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ORIGINAL ARTICLE

Influence of western boundary reflection on seasonal circulation in the equatorial Indian Ocean

Jing Wang[1] · Dongliang Yuan[1] · Xia Zhao[1]

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Abstract
The influence of western boundary reflection (WBR) of Rossby waves on the seasonal circulation in the equatorial Indian Ocean is investigated using an ocean model LICOM , forced by daily winds and surface fluxes of the National Centers for Environmental Prediction (NCEP) reanalysis I during 2000–2010. LICOM has reproduced seasonal variations of Ocean Surface Current Analysis Real-time (OSCAR) zonal currents and satellite altimeter sea level well. Comparisons of the experimental results with and without WBR suggest that the WBR enhances the zonal currents and sea level variations in the central and eastern equatorial Indian Ocean. Long equatorial wave dynamics analyses suggest that the difference of the second baroclinic mode waves with and without WBR are evidently larger than those of the first baroclinic mode, suggesting the importance of the second baroclinic mode waves in controlling the sea level and zonal current seasonal variations. Analyses also suggest that reflected Kelvin waves from the first and second baroclinic modes have a much larger contribution to the semiannual oscillations of the sea level than Rossby waves. The first meridional Rossby wave of the first and second baroclinic modes have larger contribution to zonal currents than the Kelvin waves from the WBR. These results suggest the important role of the WBR in controlling the seasonal circulation in the equatorial Indian Ocean.

Keywords Western boundary reflection · Indian Ocean · Seasonal circulation · Kelvin wave · Rossby wave · Wyrtki Jets

1 Introduction

Indian Ocean circulation is mainly forced by the strongest monsoon in the world. Previous studies have shown the effects of surface winds on upper ocean circulation in the Indian Ocean (Luther and O'Brien 1985; Woodbury et al. 1989; McCreary et al. 1993). Zonal surface currents in the equatorial Indian Ocean flow strongly eastward in spring and fall, westward in summer and winter, exhibiting strong semiannual oscillations (Schott and McCreary 2001). The eastward surface zonal currents are intense and narrow within 2° north and south of the equator during the monsoon transition time, and are referred to as Wyrtki Jets (Wyrtki 1973; O'Brien and Hurlburt 1974). Wyrtki Jets are mainly forced by semiannual winds over the equatorial Indian Ocean (Jensen 1993; Han et al. 1999).

At the western boundary, the equatorial and off-equatorial Rossby waves are reflected into the equatorial Kelvin waves. The western boundary reflection (WBR) in this paper is defined as the total number of Kelvin waves leaving the western boundary, which includes the reflection of equatorial and off-equatorial Rossby waves, alongshore winds, and nonlinear processes near the western boundary (Yuan and Han 2006; Yuan and Liu 2009; Yuan et al 2011; Wang and Yuan 2015). Semiannual oscillations dominate seasonal sea level in the western and eastern Indian Ocean, while annual oscillations dominate in the central equatorial Indian Ocean and coexist with the dominant semiannual oscillations of zonal currents (Reverdin 1987; Yuan and Han 2006; Nagura and McPaden 2010). Equatorial Kelvin waves and Rossby waves propagate eastward and westward, respectively, and reflections at the eastern and western boundaries in the Indian Ocean can induce resonant oscillations (Clarke and Liu 1993; Jensen 1993; Han et al. 1999; Nagura and McPaden 2010). These oscillations are known as equatorial basin modes (Cane and Moore 1981), which represent standing equatorial modes in

✉ Jing Wang
wangjing@qdio.ac.cn

[1] Key Laboratory of Ocean Circulation and Waves, Institute of Oceanology, Chinese Academy of Sciences and Qingdao National Laboratory for Marine Science and Technology, Qingdao, China

zonally bounded basins. The resonance periods are a function of basin geometry and gravity wave speed of a particular baroclinic mode (Han et al. 2011). Variability at the semi-annual time scale in the Indian and Atlantic Oceans is associated with the basin mode of the second baroclinic mode, which resonates with the semiannual wind forcing (Jensen 1993; Han et al. 1999; Thierry et al. 2004; Ding et al. 2009). The WBR enhances semiannual oscillations of surface zonal currents, while it reduces the semiannual oscillations of the sea level (Yuan and Han 2006). Rossby waves have much larger contribution to the semiannual oscillation of surface zonal currents than Kelvin waves (Yuan and Han 2006; Nagura and McPaden 2010). Kelvin and Rossby wave dynamics have comparable contributions to sea level variability in the central equatorial Indian Ocean (Yuan and Han 2006; Nagura and McPhaden 2010; Nagura 2010). The study of Han et al. (1999) has demonstrated that eastern boundary reflected Rossby waves play an important role in the strength and structure of the equatorial zonal currents (Han et al. 1999). Indonesian Throughflow (ITF) can also influence seasonal circulation in the equatorial Indian Ocean through western and eastern boundary reflection processes. ITF blockage does not change the structure of equatorial seasonal circulation in the Indian Ocean, but amplifies the amplitudes of zonal velocities across the whole Indian Ocean and dynamic heights in the eastern Indian Ocean. The impact of ITF on the equatorial seasonal circulation is modulated by the eastern boundary reflection processes, further by the reflection of equatorial Rossby waves at the western boundary. The modulation is established by equatorial processes, but off-equatorial processes are not involved (Wang et al. 2017).

The study of Yuan and Han (2006) demonstrated that the WBR involves strong nonlinear processes. They have explained the interactions between reflected equatorial waves and wind-forced equatorial waves, which excite seasonal variations of equatorial Indian Ocean circulation. A question not answered is how the seasonal equatorial circulation would be if the WBR is absent. The LICOM model with complete dynamics of ocean circulation will be used to quantify the role of WBR.

Model configurations and data used in this study will be described in Sect. 2. In Sect. 3, model simulated results, equatorial wave coefficients and the reconstructed sea level and zonal currents are analyzed. Conclusions and discussion are presented in Sect. 4.

2 Model and data description

The ocean general circulation model (OGCM) used in the paper is LICOM 1.1 from the Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics (LASG/IAP). The model configuration details are described in Liu et al. (2004, 2005). The model domain covers the quasi-global ocean with a free sea surface between 90°N and 78.5°S with a horizontal resolution of 0.5° longitude × 0.5° latitude. There are 30 vertical levels with a grid size of 25 m in the upper 300 m. LICOM topography is derived from the Digital Bathymetric Data Base 5-min (DBDB5) from the Naval Oceanographic Office. Topography data were first averaged onto a horizontal grid of (1/3)°, then interpolated onto a (1/2)° grid. The model has been spun up for 900 years using Levitus climatological forcing from rest. The model surface temperature and salinity are relaxed to the Levitus climatology at a time scale of a half-year (Levitus et al. 1998). The horizontal viscosity of LICOM is set to $5 \times 10^3\ m^2\ s^{-1}$ between 50°S and 50°N ($1 \times 10^4\ m^2\ s^{-1}$ for the first 10 years of integration). A larger horizontal viscosity (e.g., 2×10^4 $m^2\ s^{-1}$) is used at higher latitudes.

A control run (CNTR) is conducted for 11 years from 2000 to 2010 using the daily forcing of surface wind stress and heat flux from the National Centers for Environmental Prediction (NCEP) reanalysis I data. To suppress the effects of the WBR, a sensitivity run (DAMP) is conducted with the same forcing by damping the equatorial western boundary region in the Indian Ocean during the same period. This damping method follows Tozuka et al. (2014), where the horizontal viscosity in the equatorial western boundary region (i.e., 45°E–65°E, 7.5°S–7.5°N) is amplified by a factor of 10 so that waves are damped or eliminated. Therefore, the difference between the DAMP and the CNTR represents the effects of the WBR on the equatorial Indian Ocean circulation. The analyses in this paper are based on the monthly averaged output of the LICOM during 2000–2010.

Observed monthly sea level anomalies (SLA) during 2000–2010 from the Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO; Ducet et al. 2000) are used to study the seasonal variations of SLAs in the equatorial Indian Ocean. Monthly Ocean Surface Current Analyses Real-Time (OSCAR) data during 2000–2010, with a horizontal resolution of 1° × 1° (Bonjean and Lagerloef 2002), are used to validate the seasonality of the surface zonal currents along the equator with the LICOM simulation.

The wave decomposition method is used to study wave dynamics of seasonal circulations in the equatorial Indian Ocean. Equatorial waves are extracted from the DAMP and CNTR experimental outputs. The wave decomposition method is based on the orthogonal relations of long equatorial Kelvin and Rossby mode functions and projects the model output onto the mode functions of these waves. The first three baroclinic Kelvin wave phase speeds are 2.7, 1.7, and 1.0 ms^{-1}, and are calculated from a density profile averaged between 5°S and 5°N in the Indian Ocean. These values are close to characteristic speeds in Moore and McCreary (1990). The projection includes the nonlinear effects of the

LICOM simulation on the wave coefficients by treating the nonlinear terms of the LICOM momentum equations as forcing terms. The three-dimensional dynamic height and zonal velocity in reference to the 2500 m depth, are projected onto the eigen-functions to extract the wave coefficients associated with each baro-clinic mode. These wave coefficients are decomposed into equatorial Kelvin and Rossby waves. The corresponding procedure for wave decomposition can be found in Yuan et al. (2004). The difference in equatorial wave coefficients between the DAMP and the CNTR represent the effects of the WBR on equatorial long waves.

3 Results

In this section, seasonal cycles of zonal currents and sea level from the CNTR simulation are validated with the OSCAR data and the AVISO altimeter data, respectively. In addition, the seasonal variability of sea level and zonal currents between the CNTR and the DAMP are compared to study the influence of the WBR on seasonal variations of the equatorial Indian Ocean circulation between the CNTR and the DAMP. Furthermore, equatorial wave dynamics are disclosed by extracting equatorial long wave coefficients using the wave decomposition method.

3.1 Model validation

Figure 1 shows the OGCM-simulated seasonal evolution of surface zonal current and surface dynamic heights in comparison with the OSCAR current data and the AVISO altimeter data, respectively. Seasonal climatologies of zonal currents and sea level from 2000 to 2010 are extracted. The dynamic height from the OGCM is adjusted with NCEP seasonal atmospheric surface pressure. However, the adjustment turned out to be small. The OGCM-simulated seasonality of surface zonal current and sea level agree well with observations from the OSCAR data and the AVISO altimeter data. However, the OGCM-simulated the equatorial currents are slightly weaker in comparison with the OSCAR data, which may be due to the selection of the drag coefficient in the wind stress calculation. The OGCM can reproduce the dominant semiannual oscillation of equatorial zonal currents

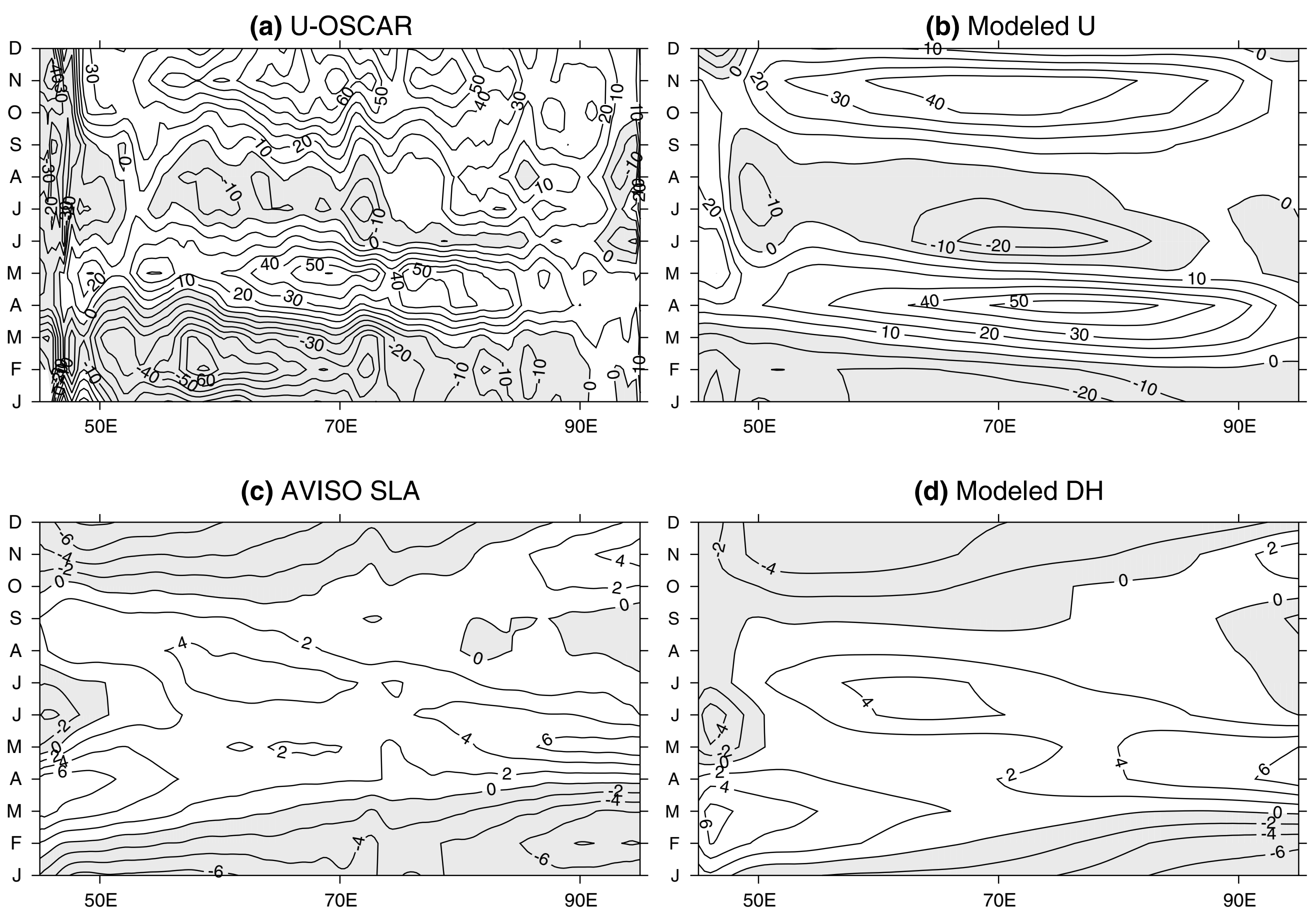

Fig. 1 comparison of the CNTR simulated seasonal evolution of the surface dynamic height (cm) with AVISO altimeter data and zonal current (cm/s) along the equator with OSCAR data

well in comparison with the OSCAR data, as well as the dominant semiannual oscillation in sea level in the western and eastern Indian Ocean, and the annual oscillation in the central Indian Ocean in comparison with the AVISO altimeter data except for a slight phase lag. It is beyond the scope of this study to examine the reasons for the generation of the phase lag since we note that the phase lag does not influence the analyses of the seasonal circulation in the equatorial Indian Ocean. Therefore, OGCM simulations can be used to evaluate the influence of the WBR on seasonal circulation of the equatorial Indian Ocean.

LICOM can reproduce vertical profiles of mean density and buoyancy frequency squared averages over the entire Indian Ocean from the CNTR run during 2000–2010, which has a good agreement with the WOA13 data, suggesting that the model can realistically simulate mean stratification. The vertical profiles of mean density and buoyancy can be found in Wang et al. (2017).

3.2 The role of WBR on equatorial seasonal circulation

Figure 2 shows OGCM-simulated seasonal surface zonal currents from the CNTR in comparison with the DAMP experiment. The DAMP experiment simulates a similar seasonality for zonal currents compared to the CNTR experiment. In addition, the semiannual oscillation of zonal currents dominates in the DAMP experiment with the suppression of the WBR. The difference (Fig. 2c) between the DAMP and the CNTR suggests DAMP experiment can simulate weaker amplitudes of zonal currents including Wyrtki Jets and westward equatorial currents. This suggests that the WBR suppression would decrease the amplitudes of the Wyrtki Jets and the westward equatorial jets, but would not change the phases of the equatorial currents. In other words, the WBR provides an amplifying effect for equatorial zonal currents in the Indian Ocean. The largest amplitudes for zonal current differences reach over 50% of the surface currents. Therefore, the influence of the WBR on zonal currents needs further attention. Noticeably, zonal current differences between the two experiments also exhibit a semiannual

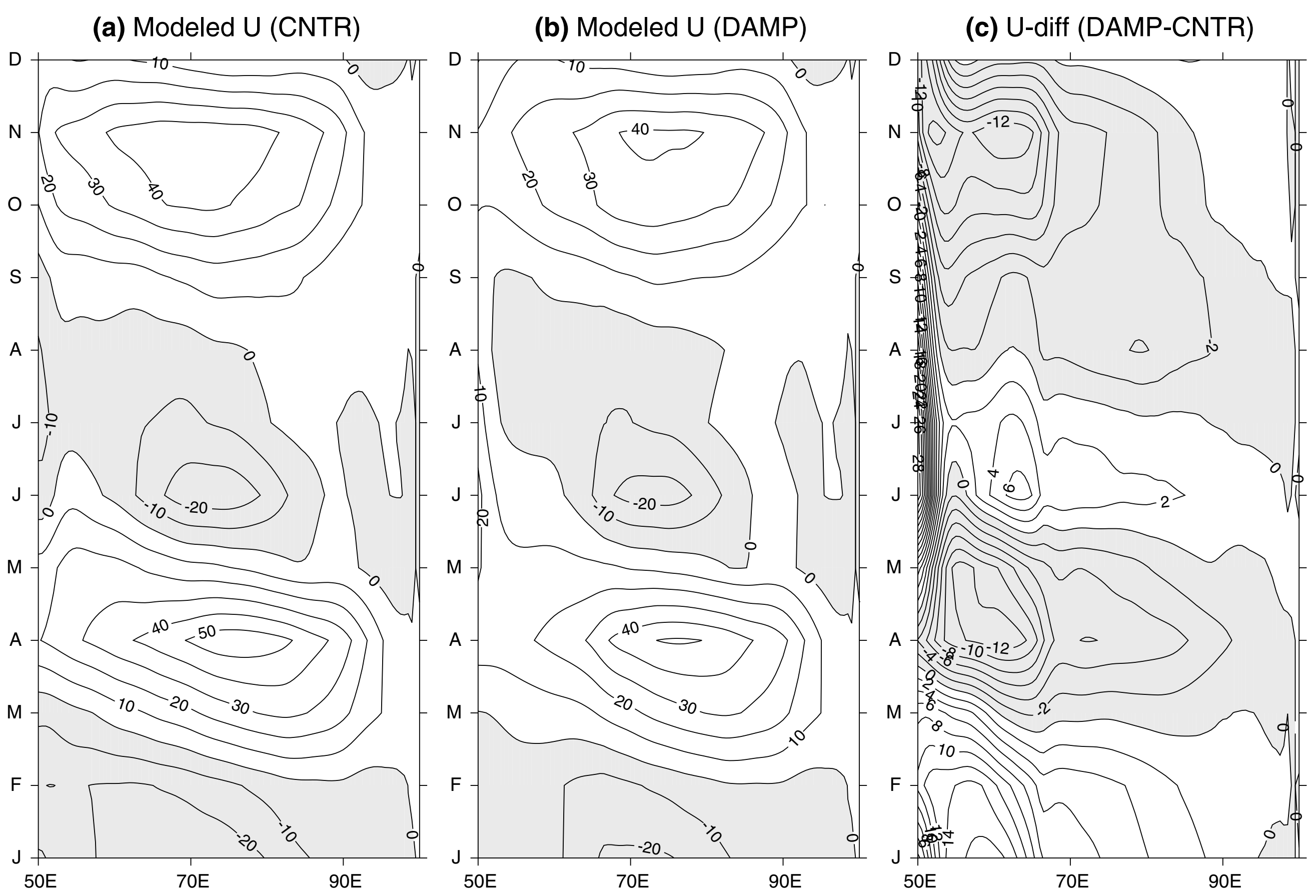

Fig. 2 Hovmöller plots of seasonal zonal currents between 5°S and 5°N along the equator **a** from the DAMP run; **b** from CNTR run; **c** difference between DAMP and CNTR. Unit: cm/s

oscillation (Fig. 2c), suggesting a net influence from the WBR related to the semiannual oscillation. The suppression of the WBR results in missing Kelvin waves from the western boundary in the DAMP run and furthers the absence of reflected Rossby wave from the eastern boundary. This will surely affect the basin mode at the semiannual period, which is consistent with Han et al. (2011). The 180-day basin resonance associated with the second baroclinic mode had one zonal-current maximum in the central basin and the 90-day basin resonance had two relative maxima of zonal currents in the eastern and western basins. Without considering the damping region, zonal current differences between the DAMP and the CNTR exhibit one maximum in the central Indian Ocean. This suggests that the 180-day resonance for the second baroclinic mode appears to be most affected by the suppression of the WBR.

Figure 3 shows the OGCM simulated seasonal sea levels from the CNTR in comparison with the simulation from the DAMP experiment. The DAMP experiment can simulate a similar seasonality of sea level to the CNTR run except for the difference in amplitude. The semiannual oscillation in the eastern Indian Ocean and the annual oscillation in the central Indian Ocean of sea level dominate in both experiments. Differences between the two experiments also show a semiannual oscillation across the entire Indian Ocean but there are inconsistent amplitude variations in the western and central-eastern Indian Ocean. The propagation of sea level can be seen from west to east, suggesting that the influence of the WBR on sea level is related to the propagation of equatorial waves. The contrasting behavior between simulated sea levels and DAMP and CNTR difference suggests possibly different dynamics based on the influence of the WBR in the western and eastern Indian Ocean. Comparisons in sea levels and zonal currents between the DAMP and the CNTR suggest that suppression of the WBR cannot change the seasonal structure of sea level (Fig. 3a, b) or surface zonal currents (Fig. 2a, b) but rather the amplitude of sea level and surface zonal currents. Damping in the western boundary region would suppress the reflective effects of the WBR from equatorial Rossby waves, off-equatorial Rossby waves, and wind-forced Kelvin waves near the western boundary. Based on the amplitude difference between sea level and surface zonal currents, the effects of WBR are very important.

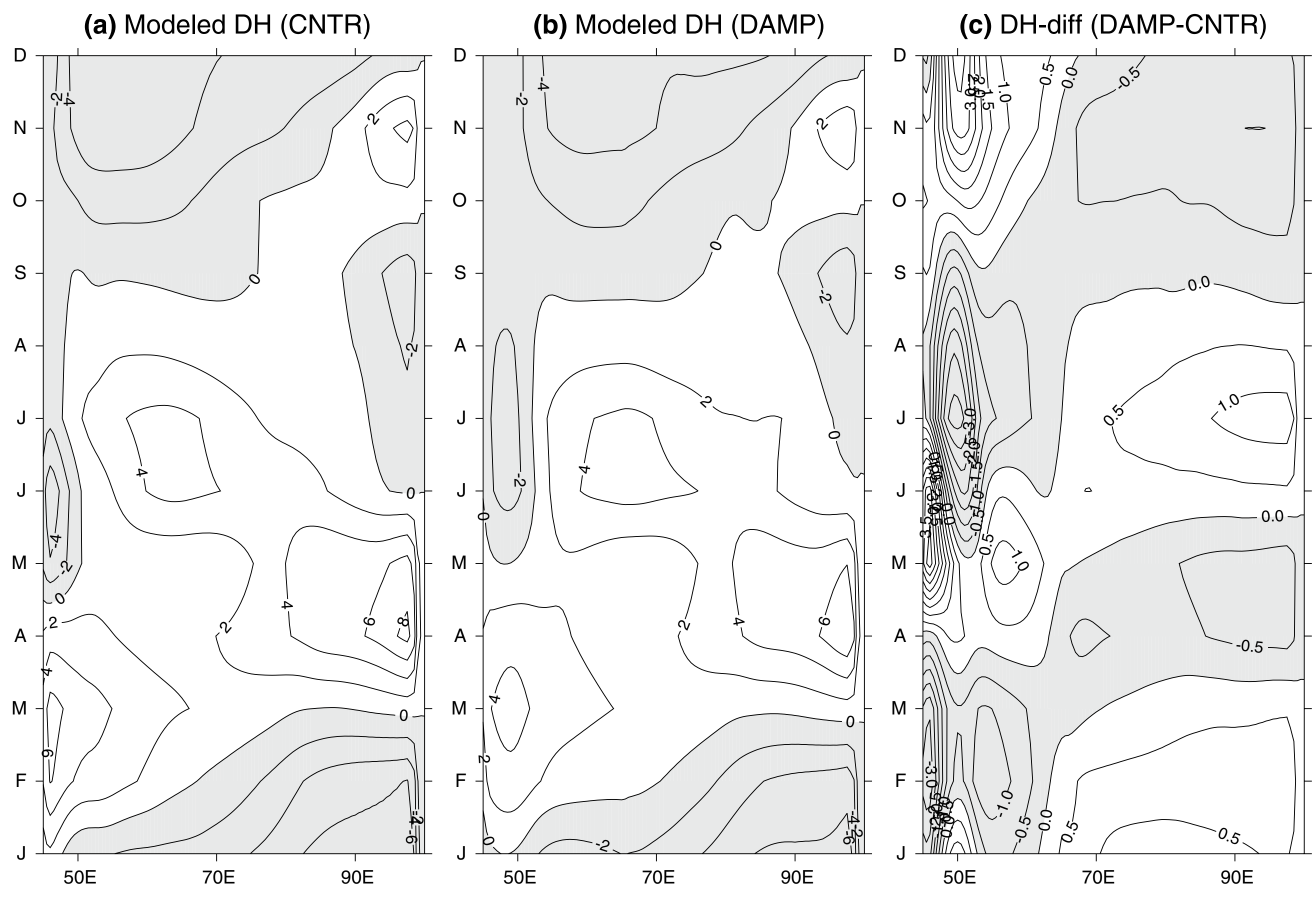

Fig. 3 Hovmöller plots of seasonal surface dynamic height between 5°S and 5°N along the equator **a** from the DAMP run; **b** from CNTR run; **c** difference between DAMP and CNTR. Unit: cm

3.3 The role of the WBR on equatorial wave dynamics

To study the role of the WBR from equatorial and off-equatorial Rossby waves, long equatorial Kelvin and Rossby wave coefficients are extracted from the model simulations to study the sea level and zonal current wave dynamics in the equatorial Indian Ocean. Figure 4 shows the decomposed Kelvin wave and the first meridional-mode Rossby wave coefficients of the first baroclinic mode from the DAMP and the CNTR runs. The difference in Kelvin and Rossby wave coefficients are shown in the bottom panel (Fig. 4). Equatorial wave coefficients from the second baroclinic mode are shown in Fig. 5. Shading indicates negative values. Positive (negative) values represent downwelling (upwelling) waves throughout the paper. Although the second meridional-mode Rossby waves involved in the WBR in the Indian Ocean in the linear theory due to the inclined western boundary, wave coefficients with small amplitudes are not discussed here for simplicity (Cane and Gent 1984). The structure of equatorial wave coefficients is similar to the SLA evolution as shown in Fig. 1. Kelvin waves originate from the western boundary and propagate eastward, and Rossby waves propagate westward. Kelvin waves are mainly from the WBR and equatorial wind forcing in the CNTR run. When damping the western boundary region, Kelvin waves in the DAMP run only occur from equatorial wind forcing. For the first baroclinic mode, the structure of Kelvin waves between DAMP and CNTR experiment is consistent except for a slight difference in amplitude, as shown in Fig. 4a, c). Kelvin wave coefficients exhibit an annual oscillation across the entire Indian Ocean (Fig. 4a). However, the difference in Kelvin wave coefficients between the DAMP and the CNTR experiments exhibits a semiannual oscillation, which is consistent with the reversal of equatorial zonal currents in the Indian Ocean. This suggests that the WBR plays an important role in the reversal of equatorial zonal currents. For the second baroclinic mode, the structure of the Kelvin wave coefficients exhibits an annual oscillation from the DAMP experiment (Fig. 5c) and a semiannual oscillation from the CNTR experiment (Fig. 5a), suggesting that wind-forced Kelvin waves exhibits an annual oscillation and WBR-forced Kelvin waves exhibit a semiannual oscillation for the second baroclinic mode. Considering the above results, WBR-forced Kelvin waves from both runs exhibit semiannual oscillations. Based on Han et al. (2011), semiannual oscillations mainly occur for the second baroclinic mode, which suggests that WBR effects contribute more to the second baroclinic mode than the first baroclinic mode. Comparing the difference in model design between the CNTR and DAMP experiments, difference in Kelvin waves and Rossby waves can only be caused by the suppression of the WBR. The difference in Kelvin waves is typically from the reflection of the equatorial Rossby wave and off-equatorial Rossby wave. Semiannual harmonics of Kelvin waves originate from the linear reflection of equatorial Rossby waves (Yuan and Han 2006), suggesting that the influence of the WBR on seasonal equatorial circulation mainly occurs in the equatorial Indian Ocean, not the off-equatorial Indian Ocean. Kelvin wave and Rossby wave coefficients for the first and second baroclinic mode also suggest the important role of equatorial Rossby waves from evident reflection of the equatorial Kelvin wave, which can be seen in Fig. 5a, b.

3.4 The reconstructed sea level and zonal current

To analyze further the contributions of the WBR on zonal currents and sea levels, we use equatorial wave coefficients to reconstruct zonal currents and dynamic heights. Here, we only show the results from the first two baroclinic modes because the contributions of higher baroclinic modes are small (Han et al. 2011). Figures 6 and 7 show reconstructed equatorial averaged sea level and zonal currents forced by the WBR of the first baroclinic mode and the second baroclinic mode, respectively. Reconstructed fields such as seasonal variations in simulated zonal currents and dynamic heights have been reproduced in previous studies (Yuan and Han 2006; Wang et al. 2017). Here, we only show reconstructed the difference of sea level and zonal currents between DAMP and CNTR experiments to study the role of equatorial long waves forced by the WBR.

The sea level difference between the DAMP and CNTR that are reconstructed from the Kelvin wave, the first meridional-mode Rossby wave and the superposition of Kelvin and Rossby waves can be seen in the left panel, subsequently (Fig. 6a, c, e). The reconstructed dynamic height difference between the Kelvin wave and the first meridional Rossby wave of the first baroclinic mode exhibits a consistent semiannual oscillation, which is in good agreement with the difference in sea level between the DAMP and CNTR experiments (Fig. 3c). In addition, Kelvin waves play a more important role than the first meridional mode Rossby wave. However, the first meridional mode Rossby wave has a larger contribution to zonal currents than the Kelvin wave for the first baroclinic mode. The superposition of the Kelvin and Rossby wave of the first baroclinic mode only slightly increases the amplitude of the dynamic height and zonal velocity difference (Fig. 6e, f). A similar pattern occurs for the second baroclinic mode, with the exception of the larger contributions than those of the first baroclinic mode. Sea level reconstructed from Kelvin waves and zonal currents reconstructed from the first meridional Rossby waves have larger amplitudes, which are more similar to the

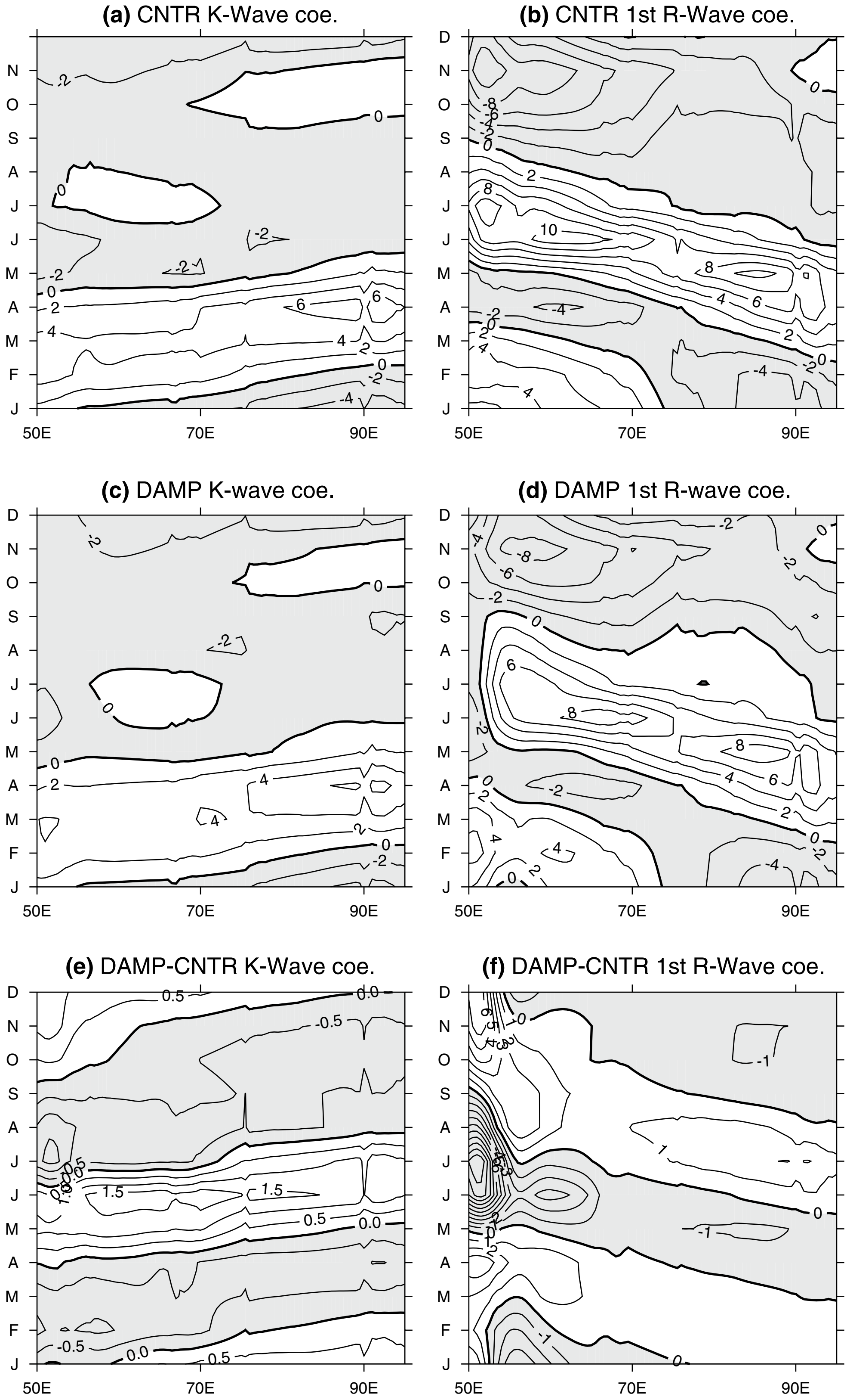

Fig. 4 Decomposed Kelvin wave coefficients (**a**) and the first meridional mode Rossby wave coefficients (**b**) from DAMP run; Decomposed Kelvin wave coefficients (**c**) and the first meridional mode Rossby wave coefficients (**d**) from CNTR run; the difference (**e**) between **c** and **a** and the difference (**f**) between **d** and **b** of the first baroclinic mode. The contour units correspond to 0.33 m and 1.31 cm/s for Kelvin wave sea level and surface zonal current on the equator, 0.14 m and − 1.61 cm/s for the first meridional-mode Rossby waves. The wave coefficients are multiplied by 100 times for conciseness

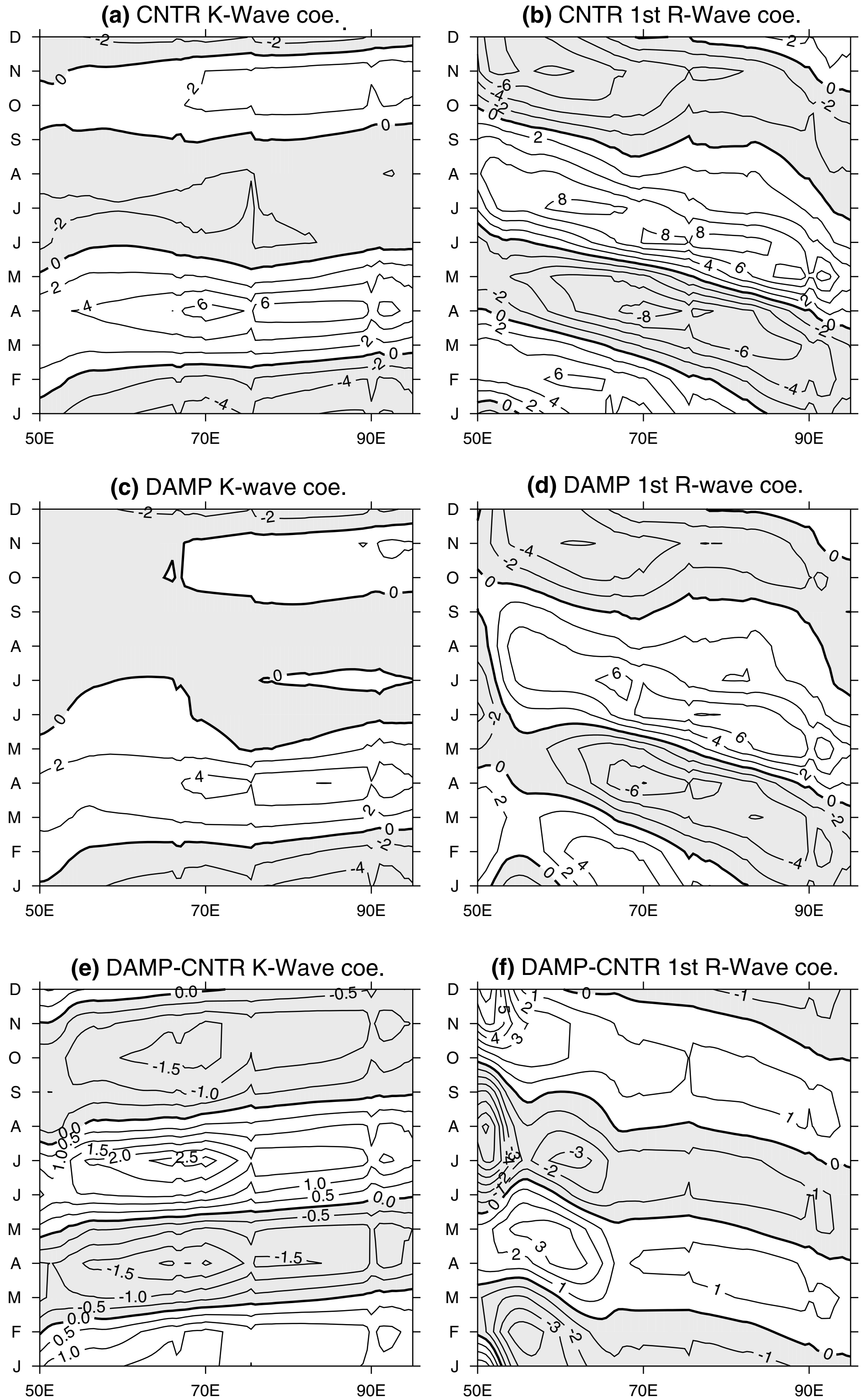

Fig. 5 Decomposed Kelvin wave coefficients (**a**) and the first meridional mode Rossby wave coefficients (**b**) from DAMP run; Decomposed Kelvin wave coefficients (**c**) and the first meridional mode Rossby wave coefficients (**d**) from CNTR run; the difference (**e**) between **c** and **a** and the difference (**f**) between **d** and **b** of the second baroclinic mode. The dimensional amplitudes for sea level and surface zonal current on the equator represented by unit wave coefficients are those of the second baroclinic mode waves multiplied by c_2/c_1=0.58 for surface zonal current and $\frac{c_2^2}{c_1^2}=$ 0.34. The wave coefficients are multiplied by 100 times for conciseness

differences for averaged equatorial sea level and zonal currents. This suggests that the influence of the WBR on seasonal equatorial circulation mainly occurs for the second baroclinic mode. In comparison, the ITF modulates seasonal equatorial circulation mainly through the first baroclinic mode (Wang et al. 2017). The reflection of equatorial Rossby wave at the western boundary plays an important role in ITF-forced and WBR-forced equatorial

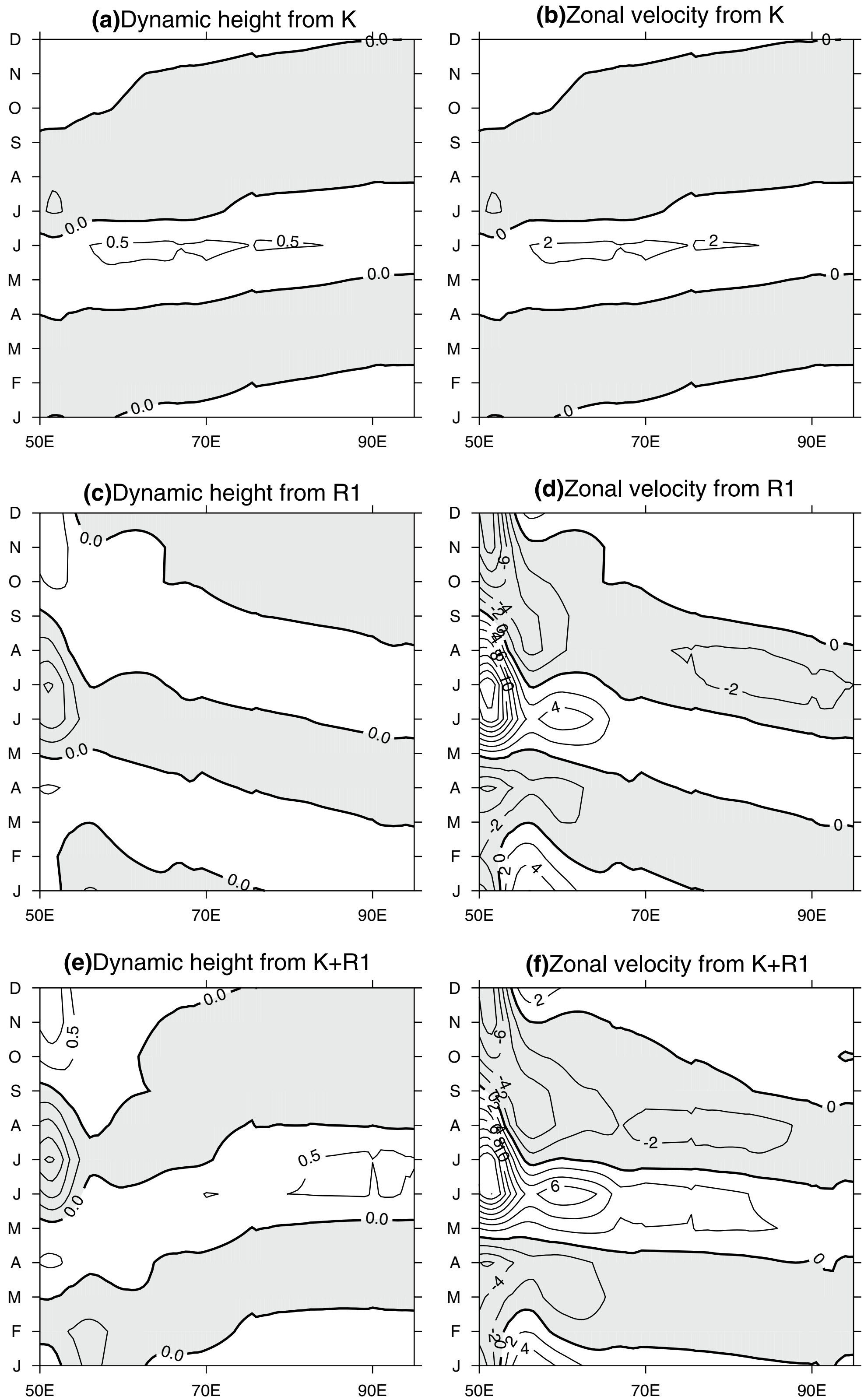

Fig. 6 Reconstructed surface dynamic height from **a** Kelvin wave; **c** the first meridional-mode Rossby wave; **e** the superposition of **a** and **c**; and reconstructed zonal velocity from **b** Kelvin wave; **d** the first meridional-mode Rossby wave; **f** the superposition of **b** and **d** of the first baroclinic mode. The contour interval of dynamic height in the left panel is 0.5 cm and zonal current in the right panel is 2 cm/s

seasonal circulation in the Indian Ocean. In addition, the ITF closure mainly influences the WBR of equatorial Rossby waves through the process of eastern boundary reflections (Wang et al. 2017).

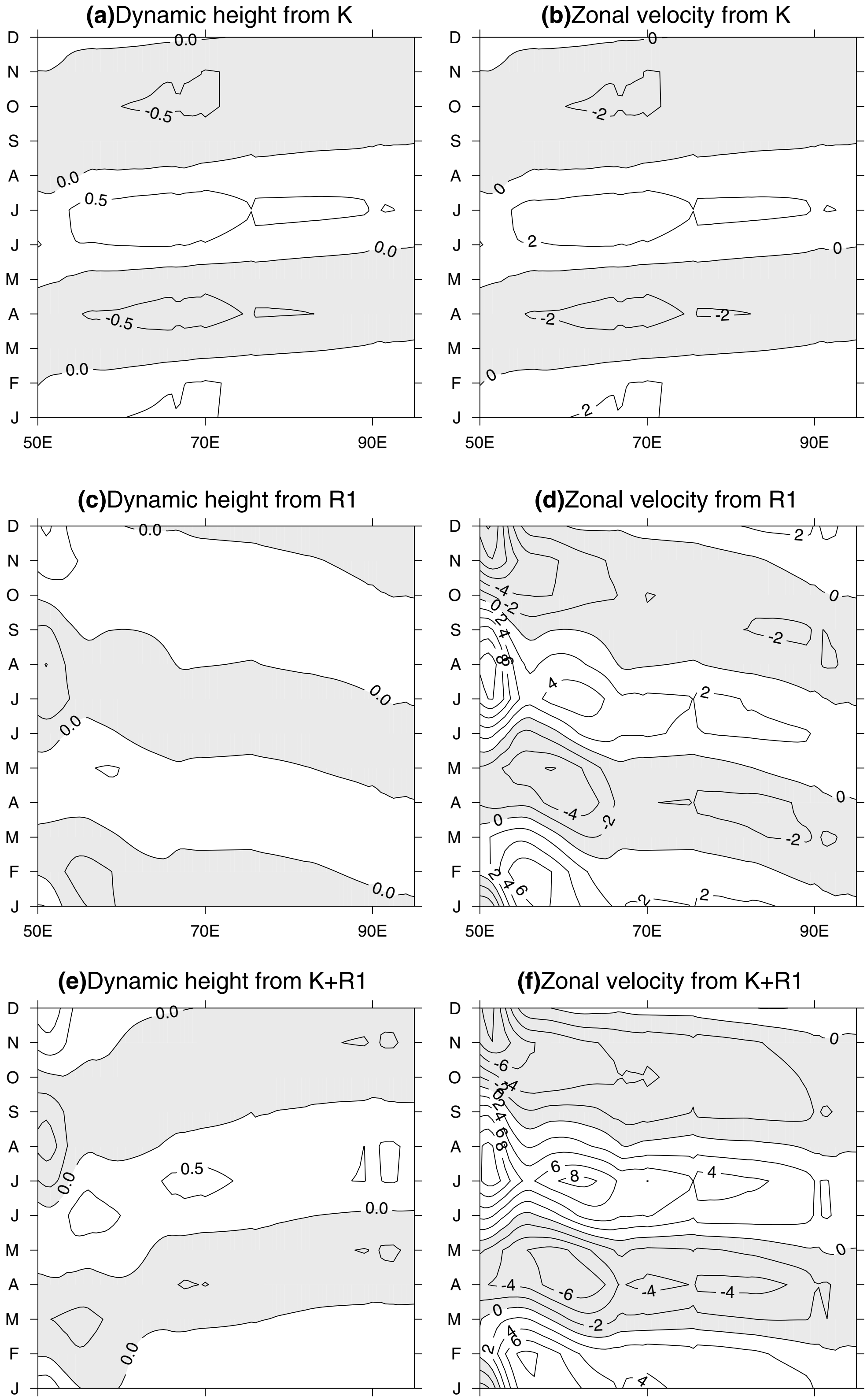

Fig. 7 Reconstructed surface dynamic height from **a** Kelvin wave; **c** the first meridional-mode Rossby wave; **e** the superposition of **a** and **c**; and reconstructed zonal velocity from **b** Kelvin wave; **d** the first meridional-mode Rossby wave; **f** the superposition of **b** and **d** of the second baroclinic mode. The contour interval of dynamic height in the left panel is 0.5 cm and zonal current in the right panel is 2 cm/s

4 Conclusion

The influence of WBR on the seasonal circulation in the equatorial Indian Ocean is studied using LICOM simulations. The model (a.k.a. CNTR run) forced by daily surface wind stresses and fluxes of the NCEP reanalysis I data has reproduced the seasonal variations of the sea level in the AVISO altimeter data and of the surface zonal currents in the OSCAR data in the equatorial Indian Ocean during 2000–2010. A sensitivity experiment (a.k.a. DAMP run) is conducted with an amplified horizontal viscosity by a factor of 10 specified near the equatorial western boundary of the Indian Ocean. The differences between the two experiments represent the influence of WBR on the seasonal circulation in the equatorial Indian Ocean.

Analyses of the differences between the DAMP and CNTR runs demonstrate that WBR can only influence the amplitudes of the sea level and zonal currents, but not the phases of the seasonal variations. The damping of the WBR decreases the amplitudes of the sea level and zonal currents in the central and eastern Indian Ocean due to the absence of the equatorial Kelvin waves. The significant reduction of the semiannual oscillations suggests that the resonance of the second baroclinic mode is strongly dependent on WBR. Our results confirm earlier findings that WBR plays an important role in the interactions between the reflected and wind-forced equatorial waves and highlights effects forced by the WBR. The semiannual oscillation of the second baroclinic basin mode is suppressed when WBR is absent.

To analyze the equatorial wave dynamics associated with WBR, equatorial wave coefficients are extracted from the experiments showing that the influence from WBR on the semiannual oscillations of sea level and zonal currents is primarily in the equatorial instead of the off-equatorial Indian Ocean. Analyses have shown that the Kelvin waves of the first and second baroclinic modes from the western boundary have larger contributions to the semiannual oscillations of sea level than the Rossby waves. In comparison, the first meridional-mode Rossby waves of the second baroclinic mode have a much larger contribution to the zonal currents semiannual oscillation than the Kelvin waves. The second baroclinic mode has a larger contribution on the seasonal variations of the equatorial sea level and zonal currents than the first and other higher baroclinic modes. These results suggest that the WBR mainly influence the seasonal variations of the equatorial Indian Ocean through the basin resonance of the second baroclinic mode.

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