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Review

Coral reef hydrodynamics from different perspectives [version of record]

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ABSTRACT

In this review, the state-of-the-art research advances on coral reef hydrodynamics are introduced from ecology, hazard, geomorphology and engineering perspectives, including reef-top wave-current characteristics and their significance to the reef health, infragravity wave motions around the reef coast and their implications to the coastal flooding mitigation, coral sand movement and consequent reef island evolution, as well as wave interaction with reef-flat engineering structures such as breakwaters and excavation pits. Finally, this review proposes future research directions for the four aforementioned aspects, respectively.

KEYWORDS

Hydrodynamics, ocean waves, carbonate sediment, coastal engineering, coral reef.

1 Introduction

Coral reefs form over centuries to millennia through the accumulation of calcium carbonate skeletons from coral polyps and thrive in shallow tropical and subtropical seas. Coral reefs are among the world's most remarkable sources of beauty and wonder, hosting over 4,000 species of fish and 800 types of corals. They are known as the "rain forests of the sea," which are among the most biologically rich and productive ecosystems on earth (Burke et al., 2011). Millions of people in the coastal areas also benefit from their valuable ecosystem. Among various kinds of coral reefs, fringing reefs, barrier reefs, and atolls are the three most commonly seen. A typical profile of reef coast is featured with a steep fore-reef and a relatively horizontal shallow reef flat (Figure 1). The reef flat often has a raised crest where it meets the fore-reef slope, and there may be a deeper lagoon between the reef flat and the shore.

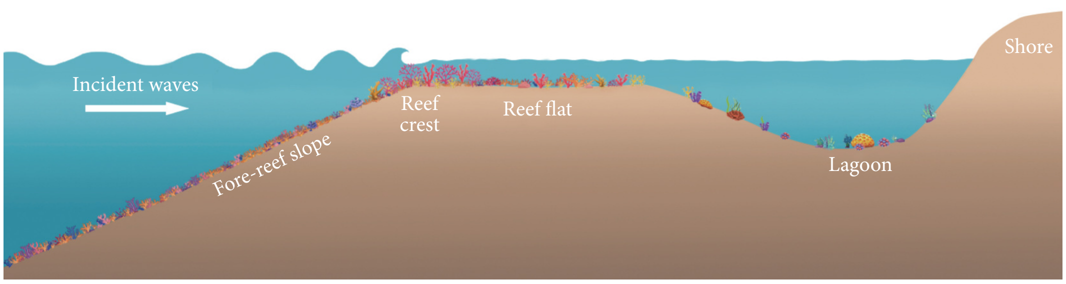

Fig. 1 A typical coral reef profile.

As shallow, natural barriers, coral reefs are able to offer substantial coastal protection from large wind waves (e.g. during storms) and tsunamis through dissipating wave energy via breaking and interaction with seabed roughness. The forces generated by wave breaking on reefs also drive nearshore circulation that is responsible for transporting materials (e.g. organisms, nutrients, and sediments) over reefs (Monismith, 2007), which ultimately contributes to the health of reef ecosystems and coastal landform changes behind reefs. A full understanding in coral reef hydrodynamics is the crucial step to understand a wide range of physical, chemical, and biological processes in the reef environments.

Coral reefs are continuing to face numerous threats from global and local pressures, resulting in their bleaching or even degradation (global warming, ocean acidification, coastal developments, sedimentation, etc.), resulting in physical changes to reef frameworks and bottom roughness characteristics. However, the degree to which reef hydrodynamic processes respond to such changes depends on the details in how waves, currents, water levels, etc. interact with reefs over a range of scales (Lowe and Falter, 2015), which can provide essential instructions for the reef restoration projects.

With the reef-lined shorelines frequently low-lying, those reef coastal areas are considered as being particularly vulnerable to wave-driven inundation and erosion under the impacts of both sea level rise and extreme wave events such as storms (e.g., Storlazzi et al., 2018). In order to defend reef-fronted shorelines, an amount of hazard mitigation and adaptation strategies have been increasingly proposed (varying between the 'hard' engineering solutions and the use of nature-based approaches). Proper design protocols are thus needed to protect reef coastlines while minimizing disturbance to reef ecosystems.

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Therefore, this paper is organized to review scholarly contributions from four perspectives (ecology, hazard, geomorphology and engineering) that promote our current knowledge of coral reef hydrodynamics and related processes. The aim is therefore to help different interested readers (including researchers, engineers and students) to catch the latest research advances on the above four topics ranging from fundamental to applied studies.

2 Coral reef hydrodynamics from ecology perspective

The hydrodynamics around reef coasts involve a diverse range of fluid motions. It ranges from tidal movements over the entire reef atoll on a macroscale, typically exceeding 10 kilometers, to wave motions across the horizontal reef flat that span hundreds to thousands of meters. In addition, it also covers the turbulent flows occurring within the reef canopy and its branch structures, which are less than a meter in scale. Each type of these fluid motions is essential for keeping the health of reef ecosystem.

Scholars have traditionally concentrated on the variability of tidal level as evidenced by Becker et al. (2014), who found that tidal levels significantly modulate wave dynamics over coral reefs. However, a subsequent global survey by Lowe and Falter (2015) reported that the circulation at one-third of the world's reef sites is predominantly driven by tides. Consequently, the impact of tidal currents has garnered increasing attention in recent years (e.g., Green et al., 2018; Grimaldi et al., 2022). This is because tidal forcing can play a more important role in hydrodynamics for such reef systems where the tidal range is notable, and the local water level gradient due to tide could exceed that caused by wave setup. The movement of tidal currents influences the water exchange between the lagoon and the open sea, thereby determining the water quality in the reef atoll system. Particularly, the lagoonal water residence time is an important ecological indicator of the strength of tidal or wave flushing (e.g., Dumas et al., 2012).

For the mesoscale wave-reef interaction, it is well recognized that (e.g., Yao et al., 2019) as incident waves originated from the open sea shoal over the steeper fore-reef slope, they typically break near the reef crest, attenuating most of wave energy. The surf zone often covers a certain extent across the reef flat. When wave breaking ceases, very small waves reform behind the surf zone, and they continuously propagate towards the shore on the reef flat. Under normal sea state, 70%-90% of incident wave energy is found to be dissipated due to breaking waves around the outer reef flat (e.g., Ferrario et al., 2014). The remaining energy can be additionally damped by bed friction on the reef surface, thus wave energy reaching the shoreline may be negligible. During the process, there may be a notable broadening of wave spectrum over the reef flat because part of incident wave energy can shift to both higher and lower frequency bands (e.g., Pomeroy et al., 2012). In the meantime, wave breaking around the reef crest can produce a pile-up of wave level in the reef surf zone known as a wave setup, which can force an onshore current across the shallow reef flat. Meanwhile, since the reef-flat distribution along the coast is commonly discontinuous, with separated rip channels connecting the lagoon to the open sea, the uneven setup distribution along the coast can also drive longshore currents both on the reef flat and within the lagoon. These currents can eventually flow back to the open sea through rip channels, forming a wave-driven circulation cell in a horizontally two-dimensional reef-lagoon-channel system (see Figure 2 for an example), which is identical to the rip currents on the sandy coast. This current is controlled by such factors as the width of reef flat, the size and location of rip channels, and the roughness of reef surface, etc. Such type of circulation pattern is vital to the transport, dispersal and retention of nutrients, larvae, coral sands, and other materials in the reef environments (Lowe et al., 2009). It also plays a critical role in the sediment transport as well as the consequent morphological change of reef coastline.

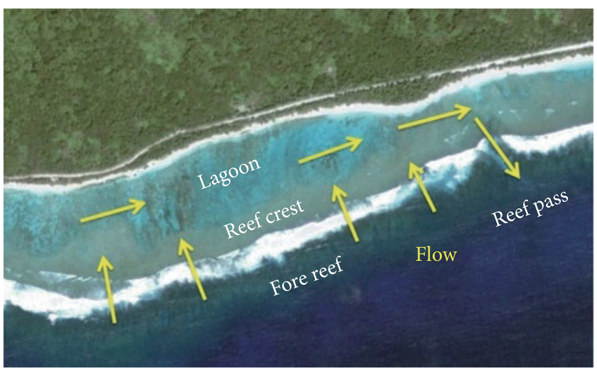

Fig. 2 Wave-driven circulation cell on the south shore of Ofu, American Samoa. Reproduced with permission from Monismith, 2014, © Springer-Verlag Berlin Heidelberg 2013.

On the smallest scale, the flow through the skeleton structure of coral colonies is typically referred to as 'canopy flow' (e.g., Lowe et al., 2008). The flow dynamics within the coral reef canopy are analogous to those through terrestrial canopies (such as forests or urban buildings) and aquatic vegetation canopies (such as seagrass or mangroves). However, flows through the reef canopy are unique due to the nonuniform coral internal structure exposed to both tide cycle and wave action (Asher and Shavit, 2019). Reef canopy flows control the turbulence transfer between the reef boundary layer and the overlying water, thereby governing the vertical transport of heat, nutrients, coral larvae, and other materials (Davis et al., 2021). Consequently, they determine the key metabolic processes of corals such as feeding, photosynthesis and reproduction.

3 Coral reef hydrodynamics from hazard perspective

Although coral reefs are generally recognized by scholars as natural barriers against the flooding hazards along the reef-lined coast, wave-driven flooding events around some low-lying reef atolls during storm surges have been occasionally observed (e.g., Hoeke et al, 2013;

Merrifield et al., 2014). Wave runup (it is commonly used in the risk assessment of coastal inundation) on the back-reef beach is comprised of sea and swell (SS) waves (frequency band between 0.04 and 0.4 Hz), infragravity (IG) waves (frequency band between 0.001 and 0.04 Hz) and wave setup originally produced by wave breaking around the reef crest (Merrifield et al., 2014). Since a majority of wave energy associated with incident SS waves can be dissipated by both wave breaking in the reef surf zone and seabed friction during transmitted wave propagation on the reef flat, the shoreline run-up is more likely to be dominated by IG waves.

There are two mechanisms involved in the literature explaining the production of IG waves over a reef profile. The first one is due to the bound long wave (BLW), which is 180° out of phase with the incident wave group (Longuet-Higgins et al., 1962). BLW is released during SS wave breaking (Janssen et al., 2003), subsequently propagating to the coast as free long waves (FLW). After being reflected from the shore behind the reef, FLW may return to the open sea or generate edge waves near the shoreline. The second one is due to the breakpoint-forced long wave (BFLW), which is generated via the spatial movement of wave breakpoint (Figure 3). The breakpoint oscillates with the frequency of wave group to generate such a wave (Symonds et al., 1982), thus it is expressed as a time-varying dynamic wave setup on the reef flat modulated by the wave group. According to the generation mechanism of BFLW, the breakpoint will generate two types of long waves: one is propagating towards the shore and in phase with the wave group, and the other is propagating offshore and in anti-phase with the wave group. Once they are released, those waves may be further dissipated through bed friction, transfer energy to other frequency waves, or superimpose with reflected waves to form standing wave pattern on the reef flat (Baldock, 2012). Fore-reef slopes are generally steep (typically >1:20), where energetic wave breaking occurs within a relatively narrow surf zone, dissipating the BLW component before it can satisfy the shallow-water dispersion condition and transform into FLW at shallower waters (Baldock, 2012). Meanwhile, LW generation due to strong oscillation of the moving breakpoint is also enhanced on steep fore-reef slopes. Consequently, the BFLW mechanism typically dominates IG wave generation in the reef environment, which is consistent with existing field observations. (Péquignet et al., 2009; Pomeroy et al., 2012)

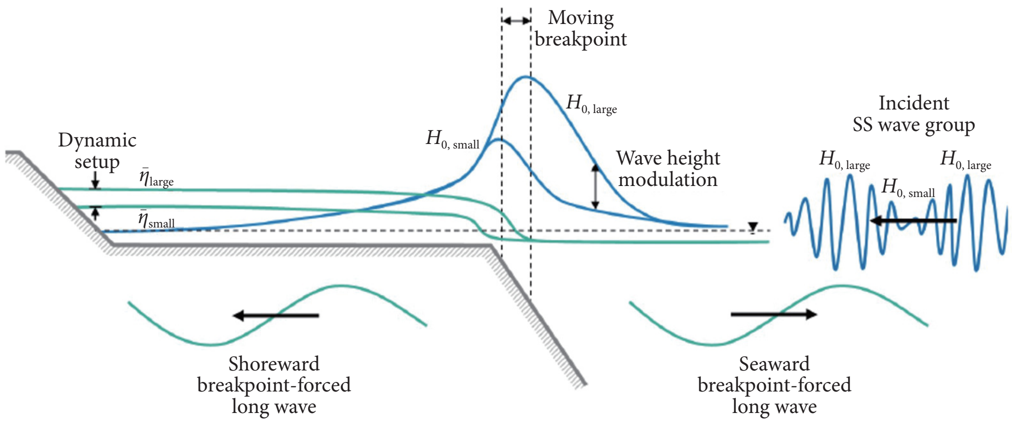

Fig. 3 A sketch of breakpoint-forced long wave generation and propagation over the reef profile. Reproduced with permission from Pearson, 2016, © Pearson, S. G. 2016.

Since the typical cross-shore reef profile as illustrated in Figure 1 is semi-enclosed, like the theoretical open-ended basin system, IG wave motions over such a reef may excite different resonant modes under certain combinations of wave period and reef-flat submergence. For fringing reefs, existing investigations (e.g., Becker et al., 2016; Yao et al., 2020a) have confirmed that during storm surge associated with astronomic high tide level, IG waves are more possible to excite resonant oscillations over the reef flat that can cause an amplification of wave runup near the reef coastline, thereby enhancing the risk of wave-driven flooding. For a barrier reef profile with reef-lagoon configuration, Yao et al. (2023) has identified that four types of resonant modes may exist, namely: reef-flat open-ended basin, reef-flat-lagoon open-ended basin, reef-flat open basin and lagoon closed basin. The first two are found to be dominant across a reef-lagoon profile, amplifying the wave energy within IG band both on the inner reef flat and at the shoreline.

In summary, due to the unique reef configuration with steep fore-reef slope and semi-closed horizontal reef flat, IG waves play more important role in contributing the coastal wave runup in comparison to that at ordinary sandy coast during the storm events, which is more likely to induce coastal flooding hazard, particularly when a storm surge coincides with an astronomic high tide. Therefore, IG wave motions have received extensive attentions in the studies of coral reef hydrodynamics in recent years (e.g., Cheriton et al., 2020; Liu et al., 2023, and many others). An in-depth understanding of IG wave processes over coral reefs is an essential step during the decision-making phase of coastal hazard prevention and mitigation.

4 Coral reef hydrodynamics from geomorphology perspective

Carbonate sediments in a reef system are primarily formed by the growth and breakdown of carbonate-producing reef organisms (corals, crustose coralline algae, molluscs and echinoderms, etc.) along with physical, biological, and chemical processes (e.g., Ford and Kench, 2012; Morgan and Kench, 2016). A recent review of the studies on sediments over coral reefs (Schlaefer et al., 2021) highlighted the importance in taking hydrodynamic measurements along with the sedimentary measurements to provide more important insights into the sediment dynamics. Regarding the sediment incipience, Madsen et al. (1976) optimized the Shields curve (Shields, 1936), proposed to replace the bed shear stress with the maximum instantaneous shear stress, and obtained a new starting Shields number for carbonate sediments. Subsequent studies of the incipient motion of carbonate sediment by means of laboratory experiments found that irregular particles with the same particle size were easier to be initiated than regular particles (e.g., Smith and Cheung, 2004). Meanwhile, the particle settling velocity is fundamental to analyze the sedimentary processes. De Kruijf et al. (2021) systematically reviewed the settling hydrodynamics of carbonate sediments in view of grain shape, size and density, and emphasized the importance of physical properties of carbonate sediment particles on the sedimentation velocity.

Waves-induced transport of sediments over coral reefs can be efficient, and such process is crucial in governing the health and function of reef ecosystem (e.g., Lowe and Ghisalberti, 2016). Scholars (e.g., Cuttler et al., 2019; Dawson and Smithers, 2014; Pomeroy et al., 2018) have reported that corals living upon the fore-reef slope are broken by large swells initiating from the open sea, they are subsequently transported over the reef crest, and threw onto the outer reef flat. In contrast to the coarse sediments commonly covered by coral algae and attached to the reef surface, energetic breaking waves around the outer reef flat further drive the loose sediments towards the shoreline. These carbonate sediments are eventually accumulated as coral sands in the lagoon (if it exists), or otherwise accreted on the back-reef beach. In addition, a small number of sediments may also be transported alongshore and exported from the reef system through rip channels. As previously described, the unique steep reef topography leads to the incident wave energy shifting to both SS and IG frequency bands; thus, wave spectrum usually exhibits bimodal characteristics that has an important impact on sediment transport (e.g., Pomeroy et al., 2015). Due to the shielding effect of reef canopy on the carbonate sediment movement, it is also recommended that the reef roughness should be considered when examining the sediment transport over the reef flat (e.g., Pomeroy et al., 2017).

As shown in Figure 4, reef islands are formed by carbonate sediment deposition. They have loose structure and variable size, generally ranging from hundreds of meters to dozens of kilometers in width, and may be divided into several individual geomorphic units by the ocean (Kench et al., 2012). Previous research (e.g., Storlazzi et al., 2015) has shown that future inhabitation on those low-lying islands is risky due to a rise in wave-driven flooding under the impacts of sea level rise and anthropogenic climate change, but this prediction is assuming that reef island is a geomorphologically inert landform. Latest laboratory studies (Tuck et al., 2019a; 2019b) and numerical investigations (Masselink et al., 2020; 2021) have provided growing evidence that the reef island morphology can make a positive adjustment to the climate change. As the incident wave height (representing increased storminess) and reef-flat water level (representing sea level rise) increase, reef islands accrete vertically and migrate lagoonwards, thus they can potentially offset future flooding events. Meanwhile, the sediment supply (representing the coral growth) can promote the island elevation but slow down its migration. These insights highlight the pressing necessity to have the island's morphodynamic response integrated into the coastal flood models, thus the island's future persistence and stability could be better resolved.

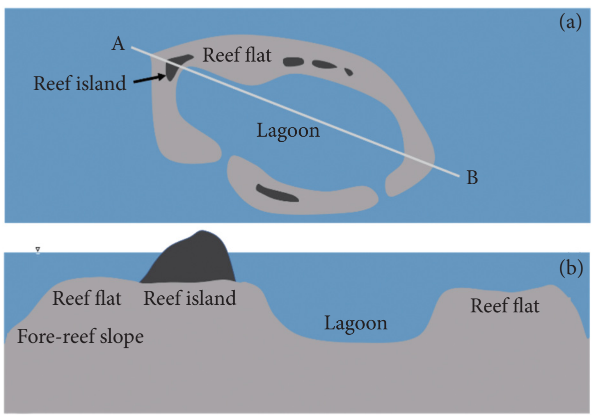

Fig. 4 Reef islands and their locations on the reef atoll. Reproduced with permission from Ortiz and Ashton, 2019 © Elsevier B.V. 2019. (a) A typical reef atoll; **(b)** The island profile along the transect A–B in (a).

5 Coral reef hydrodynamics from engineering perspective

In the past decade, China has successfully implemented sea reclamation projects around several reef islands in the South China Sea, requiring the construction of coastal defense structures on the reef flat to safeguard the newly established facilities. At that time, there was a lack of design criteria for such kind of structure in the engineering community because traditionally breakwaters are built on mild sandy beaches or behind the reef flat if used in the reef environments. Figure 5(a) shows an example of a reef-flat breakwater located on the Yongxing island in the South China Sea.

Breakwaters, seawalls, etc. are commonly used coastal structures to protect the landscape and facilities from large waves. Among various design parameters, wave overtopping discharge over the coastal defense structure is the most important one. A significant improvement on interpreting the overtopping process is the CLASH (Crest Level Assessment of Coastal Structures by Full-scale monitoring, wave basin experiments and numerical simulations) project which offers a database for wave overtopping including more than 10,000 scenarios (De Rouck et al., 2009; Van der Meer et al., 2009). Many scholars (e.g., Pullen et al.,2007; Goda 2009) have analyzed the data in the database and provided a variety of empirical formulas (such as EurOtop) to predict the wave overtopping associated with wave interacting with coastal defense structures on sloping sandy beaches. Since a reef profile configuration differs a lot from the plane beach, directly applying those overtopping formulas proposed for beaches to reefs is still questionable.

In the literature, for examples, Wen et al. (2019) adopted a smoothed particle hydrodynamic (SPH) numerical model to examine the effects of an impermeable vertical seawall located on a reef flat on wave-induced setup, wave-driven current and wave run-up.

Subsequently, Chen et al. (2020) improved the EurOtop formula for the prediction of overtopping rate over a vertical seawall on the reef flat by taking the reef geometry into consideration. Meanwhile, they also proposed an empirical formula to predict wave load on the seawall considering both impacts of incident waves and reef geometry. Liu et al. (2020) applied an Artificial Neural Network to predict the overtopping rate over a vertical seawall on a reef flat using a set of laboratory data to train the network. We remark that the current knowledge about coastal defense structure design in the reef environments is still developing. The above findings are based on scaled and well-controlled laboratory experiments and/or numerical simulations. Their applications to the realistic field conditions need to be taken with caution.

Owing to the demand of massive infrastructure construction in some coastal areas with dense population, onsite coral sand dredging on the reef flat becomes a relatively low-cost engineering solution on several reef atolls in the Republic of the Marshall Islands, see also Figure 5(b) for examples of excavation pits caused by dredging. Such anthropogenic modification of the reef geometry can possibly alter the coastal processes such as wave-induced coastal inundation and back-reef beach evolution, thus it attracts more and more attentions in the coastal research community.

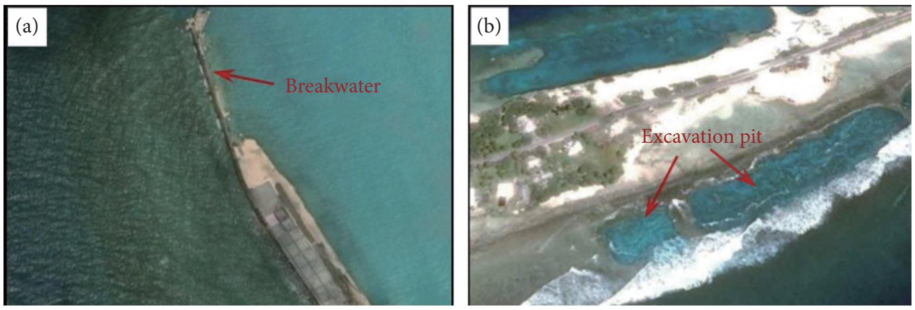

Fig. 5 (a) Breakwaters on a reef flat at Yongxing island in the South China Sea; (b) Excavation pits at Majuro Atoll in the Republic of the Marshall Islands (images from Google Map).

Ford et al. (2013) conducted pioneering investigation on the influences of excavation pits on the wave processes over reefs. They performed field observations on two adjacent transects at Majuro Atoll in the Republic of the Marshall Islands, comparing wave motions across the reef flat with and without an excavation pit. Regarding the laboratory study, we are only aware that Yao et al. (2020b) are the pioneers to perform a series of innovative experiments in a wave flume based on the surveyed horizontally one-dimensional reef profile from Ford et al. (2013). As for numerical studies, the impacts of varying pit widths and locations were numerically examined by both Yao et al. (2016) and Klaver et al. (2019) with different numerical models using the same reef profile from Ford et al. (2013). Recently, the numerical investigation has been extended to a horizontally two-dimensional fringing reef configuration by Yao et al. (2024) who studied the pit effects on both the alongshore wave dynamics and the wave-driven current. All these investigations have recognized that shoreline SS waves can either increase or decrease due to the pit existence, depending on the relative contributions of the following mechanisms around the pit: increased wave reflection, reduced breaking-wave amplitude, declined nonlinear wave-wave interaction, and the exciting of resonance. It also has something to do with the pit width. Meanwhile, the shoreline IG waves consistently decline with the existence of pit, and such drop is more evident with larger pit width. This is supposed to be a superposition of disrupted reef-flat wave resonance by pit and increased wave reflection from pit. All above findings can provide references for further understanding the reef-top sediment transport and subsequent shoreline erosion or accretion, which is usually a primary concern in the coral sand dredging projects.

6 Conclusions

Understanding the advanced knowledge of coral reef hydrodynamics is of significant importance from the ecological, hazard, geomorphological, and engineering perspectives. This review first describes the reef-top wave and current characteristics in various scales and their implications to the health of reef ecosystem. It then explains the IG wave generation and resonance over reefs, highlighting their contribution to the coastal flooding in the context of climate change. It subsequently introduces the transport characteristics of carbonate sediments, as well as the consequent evolution of reef islands. Finally, it briefly presents predictive methods for the design parameters of reef-flat seawalls, as well as reports the impacts of reef-flat excavation pit on the wave processes.

In this review, we also point out that future research on these issues can be directed to the following aspects:

(1) An in-depth understanding of coral reef hydrodynamics associated with waves and currents, and their impacts on the reef ecosystem requires the knowledge from multiple disciplines, including oceanography, biology, ecology, geology, etc., thus interdisciplinary methods or tools should be used.

(2) Compared to the traditional process-based numerical tools, the data-driven approaches based on the machine learning technique are more appropriate to the fast forecast of coastal flooding, which can be potentially integrated into the hazard warning system established for the reef coast.

(3) Despite the challenges in field data collection, the observation database for the long-term morphological response of reef islands to the global climate change needs to be enriched to improve our current understanding on the future persistence and stability of the islands.

(4) Aside from waves, there are other oceanic drivers such as tides, local winds, etc. The influences of such reef-flat engineering activities as coastal defense structures and excavation pits on the surrounding reef environment need to be interpreted in more complicated ocean forcing conditions.

Acknowledgments

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

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