Baroclinic Tides Simulation in the Red Sea: Comparison to Observations and Basic Characteristics

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Abstract The baroclinic tides in the Red Sea are simulated using a three-dimensional, nonhydrostatic, high-resolution Massachusetts Institute of Technology general circulation model. Various observations have been used to validate the simulation results. A good match between the model results and observations from five tidal gauges has been obtained. Tidal amplitude and phase data from 21 tidal stations present high correlation coefficients and low deviations with the model results. Comparisons between model and Oregon State University Tidal Inversion Software data suggest consistent results, with only small discrepancies at the locations of the amphidromic points. Tidal currents from four mooring observations are in good agreement with the simulation results, with discrepancies appearing in shallow areas and those with complex bottom topography. Based on the simulation results, the basic characteristics of baroclinic tides in the Red Sea are analyzed. The properties of barotropic tides, and distribution of the forcing function parameter, indicate that the baroclinic tides are generated mainly in four areas: the Bab-el-Mandeb (BAM) Strait, the southern Red Sea, the Gulf of Suez, and the Strait of Tiran. This is confirmed by the spatial distributions of baroclinic tidal kinetic energy and energy flux. The properties of the conversion rate from barotropic tides to baroclinic tides, and the divergence of baroclinic energy flux, further reveal quantitatively that the southern Red Sea features the most of the generated baroclinic energy. The majority of the baroclinic energy disappears within the four areas, either dissipating due to friction and bottom drag or converting back to barotropic energy.

Plain Language Summary Baroclinic tides, as generated from the interaction between barotropic tides and bottom topography, are important for the coastal regions such as the Red Sea. We use high-resolution numerical methods to simulate the baroclinic tides in the Red Sea. We compared the model results with several observations and found overall a good match between them. These data sets include sea level data and tidal parameters from tidal gauges, Oregon State University Tidal Inversion Software barotropic tidal model, and several mooring current data. Based on the model results, the general mechanism for the generation of baroclinic tides in the Red Sea can be inferred. As the energetic tides from the open ocean enter the Red Sea through the Strait of Bab-el-Mandeb, they propagate northward along the coast and then form different amphidromic systems. During this process, baroclinic tides generate mainly at four areas: the Bab al-Mandeb Strait, the southern Red Sea, the Gulf of Suez, and the Strait of Tiran.

1. Introduction

Baroclinic tides are ubiquitous in the oceans globally (Garrett & Kunze, 2007; Simmons et al., 2004) and are primarily generated by barotropic tides flowing over topographic features in a stratified ocean. They play crucial roles in determining the ocean circulation and climate change through diapycnal mixing processes (Munk & Wunsch, 1998; Wunsch & Ferrari, 2004). The oscillation and vertical mixing across the pycnocline, caused by baroclinic tides and associated breaking and mixing processes, could also affect the transport of nutrients and neustonic larvae and thus influence ocean ecosystems (Pineda, 1994).

The Red Sea is a long, narrow sea that extends approximately 2,000 km from north to south. Its average width is about 280 km, with a maximum breadth of 306 km in the southern basin (Bower & Furey, 2012). The only connection to the Indian Ocean is through the narrow and shallow Bab-el-Mandeb (BAM) Strait. With a meridional range of about 20°, the Red Sea exhibits a significant difference in the vertical seawater structure between
Figure 1. Bottom topography of the Red Sea. Five sea level elevation stations (Duba, Yanbu, Rabigh, Jeddah, and Jizan) are indicated with green squares, blue circles show the locations of 21 tidal stations, and red solid circles indicate the locations of mooring observations (M1, M2, M3, and M4).

the southern and northern regions. Seasonal variations in the general circulation also greatly modulates the water stratification, especially in the southern Red Sea and at the entrance to the BAM Strait (Yao, Hoteit, Pratt, Bower, Zhai, et al., 2014; Yao, Hoteit, Pratt, Bower, et al., 2014), which may have an important impact on the generation of baroclinic tides. The Red Sea contains a unique large marine ecosystem and most of its coastline is bordered by a coral reef system (Madah et al., 2015; Rait sos et al., 2013, 2017). Therefore, studying the properties of baroclinic tides and the associated breaking and mixing processes is crucial to understand not only the physical processes but also the ecological and environmental system.

To date, the studies on the tides in the Red Sea, especially baroclinic tides, have been quite limited and fragmentary. Da Silva et al. (2012) reported, based on satellite observations, that the southern Red Sea was a new hot spot for internal solitary waves (ISWs). Guo et al. (2016) further explored the generation processes of the ISWs using a 2-D numerical model, revealing that the dominant mechanism is the nonlinear evolution of an internal tide. The tidal characteristics in the BAM Strait has been explored using in situ observations (Jarosz, Murray, & Inoue, 2005) and a 2-D numerical model (Jaros, Blain, et al. 2005), with main focus on the activities of barotropic tides. Monismith and Genin (2004) studied the variations in tidal currents and elevations in the Gulf of Aqaba using observational data, suggesting these to be associated with internal waves generated at the Strait of Tiran. More recently, Madah et al. (2015) shed the first light on the characteristics of barotropic tides in the Red Sea as a whole system by applying a 2-D numerical model based on the Delft3D modeling system. All previous studies either focused on particular regions or only on the properties of barotropic tides in the Red Sea. The characteristics of baroclinic tides in the Red Sea are yet to be studied as a complete system.

To fill this gap, this work configured a three-dimensional, non-hydrostatic, high-resolution Massachusetts Institute of Technology general circulation model (MITgcm) to study the characteristics of the baroclinic tides in the Red Sea. The model was implemented with realistic bottom topography and atmospheric and tidal forcing. Several available observations have been collected for validating the simulation results, based on which the basic characteristics of baroclinic tides in the Red Sea are for the first time analyzed and discussed.
The remainder of the paper is organized as follows. The model configuration is presented in section 2, followed by extensive comparisons to available observations in section 3. The analysis of the basic characteristics of baroclinic tides in the Red Sea is described and discussed in section 4. Finally, section 5 provides a summary of the main result.

2. Model Configuration

The MITgcm is a general ocean circulation model (http://mitgcm.org/) designed for the study of the atmosphere, ocean, and climate. Its nonhydrostatic formulation enables it to simulate fluid phenomena over a wide range of scales (Marshall et al., 1997). Version c65x of the MITgcm was employed to simulate the baroclinic tides in the Red Sea. Considering the significant spatial and temporal variability, the tide simulation was conducted based on an ocean circulation model with realistic forcing that was successfully used to describe the overturning circulation (Yao, Hoteit, Pratt, Bower, Zhai, et al., 2014; Yao, Hoteit, Pratt, Bower, et al., 2014), seasonal variability (Zhan et al., 2014), and kinetic energy budget (Zhan et al., 2016) of mesoscale eddies and ensemble data assimilation (Toye et al., 2017) in the Red Sea.

The domain of the Red Sea Tide (RS_Tide) model includes all of the Red Sea, Gulf of Suez, Gulf of Aqaba, and most of the Gulf of Aden, where the only open boundary is prescribed at 50°E (see Figure 1). The model topography used was derived from the General Bathymetric Chart of the Oceans (GEBCO) digital atlas, in 30-arcsec intervals. Some modifications to the bathymetry near the BAM Strait were applied in shallow areas (with water depths in the range of 100 to 138 m) of the Hanish Sill region, according to Sea Chart no. 3661, 3rd edition, printed in May 2003. The coastline was also improved using the Global Self-consistent, Hierarchical, High resolution Geography Database. The horizontal resolution of the model is 0.01°, with 50 vertical layers, with a minimum thickness of 4 m near the surface and a maximum thickness of 300 m near the bottom. A nonslip condition is set to the bottom boundary with a spatially constant, quadratic drag coefficient \( C_d \) equal to 0.002.

2.1. Model Forcing

Tidal forcing was implemented by importing barotropic currents from the open boundary in the east. Amplitudes and phases of tidal currents were obtained from the inverse barotropic tidal model TPXO 7.2 Indian Ocean (Egbert & Erofeeva, 2002), which has a horizontal resolution of 1/16°. Eight major tidal components of semidiurnal and diurnal frequencies \( M_2, S_2, N_2, K_2, K_1, O_1, P_1, \) and \( Q_1 \), ordered according to their amplitudes in the Red Sea) were included. To account for the 18.6-year cycle of astronomical tide-generating potential, nodal correction (Pawlowicz et al., 2002) was applied to the derivation of barotropic currents amplitudes and phases, which has proven essential to obtain accurate barotropic tidal simulations.

Atmospheric forcing was derived from the European Reanalysis-Interim (ERA-Interim) of the European Centre for Medium-range Weather Forecasts (ECMWF; Dee et al., 2011) available on a 0.750° spatial and 6-hourly temporal resolution. Lateral boundary conditions were extracted from the monthly assimilated horizontal velocities, temperature, and salinity of the 1/3° GECCO2 ocean global reanalysis (Köhl, 2015).

2.2. Operational Considerations

The circulation model was initialized from a state of no motion using the annual mean temperature and salinity from the World Ocean Atlas 2013. A nonhydrostatic configuration is implemented. The model spin up was performed over a 6-year period using daily ECMWF climatology forcing and it was driven by monthly-mean \( U, V, T \), and \( S \) from GECCO2 data in the open boundary. After the 6-year simulation the model showed a quasi-stationary upper 100-m depth-averaged kinetic energy. The time series of salinity also showed no increasing trend anymore. Those two parameters were used to justify the change of forcing from the climatology forcing to the real-time atmospheric forcing of ECMWF. After that, the circulation model was integrated over the period 1989–2012 to provide the varying background stratification. Based on that, the tidal simulation was conducted at four different months representing four different seasons in the year 1995–1996: case199504, case199507, case199510, and case199601; the run of case199504 is analyzed as the standard case; the simulations were conducted in the year 1995–1996 for comparison with observations from
3. Comparisons to Observations

To validate the RS_Tide model, different data sets have been collected, including sea level elevation from tidal gauges, tidal elevation amplitudes and phases from tidal stations, barotropic tide elevations from the Oregon State University Tidal Inversion Software (OTIS), and tidal currents data from mooring observations. The comparisons between the model results and the observations are presented in the following subsections.

3.1. Sea Level Elevation Time Series

Sea level elevation time series data were collected from five tidal gauges along the eastern coastline of the Red Sea. The gauges were located at Duba, Yanbu, Rabigh, Jeddah, and Jizan, as indicated with green squares in Figure 1. The comparisons between the simulated results and the observations are outlined in Figure 2, where the blue lines refer to the RS_Tide model results and the red lines indicate the tidal gauge data. The study period begins on 1 April 2012 and lasts for 30 days. To extract the tidal elevation signal, harmonic analysis was applied to both the model results and the observations, retaining the first eight main tidal components (\(M_2\), \(S_2\), \(N_2\), \(K_2\), \(K_1\), \(O_1\), \(P_1\), and \(Q_1\)). Overall, the model results are clearly in good agreement with the observations, despite the slight negative time lag at Duba, Yanbu, Rabigh, Jeddah and slight positive time lag at Jizan. The lags could be attributed to the complex bottom topography; since the tides enter through the narrow Strait of BAM, the phase simulation is very sensitive to the bottom topography, especially at the strait. Also, the phase gradient is larger near Jeddah, as seen from the spatial distribution of \(M_2\) in Figure 3, making the time lag most pronounced at this station. The results also suggest that the amplitudes of tidal elevation are relatively large in the south (Jizan) and north (Duba), while they are relatively small near the central Red Sea (Jeddah). This will be further interpreted by the analysis of the spatial distribution of tidal elevations in section 3.3.

3.2. Tidal Elevation Amplitudes and Phases

Tidal elevation amplitude and phase data from 21 sea level elevation stations along the Red Sea were collected from Jarosz, Blain, et al. (2005); their locations are indicated by the solid blue circles in Figure 1. Table 1 lists the results of a comparison between simulated and observed tidal elevation amplitudes and phases of the first four main tidal components (\(M_2\), \(S_2\), \(K_1\), and \(O_1\)). The model tidal amplitudes and phases are calculated...
by harmonic analysis from 1-month sea level time series, while the parameters are directly obtained from the study of Jarosz, Blain, et al. (2005). The results consistently show that tidal elevation amplitude values are larger in the northern and the southern Red Sea and smaller in the central Red Sea.

To further evaluate the agreement between the model results and observations, correlation coefficients of the amplitudes and phases are examined. Table 2 lists these coefficients and the standard deviations of the differences between the simulated and observed values. In addition, the parameter H, which is a measure of the overall performance computed as an average difference between the observations and model solution, is presented. This parameter is estimated from the following expression (Davies et al., 1997):

$$H = \frac{1}{N} \sum_{k=1}^{N} \left( |A_{\text{obs}} \cos g_{\text{obs}} - A_{\text{mod}} \cos g_{\text{mod}}|^2 + |A_{\text{obs}} \sin g_{\text{obs}} - A_{\text{mod}} \sin g_{\text{mod}}|^2 \right)^{1/2},$$

where $N$ is the number of the sea level stations; $A$ and $g$ are amplitudes and phases, respectively; and the suffixes $\text{mod}$ and $\text{obs}$ denote the modeled and observed harmonic constants, respectively. Generally, since $H$
describes the overall difference between the model outputs and the observations, a higher $H$ implies poor simulation results.

The very high correlation coefficients (above 0.97 for both the amplitudes and phases) coupled with small $H$ values (<4 cm) and low standard deviations (<2.1 cm for amplitudes and 21° for phases) indicate an accurate replication of the diurnal components by the model. For the major semidiurnal constituents $M_2$, the model computations also compare reasonably well with the observations; the correlation coefficient is around 0.92 for amplitudes and phases, and $H$ is 14 cm. Since the $M_2$ tidal component is dominant, it might accumulate more errors (differences in parameter $H$) than other components. For the tidal component $S_2$, the correlation coefficients of amplitudes, phases, and parameter $H$ are 0.97, 0.98, and 3.3, respectively; the results are comparable with previous studies (Chen et al., 2014; Jarosz, Blain, et al., 2005) and suggest a good match between the model and observations.

### 3.3. OTIS Barotropic Model Data

OTIS, which implements an efficient representative calculation scheme that forms the basis for a practical and relocatable tidal data inversion package, has been widely applied to generate tidal forcing for numerical studies of tide (Egbert et al., 1994; Egbert & Erofeeva, 2002). The barotropic tidal elevation data from a high-resolution (1/60°) OTIS product for the Red Sea is employed here for comparison with the model results and for exploring the spatial distribution of tidal elevations in the Red Sea.

Figure 3 presents the comparisons of tidal elevation amplitudes (colored gradient) and phases (white lines) for the dominant semidiurnal tidal component ($M_2$) and diurnal tidal component ($K_1$) between the OTIS (left-hand panels) and RS_Tide (right-hand panels) models. A consistent pattern is seen for both model and OTIS data: both $M_2$ and $K_1$ tidal components are represented by an anticlockwise amphidromic system, with the amphidromic points located at the central and southern parts of the Red Sea, respectively, according to their different wavelengths. However, the RS_Tide model suggests both more complex phase structures and discrepancies in the locations of the amphidromic points because of the complexity of 3-D baroclinic model and the high-resolution bottom topography. A previous study of barotropic tide simulations in the Red Sea using the Delft3D modeling system (Figure 5 in Madah et al., 2015), presented locations of amphidromic points that were more consistent with the results of our model, implying that high-resolution bottom topography is crucial for tide simulation in the Red Sea. The tidal amphidromic systems not only agree well but also reflect the fact that the tidal elevation amplitudes are small in the central Red Sea, but are relatively large in
3.4. Tidal Currents From Mooring Data

For a tidal model, accuracy in sea level elevation with respect to the observational data does not guarantee the accuracy of velocity data. Thus, velocity data were gathered from four mooring observations to reveal the features of tidal velocities and to validate the model.

Figure 4 compares the ellipses of tidal velocities at different locations and the different depth levels between the model results and the mooring observations. The locations of the mooring stations are indicated with solid red circles in Figure 1, with two of them (M1 and M2) located near the BAM Strait, collected from Murray and Johns (1997) one (M3) near Duba, and the last (M4) at the near-shore close to Jizan. The comparisons of tidal velocities show a good consistency between model results and observations near the BAM Strait (M1 and M2), featuring a pattern with the main direction along the strait and the first two dominating tidal components of M_2 and K_1 dominating. The model-data agreement in M3 and M4 is not as good as that in M1 and M2: in M3, the tidal velocities are relatively small as a result of the conservation of water volume; discrepancies are present in the tidal component O_1 at a depth of 599 m and in K_1 at a depth of 455 m, indicating that the complex baroclinic background currents created by circulations and eddies may affect simulation performance. The comparison of velocities near Jizan further imply that with shallower and more complex bottom
topography, it is difficult to resolve tidal dynamics accurately. Considering complicated small-scale physical processes such as turbulence and mixing, a higher-resolution model may be required to obtain more accurate simulation results.

4. Basic Characteristics

Based on this high-resolution model simulation, the basic characteristics of baroclinic tides and the associated properties of barotropic tides have been explored. The results are presented in the following subsections.

4.1. Barotropic Tides

Based on the model results and the comparisons to available observations in section 3, a general feature can be observed of the barotropic tides in the Red Sea: they feature anticlockwise amphidromic systems as they enter the Red Sea through the BAM Strait and then propagate northward along the right-hand coast and rotate anticlockwise back when they reach the northern boundary. The locations of amphidromic points vary according to the wavelengths of the different tidal components. In general, they are located in the central part of the Red Sea for semidiurnal components such as $M_2$, $S_2$, $N_2$, and $K_2$, and the southern part of the Red Sea for diurnal components such as $K_1$, $O_1$, $Q_1$, and $P_1$ (see Figure 3). The modeled process is consistent with previous study (Madah et al., 2015).
Figure 7. The spatial distribution of the magnitude (absolute value) of the depth-integrated forcing function
\[ F_{\text{forcing}} = (-\bar{U} \frac{\partial H}{\partial x} - \bar{V} \frac{\partial H}{\partial y}) \times (-zH) \times |\frac{\partial \rho_0}{\partial z}|. \]

The relative importance of the diurnal and semidiurnal tidal components are estimated by calculating the form factor as follows (Pugh, 2004):

\[ FF = \frac{H_{k1} + H_{m2}}{H_{m2} + H_{s2}}, \]  

(2)

where \( H_{k1}, H_{o1}, H_{m2}, \) and \( H_{s2} \) are the elevation amplitude for the main four tidal components. In terms of form factor (FF), the tides are classified as follows:

- \( FF = 0 \) to 0.25: Semidiurnal tide
- \( FF = 0.25 \) to 1.50: Irregular semidiurnal tide
- \( FF = 1.50 \) to 3.00: Irregular diurnal tide
- \( FF = \) greater than 3.0: Diurnal tide

Figure 5 depicts the spatial distribution of these tides according to the form factor based on the model results. It shows that in the central part of the Red Sea, at approximately 19°N, the diurnal tide (in yellow) dominates; otherwise, it is dominated by the mixed tides (green), mainly diurnal components. The rest of the central Red Sea, most parts in the north, and the BAM Strait show mixed tides of mainly semidiurnal components.

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Figure 8. Spatial distribution of depth-integrated baroclinic tidal kinetic energy based on the equation \((\int \frac{1}{2}(U'^2 + V'^2)dz)\). The red filled circle at the Strait of BAM indicates the maximum value of 7.86 kJ/m².

(light blue). The southern Red Sea, Gulf of Aqaba, and northern part of the Gulf of Suez are dominated by the semidiurnal tidal components.

The properties of barotropic tidal velocity are crucial to explore the formation of baroclinic tides. The tidal velocity is more complex than the elevation as it not only follows the tidal elevation but is also affected by the bottom topography, featuring more intensified velocities in the shallow areas. Figure 6 shows four snapshots of barotropic tidal velocities in the Red Sea in one semi-diurnal period (half the diurnal period). Generally, large values for barotropic tidal velocities are present in the BAM Strait, the southern Red Sea, the Gulf of Suez, and the Strait of Tiran. Their periodic appearances are consistent with the local dominant tide form (Figure 5): semi-diurnal for the southern Red Sea and mixed semi-diurnal and diurnal for the other three areas. Considering the crucial role of the intensity of the velocity of the barotropic tide, these four areas are the most likely spots for the generation of baroclinic tides. This has been examined further by introducing the forcing function (Baines, 1982):

\[
F_{\text{forcing}} = \left(-\frac{\partial H}{\partial x} - \frac{\partial H}{\partial y}\right) \times \frac{1}{H} \times \frac{\partial \rho_0}{\partial z},
\]

(3)
Figure 9. Spatial distribution of (a) the depth-integrated baroclinic energy flux \( \left( \int_{-H}^{H} (U'P' + V'P') \, dz \right) \) and (b) the depth-averaged of (a). where \( \frac{\partial H}{\partial x} \) and \( \frac{\partial H}{\partial y} \) are the bottom slopes in the x and y directions, respectively. The spatial distribution of the magnitude (absolute value) of the depth-integrated forcing function is given in Figure 7. Large values appear in the four areas mentioned above, concentrated around the edges of slopes, revealing the areas in the Red Sea with the most potential to generate baroclinic tides.

4.2. Baroclinic Tides

Considering that the simulation could not well reproduce the details of small-scale baroclinic processes, such as nonlinear steepening and breaking of internal solitary waves, even at a horizontal resolution of 1 km, the analysis is focused on revealing the general picture of baroclinic tides in the Red Sea, based mainly on the energetics. Following Niwa and Hibiya (2004), the governing equation for depth-integrated baroclinic energy is

\[
\frac{\partial E_{bc}}{\partial t} = - \left( \frac{\partial P' \bar{U} D}{\partial x} + \frac{\partial P' \bar{V} D}{\partial y} \right) + \rho' \bar{w}_{bc} D + DIS_{bc} + ADV_{bc},
\]

(4)

where the variable \( E_{bc} = \frac{1}{2} \int_{-H}^{H} P_0 \left[ N^2 |\bar{\zeta}|^2 + (U'^2 + V'^2) \right] \, dz \) is the baroclinic energy density; \( \bar{\zeta} \) is the displacement of the isopycnal surface; \( \bar{w}_{bc} \) is the Cartesian vertical velocity associated with the barotropic flow; \( DIS_{bc} \) and \( ADV_{bc} \) denote the dissipation and advection, respectively, of the baroclinic energy; The term \( D \) is the total depth and \( P \) is the pressure; \( - \left( \frac{\partial P' \bar{U} D}{\partial x} + \frac{\partial P' \bar{V} D}{\partial y} \right) \) is the divergence of the depth-integrated baroclinic energy flux; and \( \rho' \bar{w}_{bc} D \) represents the rate of conversion from barotropic to baroclinic energy integrated over the entire water column. In this work, the baroclinic tidal velocity \( U' \) and \( V' \) are defined as the difference between the tidal velocity and the barotropic tidal velocity, and the tidal velocity is defined as the difference between the two model runs with and without tides.
Figure 10. Spatial distribution of (a) the conversion rate from barotropic tides to baroclinic tides \( \langle (g \int_{-H}^{\eta} \rho' w_{bt} d\eta) \rangle \), (b) the divergence of baroclinic tide energy flux \( \langle (\int_{-H}^{\eta} \left( \frac{\partial U'}{\partial x} + \frac{\partial V'}{\partial x} \right) d\eta) \rangle \), and (c) the difference between (a) and (b).

### 4.2.1. Baroclinic Tidal Kinetic Energy

First, the depth-integrated baroclinic tidal Kinetic Energy (KE) \( \langle \int_{-H}^{\eta} 1/2(U'^2 + V'^2) d\eta \rangle \) was estimated based on the simulation results; the spatial distribution is shown in Figure 8. Hereafter, angle brackets \( \langle \rangle \) refer to time averaged within 15 days. It consistently presents high values of KE within the four areas of potential baroclinic tide generation indicated by the forcing function. Among them, the narrow entrance at the Strait of BAM features higher values of KE than the other three areas. The maximum value of 7.86 kJ/m² also appears at the entrance of the BAM Strait; this value is larger than the maximum eddy KE value of 6 kJ/m² (Zhan et al., 2016).

In the southern Red Sea, two long areas with high KE values along the edges of slopes, with higher values at the western side, indicate that baroclinic tides are mostly generated near the slopes and propagate toward the center of the trench. This is consistent with previous studies of ISWs in the southern Red Sea based on satellite observations (Da Silva et al., 2012) and numerical models (Guo et al., 2016), which revealed that the ISWs are formed from internal tides generated at the slopes on both sides of the sea and propagated toward the center. In most parts of the central and northern Red Sea, the KE of baroclinic tides are below 0.1 kJ/m², indicating very little baroclinic tide activity; in the north, there are intense signals exhibiting at the edge of the slope at the entrance of the Gulf of Suez and near the steep sea ridge at the Strait of Tiran.

### 4.2.2. Baroclinic Tidal Energy Flux

Figure 9a depicts the spatial distribution of the depth-integrated baroclinic energy flux \( \langle \int_{-H}^{\eta} (U'P' + V'P') d\eta \rangle \) in the Red Sea. The colors indicate the density of the baroclinic energy flux. Figure 9b shows the same data but with values averaged by depth to eliminate the overestimation from the depth integration. Compared to the KE, the baroclinic energy flux includes the potential energy caused by oscillation of the isopycnals. The depth-integrated baroclinic energy flux density shows a high value zone in the trench of the southern Red Sea that is much larger than the other three areas (Figure 9a). This is partly due to the depth integration, since the water in this area is deeper than in other areas. After averaging by depth, the intense signals within and at the north of the BAM Strait are comparable to those in the southern Red Sea, even though the maximum value of 0.135 Kw/m² is still seen at the western slope of the latter. Furthermore, the high values are concentrated along the edges of the two slopes in the southern Red Sea, instead of being spread over the whole trough; this is more consistent with the distribution of the KE. One feature of all of these areas is that the directions of...
the baroclinic energy flux are complex and disordered, which could be due to the complex bottom topography. Compared to the other three areas, the fluxes in the southern Red Sea are oriented in relatively ordered directions: approximately perpendicular to the slope edges on both sides.

### 4.2.3. Sources and Sinks

Figure 10 shows the conversion rate from barotropic to baroclinic tide ($\langle g \int_{h}^{\eta - H} \rho w_{bt} dz \rangle$ (a); the divergence of baroclinic tide energy flux ($\langle \int_{-N}^{N} \left( \frac{\partial P\prime U\prime}{\partial x} + \frac{\partial P\prime V\prime}{\partial x} \right) dz \rangle$ (b); and the difference between the two (c), which is considered as the dissipation rate assuming that the advection of baroclinic energy is negligible (Niwa & Hibiya, 2004). Calculations are based on the model output of the last 2 weeks. The spatial distribution of the positive conversion rates indicates areas where the interaction between barotropic currents and bottom topography occurs. This is the main source of the baroclinic tides, and it is quite consistent with the results of the forcing function (Figure 7) and the positive values of the divergence of the baroclinic energy flux (Figure 10b). The negative conversion rates do not correspond to turbulent energy dissipation; instead, they are measures of the energy transfer from the baroclinic to the barotropic tides due to pressure (Hsieh et al., 2009). The total values of the conversion rates from barotropic to baroclinic tides for the BAM Strait, the southern Red Sea, the Gulf of Suez, and the Gulf of Aqaba are 0.097 GW, 0.109 GW, 0.013 GW, and 0.006 GW, respectively; from baroclinic to barotropic tides, these values are 0.029 GW, 0.017 GW, 0.007 GW, and 0.002 GW; the net values are 0.068 GW, 0.079 GW, 0.006 GW, and 0.003 GW. The values are calculated after spatial integration within the four areas indicated by dash boxes in Figure 10a.

The distribution of the divergence of the baroclinic energy flux indicates areas where the baroclinic tide was generated (positive values) and dissipated (negative values). It is consistent for the areas of positive values on the conversion rate map, as the main source of baroclinic tides is from the interaction between barotropic currents and bottom topography. The negative values are spread more widely because the baroclinic energy sink comes partly from the dissipation. The positive values of the divergence of the baroclinic energy flux for these four areas are 0.098 GW, 0.117 GW, 0.023 GW, and 0.006 GW, respectively; the negative values are 0.095 GW, 0.110 GW, 0.022 GW, and 0.005 GW; and the net values are 0.003 GW, 0.007 GW, 0.001 GW, and 0.001 GW. Most of the baroclinic energy disappears within the four areas, either being transferred into barotropic energy due to pressure or dissipated due to friction and bottom drag.

### 4.2.4. Seasonality

As mentioned in section 1, seawater properties in the Red Sea, particularly stratification, not only differ widely in terms of spatial distribution but also vary significantly with the seasons, as modulated by seasonally varying general circulations (Sofianos & Johns, 2003; Yao, Hoteit, Pratt, Bower, Zhai, et al., 2014; Yao, Hoteit, Pratt, Bower, et al., 2014). In the southern Red Sea, in particular, water from intermediate Gulf of Aden intrudes from June to September, while the thermocline stays uplifted above pre-June levels till December and the inflow penetrates to 24°N (Sofianos & Johns, 2003; Yao, Hoteit, Pratt, Bower, Zhai, et al., 2014; Yao, Hoteit, Pratt, Bower, et al., 2014). As a result, there are significant differences in the stratification between summer and winter that could potentially affect the process of baroclinic tide generation. Hence, the conversion rate from barotropic to baroclinic tides in the four regions has been calculated for the months of January, April, July, and October, representing winter, spring, summer, and autumn, respectively. The results are presented in Figure 11.

For each case, a 15-day average has been applied to eliminate the tidal intensity variations during the 2-week cycle. In the BAM Strait, the generation of baroclinic tides appears to show seasonal variability: the maximum value is seen in October, while minimum value is seen in April. Similarly, in the southern Red Sea, even though their values are comparable for January and April, the difference between January and October is even higher than that in the BAM Strait. In the Gulf of Suez and the Strait of Tiran, the generation of baroclinic tides exhibits weak seasonal variability.

### 4.2.5. Discussion

From the analysis of simulation results above, the general picture of the baroclinic tides in the Red Sea can be inferred. The barotropic tides enter the Red Sea through the BAM Strait, bringing a large amount of energy from the open ocean. The narrow and shallow topography at the strait intensifies the speed of barotropic tides, on the one hand, while on the other, it interacts with barotropic currents to generate baroclinic tides.
Because of the complex bottom topography, the baroclinic tides do not propagate long before they partly convert back to barotropic tide and partly dissipate due to the bottom drag and friction. After entering the Red Sea, the barotropic tides propagate northward along the east coast and rotate anticlockwise back when they reach the northern boundary and generate different amphidromic systems according to the wavelengths of the tidal components. The Southern Red Sea has the densest baroclinic tide energy flux as a result of relatively large barotropic tidal currents and the long and steep slope edges on both sides of the trough. The depth of trough also provides ideal conditions for the development of baroclinic tides, which could explain why this region has been reported as a hot spot for internal solitary waves in the Red Sea (Da Silva et al., 2012). The central and northern Red Sea have very few baroclinic tidal signals due to the relatively weak tidal currents and absence of rough bottom topography to provide the initial perturbation. In the Gulf of Suez, the shallow and narrow basin topography intensifies the tidal currents and baroclinic tides are generated, especially at the strait. A similar mechanism is seen at the Strait of Tiran, where the bottom topography features a steep ridge at the narrow entrance that serves as a generator when barotropic tides oscillate through the strait. Since the average depth in the Gulf of Aqaba is much deeper than that in the Gulf of Suez, very few baroclinic tides are generated inside the Gulf of Aqaba.

For the seasonal variation, the generation of internal tides depends on the barotropic tidal currents and the stratification. Even though the barotropic tidal velocity amplitude does not change with time, it could be strengthened or weakened by the background current under a Doppler effect and may further influence the generation of baroclinic tides. Therefore, the eddy activities or background general circulations can affect the variations of the generation of baroclinic tides. In the meantime, the contribution from changes in stratification cannot be neglected. The interplay between these processes should be investigated in future studies.

5. Summary

Baroclinic tides and their associated processes are important in the Red Sea, which features a unique and large marine ecological system. Limited information are, however, available on the tide circulation in the Red Sea, especially about the characteristics of baroclinic tides. Numerical simulations of the baroclinic tides conducted for the first time in the Red Sea using a three-dimensional, nonhydrostatic, high-resolution MITgcm.

Several available observations were first used for validating the simulated results. Overall, a good match was obtained between the model outputs and sea level elevation time series observations from five tidal gauges along the eastern coastline of the Red Sea, with minor phase discrepancies. Available tidal elevation amplitudes and phases at 21 coastal stations were also used to examine the correlation coefficients and other statistical parameters. High correlation coefficients and low standard deviations for diurnal components, and reasonable simulation results for the dominant semi-diurnal components \(M_2\), were accomplished. Comparisons between model and OTIS data are consistent in general, with small discrepancies at the locations of amphidromic points, implying that high-resolution bottom topography is crucial for the simulation of tides in the Red Sea. Tidal currents from four moorings show overall a good agreement with the simulation results, with some discrepancies in the regions of shallow water and complex bottom topography. More accurate simulation of baroclinic tidal currents could be obtained with more precise, higher-resolution bottom topography.

Based on this high-resolution model simulation, the characteristics of baroclinic tides and the associated barotropic tides have been analyzed and discussed. The properties of barotropic velocities combined with the forcing function reveal four potential areas for the generation of baroclinic tides in the Red Sea: the Strait of BAM, the southern Red Sea, the Gulf of Suez, and the Strait of Tiran. These were then confirmed by the spatial distribution of baroclinic tidal KE and energy fluxes. The conversion rate and the divergence of baroclinic energy fluxes further show, quantitatively, that the southern Red Sea features most of the generated baroclinic energy. The majority of this baroclinic energy disappears within the four areas, either dissipating due to friction and bottom drag or being converted back into barotropic energy due to pressure. Seasonal variations in the generation of baroclinic tides are presented in the BAM Strait and in the southern Red Sea, potentially due to modulated variations in stratification from the summer water intrusions from the Gulf of Aden.

Based on the model results, the general mechanism for the generation of baroclinic tides in the Red Sea can be inferred. As the energetic tides from the open ocean enter the Red Sea through the Strait of BAM, they propagate northward along the coast and then form different amphidromic systems. During this process,
barotonic tides generate mainly at the four areas mentioned above, due to the interaction between intense barotropic tidal currents and the steep bottom topography. Those baroclinic tides do not propagate far away from their generation places before breaking and dissipating because of the complexity of the bottom topography. Under the limitation of the model resolution, detailed processes regarding the generation and breaking and dissipation of the ISWs cannot be well reproduced in this model. Therefore, higher-resolution simulations with particular focuses on the four main areas in the Red Sea will be the future tasks.

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