Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

An internal wave investigation in the Bay of Bengal

To cite this article: X Dang *et al* 2025 *J. Phys.: Conf. Ser.* **3007** 012013

An internal wave investigation in the Bay of Bengal

X Dang[1], Y Sui[2] and D Tang[1*]

[1] Guangdong Remote Sensing Center for Marine Ecology and Environment, Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou 511458, China
[2] Institute for Ocean Engineering, Shenzhen International Graduate School, Tsinghua University, Shenzhen 518055, China

[*]Email: lingzistdl@126.com

Abstract. So far, knowledge of internal waves in the Bay of Bengal is still limited, and there is a gap in understanding their propagation characteristics. Because of the stochastic nature of internal waves, there are few opportunities to observe internal waves through the surface field, and currently no internal waves have been observed from the surface in the Bay of Bengal. Recently, we captured a surface image of internal waves in the Bay of Bengal and matched the satellite image of internal waves with positional information. Subsequently, the evidence of the existence of internal waves was verified using Biogeochemical-Argo data and satellite images of the region where the internal waves occurred, and satellite images of different phases were used to reveal important features of the sources, propagation paths, and velocities of the internal waves in the Bay of Bengal. Finally, we have determined that these waves have a generation period that coincides with the semidiurnal tidal cycle and that their origin is the Nicobar Islands. During their westward propagation in the Bay of Bengal, the internal waves collide and merge with each other, and their propagation velocity is 2.66 m/s. The merged internal wave packets continue to propagate westward, and the propagation velocity increases to a maximum of 3.23 m/s in the open sea, while the wavelength of the wave packets exceeds 220 km. The consistency with the results of internal wave studies in the Andaman and the South China seas illustrates the reliability of this study's findings.

1. Introduction

Internal waves are ubiquitous oceanographic phenomenon, widely distributed in the global oceans, especially concentrated in shallow shelf and marginal seas, generated in seawater with stable stratification of seawater density, with maximum amplitudes occurring in the ocean depths, and with both tidally induced and source-induced generation mechanisms [1]. By affecting the vertical mixing of seawater and altering the thermohaline structure of seawater, internal waves play an important role in the transfer large- and mesoscale kinetic energy, while they are usually non-dissipative and can propagate over long distances, and those generated at great distances from a given site can have a large impact on the local ecosystem [2]. Meanwhile internal waves usually carry a large amount of energy, and in the process of propagation can lead to the formation of strong convergence and sudden strong currents in part of the sea surface, posing a serious threat to marine engineering, oil drilling platforms, submarine oil pipelines and military submarine activities [3]. Therefore, the study of internal waves in the ocean has been of great interest [4,5].

Due to the complexity of the internal wave generation mechanism, the study of internal waves has been a hot and difficult issue in the marine field [6,7]. So far, the studies on internal wave have been concentrated in the South China Sea and the Andaman Sea, etc. [8,9], and little has been done in the Bay of Bengal [10]. The knowledge of internal waves in the Bay of Bengal is still limited, and there is a gap in the understanding of their propagation characteristics. The Bay of Bengal is the marginal sea of the Northeast Indian Ocean, which is an important channel for the northward transportation of water vapor in the Indian Ocean, and is also a necessary route of the 21st Century Maritime Silk Road (Figure 1), Therefore, the study of internal waves in the Bay of Bengal is of great practical significance.

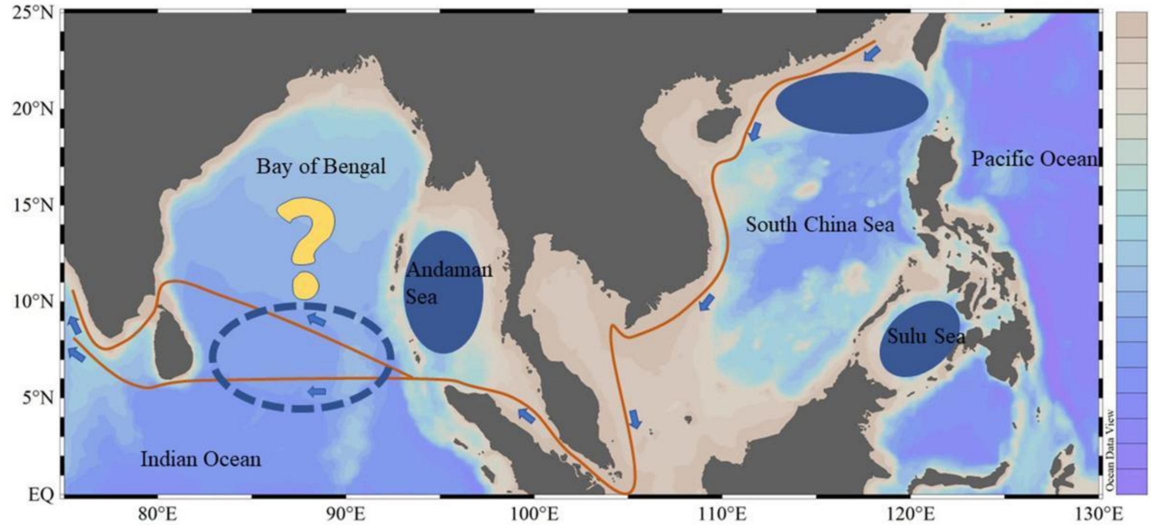

Figure 1. The approximate locations of the more studied high internal wave-incidence areas (northern South China Sea, Sulu Sea and Andaman Sea) and the unknown areas (Bay of Bengal) of internal waves that are less studied by internal waves. And the route of the Chinese Maritime Silk Road (orange line).

Because of the stochastic nature of internal waves, there are few opportunities to observe internal waves through the surface field, and currently no internal waves have been observed from the surface in the Bay of Bengal [10]. Recently, we captured a surface image of internal waves in the Bay of Bengal and matched the satellite image of internal waves with positional information. Then, the evidence of the existence of internal waves was verified using Biogeochemical-Argo (BGC-Argo) data and satellite images of the region where the internal waves occur, and satellite images of different phases were used to reveal important features of the sources, propagation paths, and velocities of the internal waves in the Bay of Bengal.

2. Data

Images of internal waves captured at the surface in the Bay of Bengal (Figure 2)， The smooth water and rough water phenomena were observed at 89.12°E, 6.23°E on March 23, 2023 at 8:58 am. The use of satellite data for monitoring of internal waves is more commonly used. The data used in this paper to validate the in situ photographs of internal waves in the Bay of Bengal include MODIS and Sentinel3 Sea and Land Surface Temperature Radiometer (SLSTR) data. The Moderate Resolution Imaging Spectroradiometer (MODIS) carried by the Aqua and Terra satellites in sun-synchronous orbits has become the most widely used optical sensor for observing IWs. With a spatial resolution of up to 250 m and a swath bandwidth of up to 2,330 km, MODIS is easily accessible for regional surveys of IWs [11,12] and is also suitable for this study. However, due to the unpredictability of the occurrence of internal waves, Sentine-3 satellite data were used as a complementary satellite for internal wave validation. Sea and SLSTR is a dual-view scanning temperature radiometer that travels in low-Earth orbit (800-830 km above sea level). The spatial resolution is 500m-1000m [13].

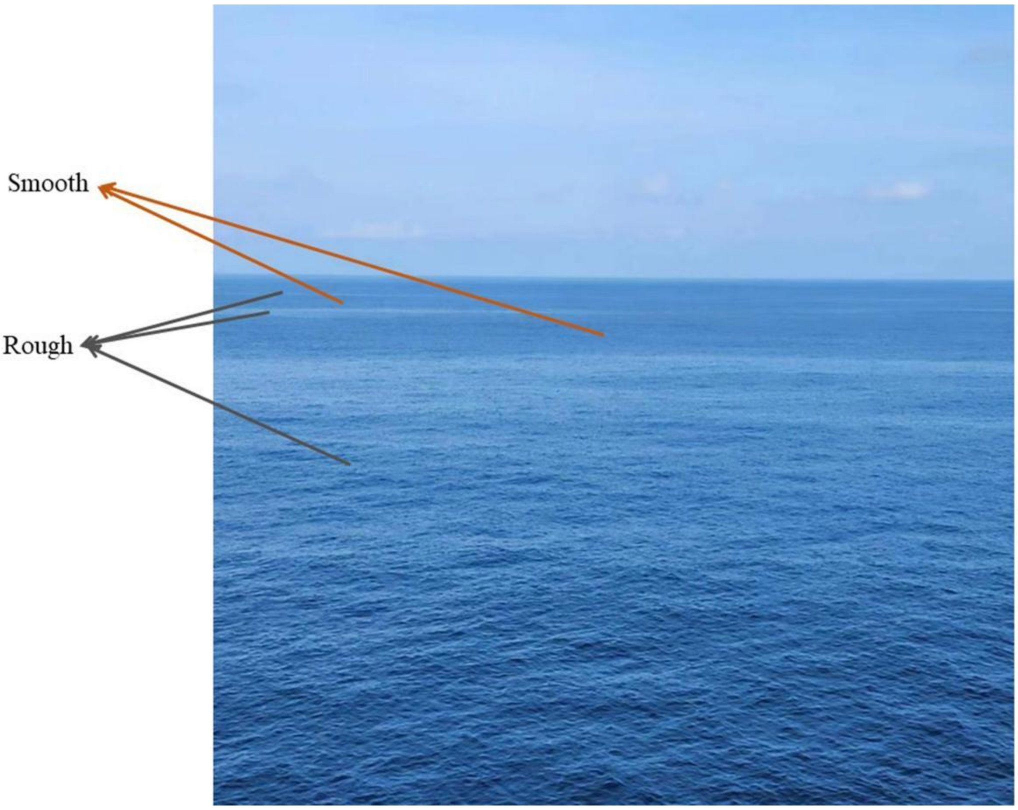

Figure 2. Photograph of internal waves observed in situ at 89.12°E, 6.23°N in the Bay of Bengal.

Measurement data is also the most intuitive means to verify the existence of internal waves, but in view of the safety and cost considerations, there is no precision instrument deployed in the Bay of Bengal region for the verification of internal waves. In this paper, using BGC-Argo data, the possibility of internal waves occurring at this location is determined by the internal conditions of the ocean where the waves are generated (Figure 3(a)). BGC-Argo data, as an important oceanographic instrument, is able to measure the vertical distribution of physical parameters of the ocean, which mainly includes temperature and salt currents at each altitude, and the data transmission is carried out at a cycle of every 10 days [14].

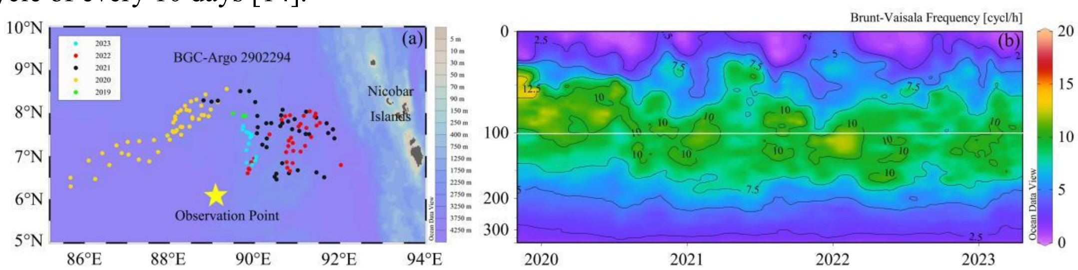

Figure 3. Location of BGC-Argo movements and Brunt-Vaisala frequencies in the study area. (a) Bathymetric map of the study area. The dots of different colors indicate the Argo float positions in different years, and the yellow pentagram is the position of the internal wave in the Bay of Bengal taken on site on March 23, 2023 at 8:58 pm. (b) Distribution of Brunt-Vaisala frequencies in the oceanic profile obtained from BGC-Argo data in the sea where the internal waves occur, and white line indicates the frequency at a depth of 100m.

3. Results and discussion

The Bay of Bengal, located in the northern Indian Ocean, with the well-known internal wave-prone Andaman Sea to the east. Consistent with the occurrence of internal waves, the surface current and deep current are in opposite directions, resulting in alternating converging and diverging zones visible from the surface, with the diverging (converging) zones appearing as smooth (rough) waters. On satellite images, internal waves appear as light and dark stripes in the form of internal solitary waves or internal wave packets. Therefore, internal waves could have occurred here and could have appeared in the form of wave packets due to the small spacing between the rough and smooth areas of the sea surface. At the same time, a search was made for matching internal waves in the satellite images, and fortunately the image on Sentinel-3 SLSTR at 4:24 on the same day was obtained (Figure 4). There are two distinct internal solitary waves near the observation point, and two groups of isolated waves to the west of the observation point, with numerous wave packets between the third and the second group of isolated waves. Name each group of isolated waves as a wave packet. The distance between wave packet 1 and wave packet 2 is 124 km, and the distance between wave packet 2 and wave packet 3 is 146 km. The lengths of the leading peak lines of wave packets 1, 2 and incomplete wave packet 3 are 68km, 220km, and 156km, respectively (Figure 5(a)). Meanwhile, on the satellite data Aqua MODIS images of the day before and after the occurrence of this internal wave (4:40 am on March 22 and 4:25 am on March 24), similar internal waves were found at similar times and locations, so it is judged that there is a stably occurring internal wave in the Bay of Bengal and stable stratification is one of the necessary conditions for the occurrence of internal waves. For a two-layer fluid with stable stratification, the maximum value of the floating frequency occurs in the pycnocline layer. From Figure 3(b), it can be seen that except for the region with shallow water, there is a stable stratified structure in the deep-water ocean where the internal wave occurs, and the pycnocline layer is located at a water depth of about 100m.

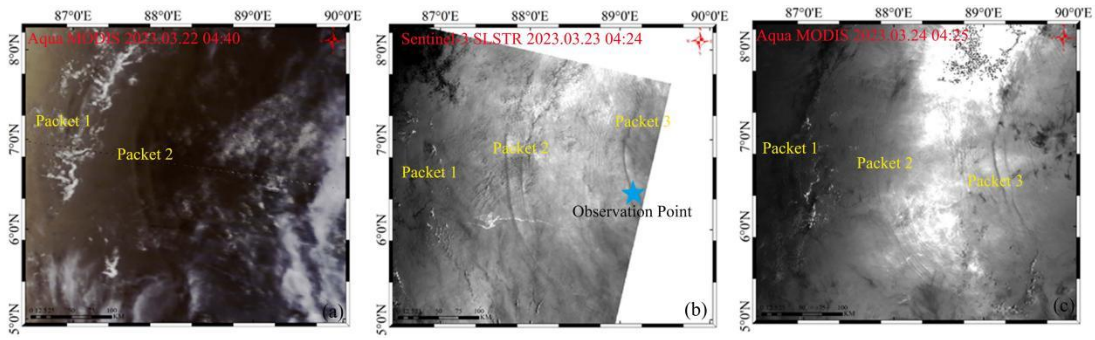

Figure 4. The internal waves in the Bay of Bengal observed by MODIS and Sentinel-3 satellites for three consecutive days (March 22, 2023 to March 24, 2023) in the same area at nearly the same time, respectively, and the blue pentagram is the position of the internal waves photographed in-situ in the Bay of Bengal at 08:58 on March 23, 2023.

In order to explore the source, period, propagation path and other characteristics of internal waves in the Bay of Bengal, remote sensing data with continuous observations are more helpful for internal wave studies. Remote sensing images of Aqua MODIS data at 7:35 on March 22 and 7:20 on March 24 with the same propagation location of internal waves at different times are matched. The multi-temporal image method is used to calculate the propagation velocity and generation period of internal waves based on the feature that multiple images contain multiple homologous internal wave packets. According to wave packet 2 propagated 30km from 4:40 to 7:35 on March 22, 2023. (Figure 5(b)), the propagation velocity of internal wave between 87°-88°E is obtained as 2.85m/s, and similarly, the propagation velocity of wave packet 3 at 88°-89°E is obtained as 3.23m/s, and the propagation velocity of wave packet 4 at 92°-93°E is obtained as 2.66m/s. Then utilizing the propagation distance of different internal isolated waves on the same day, the generation period of wave packet 2 to wave packet 1 is found to be 12.1 h, and that of wave packet 3 to wave packet 2 is 12.5 h. The propagation velocity of the internal waves changes during the propagation process due to the influence of the background current field and water stratification, which leads to the small difference between the actual propagation time and the calculated value, but it does not affect the analysis of the results. The calculation results of the three internal wave packets show that the period of internal wave generation in the Bay of Bengal coincides with the semidiurnal tide period (12.4h). Meanwhile, the source of the internal wave generation in the March 24, 2023 image was determined to be located in the Nicobar Islands using a tracking method that extracts wave lines. As shown in Figure 5(d), the internal wave propagates mainly to the west after being generation, and the internal waves generated by different sources collide and superimpose with each other during the propagation process (Figure 5(e)), and eventually merge to form a wave packet propagating on the open sea surface. And in the northeast part of the figure (Figure 5(e)) is the famous Andaman Sea internal wave.

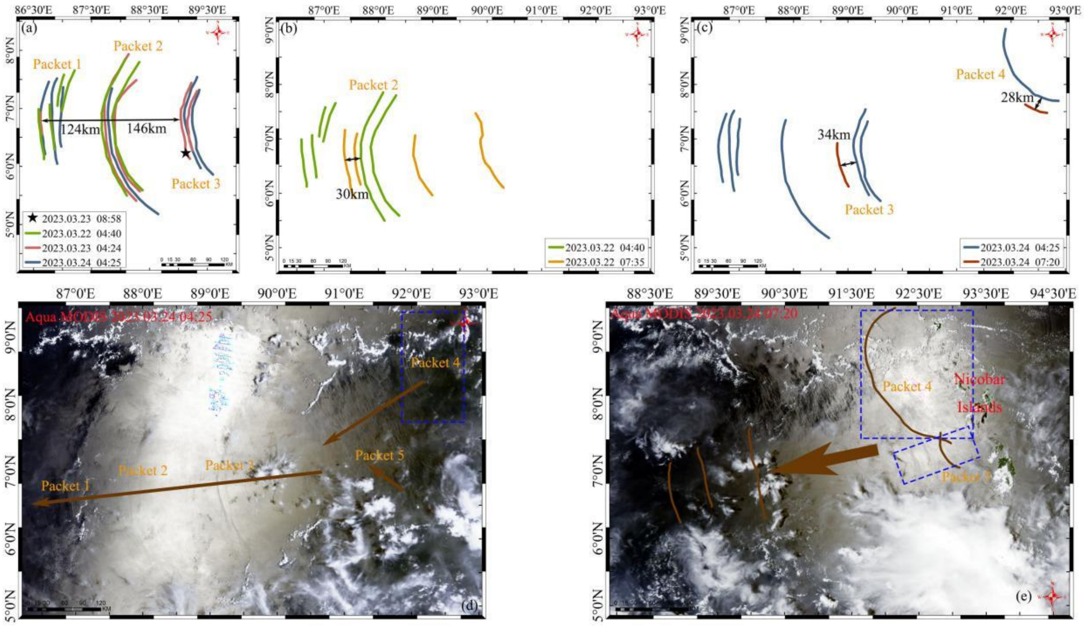

Figure 5. Propagation path of internal waves in the Bay of Bengal. (a) The leading peak lines of the internal waves traced in the Figure 4, with the black pentagram showing the location of the site captured on March 23, 2023 at 8:58 am. (b) Different positions of the same internal wave captured on March 22, 2023 at 4:40 and 7:35 am. (c) Same as (b), but for March 24, 2023 at 4:25 and 7:20 am. (d) Distribution of internal waves captured by Aqua MODIS image at 4:25 on March 24, 2023, with brown arrows showing the direction of propagation of the internal waves in the Bay of Bengal. (e) Same as (d), but for March 24, 2023 at 7:20 am, with the internal wave in the blue box (Packet 4) is the position nearly three hours after the propagation of the internal wave in the blue box of (d), which was reconnected with another wave packet (Packet 5) at this time. The brown arrow shows the propagation direction of the internal wave after collision with the superimposed wave, and the brown curve is the waveform of the internal wave.

In addition, the internal waves in the Andaman Sea, which have the same origin and generation period as the internal waves in the Bay of Bengal, have propagation velocities ranging from 0.5 to 2.7 m/s, which are positively correlated with the water depth [15,16]. However, the water depth in the propagation area of the internal wave in the Bay of Bengal is deeper than 3000 m, except for the 90° East Longitude Ridge in the Indian Ocean, so the propagation velocity of the internal wave has little relationship with the water depth, and is almost unaffected by the seafloor topography [17,18]. The propagation velocity in the Bay of Bengal is very high, which is consistent with the internal wave velocity in the deep-sea region of the South China Sea (more than 3m/s) [19]. The consistency with the results of internal wave studies in the Andaman Sea and the South China Sea illustrates the reliability of this paper's findings. This discovery not only shows the first sea surface photographs of internal waves in the Bay of Bengal, but also reveals the physical characteristics of internal waves in the Bay of Bengal through the combination of satellite imagery, sea surface imagery and subsurface data, which contributes to the development of the study of the fundamental characteristics of global internal waves.

Journal of Physics: Conference Series **3007** (2025) 012013 doi:10.1088/1742-6596/3007/1/012013

4. References

[1] Woodson, C. B. (2018). *The fate and impact of internal waves in nearshore ecosystems.* Ann Rev Mar Sci, 10, 421-441.

[2] Chen, T., & Li, Z., Nai, H., Shan, H., & Jia, Y. (2023). *Seabed dynamic responses induced by nonlinear internal waves: New insights and future directions*. J. Mar. Sci. Eng, 11: 395.

[3] Sun, H., Feng, A., You, Y., & Chen, K. (2022). *Influence of the internal solitary waves on the deep sea mining system*. Ocean Eng, 266, 113047.

[4] Yadidya, B., & Rao, A. D. (2022). *Interannual variability of internal tides in the Andaman Sea: An effect of indian ocean dipole*. Sci. Rep, 12, 11104.

[5] Bai, X., Lamb, K. G., Liu, Z. & Hu, J. (2023). *Intermittent generation of internal solitary-like waves on the northern shelf of the South China Sea*. Geophys. Res. Lett, 50, e2022GL102502.

[6] Chen, L., Zheng, Q., Xiong, X., Yuan, Y., & Xie, H. (2018). *A new type of internal solitary waves with a re-appearance period of 23 h observed in the South China Sea*. Acta Oceanol Sin, 37, 116-118.

[7] Koohestani, K., Stepanyants, Y., & Allahdadi, M. N. (2023). *Analysis of internal solitary waves in the Gulf of Oman and sources responsible for their generation*. Water, 15: 756.

[8] Zhang, H., Meng, J., Sun, L., & Li, S. (2022). *Observations of reflected internal solitary waves near the continental shelf of the Dongsha Atoll*. J. Mar. Sci. Eng, 10, 763.

[9] Yadidya, B., & Rao, A. D. (2022). *Projected climate variability of internal waves in the Andaman Sea*. Commun. Earth Environ, 3: 252.

[10] Jackson, C. (2007). *Internal wave detection using the Moderate Resolution Imaging Spectroradiometer (MODIS)*. J. Geophys. Res, 112, C11012.

[11] Meng, J., Sun, L., Zhang, H., Hu, B., Hou, F., & Bao, S. (2022). *Remote sensing survey and research on internal solitary waves in the South China Sea-Western Pacific-East Indian Ocean (SCS-WPAC-EIND)*. Acta Oceanologica Sinica, 41(10), 154-170.

[12] Zhang, H., Meng, J., Sun, L., & Li, S. (2022). *Observations of reflected internal solitary waves near the continental shelf of the Dongsha Atoll*. Journal of Marine Science and Engineering, 10(6), 763.

[13] Yang, J. J., Zhou, J, Göttsche, F. M., Long, Z. Y., Ma, J. & Luo, R. (2020). *Investigation and validation of algorithms for estimating land surface temperature from Sentinel-3 SLSTR data*. International Journal of Applied Earth Observation and Geoinformation, 91. 102136.

[14] Jayaram, C., Udaya, B., Tvs, Chacko, N., Rao, K., & Prakash, S. (2021). *Spatio-temporal variability of chlorophyll in the northern Indian Ocean: A Biogeochemical Argo data perspective*. Deep Sea Research Part II Topical Studies in Oceanography, 183.

[15] Zhang, H.， Meng J. M., & Sun L. N. (2020). *Research on characteristic parameter distribution and generation period of internal waves in the Andaman Sea with MODIS*. Haiyang Xuebao, 42, 110-118.

[16] Sun, L., Liu, Y. L., Meng, J. M., Fang, Y., Su, Q. L., Li, C. & Zhang, H. (2024). *Internal solitary waves in the central Andaman sea observed by combining mooring data and satellite remote sensing*. Continental Shelf Research. 277, 105249.

[17] Hao, X., Cao, T., & Shen, L. (2021). *Mechanistic study of shoaling effect on momentum transfer between turbulent flow and traveling wave using large-eddy simulation*. Physical Review Fluids, 6(5).

[18] LIU, Z. Y., BAI, X. L., MA, J. J. (2022). *Evolution and dissipation mechanisms of shoaling internal waves on the northern continental shelf of the South China Sea*. Advances in Marine Science, 40(4), 791-799.

[19] Sun, L. N., Zhang, J., & Meng, J. M. (2018). *On Propagation Velocity Of Internal Solitary Waves In The Northern South China Sea With Remote Sensing And In-Situ Observations Data*. Oceanologia Et Limnologia Sinica, 49, 471-480.

Acknowledgments
The authors thank Antony Liu for the photographs of the internal waves in the Bay of Bengal and NASA and the European Space Agency for providing the Aqua MODIS and Sentinel satellite data. This research is supported by the Key Special Supporting Talent Team Project of Guangdong (2019BT02H594), PI Project of Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou) (GML2021GD0810), and the Major Project of National Social Science Foundation of China (21ZDA097).