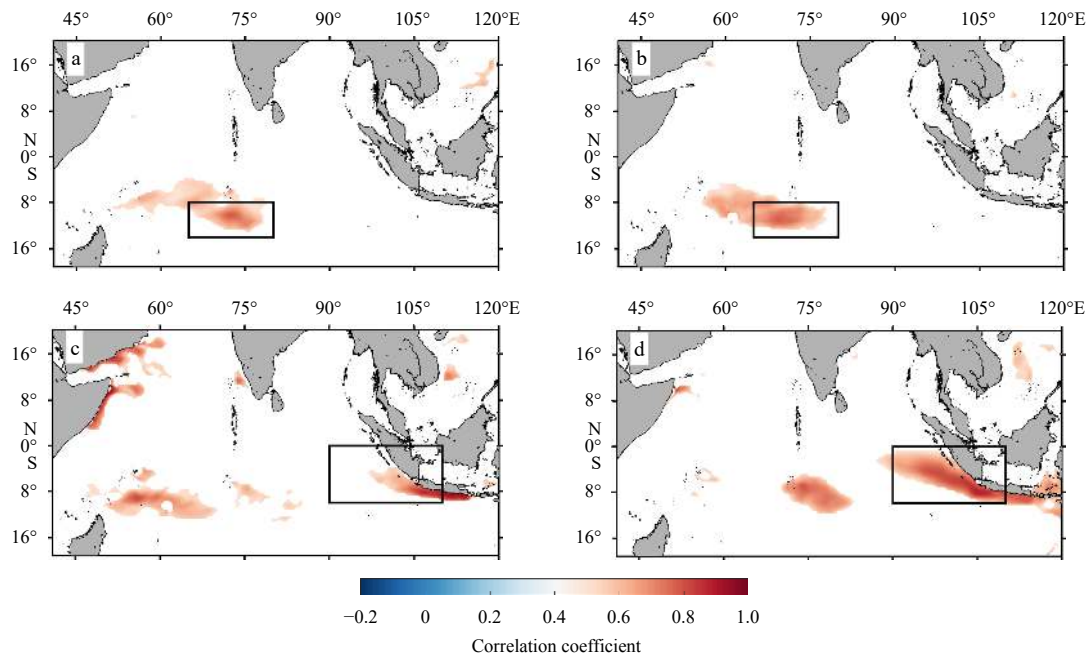


Fig. 2. Seasonal variation in the correlation coefficient between the D20 anomaly and SST anomaly in the Indian Ocean in January (a), April (b), July (c) and October (d) based on the SODA 3.4.2 dataset. Values exceeding the 95% significance level are shaded. The black rectangles denote the location of the southwestern Indian Ocean and the southeastern Indian Ocean.

is a significant positive correlation from July to December in the southeastern Indian Ocean that peaks in the autumn. The correlation coefficient between the D20 anomaly and the SST anomaly shows pronounced decadal variations in these months. The correlation coefficient shows a rapid increase before about 2002 from about 0.6 to >0.8 and then decreases. The positive correlation persists through winter and spring in the southwestern Indian Ocean and the decadal variation is the most significant in these two seasons (Fig. 3b). Similar to the southeastern Indian Ocean, the decadal trend of the southwestern Indian Ocean reversed at the start of this century and the correlation coefficient was greater than 0.8. We compared the decadal trends of the correlation in their peak months based on different datasets in Figs 3c and d. As different datasets use different models and methods in data assimilation, the results of them are slightly different. Argo data has been added to all the four data sets since 2000, which improved the data quality considerably. The four datasets all captured the basic characteristics of the decadal variations in the correlation coefficient in the two regions. It is also evident that our results showed better consistency after 2000 (Figs 3c and d).

In addition to the correlation coefficient, the regression coefficient between the SST anomaly and the D20 anomaly is also an important indicator used to measure the significance of the thermocline-SST feedback. The value of the regression coefficient represents the intensity of the response of the SST anomaly to the D20. A larger regression coefficient implies a greater SST response to a unit of change in the D20.

To further analyze the decadal variation in the thermocline-SST feedback, we compared the regression coefficients and correlation coefficients of the SST anomaly and the D20 anomaly during the study period. We selected the months with the strongest correlation between D20 anomaly and SST anomaly in the tropical Indian Ocean—that is, July–November in the tropical southeastern Indian Ocean and April–June in the tropical southwestern Indian Ocean. Figure 4 shows that the decadal vari-

ations in the correlation and regression coefficients are highly consistent with each other. They both first strengthened and then weakened during the study period. The thermocline-SST feedback was therefore strongest at the beginning of the twenty-first century from both the perspective of the synchronicity and the intensity of the response between changes of D20 anomaly and SST anomaly.

4 Mechanisms of the decadal variations in the thermocline-SST feedback

Previous studies have shown that D20 and vertical velocity are the two most important factors in the variation of the thermocline-SST feedback. This section explores their changes during the study period and examines their contribution to the decadal variation in the thermocline-SST feedback.

The decadal variations of D20 and the correlation between D20 anomaly and SST anomaly are in good agreement in the seasons with a significant thermocline-SST feedback. The thermocline rises before 2002 and deepens in the following years (Fig. 5). When the thermocline rises, it is closer to the sea surface and therefore variations could influence the SST more directly and quickly, which favors an increase in the thermocline-SST feedback. The D20 in the southeastern Indian Ocean is shallowest in about 2002 (Fig. 5a), which coincides with the time when the thermocline-SST feedback is strongest in the study period (Fig. 3a). The thermocline in the southwestern Indian Ocean rises before 2003 and deepens in the following years (Fig. 5b), which is also consistent with the variation in the correlation between D20 anomaly and SST anomaly in this region (Fig. 3b). For the same reason as Figs 3c and d, the results of the four data sets are slightly different in Figs 5c and d. The four datasets all captured the basic characteristics of the decadal variations of D20 in the two regions. The results also showed better consistency after 2000. These results confirm the importance of D20 in the decadal variation of the thermocline-SST feedback. Besides,

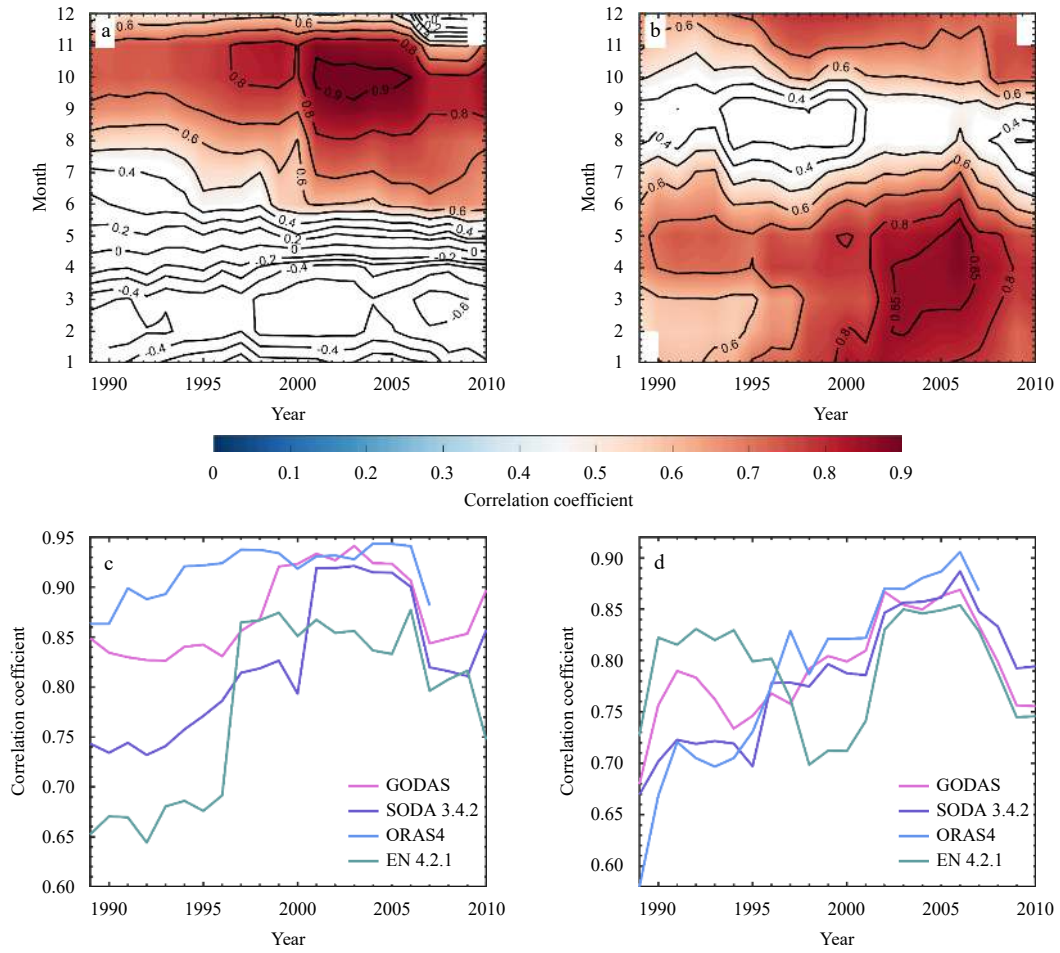


Fig. 3. Decadal variation in the correlation coefficient between the D20 anomaly and SST anomaly in the southeastern (a) and the southwestern (b) Indian Ocean based on the SODA 3.4.2 dataset (values exceeding the 95% significance level are shaded); and the decadal variations of the correlation coefficient between the D20 anomaly and SST anomaly in the southeastern Indian Ocean during October (c) and the southwestern Indian Ocean during April (d) based on multiple datasets.

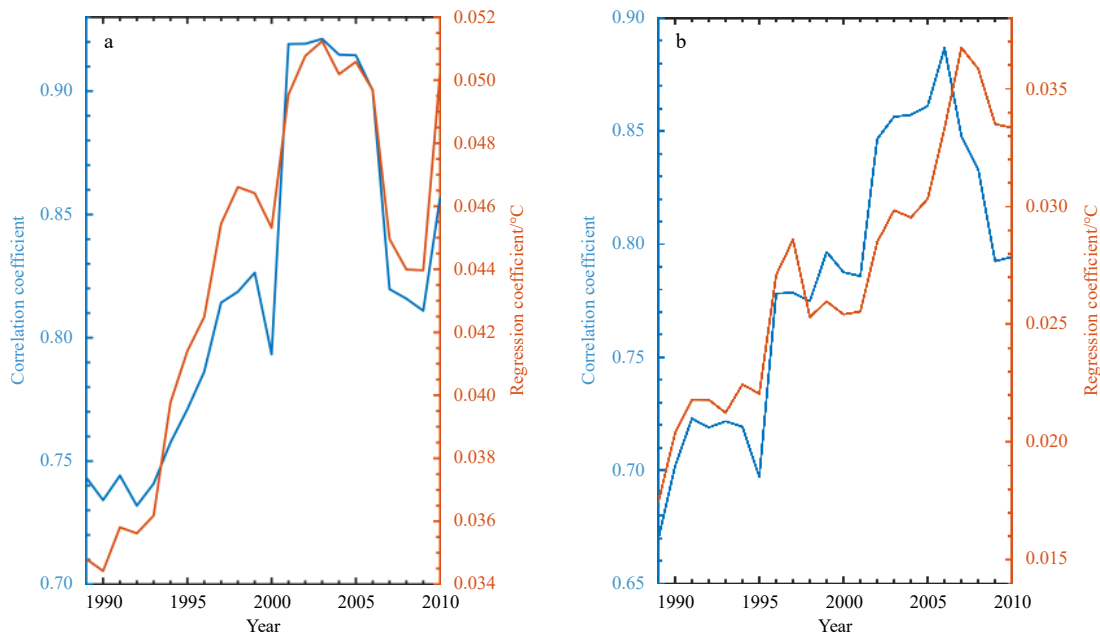


Fig. 4. Correlation coefficient (blue line) and regression coefficient (orange line) of the D20 anomaly and SST anomaly in October in the southeastern Indian Ocean (a) and in April in the southwestern Indian Ocean (b) based on the SODA 3.4.2 dataset.

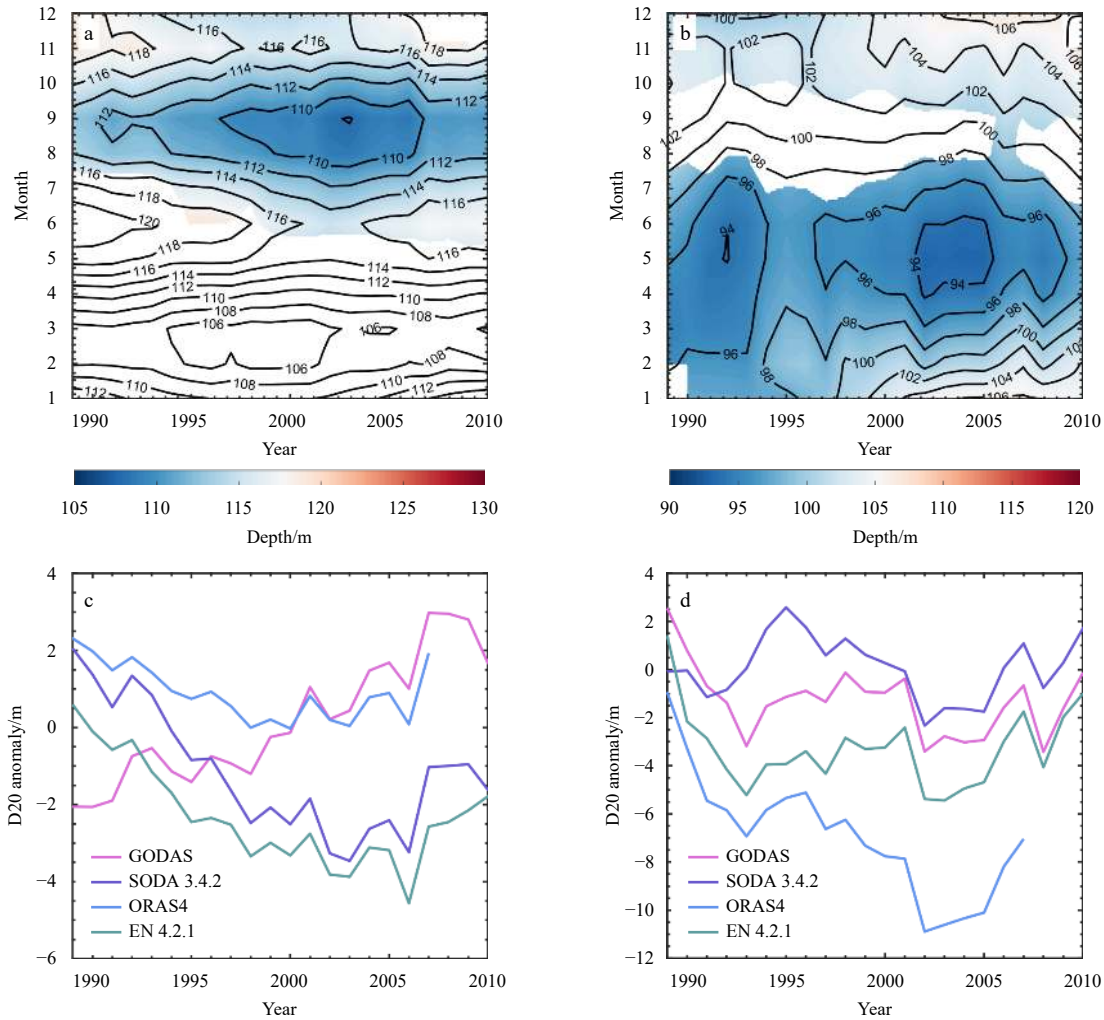


Fig. 5. Decadal variation in the thermocline depth in the southeastern (a) and the southwestern (b) Indian Ocean based on the SODA 3.4.2 dataset (the values of correlation coefficients between D20 anomaly and SST anomaly exceeding the 95% significance level are shaded as in Figs 3a and b); and decadal variations in the D20 anomaly in the southeastern Indian Ocean during October (c) and the southwestern Indian Ocean during April (d) based on multiple datasets. D20 anomaly less than 0 represents a shallower thermocline.

decadal variations in D20 are also important for the equatorial zonal wind-thermocline feedback, which is another component of Bjerknes feedback (Bjerknes, 1969). This feedback also strengthens when D20 gets shallower. Because the zonal wind could force the thermocline more directly when thermocline is closer to the sea surface.

Although the decadal variations of D20 and the intensity of the thermocline-SST feedback are generally consistent, there are some differences in certain months. For example, the correlation coefficient between D20 anomaly and SST anomaly in the southwestern Indian Ocean shows significant decadal changes in February and March and peaks in about 2003 (Fig. 3b). However, the variation of D20 is weak in these months (Fig. 5b). This implies that thermocline is not the only contributor to variations in the thermocline-SST feedback.

To find the cause of this phenomenon, we analyzed the decadal changes in upwelling in the region. Because upwelling is strongest at about 40–60 m (Figs 6a and b), we plot the decadal variation in upwelling within this depth range (Figs 6c and d). The decadal variation of D20 in the southeastern Indian Ocean does not agree completely with the variation in the thermocline-SST feedback. Upwelling has experienced a weakening-strength-

ening-weakening trend in summer in recent decades (Fig. 6a). The thermocline-SST feedback increased before 1995 (Fig. 3a), but local upwelling weakened (Figs 6a and c). During this period, the feedback intensity was mainly controlled by the variation of the D20. The climatology upwelling of the background field is in summer, thus the temperature anomalies caused by thermocline fluctuations can be still effectively transported to the surface layer even if the intensity of upwelling changes slightly. After 1995, the variation of upwelling was consistent with that of the feedback intensity.

In the southwestern Indian Ocean, the decadal variation in the vertical velocity is greatest in February–March (Fig. 6d) and leads the variation in the thermocline depth for two months. The decadal variation in the thermocline-SST feedback in these months is therefore induced by variations in upwelling rather than D20. Enhanced upwelling helps to bring the subsurface sea temperature anomalies to the surface and strengthens the correlation between D20 anomaly and SST anomaly. The situation is reversed for weakened upwelling. The strength of upwelling in April–June is stable on a decadal timescale. Consequently, the decadal variation in thermocline-SST feedback is influenced by variations of D20 in these months. This is because the D20 does

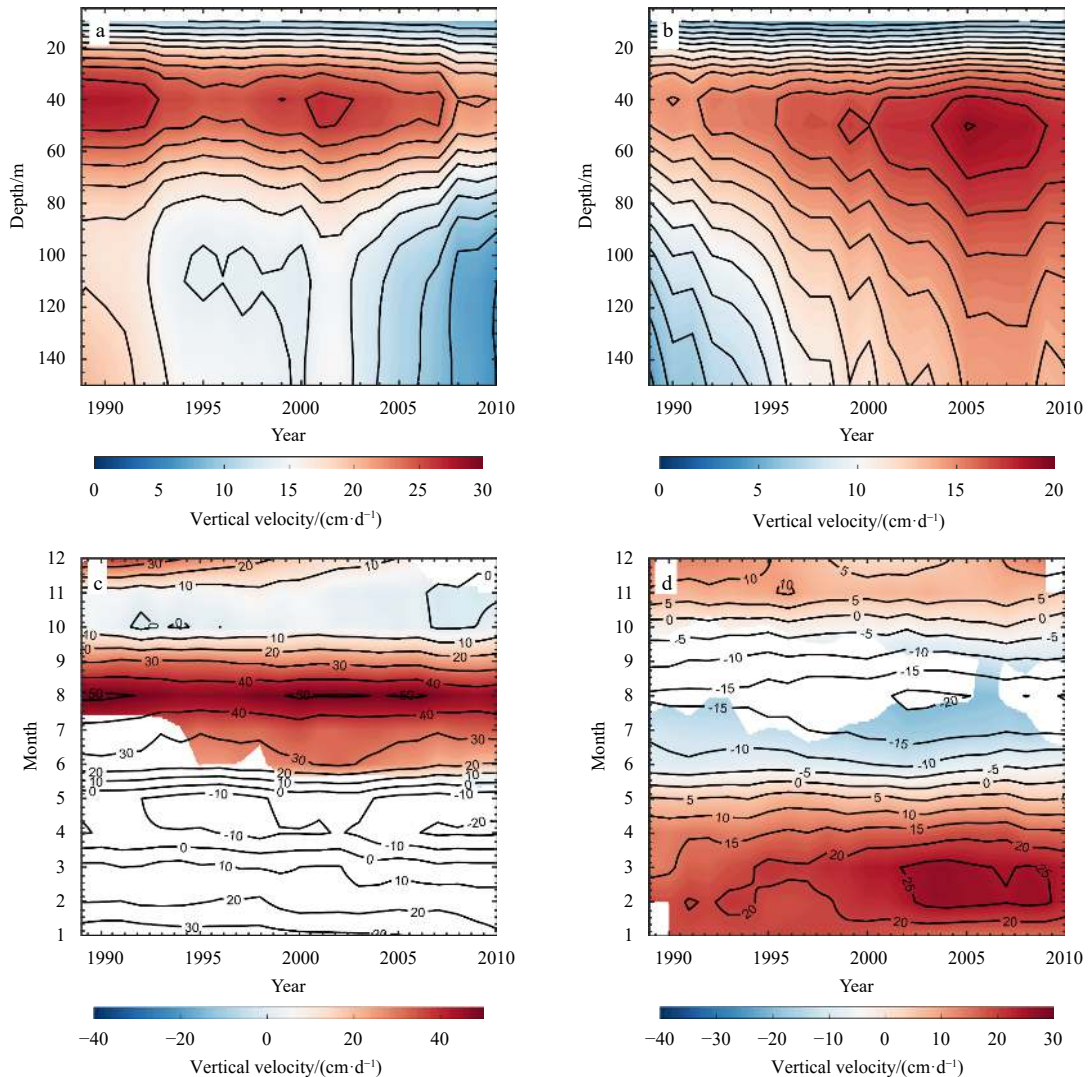


Fig. 6. Decadal variation in the vertical velocity in the southeastern Indian Ocean from June to November (a) and the southwestern Indian Ocean from January to May (b) based on the GODAS dataset; and decadal variations in the vertical velocity at 40–60 m in the southeastern (c) and the southwestern (d) Indian Ocean based on the GODAS dataset. The values of correlation coefficients between D20 anomaly and SST anomaly exceeding the 95% significance level are shaded (as in Figs 3a and b).

not change synchronously with the vertical velocity in the southwestern Indian Ocean, but responds to the gradient in vertical velocity with respect to time, which lags the vertical velocity by about two months (Hermes and Reason, 2008).

From the above analysis, we conclude that the intensity of upwelling and D20 are the key factors that affect the decadal variation in the thermocline-SST feedback. What are the causes for the decadal variation in upwelling and D20? To answer this question, we analyzed the relationship between the D20 and surface wind on decadal time scale. We select September and May, when the D20 variation is most robust, for the southeastern and southwestern Indian Ocean, respectively (Figs 5a and b). Results show that the D20 in southeastern Indian Ocean is significantly correlated with the equatorial zonal wind (Fig. 7a). Meanwhile, the D20 of southwestern Indian Ocean is mainly associated with the wind stress curl variation in the southeastern Indian Ocean (8°–16°S, 85°–105°E) (Fig. 7b).

We further examine the relationship between the D20 and surface based on lead-lag correlations (Figs 7c and d). The D20 and upwelling in southeastern Indian Ocean are best correlated

with the equatorial zonal wind at the same month, with correlation coefficients of about 0.8 (Fig. 7c). The equatorial zonal wind anomaly can lead to the anomalous horizontal advection, which directly induce opposite changes in the vertical velocity of the eastern and western equatorial Indian Ocean and modulate the D20. However, the variations of upwelling and D20 of southwestern Indian Ocean lag that of the wind stress curl for 2 months and 4 months, respectively (Fig. 7d). Wind stress curl in the southeastern Indian Ocean could influence the local Ekman pumping, and the D20 varies accordingly. The signal is transmitted to southwestern Indian Ocean via Rossby waves. As suggested by Xie et al. (2002), this process takes about 2 months. The D20 needs another 2 months to adjust to the upwelling change as discussed above, thus there is a notable delay between thermocline variation and that of wind stress curl.

5 Summary

We analyzed the decadal variation in the thermocline-SST feedback in the tropical Indian Ocean during the rapid warming period and the global warming hiatus period and discussed its

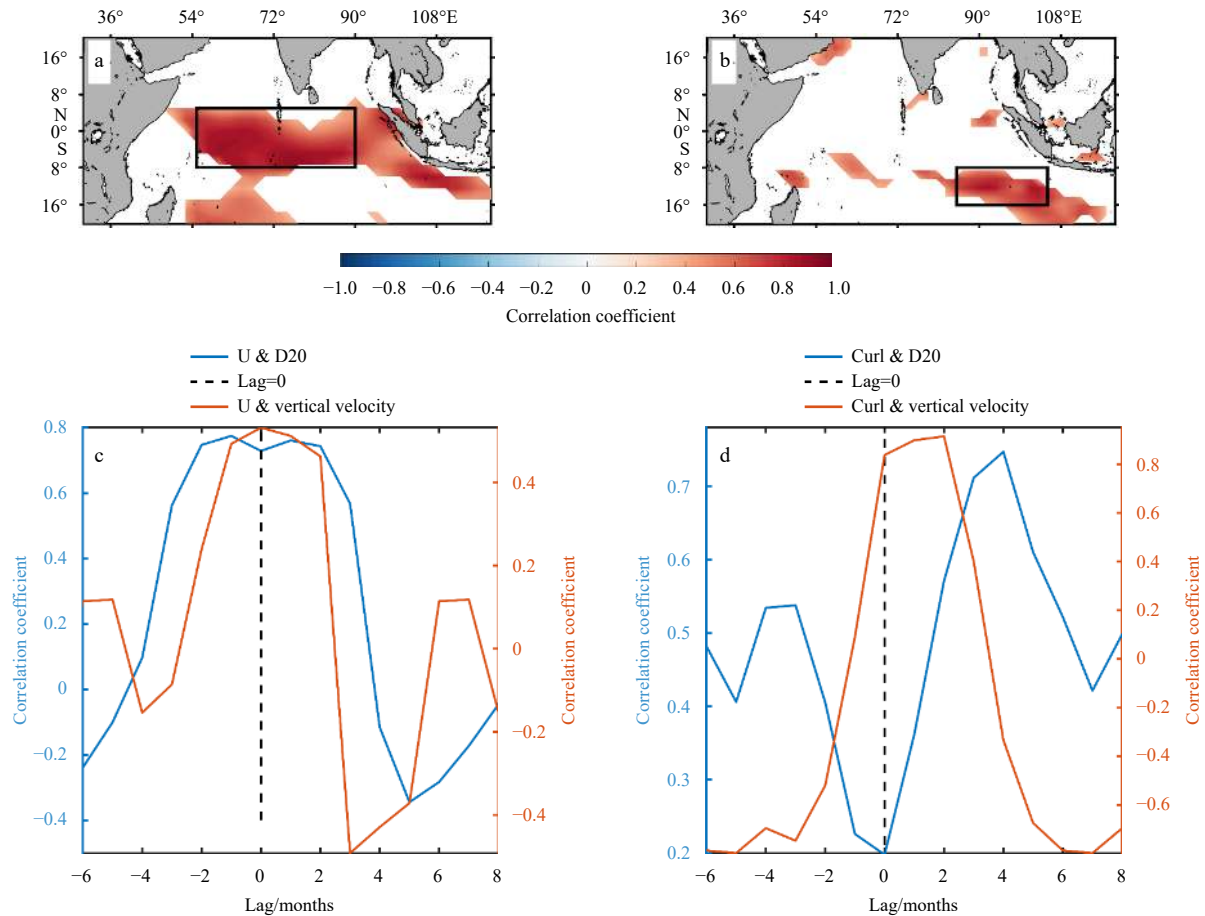


Fig. 7. Correlation coefficient between decadal variations in D20 anomaly of southeastern Indian Ocean in September and zonal wind in August (a), between decadal variations in D20 anomaly of southwestern Indian Ocean in May and the wind stress curl in February (b); and lead-lag correlation coefficient between equatorial zonal wind in August and the D20 anomaly (upwelling anomaly) in the southeastern Indian Ocean (c), between wind stress curl in the southwestern Indian Ocean in February and the D20 anomaly (upwelling anomaly) in the southwestern Indian Ocean (d). In a and b, the black box denotes the location of the equatorial zonal wind (5°N – 8°S , 55° – 90°E) and the critical areas of wind stress curl (8° – 16°S , 85° – 105°E), respectively. Values exceeding the 95% significance level are shaded. In c and d, lag>0 denotes the variation of D20 and upwelling lags behind the equatorial zonal wind and wind stress curl. Among them, temperature data, vertical velocity data and wind field data are based on EN4.2.1, GODAS and NCEP, respectively.

underlying mechanisms. The results for the last 40 a show that the thermocline-SST feedback first strengthened and then weakened and its intensity peaked at the beginning of the twenty-first century.

The thermocline-SST feedback was strongest in the southeastern and southwestern Indian Ocean, where there was significant feedback in summer-autumn and winter-spring, respectively. In these regions, the thermocline depth and upwelling both contributed to the variations in the thermocline-SST feedback, but their relative importance varies with season. The variation of D20 in the southeastern Indian Ocean is highly consistent with the strength of thermocline-SST feedback on a decadal scale. The feedback strengthens when the thermocline rises and weakens when it deepens. By contrast, the decadal variation of the thermocline-SST feedback in the southwestern Indian Ocean is mainly forced by the intensity of upwelling in February–March and controlled by variations in the D20 in April–June. The D20 and upwelling of southeastern Indian Ocean are mainly affected by the equatorial zonal wind. Whereas the wind stress curl over the southeastern Indian Ocean is the main factor affecting D20 and upwelling in southwestern Indian Ocean. Thermocline and

upwelling in southeastern Indian Ocean respond quickly to zonal wind without significant delay, while the thermocline and upwelling in southwestern Indian Ocean lag the wind stress curl by 4 and 2 months, respectively.

The thermocline-SST feedback has experienced pronounced decadal variation in recent decades. These changes will inevitably affect the overall strength of the Bjerknes feedback and therefore influence the air-sea coupling modes of the Indian Ocean. The results of this study will help us to understand the ocean surface-subsurface interactions in the Indian Ocean and improve the accuracy of regional climate prediction.

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