Observations of hydrodynamic processes on atolls in the South China Sea with deep reef flats (> 10m) with implications for sediment transport potential

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Abstract: The Nansha Islands comprise the largest atoll archipelago in the South China Sea, accommodating 15% of global atolls. In contrast to reef flats found elsewhere in the Indo-Pacific region that typically have grown close to modern sea level, a considerable portion of atoll rims there are composed of 10-20-m-deep reef flats. To better understand modern processes, particularly whether these deep reefs are host to modern physical reworking or instead may be relict features abandoned by sea-level rise, we conducted a mooring hydrodynamic observation from January to September on a 12-m-deep southwest-facing reef flat. These measurements show a predominance of seasonally-varying waves and stable, moderate tide-driven currents, similar to short-term observations at three adjacent deep-reef-flats. While the reef flat was protected from the northeast monsoon from January to May, the southwest monsoon from June to September caused prolonged exposure to large waves (mean H_S of 1.3 m; orbital velocity 0.22 m/s) and consistent cross-flat currents (0.08 m/s on average), resulting in near-bed skin-friction shear velocities of 0.02 m/s on average. These wave conditions are capable of forming and mobilizing bed ripples while entraining coarse coral sand (d_{50} = 1 mm) for over half a year. Estimates of potential sediment flux suggest the capability for combined waves and advective currents to deflate the 12-m-deep reef rim by up to 28 mm in 8 months. As these potential losses are similar to reef accretion rates, our measurements imply that modern processes could play a significant role in the maintenance of deep reef flats.

Key Points:

Hydrodynamic observations at deep reef flats of four South China Sea atolls demonstrate strong nonbreaking waves with moderate currents.

Combined orbital motions and net currents exert significant shear stresses that sediment can be mobile for over 70% of 8-month observations.

Modern processes may be active on deep reef flats, which may be actively maintained and not relict sedimentary systems.

Plain Language Summary: A large portion of the atolls in the South China Sea (SCS) are comprised of deep reef flats with rims whose shallowest points remain 10-20 m below sea level, far deeper than typical reef flats found across the Pacific and Indian Oceans. By conducting an 8-month mooring observation on the deep reef flat of one atoll and one-tidal-cycle measurements at three other atolls in the SCS, we found that strong, nonbreaking waves along with persistent moderate mean currents can lead to large near-bed shear stresses and ripple formation such that a significant quantity of sediment could be mobilized on the reef flat and potentially transported off the rim into the lagoon or offshore, equivalent to a rim height deflation on the order of 28 mm in 8 months of a year. The deep reef flats (> 10 m depth) that are widespread in, but not limited to, the SCS could be active systems maintained by modern processes rather than give-up reefs abandoned and drowned by deglacial sea-level rise.

1 Introduction

Numerous atolls (ring-shaped reefs) are scattered across the Nansha Islands – the largest reef archipelago in the South China Sea (SCS, Figure 1a)— accounting for approximately 15% of the global areal extent of atolls [*Purdy and Winterer*, 2001]. While the cross-reef morphology of many Pacific and Indian atolls is characterized by a reef flat that can be hundreds to several thousand meters wide and has grown up close to sea level (0-2 m deep), often containing subaerial reef islands [*Colin et al.*, 1986; *Purdy and Gischler*, 2005], a considerable portion (at least 30%) of the Nansha Islands atoll perimeter consists of deep reef flats that remain 10-20 m below the water surface. Atoll rims that have not accumulated to modern sea level are typically considered to be give-up reefs, relict features abandoned during rapid deglacial sea-level rise [*Kim et al.*, 2012; *Toomey et al.*, 2013; *Woodroffe and Webster*, 2014]. However, separate reconnaissance investigations in 2017 at three such deep reef flats of the Zhenghe Islands and Daoming Islands – two large atoll groups in the northern part of the Nansha Islands (Figures 1b and 1c) – show that these deep reef flats commonly have a mixed coverage of living coral colony (>60%) and bare sandy bed (Figure 2), similar to the bed composition of the regular shallow reef flats in the Pacific and Indian Oceans, except with a larger portion (>20-30%) of sandy bed coverage.

In this study, to determine if these deep reef flats may be geomorphically active, we conducted an 8-month hydrodynamic observation on a 12-m-deep southwest-facing reef flat of Tiexian reef in the northern part of the Nansha Islands (Figures 1b and 1d). We then used these measurements to calculate bed shear stresses, which were then interpreted to compute potential sediment transport across the reef flats. The information is used to illustrate the extension of wave effects from shallow, 0-3 m deep, reef flats to deep reef flats with depths over 10 m. For deep reef flats, although currents are more subtle than in shallow environments, intense wave orbital motions exert significant shear stresses, leading to ripple development and sediment movement, both of which will affect the development of deep reef flats.

2 Background

Hydrodynamic processes play an important role in reef sediment redistribution and geomorphology evolution over both geologic and modern timescales [Barrett and Webster, 2012; Camoin and Webster, 2015; Gao and Collins, 2014; Kench, 2011; Scoffin et al., 1980; Toomey et al., 2016]. The hydrodynamic knowledge of coral reefs and local hydroodynamic conditions mainly in the north part of the SCS area that is closest to the Nansha Islands with available hydrodynamic information in the pieces of literature, as well as the geologic sedimentary settings of atolls in the Nansha Islands were introduced briefly below.

2.1 Previous studies of coral reef hydrodynamics

Coral reefs protect coastal areas by reducing the power of waves hitting the coast [*Harris et al.*, 2018], and provide an important ecosystem for life underwater by building homes for millions of species of marine life and supporting healthy ocean food webs [*Hughes et al.*, 2017]. Local subsidence and sea level oscillations determine long-term reef growth, for example, coral atolls grow when islands completely subside beneath the ocean, leaving a coral ring with an open lagoon in its center [*Toomey et al.*, 2016]. Due to the shallow reef morphology (i.e. steep fore-slope and shallow reef flat) and reef community canopy structure (e.g. large immobile structures creating large bottom roughness), sea-swell waves transform and break vigorously on shallow reef flats, generation of infragravity waves (periods 25–250 s) and mean wave-driven currents are observed across many reef systems in the Pacific and the Indian Ocean [*Davis et al.*, 2021; *Lowe and Falter*, 2015; *Monismith*, 2007]. Incident swells transform at the fore-reef slope and break at the reef crest, with the wave energy being dissipated via both wave breaking in the surf zone and bottom friction due to the large bottom roughness over the entire reef platform [*Lowe et al.*, 2005; *Masselink et al.*, 2019; *Monismith et al.*, 2013; *Monismith et al.*, 2015; *Storlazzi et al.*, 2004]. Infragravity waves are generated and propagated seaward/shoreward resulting from the incident sea-swell waves breaking [*Péquignet et al.*, 2014; *Pomeroy et al.*, 2012]. Both the infragravity waves and smaller incident sea-swell waves that do not break in the surf zone propagate shoreward across the reef flat [*Monismith et al.*, 2013; *Pomeroy et al.*, 2012]. The wave energy partition between high-frequency (sea-swell, short-to-medium period <20s) and low-frequency (infragravity, long period 20-100s) wave bands results in a distinct bimodal spectrum of wave conditions on many coral reef flats and lagoons [*Brander et al.*, 2004; *Hardy and Young*, 1996; *Harris et al.*, 2014; *Lugo-Fernandez et al.*, 1998; *Pomeroy et al.*, 2012; *Pomeroy et al.*, 2018; *Van Dongeren et al.*, 2013].

Cross-reef mean currents are generated by wave setup (cross-shore pressure gradients; mean water level gradients) that is induced by the radiation stress spatial gradients [*Longuet-Higgins and Stewart*, 1964] as the incident sea-swell waves break in the surf zone [*Hench et al.*, 2008; *Lowe et al.*, 2009; *Symonds et al.*, 1995]. The magnitude of cross-reef mean currents and the proportion between sea-swell and infragravity wave energy also change with fore-reef slope, reef flat width, water depth, and reef bottom roughness [*Gourlay and Colleter*, 2005; *Hearn*, 1999; *Symonds et al.*, 1995]. The large reef bottom roughness attenuates both wave energy and mean wave-driven currents through frictional dissipation [*Lowe et al.*, 2005; *Pomeroy et al.*, 2012; *Rosman and Hench*, 2011].

Cuttler et al. [2018] suggested that the combination of infragravity-band motions with incident sea-swell-band motions is important in mobilizing sediment and the migration of seafloor bedforms; as such, in shallow, wave-breaking-dominated regions, overlooking infragravity contributions to hydrodynamics could significantly result in underestimation of bedload transport on a coral reef. The distinct bimodal spectral wave (from sea-swell and infragravity waves) and mean flow conditions as well as sediment availability and grain size determine the magnitude and direction of sediment transport and ripple migration rate [*Cuttler et al.*, 2018; *Rosenberger et al.*, 2020] and suspended sediment concentration and flux [*Pomeroy et al.*, 2018; *Pomeroy et al.*, 2021; *Storlazzi et al.*, 2004]. The transported sediment can be deposited in the inner part of the reef flat [*Harney and Fletcher III*, 2003; *Storlazzi et al.*, 2009], back reef sand apron [*Harris et al.*, 2014], into lagoons [*Kench*, 1998; *Kennedy and Woodroffe*, 2002], or exported via reef channels offshore [*Pomeroy et al.*, 2018; *Storlazzi et al.*, 2004].

Swell-wave-induced bed shear stress is the key driver of suspended sediment concentration (SSC) variability across the reef flat and lagoon, and initiates sediment motion and keeps sediment in suspension [*Pomeroy et al.*, 2018; *Pomeroy et al.*, 2021; *Storlazzi et al.*, 2009; *Storlazzi et al.*, 2002], while infragravity waves represent a secondary driver to SSC variability and become increasingly important shoreward of reef flat [*Cheriton et al.*, 2016; 2020; *Pomeroy et al.*, 2018; *Pomeroy et al.*, 2015; *Storlazzi et al.*, 2002; *Storlazzi et al.*, 2004]. Swell and infragravity wave nonlinearities, i.e. asymmetric and skewed wave shapes, have been shown to make a significant contribution to sediment flux across a shallow reef [*Bramante et al.*, 2020a; *Cheriton et al.*, 2016; 2020; *Pomeroy et al.*, 2018; *Pomeroy et al.*, 2015; *Storlazzi et al.*, 2002; *Storlazzi et al.*, 2004]. Suspended sediment flux is affected by phase coupling between sea-swell and infragravity waves with resuspended sediment concentration from seabed. However, in many reef environments, mean currents are the primary transport mechanism and responsible for almost 2 orders of magnitude more suspended-sediment flux than sea-swell and infragravity waves [*Pomeroy et al.*, 2021]. Bedload transport through ripple migration on reef flat and lagoon can also be three to four times higher than sediment transported in suspension [*Rosenberger et al.*, 2020].

The seabed roughness on a reef bed, mainly the immobile canopy structure on the reef flat affects wave dissipation and greatly affects estimates bedload fluxes; however, this bed characteristic can be difficult to parameterize and can span orders of magnitude in reef environments. The resultant shear stress represents the wave stress acting on the coral colonies (similar to the form drag exerted on the surface of mobile ripples), and could be much larger than the stress acting on sediment in motion [*Pomeroy et al.*, 2017; *Storlazzi et al.*, 2009]. Due to the large physical roughness height associated with reef canopy structure, reported values of wave friction factor for coral colonies can be as large as 10^{-1} to 10^{0}, in contrast to the values of 10^{-3} or smaller that was used to describe the skin friction of sediment particles themselves. For example, a value of 0.1-0.3 for wave friction factor was found for the reef flat of Kaneohe Bay [*Lowe et al.*, 2005], the forereef and shallow reef flat of Moorea [*Harris et al.*, 2018; *Monismith et al.*, 2013], and Ningaloo Reef in Western Australia [*Pomeroy et al.*, 2012], with a value as large as 1.8 on the south forereef of Palmyra Atoll [*Monismith et al.*, 2015]. These latter values of wave friction factor, occurring at depths of 0.5-15 m, are associated with thick coral canopies.

2.2 Geologic and sedimentary setting

The Tiexian Islands are part of a large elliptically shaped atoll archipelago in the northern part of the Nansha islands, with a major axis of ~75° (Figure 1). Since the drilling of two long cores on the SW reef flat of the Yongshu Reef (Figure 1a) between the 1980s and 1990, i.e., Nanyong-1 and Nanyong-2 with a bottom depth of about 151 m and 413 m, respectively, [*Zhao et al.*, 1992; *Y Zhu et al.*, 1997], Yongshu Reef system has become one of the best-studied atolls of the SCS, serving as the exemplar representative for the atolls in the Nansha Islands as well as the entire SCS. The paleo-facies analysis of these cores and the geomorphology, geology, and sedimentary studies of modern deposits on the Yongshu Reef, together with other atolls and reef islands of the Nansha Islands, are summarized as follows:

(i) The bulk accumulation of atolls in the Nansha Islands consists of coral branches, rubble, and fragments as well as crustose coralline algae. Reef fragments and rubble account for over 60% of the uncemented Holocene atoll deposition as revealed in both the two Yongshu cores (from which atoll development since late-Pleistocene ~150 ka and late-Miocene ~7 Ma were reconstructed, respectively). This make-up is consistent with the prominent contribution of reef detritus (coral rubble, gravel, and rudstone, as well as carbonate sand) over *in situ* stony corals (the reef framework) found by *Montaggioni* [2005] in all 53 of the 684 cores drilled on Indo-Pacific reefs. One interesting distinction is that the atolls in the Nansha Islands have developed mainly on the basement of the continental slope, in contrast to the commonly volcanic basements of atolls in the Indian and Pacific Oceans.

(ii) Atolls of the Nansha Islands are commonly characterized by an elliptical- (or spindled-) shape, with the major axis extending in an approximately NE-SW direction and reef platforms on the SW side being wider than the NE counterpart. Two hypotheses were proposed to account for this orientation [*Zeng*, 1984]. One possibility is that tectonic formation controls the seafloor geometry and therefore where atolls grew. That is, the structural line in the NE-SW direction determined the SW-NE basal structure that underlies these atolls. The other, perhaps less likely, hypothesis suggests that monsoon circulation (northeast and southwest monsoons dominate the SCS alternatively in winter and summer, e.g. the wind rose in Figure 1a) promoted atoll extension in the SW-NE direction.

(iii) Corals at some parts of atoll rims, particularly the wide corners, can grow up to a few meters below the water surface, becoming exposed subaerially at low tide (intertidal reef flats) or even hosting reef islands as observed on numerous atoll rims in the Indo-Pacific region. However, a considerable fraction of the atoll rims is submerged at depths of over 6 m (typically 10-20 m). There, the bed is typically characterized by a patchy reef of living coral colonies growing upon the seabed with a patchy veneer of bioclastic reef sediment covering the remainder of the seabed (Figure 2). The atoll rims can be also interrupted by wide channels (passes) that connect central lagoons of average depth of 30-40 m to the deep open ocean (100 m to >1km deep). Rarely do coral colonies grow in these channels.

2.3 Climate and hydrodynamics of the South China Sea

The East Asian Monsoon affects the climate and hydrodynamics of the SCS, with occasional synoptic systems such as fronts and tropical cyclones causing temporally and spatially varying wind and wave fields in the northern SCS [*Chu et al.*, 1999; *Chu et al.*, 2000; *Zhou et al.*, 2012]. From early November to mid-March, the northeastern winter monsoon (with winds approaching from the northeast) dominates across the entire SCS, with a longer duration and larger winds and waves than the southwestern (SW) summer monsoon, which prevails from early June to mid-September. Transitions between the monsoon season have less defined wind direction and gentler wind speeds. Wind speeds are the largest from December to February and tend to be slightly weakened but still large during the summer monsoon [*Zhou et al.*, 2012].

As a result, hydrodynamic and physical oceanographic features, including wind waves, seasonal ocean circulation [*Hu et al.*, 2000], sea surface temperature, and salinity in the upper water exhibit an overall bimodal seasonal variability in a year.

Tides are irregularly diurnal – essentially a primary diurnal tide K1 and O1 and a secondary semi-diurnal tide M2 – with a mean tide range of 0.89 m based on the statistics of different cruising measurements in the Yongshu Reef between 1992 and 2002 [*L Zhu et al.*, 2005]. Field-based hydrodynamic studies on any of the atolls in the Nansha Islands are rare, except on the same SW reef flat of Yongshu Reef where the two long cores were drilled, where wave measurements were taken only by sight for 22 years (1988-2009) at the Yongshu Reef station at over 20 m depth (the accurate water depth data is not available). From these data, *Wang et al.* [2012] summarized that sea-swell waves dominate the area with an annual mean and maximum wave height of 1.2 and 8.0 m, respectively, and an annual mean period of 4.5 s, with wave propagation direction generally consistent with that of regional wind. This highlights the need for more accurate hydrodynamic observations in this region.

2.4 Outline

Here, we present measurements of waves and currents from deep reef flats (>10 m) in the Nansha Islands, covering periods when the reef was leeward and windward of the dominant waves, providing a unique *in situ* measurement from a little-studied ocean setting. Section 3 provides the measurement methodology as well as the approach used to calculate bed shear stresses, which, in turn, are used to compute potential sediment transport across the deep reef flats. The measurements show intense wave orbital motions that should exert significant shear stresses on the bed, and our computations suggest ample ripple development and significant sediment movement (Results in Section 4). We then discuss the implications of these findings, which suggest that wave impact on reef flats is not limited to shallow, 1-3 m-deep environments, and that deeper flats (>10 m) may be geomorphologically active as waves and currents can be sufficiently strong to actively rework and contribute to the development of deep reef flats (Discussion in Section 5).

3 Methods

3.1 Field observations on the SW-facing reef flat, Tiexian Reef

From January 14 to September 19, 2018, an *in situ* observation was conducted continuously for 249 days (ca. 8 months) on the SW portion of the 12 m deep Tiexian reef flat (TX, (114°12'29.16"E, 11°01'48.78"N), Figure 1d and Figure 2). This 8-month observational period includes the seasonal transitions of winds and waves, including both leeward and windward periods; no tropical cyclones affected the reef over the observation period.

A tripod was deployed on the sandy bed, more than 5-10 m away from living reef complex structures. An RBRsolo was tied to the tripod to record wave conditions (significant wave height, H_s, and peak wave period, T_p) and water level. A 6 MHz Nortek Acoustic Doppler velocimeter (ADV) was also located on the tripod to measure current velocity at height z_1 = 0.5 m above the sandy seabed, $u_{0.5}$, and representative near-bed orbital velocity, u_{br}. The ADV measured in the burst mode with a sampling frequency of 16 Hz, with the burst interval and working duration set to 30 min and 256 s, respectively, i.e., 4096 data points were recorded for over 4 minutes every 30 min. Note that there was a 3-day data gap between March 27 and 30, 2018, due to the replacement of batteries. The local east, north, up (ENU) coordinate was utilized in the ADV instantaneous measured horizontally (*u*, *v*) and vertically (*w*) velocity data. The vertical coordinate was taken as positive upward from the seabed. Field experiment instrumentations are summarized in Table 1. Variables involved in the measurements and calculations were listed in Table S1.

To trap suspended sediment in the water column (if present during the observation), two plastic bottles (500 ml) were tied to the tripod at 0.1 and 0.5 m above the seabed. During an underwater observation on March 30, 2018, when the NE monsoon dominates the TX site (a leeward reef), well-developed ripples were observed on the sandy bed next to the tripod (Figures 1d and 2). Ripple height was be 5-10 cm by visual estimation. Ripple mobilization and sediment sliding along the ripple surface were observed and recorded in diver video (please see the supplement video). Loose sediment samples were collected both on the ripple surface and under a tripod for grain-size analyses. The tripod for instrumentation was stabilized on a quasi-bare sandy seabed (Figure 2) so that the calculated shear stresses computed with the bottom boundary layer model for combined waves and current [*Grant and Madsen*, 1986; *Madsen*, 1994] can represent shear stresses associated with sediment grains, and thus are suitable for the development of ripples, allowing us to calculate bedload transport under symmetric waves and currents.

Prior to this 8-month observation, 25-40 hour *in situ* both tripod mooring and shipboard profiling observations were undertaken in September 2017 on the nearby deep reef flats of Daoming Islands and Zhenghe Islands, which are two of the other main elliptical atolls in the northern part of Nansha Islands (Figure 1). On the tripod, the same 6 MHz Nortek ADV was installed at 0.4-0.7 m above the seabed to measure current velocity at the three sites, using burst mode with a sampling frequency of 16 Hz (Table 1). Within every 10-minute burst, the ADV sampled for 512 s and recorded 8192 data points. Also, a CTD with a turbidity sensor (SD204, a product of SAIV A/S, Norway) was installed at 0.8-1.2 m above the seabed at the three sites, respectively, to measure water depth, temperature, salinity and turbidity with a sampling interval of 1 minute. An uplooking TRDI 1200kHz ADCP was installed at 1.4-1.7 m above seabed to measure the current velocity profile with a bin size of 0.25m every 30 s. The shipboard profiling included an OBS3A to measure the water depth, temperature, salinity, and turbidity. Finally, three layers of water samples were collected in the surface, middle, and bottom water column and subsequently obtained suspended sediment concentration by filtration in the laboratory (Supporting Information, Tables S2-S4).

For grain size analysis, loose sediment samples were also collected on the sandy seabed where tripods were stabilized at all the four sites. Grain size analysis was performed with a sonic vibrating screening granulometer/sieve (Type SFY-D, made by Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences), with eight sieve bins of 4.0, 2.0, 1.0, 0.710, 0.500, 0.355, 0.250 and 0.125 mm, corresponding to -2, -1, 0, 0.5, 1, 1.5, 2 and 3ϕ. These sieved sample grain-size distribution statistics were then analyzed to determine the median grain size, d_{50} (corresponding to the 50th percentile on a cumulative curve, measured by weight). Additionally, four surface coral sand samples were taken for a dynamic image analysis using a CAMSIZER (a product of Microtrac MRB, Germany) to obtain the particle size and shape as well (Figure S4).

Local wind field data was calculated as the average of wind velocities at the four control grid-points surrounding the TX site (10°56'13.20"N and 11°8' 29.04"N, 114°20'27.60"E and 114°08'9.60"E) from the NCEP Climate Forecast System Version 2 (CFSv2), using the 6-hour forecast data of wind velocity (U_{10}) at 10 m above the sea surface [*Saha et al.*, 2014] (Figure 4b).

Table 1 Instrumentation for near-bed tripod mooring observations at four deep flat sites

Reef	Site	Longitude Latitude	Depth	Instrumentation installation height above seabed z_1	Observation duration
Tiexian	TX	114°12'29.16"E, 11^{0}01'48.78"N	12.3 m	ADV, 0.5 m; RBRsolo, 1.5 m	January 14 to September 19, 2018 (ca. 251 days, 8 months)
Xiaonanxun	NX	114°16'15"E, 10°9'40"N	17.4 m	ADV, 0.4 m; CTD, 0.8 m; ADCP, 1.4m	September 2 to 3, 2017 (ca. 25 hours)
Anda	AD	114°37'14"E, 10°19'48"N	16.3 m	ADV, 0.7 m; CTD, 1.1 m; ADCP, 1.7m	September 5 to 6, 2017 (ca. 25 hours)
Kugui	KG	114°35'10"E, 10°45'24"N	15.9 m	ADV, 0.6 m; CTD, 1.0 m; ADCP, 1.6m	September 7 to 9, 2017 (ca. 40 hours)

3.2 Data treatment

3.2.1 Wave and current data

Water level change and wave parameters (significant wave height H_s, peak wave period T_p) are derived from the pressure spectra measurement by RBRsolo. The unified tidal analysis is performed on water level data series using the UTide code [*Codiga*, 2011]. Spikes were removed from the ADV measurements prior to all calculations with the bivariate kernel density function and the removed elements are replaced by linearly interpolated values [*Botev et al.*, 2010]. The representative bottom orbital velocity u_{br} [*Madsen*, 1994] represents the amplitude of a monochromatic wave orbital motion with the same variance as the full spectrum and is equivalent to the root-mean-square (rms) value of bottom orbital velocity [*Madsen*, 1994; *Soulsby*, 1987]. The near-bed velocity measurement of the ADV, u_{br}, was derived following *Wiberg and Sherwood* [2008],

$$u_{br} = \sqrt{2\sum_i S_{uv}\Delta f_i} \tag{1}$$

where S_{uv} represents the combined horizontal velocity spectrum with the summation taken over all frequency bins Δf in the spectrum. The wave propagation direction was estimated by using the associated dynamic pressure and orbital velocities.

Wave skewness and asymmetry are quantified by the Ursell number that can be computed using wave parameters H_s, T_p, and water level change, following the method proposed by *Ruessink et al.* [2012]. The computed wave skewness and asymmetry are in order of magnitude of 10^{-5} and 10^{-7}, respectively (Figure 3), suggesting weak wave transformation and the applicability of linear wave theory and bedload transport formulae under sinusoidal waves plus currents for the deep reef flats in this study [*Soulsby*, 1997; *Soulsby and Damgaard*, 2005]. Wave parameters u_{br}, T_p, and mean current at 0.5 m above seabed $u_{0.5}$, and median grain size d_{50} were used in the calculations of bottom shear velocities (stresses) using the *Grant and Madsen* [1986] and *Madsen* [1994] bottom boundary layer model for combined wave and current (referred to as GM86 model thereafter). The calculated shear velocities were then used to calculate potential ripple geometry in equilibrium and the potential bedload transport rate as described below.

The importance of wave transport owing to Stokes drift was illustrated by measurements across the fore-reef on the north shore of Moorea, French Polynesia [*Monismith et al.*, 2013]. The near-bed wave-driven Stokes drift u_1 [*Lentz et al.*, 2008] was tcalculated using linear wave theory,

$$u_1 = \frac{2\pi H_s k}{16T}\frac{\cosh[2k(z+h)]}{\sinh^2(kh)} \qquad (2)$$

where $z=-h + z_1$, h refers to water depth, z_1 refers to ADV installation height above the seabed, $z=0$ at the water surface and $z=-h$ at the seabed. The wave streaming u_2 [*Fredsoe and Deigaard*, 1992; *Longuet-Higgins*, 1958] is expressed as,

$$u_2 = \frac{3\pi^2 H_s^{\,2}}{4TL\sinh^4(kh)} \qquad (3)$$

where $k = 2\pi/L$ is the wave number, and L is the wavelength.

3.2.2 Predictions of near-bed shear stresses, transport mode, and ripple geometry

The near-bed Reynolds shear velocity is derived from ADV records, representing the total current shear velocity observation, $\rho u_{*c}^{\,2} = -\rho\overline{u'w'}$, where u' and w' are the fluctuating parts of the mainstream horizontal velocity component $u=\bar{u}+u'$ and the vertical velocity component $w=\bar{w}+w'$, respectively (the overbar refers to the burst-mean part of the velocity component).

The critical shear velocity u_{*cr} for the initiation of bedload transport as well as ripple formation are calculated with the threshold Shields parameter θ_{cr} [*Soulsby*, 1997; *Soulsby and Whitehouse*, 1997],

$$u_{*cr} = \sqrt{\theta_{cr}\left(\frac{\rho_s}{\rho_o}-1\right)g d_{50}} \qquad (4a)$$

$$\theta_{cr} = \frac{0.3}{1+1.2D_*} + 0.055[1-\exp(-0.020D_*)] \qquad (4b)$$

$$D_* = \left[\frac{g(\rho_s/\rho_o-1)}{\nu^2}\right]^{1/3} d_{50} \qquad (4c)$$

where D_* is the dimensionless grain size, g is the acceleration due to gravity, and ν is the kinematic viscosity of water. The sediment density ρ_s was measured as 1700-1850 kg/m^3 for the samples at the four sites (based on dry weight and volume), which is similar to estimates in other reef environments by *Cuttler et al.* [2018] and *Pomeroy et al.* [2021]. Here, sediment density ρ_s =1850 kg/m^3, sediment median grain size d_{50} = 1.0 mm, and seawater density ρ_o =1027 kg/m^3 were used to calculate critical shear velocities for initiation of bedload transport u_{*cr}, initiation of suspended load transport (ripple breakoff) u_{*bo}, and initiation of upper-plane bed sheet-flow sediment transport u_{*sf}.

Ripple breakoff occurs when ripple roughness decreases with bed shear stress [*Li and Amos*, 1998]. The critical shear velocity for ripple breakoff, u_{*bo}, according to *Grant and Madsen* [1982], based upon the laboratory data of *Carstens et al.* [1969] is,

$$u_{*bo} = \sqrt{\theta_{bo}\left(\frac{\rho_s}{\rho_o} - 1\right) g d_{50}} \quad (5a)$$

$$\theta_{bo} = 1.8\theta_{cr} S_*^{0.6} \quad (5b)$$

$$S_* = (d_{50}/4\nu)[(\frac{\rho s}{\rho} - 1) g d_{50}]^{0.5} \quad (5c)$$

where θ_{bo} is the threshold Shields parameter corresponding to ripple breakoff. Note that this threshold is close to the value of critical shear velocity for suspension of fine-grained materials and u_{*bo} was thus considered approximately as the critical value of initiation of suspended load transport in the following calculations and discussions.

We calculate critical shear velocity for sheet flow u_{*sf} using the formulae proposed by *Li and Amos* [1999b] based on the compilation of various preceding equations and comparison of these equations to their field observations on the Scotian Shelf,

$$u_{*sf} = \sqrt{\theta_{sf}\left(\frac{\rho_s}{\rho_o} - 1\right) g d_{50}} \quad (6a)$$

$$\theta_{sf} = 0.172 {d_{50}}^{-0.376} \quad . \quad (6b)$$

To calculate wave (subscript $_w$), current (subscript $_c$), and combined bed shear velocities (subscript $_{cw}$), we use the bottom boundary layer model of *Grant and Madsen* [1986] and *Madsen* [1994], i.e. the GM86 model. These bed shear velocities are computed based upon the hydrodynamic conditions (u_{br}, T_p, $u_{0.5}$, and angle between wave and current ϕ_{cw}) and different physical bed roughnesses k_b, i.e. sand grain roughness k_{bs}, bedload roughness k_{bb}, ripple geometry k_{br} as well as total bed roughnesses $k_b = k_{bs}+k_{bb}+k_{br}$. The resultant values correspond to skin-friction (grain-related), bedload-related, and ripple-related shear velocities, respectively, and were represented by subscripts *s*, *b*, and *r*, respectively.

Skin-friction wave shear velocity u_{*ws}, current shear velocity u_{*cs}, and combined bed shear velocity u_{*cws}. were first calculated with hydrodynamic parameters and the equivalent Nikuradse sand grain roughness ($k_{bs} = 2.5d_{50}$, hydraulic roughness $z_{0s}=k_{bs}/30$), using the GM86 model. In the calculation, an arbitrary value was firstly assumed for the ratio of wave shear velocity to current shear velocity as $C_r = 1$.

$$C_r = \frac{u_{*cws}}{u_{*ws}} = \sqrt{\frac{f_{cws}}{f_{ws}}} = \sqrt{1 + 2\left(\frac{u_{*cs}}{u_{*ws}}\right)^2 \cos\phi_{cw} + \left(\frac{u_{*cs}}{u_{*ws}}\right)^4} \quad (7a)$$

The grain-related friction factor f_{cws} was then obtained iteratively from,

$$\frac{1}{4\sqrt{f_{cws}}} + \log\left(\frac{1}{4\sqrt{f_{cws}}}\right) = \log\left(\frac{C_r u_{br}}{\omega z_{0s}}\right) + 0.14\frac{1}{4\sqrt{f_{cws}}} - 1.65 \quad (7b)$$

The friction factor f_{ws} was also approximated initially with k_{bs} and the near-bed horizontal wave-orbital excursion length A_b using [*Soulsby*, 1997],

$$f_{ws} = \exp\left[5.213\left(\frac{k_{bs}}{A_b}\right)^{0.194} - 5.977\right] \qquad (7c)$$

The timing of transport initiation as bedload can be determined by comparing the maximum combined skin friction shear velocity u_{*cws} and critical shear velocity u_{*cr},. As mentioned by *Li and Amos* [2001], several studies, however, have shown that after sediment transport was initiated or ripples were present, comparison between u_{*cws} (the shear velocity based on sand grain roughness k_{bs} alone) and critical shear velocities tended to underestimate the onset of both bedload and suspended load transport, and that the bedload-related shear velocities due to the combined grain and bedload roughness (=k_{bs}+k_{bb}) should be used for predicting the ripple geometry and the subsequent onset of sediment bedload, suspension and sheet flow transport [*Kapdasli and Dyer*, 1986; *Li and Amos*, 1998; 1999a; *Wiberg and Harris*, 1994; *Wilson*, 1989]. Thus for $u_{*cws}>u_{*cr}$, the wave, current, and combined shear velocities associated with bedload transport (u_{*wb}, u_{*cb}, u_{*cwb}) were calculated using GM86 model with the same hydrodynamic parameters and the bedload roughness height k_{bb}, which is dependent on the thickness of bedload layer h_{tm} [*Li and Amos*, 2001],

$$h_{tm} = 2.5D(\theta_{cws} - \theta_{cr})^{0.75} \qquad (8a)$$

$$k_{bb} = 180h_{tm} \qquad (8b)$$

When bedload transport occurs and/or preexisting ripples are present, the skin-friction combined shear velocity u_{*cws}, ripple-enhanced shear velocity u_{*cwe}, and the bedload combined shear velocity u_{*cwb} are all used to determine the bedform types and transport mode following *Li and Amos* [1998]. Their model separates transport and ripples into five categories: (1) no transport, (2) ripples in the weak-transport range, (3) ripples in the equilibrium range, (4) ripples in the breakoff range, and (5) upper-plane bed sheet-flow with no ripples. *Li and Amos* [1998] stressed that when $u_{*cws}<u_{*cr}$, the presence of any preexisting ripples will cause bed shear velocities to increase from ripple trough to crest [*Li and Amos*, 1998; *Wiberg and Nelson*, 1992]. Thus, this enhanced skin-friction shear velocity at the ripple crest, u_{*cwe} , should be used to determine when bedload transport, and hence the initiation of ripple movement, occurs [*Li and Amos*, 1998].

As relict ripples may exist from previous large wave events, the theoretical ripple-enhanced shear velocity from preexisting ripple height η_p and wavelength λ_p is computed following *Nielsen* [1986],

$$u_{*cwe} = u_{*cws}/(1 - \pi\eta_p/\lambda_p) \qquad (9)$$

If $u_{*cwe}<u_{*cr}$, then no transport occurs and the preexisting ripple geometry remains the same; likewise, when weak bedload transport occurs close to the ripple crest and ripples in this weak-transport range (i.e. if $u_{*cws}<u_{*cr}$, yet $u_{*cwe}>u_{*cr}$), then the ripple height is calculated with the skin-friction combined shear velocity u_{*cws} [*Li and Amos*, 1998],

$$\frac{\eta}{d_{50}} = 19.6\left(\frac{u_{*cws}}{u_{*cr}}\right) + 20.9 \qquad (10a)$$

Here, an average value of ripple steepness,

$$\frac{\eta}{\lambda} = 0.12 \qquad (10b)$$

is used, as the ripple steepness in the weak-transport range is mainly determined by the relict ripple characteristics [*Li and Amos*, 2001].

If shear velocities fall between the critical bedload shear velocity and breakoff threshold shear velocity values (i.e., $u_{*cws} > u_{*cr}$ and $u_{*cwb} < u_{*bo}$), then ripples are in the equilibrium range and bedload transport mainly occurs through ripple mobilization. Based upon the ratio between u_{*ws} and u_{*cs}, equilibrium ripples can be further divided into current-dominated ripples ($u_{*ws} / u_{*cs} < 0.75$), wave-dominated ripples ($u_{*ws} / u_{*cs} > 1.25$), and combined wave/current ripples (0.75-1.25). For wave-dominated ripples ($u_{*ws} / u_{*cs} > 1.25$) that occurred for most time of this observation, an average value of ripple steepness 0.15 is used,

$$\frac{\eta}{d_{50}} = 27.14\left(\frac{u_{*cwb}}{u_{*cr}}\right) + 16.36 \qquad (11a)$$

$$\frac{\eta}{\lambda} = 0.15 \qquad (11b)$$

For more energetic conditions, when the combined bedload-related shear velocity u_{*cwb} is larger than the critical shear velocity of ripple break-off u_{*bo} but smaller than the sheet-flow (ripple removal) criterion u_{*sf}, i.e., $u_{*bo} < u_{*cwb} < u_{*sf}$, then transport occurs as both bedload (sliding and saltation) and suspended load. Ripple wavelength is constant in the breakoff range, with ripple steepness η/λ attaining a maximum value of 0.15 at $u_{*cwb} = u_{*bf}$. Ripple steepness η/λ, and thus ripple height η, decreases towards zero until u_{*cwb} increases to the sheet-flow criterion u_{*sf}, ripple geometry is calculated as,

$$\lambda = 535 d_{50} \qquad (12a)$$

$$\frac{\eta}{\lambda} = 0.15(u_{*sf} - u_{*cwb})/(u_{*sf} - u_{*bo}) \qquad (12b)$$

In extremely energetic conditions (i.e. $u_{*cwb} > u_{*sf}$), sheet flow occurs in the upper-plane bed under combined flow and ripples are completely washed out, with zero height and wavelength.

Subsequently, the calculated ripple heights and lengths were used to obtain the 'observed' apparent ripple roughness height as k_{br},

$$k_{br} = 27.7\eta\left(\frac{\eta}{\lambda}\right) \qquad (13)$$

As a comparison, three other models of equilibrium bedform development based on sandy coasts were also applied to calculate potential equilibrium ripple geometry for comparison [*Grant and Madsen*, 1982; *Styles and Glenn*, 2002; *Wiberg and Harris*, 1994]. Many of these models primarily depend upon the horizontal wave-orbital excursion length to predict bedform dimensions. Note that the grain density of reef sediment can be less than typical quartz beach sediment, which would influence the applicability of the ripple model to the reef environment because some models use the mobility parameter and are dependent on the grain density [*Camenen*, 2009].

3.2.3 Calculation of potential bedload transport rates

Skeletons of corals and other calcifying organisms can be broken down by bioeroders and wave abrasion into sand-sized sediment [*Perry et al.*, 2011], which can then be transported by waves and currents. Because of the dominance of coarse-grained sediment on the deep flat surface, the observed limited suspended sediment in water column and the applicability of linear wave theory in the studied deep flats, we compute bedload transport rate (volume per unit width per unit time q_b , $m^3/m/s$) across the TX site with the quasi-empirical bedload formulations applicable for sinusoidal waves and currents [*Soulsby*, 1997; *Soulsby and Damgaard*, 2005]. We note that although bedload combined shear velocities u_{*cwb} and preceding ripple-enhanced shear velocities u_{*cwe} are used to determine transport mode and quantify ripple geometry above, only skin-friction shear velocities (u_{*cws} and u_{*cs}) are used when $u_{*cws}>u_{*cr}$ to calculate q_b as determined by the formulae [*Soulsby*, 1997; *Soulsby and Damgaard*, 2005], without the inclusion of enhanced effect on shear velocities and transport due to bedload transport or preexisting ripples. As such, our estimates of transport rates represent a conservative estimation of transport potential by waves and current if sediment supply is abundant.

Sand-sized sediment supply is limited by reef accretion, fragmentation, and abrasion processes in the reef environment [*Perry et al.*, 2011; *Pomeroy et al.*, 2018; *Rosenberger et al.*, 2020]. Thus, all the model calculations, including the enhancement of shear velocities due to bedload transport and preexisting ripples, ripple predictions with the model of *Li and Amos* [1998] and the other studies, as well as calculation of bedload transport q_b [*Soulsby*, 1997; *Soulsby and Damgaard*, 2005], represent predictions for when the bed is covered with sufficient sediment, and thus are upper bounds on the possibility for sediment transport [*Bramante et al.*, 2020b; *Pomeroy et al.*, 2018; *Pomeroy et al.*, 2021], and the increase of shear velocities due to the occurrence of ripple development at the TX study site. These possibilities of sediment motion and flux are further discussed in the following sections.

The dimensionless shields' parameter $\theta = \frac{{u_*}^2}{[(\rho_s/\rho_o - 1)gd_{50}]}$ and the dimensionless form of bedload transport rate Φ are used in the formulae.

If skin-friction combined wave current shear velocity $\theta_{cws} > \theta_{cr}$,

$$\Phi_{x1} = 12\theta_{cs}^{1/2}(\theta_{cs} - \theta_{cr}) \tag{14a}$$

$$\Phi_{x2} = 12(0.95 + 0.19cos2\phi)\theta_{ws}^{1/2}\theta_{cs} \tag{14b}$$

$$\Phi_x = \max(\Phi_{x1}, \Phi_{x2}) \tag{14c}$$

$$\Phi_y = 12(0.19\theta_{cs}\theta_{ws}^2 \sin 2\phi)/(\theta_{ws}^{3/2} + 1.5\theta_{cs}^{3/2}) \tag{14d}$$

$$q_{bx,y} = \Phi_{x,y}[g(\rho_s/\rho_o - 1)d_{50}^3]^{1/2} \tag{14e}$$

If $\theta_{cws} \leq \theta_{cr}$,

$$\Phi_x = \Phi_y = q_{bx} = q_{by} = 0 \tag{14f}$$

where Φ_x and Φ_y are the dimensionless components of q_b traveling in the direction of the current q_{bx} and at the right angle to the current q_{by}, respectively. The mean current direction dominates the direction of bedload, while obliquely approaching waves induce a transverse component of bedload, term Φ_y (q_{by}). Φ_x (or q_{bx}) is determined to be the larger of Φ_{x1} and Φ_{x2}, corresponding to current-dominated and wave-dominated sediment transport, respectively. Cross-shore bedload transport rates are calculated with an alongshore azimuth of 76° and an on-offshore azimuth of 346° for the TX site located at the southside of Tiexian Reef.

4. Results

4.1 Wind forcing and wave action

Meteorological conditions during the 8-month study were generally moderate to light (U_{10} between 1–11 m/s), and no frontal systems or tropical cyclones passed through the region (Figure 4b). The northeast (NE) monsoon dominated the TX site area and winds were obliquely offshore from January 14 to April 15 (referred to as the NE-wind period hereafter), whereas the southwest (SW) monsoon dominated the region and winds were obliquely onshore from June 1 to September 14 (referred to as the SW-wind period hereafter) [*Saha et al.*, 2014]. The NE-to-SW transition period with lighter winds (U_{10}<3 m/s) extended from about April 16 to May 31. The seasonal wind predominates the wave conditions (H_s, T_P, direction β_w and u_{br} in Figure 4c-4g), as well as wave and wave-current combined shear velocities, and thus also bedload transport as described respectively below.

At the beginning of the NE-wind period, waves were transmitted across the reef with a general propagation direction of β_w =110°-170° (164°–176° of the offshore direction) (Figure 4e). Waves had a significant wave height H_s of 0.3-1.5 m (mean H_s = 0.5 m), a peak period T_p of 5.5-11.8 s (mean T_p = 9.7 s), and resulted in a representative near-bed orbital velocity u_{br} of 0.05 – 0.31 m/s (mean u_{br} = 0.16 m/s) (Figure 4c, 4d and 4g). During the three small swell events that influenced this deep flat area (February 1-10, March 5-10, April 5-10, Figure 4f), wave energy was higher, with a mean H_s and u_{br} of 1.1 m and 0.23 m/s, 0.8 m and 0.18 m/s, and 0.7 m and 0.16 m/s, respectively. Wave energy was the lowest (H_s =0.1-0.3 m, u_{br} =0.05-0.1 m/s) during the NE-to-SW transition period when winds were lighter (U_{10}<3 m/s). Note that although the TX site is on a leeward position in the atoll, the deep flat on the northern side allows waves to propagate over the flat and across the lagoon.

The highest annual wave energy at the SW-facing deep flat of the TX site occurred in the SW-wind period starting in early June. The onshore propagating waves approached the reef with a general direction of β_w =40°-50° (close to the on-shore direction) (Figure 4e). The waves at the reef had a shorter T_p of 6-9 s (mean T_p of 7.1 s) and a higher H_s of 0.2-2.5 m (mean H_s of 1.4 m), and thus a much larger u_{br} of 0.1-0.6 m/s (mean u_{br} of 0.36 m/s) than that of NE-wind period (Figure 4c and 4d). Four large continuous sea-swell events of June 1-20, July 1-20, August 1-20, and September 9-15 impacted this deep flat area during this time (Figure 4f), and waves on the deep flat had a mean H_s between 1.6 and 1.8 m, mean T_p between 6 and 8 s, and mean u_{br} between 0.25 and 0.6 m/s.

Waves transmitted across the deep flat were distinctly unimodal with sea-swell wave frequencies (0.2-0.05 Hz) throughout the observation period without the appearance of low-frequency waves (<0.05 Hz) (Figure 4f), and the transformation of waves was little as quantified by skewness in the magnitude order of 10^{-5} and asymmetry in the magnitude order of 10^{-7} (Figure 3). The sinusoidal waves still influenced the bed with their symmetric orbital motion despite the considerable depth of 12 m of the site, which should affect sediment initiation, bedform development, and potential bedload transport (see below). The classic mode of bimodal wave spectrum and wave-induced current, and cross-shore transport that is driven by both skewness and asymmetry of sea-swell and infragravity waves and mean current across the fore-reef-slope, reef crest, and shallow reef flat was not observed in either this observation at the TX site or any of the three deep flats in the Nansha Islands during the day-long reconnaissance study.

4.2 Tide forcing and current measurements

Over the 8-month observation period, tidal forcing at the TX site was weaker than the wind, Observations show that the study area is characterized by an annual mean tidal range of 0.89 m (Figure 4a). Unified tidal analysis of water level observations shows that the 12-m deep reef flat is dominated by primary diurnal K1 and O1 tides with amplitudes of 0.34 and 0.27 m, respectively, with the secondary semi-diurnal tide M2 with an amplitude of 0.19 m. The top seven tide components account for 99% of the sum of tidal amplitudes, of which diurnal and semi-diurnal tide components account for 81% and 18%, respectively. As a result, the water level changes with a significant diurnal period of about 25 hours. This result is in agreement with both the statistical studies of tide observations in the Yongshu Reef [*L Zhu et al.*, 2005] and the numerical studies of tide dynamics in the SCS by *Zu et al.* [2008] discussed above.

The deep reef flat at the TX site generally experienced a moderate to weak currents with a relatively stable mean current velocity magnitude $u_{0.5}$ of 0.06-0.07 m/s throughout the 8-month observation. The current direction is approximately cross-shore, with flows oscillating between lagoonward (ca. 344 ^{o}) and oceanward (ca. 166 ^{o}) across the mixed semi-diurnal and diurnal tide period (Figure 4i). Unlike the waves, which have a strong seasonal signal, neither the direction nor the magnitude of the currents changes much with onset of monsoon winds (Figure 4b, 4h and 4i), and the contributions to mean current from wave-driven cross-shore currents (the near-bed Stokes drift u_1 and wave streaming u_2) were less than 0.01 m/s (Figure 3a), suggesting that these flows are tidally driven. Because the reef flat has a flat slope and waves are generally sinusoidal with little transformation, this non-wave-driven, moderate cross-reef current is expected to control net sediment fluxes across the deep reef flat.

4.3 Bed shear velocities

Grain size analyses show that reef sediments of the ripples at the TX site are composed of medium to very coarse sand, the fractions of the five-grain size ranges, >4.0 mm, 4.0-2.0 mm, 2.0-1.0 mm, 1.0-0.5 mm and 0.5-0.25 mm, are 19.5%, 14.12%, 32.27%, 31.14%, and 2.75% respectively (Figure 5). All sediment samples were larger than 0.25 mm in diameter in the sieving analysis. The median grain size d_{50} is 1.0 mm at the TX site, similar to that of sediment found at the neighboring deep flats of Kugui and Xiaonanxun reefs, whereas d_{50} = 0.5 mm at Anda reef (Figure 5). For sediment with measured density of 1850 kg/m^3 and median grain size of 1.0 mm, the critical shear velocities for bedload transport, ripple breakoff (close to suspension initiation), and sheet flow were calculated as u_{*cr} =1.6 cm/s, u_{*bo} = 6.5 cm/s and u_{*sf} =8.4 cm/s, respectively (red lines in Figure 6a and 7a), and were compared with various combined shear velocities to determine ripple development and sediment transport mode. Observations at other reef flat environments suggest that sediment transported in suspension was commonly finer than sediment collected on the seabed of the reef [*Pomeroy et al.*, 2018; *Pomeroy et al.*, 2021]. Accordingly, because sediment between 1.0 mm and 0.5 mm accounted for over 31% and d_{35} is 0.5 mm at the TX site, critical shear velocity for bedload transport, ripple breakoff (close to suspension initiation) of d_{35} = 0.5 mm was also calculated for potential suspended transport discussions (green lines in Figure 6a and 7a), while the bedload initiation and transport rate estimation were conducted primarily based on sediment of d_{50} = 1.0 mm.

Similar to the wave parameters H_s and u_{br}, wave skin-friction shear velocity u_{*ws} and combined skin-friction shear velocity u_{*cws} exhibit distinct seasonal variations (Figure 6a). In the NE-wind period when the TX site was leeward, u_{*cws} was larger than critical shear velocity for bedload initiation u_{*cr} almost exclusively during the three small swell events (February 1-10, March 5-10, April 5-10), with a mean u_{*cws} of 0.02-0.025 m/s (Figure 6a). During the remnant time of the NE-wind period, u_{*cws} remained below u_{*cr} with a mean value of about 0.01 m/s. In contrast, in the SW-wind period, when the SW-facing reef was windward, u_{*cws} was larger than u_{*cr} =1.6 cm/s (d_{50} = 1.0 mm) for almost the entire period with a mean u_{*cws} of 0.035-0.04 m/s, with the exception of the intervals between the two large sea-swell events in June and July (June 20-30).

During the entire observation period, the skin-friction current-shear velocity u_{*cs} was relatively small and stable with a mean value of 0.003-0.01 m/s and was not apparently influenced by seasonal wind and wave changes, although u_{*cs} could be a little bit higher during the four sea-swell events of the high energetic SW-wind period from June to September (Figure 6b). Wave shear velocities (Figure 6a) were considerably larger than current shear velocities (Figure 6b) in the bottom boundary layer as calculated with GM86 model and either the grain-related roughness height (k_{bs}), bedload roughness height (k_{bb}), or ripple roughness height (k_{br}), thus there we computed little difference between wave u_{*ws}, u_{*wb}, u_{*we}, and combined shear velocities u_{*cws},, u_{*cwb}, u_{*cwe}. The skin-friction wave shear velocity u_{*ws} almost coincided with the skin-friction combined shear velocity u_{*cws} (Figure 6a) and only u_{*cwb}, and u_{*cwe} were presented in Figure 7a and Figure 11 for visual convenience.

4.4 Transport mode and ripple development

Skin-friction-combined shear velocities u_{*cws} were all below breakoff criterion u_{*bo} (d_{50} = 1.0 mm) during both the SW-wind and NE-wind periods (Figure 6a). That is, sediment was likely mobilized for the almost whole SW-wind period and occasionally transported during the three-small swell-events of the NE-wind period. Conditions would allow bedforms (ripples) to develop and sediment transport could occur through bedload (ripple migration) simultaneously. However, bedload-combined shear velocity u_{*cwb}, which was calculated using the bedload roughness height k_{bb} at these times of bedload initiation (u_{*cws}> u_{*cr}), was found to be larger than u_{*bo} during much of the four sea-swell events in the SW-wind period, and could occasionally be even larger than the sheet-flow critical shear velocity u_{*sf} =6.9 cm/s for d_{35} = 0.5 mm during the large sea-swell events (Figure 6a). This suggests that suspension of finer sediment could be sustained close to the bare sandy seabed by combined shear velocities enhanced by the bedload transport layer as quantified by u_{*cwb} and/or preceding ripple formation u_{*cwe} if sediment supply was abundant, as discussed below for the potential bedload and suspended sediment flux (Figure 7a). The Reynolds shear velocity measured by the ADV, which should be a representative of current shear velocity u_{*c}, was found to be larger than skin-friction current shear velocity u_{*cs} (Figure 6b) but close to the total shear velocity calculation u_{*c} computed using the total physical roughness height k_b = k_{bs}+k_{bb}+k_{br} (Figure 7b). This also suggests the importance of contributions from shear velocities related to bedload transport u_{*cwb} and ripples u_{*cwe} at the TX site.

In our calculations, shear velocity enhancement by preexisting ripples u_{*cwe} was found to be important in driving sediment transport, particularly during intervals when u_{*cws}<u_{*cr} (Figure 7a). Over the deployment, this condition, u_{*cws}<u_{*cr}, where relict ripples are expected on the bed, occurred for most of the time outside of the three small swell events (February 1-10, March 5-10, April 5-10) in the NE-wind period and only for several days between large sea-swell events in the SW-wind period (June 20-30). At most of these times when u_{*cws} <u_{*cr}, u_{*cwe} increased the combined shear velocity so that sediment could be initiated for bedload transport for almost the entire SW-wind period, much of the NE-wind period, and even some days during the low-energetic transition period from mid-April to May 31 (Figure 7a). This resulted in a weak-transport mode (type 2 in Figure 8a) instead of no transport (type 1) at these relict-ripple-enhancement times with u_{*cws}<u_{*cr} yet u_{*cwe}>u_{*cr}.

During the underwater fieldwork on March 26 and April 1, well-developed ripples were observed on the sandy bed of the TX site (Figure 2) and ripple migration occurred through sediment sliding and saltation on the ripple surface as recorded by video. This supported the suggestion of a weak-transport stage using *Li and Amos* [2001] model rather than a no-transport stage if considering u_{*cws} <u_{*cr} alone. The ripple height of 5-10 cm by eye estimation (Figure 2) is also in line with the ripple height prediction η ~6.5 cm (Figure 8b) by the *Li and Amos* [2001] model. In the three small swell events of the NE-wind period and the four sea-swell events of the SW-wind period (June 1-20, July 1-20, August 1-20, and September 9-15) when u_{*cws}>u_{*cr}, the inclusion of shear velocity enhancement by preceding ripples u_{*cwe} did not substantially change the predicted transport mode, although u_{*cwe} were still larger than the shear velocity associated with bedload transport u_{*cwb} (Figure 8a).

The ripple predictor of *Li and Amos* [2001] suggested that ripples existed for almost the entire observation period by comparing critical shear velocities with u_{*cws}, u_{*cwb} and u_{*cwe} (Figure 8b). Overall, ripple height η was expected to change with seasonal wave conditions for all of the ripple predictors, since all of the models calculate ripple height as a function of either wave shear velocities [*Li and Amos*, 2001] (Figure 8b) or representative bottom orbital velocity u_{br} [*Grant and Madsen*, 1982; *Styles and Glenn*, 2002; *Wiberg and Harris*, 1994] (Figure 8c). The latter three models determined equilibrium ripple formation with skin friction shear velocities alone, and thus predicted no ripple or bedload transport for the time of u_{*cws}<u_{*cr}. According to ripple predictors of *Li and Amos* [2001], ripple heights were 5-10 cm during the three swell events in the NE-wind period, and 5-12 cm during the four large sea-swell events in the SW-wind period. Ripple heights η stayed relatively stable at ca. 4 cm for the remainder of the NE-wind and transition period.

Occasional ripple breakoff potentially occurred during the large sea-swell events (June 1-20, July 1-20, August 1-15, and September 10-15) when u_{*cwb}>u_{*bo} (type 4 in Figure 8a), ripple height η decreased sediment was likely suspended and transported across the TX site in the water column. Ripple steepness as predicted by *Li and Amos* [2001] decreased from 0.15 during the four large sea-swell events in the SW-wind period when η was decreased due to the strong incident wave activities, while ripple height remained stable at either 0.12 during the days between the sea-swell events, as well as during the entire NE-wind period and a transition period (Figure 9a).

The ripple steepness prediction by *Wiberg and Harris* [1994] and *Styles and Glenn* [2002] were similar with either a constant value of 0.15 when u_{*cws}>u_{*cr} (Figure 9b), whereas ripple steepness was predicted as about 0.28 by GM86 model [*Grant and Madsen*, 1982]. These latter predicted values are unrealistically steep-- this unrealistic result might be related to the upper limit of applicable grain size of 0.6 mm versus the d_{50} = 1.0 mm sediment at this site, although the GM86 model behaved better than other ripple predictors in the study of ripple migration across a shallow reef flat by *Rosenberger et al.* [2020]. This highlights an important potential limitation, as the ripple models used here [*Grant and Madsen*, 1982; *Li and Amos*, 2001; *Styles and Glenn*, 2002; *Wiberg and Harris*, 1994] were developed for sandy siliciclastic environments, and the application to reef environments remains uncertain because of not only the sediment supply limitation, but also the density and settling velocity difference between carbonate and quartz sediment as mentioned in section 3.2.2.

4.5 Suspended sediment concentration

The shipboard profiling of water turbidity measured by OBS3A returned all zero values in the water column at the nearby three reef flats, indicating the suspended sediment concentrations were low, beyond the measurement limitation of the OBS3A turbidity sensor. Another SD204 CTD with a high-accuracy turbidity sensor installed on the tripod at these sites showed low water turbidity of less than 0.2 FTU near the bottom (Figure S1-S3). Both the turbidity calibration and water samples indicated low suspended sediment concentrations mostly less than 10 mg/L, with many zero values during the observation periods (Tables S2-S4).

The measured drying weight of sediment trapped in the two plastic 500-ml bottles that were tied to the tripod at 0.1 and 0.5 m above the seabed during the 8 months at TX site was 0.030 g and 0.022 g, respectively. This represented a long-term accumulation of suspended transport with a possible ‘net’ SSC of 40-60 mg/L, and these sediment could be transported across the seabed through resuspension, advection and settling, at least during the peak wave period. The suspended sediment transport is sensitive to settling velocity which could be affected the particle shape effect. *Dietrich* [1982] argued that the settling velocity of such non-spherical particles with Corey shape factor of 0.7 (Table S5) could be slowed by 0.68 of that of spherical, reducing the settling rates. However, the very low SSC here demonstrated that the bedload transport dominated over suspended transport, reminiscent of the suspended transport rate which was one order lower than bedload transport across reef flat in the studies by *Pomeroy et al.* [2021] and *Rosenberger et al.* [2020]. The low probability of sediment suspension occurrence based on sediment trapped in the plastic bottles was also consistent with the relatively small backscatter values recorded by ADV (Figure 4j), as well as the zero turbidity measured by OBS-3A and very low turbidity measured by SD204 CTD (<0.2 FTU) at the nearby reefs (Figures S1-S3).

Acoustic backscatter records from the ADV are typically proportional to sediment entrained in the water column and thus can reflect SSC change qualitatively even without a defined quantification or calibration between the two parameters [*Pomeroy et al.*, 2021]. Backscatter generally followed the trend of seasonal wave changes (Figure 4j). The absolute values of backscatter in the low-energy transition period (mid-April to May) and most of the leeward NE-wind period were generally the largest of the observation period, whereas backscatter was the lowest and even close to zero during the time between the two adjacent sea-swell events in the SW-wind period (the peak wave energy period from June to September), i.e. June 20-30, July 18-31 and August 12-30. The similar lowest backscatter values also occurred approximately on March 11-26 following the small sea-swell event on March 5-10.

During the leeward NE-wind period and low-energy transition period, the high backscatter values are consistent with velocity measurements, and our calculations suggest that relatively weak wave conditions were still capable to initiate and entrain finer sediment (d_{35} =0.5 mm) into the water column, as critical skin-friction shear velocity for d_{35} = 0.5 mm (green solid line in Figure 6a) were exceeded by both the skin-friction combined shear velocity u_{*cws} and the bedload-associated combined shear velocity u_{*cwb} for almost all of these observation periods. These finer sediments could have remained suspended close to seabed in local water column yet with a low net suspended transport rate, as the critical shear velocity of suspended transport initiation for d_{35} = 0.5 mm (approximate to the value of ripple breakoff u_{*bo} as shown by the green dashed lines in Figure 6a and 7a) was rarely reached. This could account for the relatively high sustained backscatter value from January to May. That is, a certain amount of finer sediment was maintained in near-bed water column without net transport during this period.

Note that from March 11-26, subsequent to the small sea-swell event on March 5-10, backscatter is low. This suggests removal of bed-available fine-grained sediment by the large wave event, including advection of the sediment off of the reef flat. Similarly, during the four large sea-swell events of the peak wave energy period (June- September), critical shear velocity of suspended transport initiation for d35 =0.5 mm (green dashed line in Figure 6a) were reached by bedload shear velocity u*cwb, and post-event backscatter values are similarly low. This again suggests that suspended finer sediment could be advected off the reef flat during the early period of each large sea-swell event. Without supplement of finer sediment, SSC could not be sustained at the same high level, and coarser sediment (d50 = 1 mm) could not be entrained into water and sustained for suspended transport. That is, the relatively low backscatter and correspondingly low SSC following large sea-swell events could be related to the limited supply of fine sediment in reef flats. This is similar to the situation described by *Rosenberger et al.* [2020].

4.6 Bedload transport rate

The computed near-bed hydrodynamic conditions allow us to estimate the potential bedload transport rates, assuming again a bed continuously covered with sediment. Assuming sinusoidal waves, a unidirectional current bedload sediment flux q_b was computed using the skin-friction combined wave and current shear velocity (u_{*cws} and u_{*cs}) when $u_{*cws}>u_{*cr}$ [Soulsby, 1997; Soulsby and Damgaard, 2005], although transport modes were quantitatively determined with the inclusion of enhancement of shear velocities by bedload transport and preexisting ripples (u_{*cwb} and u_{*cwe}). That is, weak transport when $u_{*cws}<u_{*cr}$ yet $u_{*cwe}>u_{*cr}$, which mainly occurred mainly during the NE-wind period and the transition period in addition to some intermittent days between sea-swell events during the SW-wind period (as marked by type 2 in Figure 8a) was not included in the calculations. In particular, during the transition period of weakest wave activity (mid-April to May), shear stress (velocity) due to ripple-enhancement could have contributed to over 25% of the potential sediment transport. Transport potential enhancement due to the bedload-enhanced shear velocities (u_{*cwb}, Figure 6a), which was corresponding to the times of bedform type 3 and type 4 as marked in Figure 8a, was not included in the q_b calculation (Eq. 14), either. Meanwhile, it is noted again that the q_b calculation (Eq. 14) with median grain size d_{50} = 1.0 mm represents an upper limit or hydrodynamic potential of sediment transport assuming abundant sediment supply, similar to the limitations of the ripple calculations and enhanced shear velocities above.

As expected, both the direction and magnitude of the potential bedload transport followed the overall seasonal change along with the wind and wave condition changes. Sediment transport could occur during almost the entire SW-wind period. The largest potential bedload transport occurred during the four sea-swell events in the SW-wind period and net transport occurred generally towards the north (either northwest or northeast) and thus towards lagoon, in line with the SW-wind and the sea-swell wave that accordingly propagated towards the north (Figure 10a). We then focused on the cross-shore components of q_b that would contribute to sediment flux either towards the lagoon or offshore into the ocean; such losses of sediment from the atoll rim would affect long-term reef accretion. During the NE-wind period, oceanward bedload transport occurred more often than lagoonward transport (Figure 10a), although occasionally lagoonward currents were expected to move sediment opposite the direction of wave approach. We computed the potential for far more significant bedload transport during the sea-swell event on February 1-15, with a mean oceanward cross-transport rate of 0.66×10^{-5} m^2/s. Bedload transport was expected to be rare during the transition period (mid-April to May). In the SW-wind period, the mean potential lagoonward and oceanward cross-shore sediment transport rates were 0.25×10^{-5} m^2/s and 0.13×10^{-5} m^2/s, respectively. Integrating cross-shore transport rates over the 8-month observation period suggests the potential to transport sediment off the TX site for 1.6 m^3/m towards the lagoon and 2.4 m^3/m towards the ocean in the NE-wind period, and 6.5 m^3/m towards the lagoon and 3.4 m^3/m towards the ocean in the SW-wind period (Figure 10b). We discussed the implications of these fluxes on bed elevation change below.

Deal et al. [2023] proposed a Corey-shape-factor corrected Shields number to calculate the bedload transport rate by considering the drag and friction coefficients. The analysis directly showed that the sphericity (defined by 4π multiplied by the projected area and divide by the perimeter) ranged from 0.71 to 0.86 for the sediment sample collected at the TX reef observation site (Table S5, Figure S4). The sphericity is similar to the widely used Corey shape factor ranging from 0.66 to 0.76. Here we already consider the ripple effect and take the seabed without slope (i.e. the friction can be ignored). Then the Shields number actually can be corrected by the Corey shape factor multiple shear stress. This would yield about 10% lower bedload transport rate.

4.7 Comparison to short-term hydrodynamic observations at nearby reef flats

The conditions at the TX site are not unique, as strong waves were observed at the deep reef flats of other atolls in the Nansha Islands. The one-tidal-period ADV observations at the NX, AD, and KG sites demonstrated similar hydrodynamic conditions (characterized by relatively moderate-to-weak tidal currents) as observed at the TX site, although there were different absolute values due to leeward or windward conditions and the short period of observation (Figure 1). These measurements show modest tidal ranges of around 1 m and mean currents of 0.05 - 0.07 m/s on average in the 16-18 m deep reef flats of different atolls, Nansha Islands (Table 2). Wave activity at the NX site, with a mean H_s of 0.82 m and mean u_{br} of 0.06 m/s, was the strongest among the three sites during the brief observation, even though the water depth of 17.4 m is the deepest of the three sites. This can be attributed to the NX site, located at the SW end of the Zhenghe Islands, being exposed to the strong SW-monsoon completely during September. In contrast, wave activities were weaker at the AD and KG sites that were located at approximately the NE side of Zhenghe and Daoming Islands, respectively, as they were protected at the leeward sides from the SW-wind during the September observations.

Table 2 Wave conditions observed at the deep reef flats of NX, AD, and KG

Site	h (m)	H_s (m)	T_p (s)	u_{br} (m/s)	$u_{0.5}$ (m/s)	U_{10} (m/s)
NX	17.4	0.82	7.6	0.06	0.06	4.8
AD	16.3	0.56	8.3	0.05	0.07	1.5
KG	15.9	0.41	7.0	0.03	0.05	5.3

5. Discussion

5.1 Extensive effect of wave motions on deep (>10 m) reef flats

Persistent unimodal waves were shown to produce shear velocities that were large enough to transport sediment as bedload across a deep reef flat of 12 m depth even in the absence of tropical cyclone events (which statistically occur about twice per year on average) during observation period. The hydrodynamic domination of seasonal waves over mean currents can be clearly seen in one-day averages of wave parameters and shear velocities (Figure 11). On this deep flat, the bed would be expected to be dominated by symmetrical orbital motions rather than the wave-induced effects of Stokes drift or wave transformation as found commonly in shallow reef flats [*Monismith et al.*, 2013] (Figure 4). The lack of wave breaking also means that wave-driven currents should not affect the bed—instead we observed mild, tidally-reversing flows. The vigorous orbital motions could also contribute to abrading fragments mechanically and producing reef debris as the additional sediment supply for physical transport [*Bramante et al.*, 2020b], in addition to the biological activities that were usually presumed to be the major contributor to sediment abrasion by eroding reef skeletons [*Mumby*, 2006; *Perry et al.*, 2011].

Although currents alone are not capable of initiating sediment motion over any point of our 8-month observation (Figure 4b and 11c), the moderate currents present should be indispensable in transporting sediment reef mobilized by wave orbital motions across the reef flat and into the lagoon or deep ocean. The wave-current-combined bedload transport q_b is affected by the current and wave condition, as represented by the proportionality to mean-current-shear velocity u_{*cs} and u_{*cws}, with an approximate power of 2 and 1, respectively (Eq. 14b). The mean-current-shear velocity u_{*cs} could vary with the topography, local tide range and the wave condition, since the mean shear velocity is enhanced by the wave-induced turbulence near the bed relative to the pure unidirectional current [Grant and Madsen, 1986]. In addition to the high wave energy, the mean u_{*cs} of 0.005-0.01 m/s resulting from the moderate-to-weak and relatively stable current as observed in the deep flat sites could be a prerequisite for the potential bedload transport off the atoll rim.

5.2 Sediment transport across deep flats

Ripples were likely to be formed and to migrate during the small sea-swell events in the NE-wind period at the beginning of the observation period (Figure 8a and 8b, type 3), being preserved in the intermittent and later low-energy transition periods (Figure 8a and 8b, type 2). Ripple migration and bedload transport time were found to be constrained better by enhanced shear velocities by pre-existing ripples u_{*cwe} (Figure 6a and 11c), since these bedload times were supported at least partially by the observation of ripple migration and bedload transport underwater at the end of March 2018 and that sediment transport was supposed to be underestimated by skin-friction shear velocity u_{*cws} alone. With stable ripple maintained (Figure 8a and 8b, type 2) and occasional ripple breakoff (Figure 8a and 8b, type 3) in the NE-wind period and transient low-energy period, bedload transport occurred almost continuously and led to a relatively higher and stable sediment entrainment close to the bed. This was consistent with the relatively larger acoustic backscatter value than that of the subsequent peak energy SW-wind period (Figure 4j). The acoustic backscatter was also lowered below 10 dB after the several small swell events (e.g. March 11-26) but was still higher than that in the intermittent time between the sea-swell events in the SW-wind period. One possible explanation might be that the accumulated sediment transport off the site was less in the NE-wind period and the following sediment re-supply time could be shorter than that in the peak-energy SW-wind period (Figure 10b).

During the SW-wind period, the bedload-related shear velocity u_{*cwb} reached the critical shear velocity of suspended transport initiation for fine sediment d_{35} = 0.5 mm (which is approximate to the breakoff critical shear velocity u_{*bo} as shown by the green dashed line in Figure 11c), ripples decreased in height (Figure 8b), coarse sediment was transported through bedload (Figure 8a, type 3), and fine sediment could be transported off the site through suspension (Figure 8a, type 4). The sheet flow criterion u_{*sf} (dotted lines in Figure 6a and 7a) was rarely reached by the bedload-related shear velocity u_{*cwb}, except a few days during the four sea-swell events, June 6-9, July 5 and 9, and September 13, implying that ripples were rarely washed out and that no sheet flow occurred during the peak-energy period (Figure 8a, type 5). The bedload transport as quantified by skin-friction shear velocities (u_{*cws} and u_{*cs}) alone (Figure 10b) could cause shortage of mobile sediment in the deep flat following each sea-swell event in the SW-wind period. It might take a few days to re-supply mobilized sediment to the deep flat after sediment available to move was transported off the deep flat through mainly bedload in the large sea-swell events. This could be reflected by the lower backscatter value (ca. June 20-30, July 19-31 and August 12-31) comparing to that in the preceding low-energy transition period (Figure 4j), even though both the skin-friction and enhanced shear velocities (u_{*cws}, u_{*cwe} and/or u_{*cwb}) were much larger in the SW-wind period (Figure 11c). It was noted that the combined total shear velocity u_{*cw} as calculated from the total roughness height ($k_b = k_{bs}+k_{bt}+k_{br}$) was larger than the sheet-flow critical shear velocity u_{*sf} for fine sediment d_{35} = 0.5 mm during a few days of each sea-swell event in the SW-wind period and could swipe off the ripples and lead to sheet-flow (Figure 11c). But such a total shear velocity u_{*cw} that was theoretically calculated from the enhanced roughness due to bedload transport and ample ripple development was less likely to occur in the deep flat due to the same limitation of mobile coral sand grain supply.

According to the measurements, for over 75% of the observation time, the skin-friction combined shear velocity u_{*cws} overweighed the critical shear velocity u_{*cr} for bedload transport initiation and the orbital motions were capable to entrain reef sediment into water columns for transport across the reef flat and out of the atoll rim (Figure 10a). The fraction of time when coral sand could be initiated to move for grain size d_{50} =1.0 mm by skin-friction combined shear velocity u_{*cws} was increased largely to over 95% in the SW-wind period (Figure 11c). Since wave transformation or breaking would less likely to occur at the reef flat with a relatively depth of 12 m (>10 m) and a gentle slope, the energy dissipation of the sinusoidal sea-swell waves by deep reef friction could be small across the reef rim from ocean-side towards the lagoon. Thus sediment flux through bedload transport would change little across the reef flat assuming abundant sediment supply across the reef flat. That is, the cross-shore bedload transport rates and their integration over the 8-month observation period across the single TX site calculated above (Figure 10b) could be applicable to the whole 12-m deep reef flat. Then the potential sediment transport off the rim towards the lagoon was 8.1 m^3/m (=1.6 m^3/m in the NE-wind period +6.5 m^3/m in the SW-wind period) and towards the ocean was 5.8 m^3/m (=2.4 m^3/m in the NE-wind period +3.4 m^3/m in the SW-wind period). This implied an accumulated potential sediment export off the atoll rim for about 14 m^3/m (volume per unit width) within the 8 months, equivalent to a deflation reef height of 28 mm by dividing the bedload transport flux 14 m^3/m with the cross-reef width (estimating as 500 m). In addition, a larger potential transport flux would be estimated from the enhanced shear velocities due to bedload momentum and ripples (u_{*cwb} and u_{*cwe}), assuming sufficient sediment supply for transport (Figure 6a, 7a and 11c), in comparison to the accumulated 14 m^3/m sediment flux and 28 mm reef elevation change in the 8 months as calculated with the skin-friction shear velocity u_{*cws} (Eq. 14, Figure 10). Yet, the potential reef elevation change of 28 mm in 8 months due to physical transport are of a paramount magnitude with the maximum measured fossil reef accretion and individual coral colony growth rates, i.e. 1-20 mm per year [*Montaggioni*, 2005].

6. Conclusion

Based upon an 8-month mooring hydrodynamic observation and tidal-cycle observations at the deep reef flats of four atolls in the Nansha Islands (SCS), respectively, the deep reef flats are modulated by nonbreaking waves with significant seasonal variability under the control of East Asia Monsoon, along with a relatively stable moderate-to-weak tidal current. As the leeward side relative to the NE monsoon, the deep reef flat was less influenced by the waves from February to May than the summer SW monsoon which caused a prolonged exposure to the strong wave energy (mean H_s of 1.3 m and u_{br} of 0.22 m/s) at the SW deep reef flat from June to September. Consequently, shear velocities over 0.03 m/s were exerted across the deep flat with large skin-friction in the SW-wind period. Ripples were formed during sea-swell events, being present for the entire observation period with some breakoff but not totally removed in the large sea-swell events. Such large shear velocities are capable of abrading coral skeletons into fragments, entraining plenty of reef sediment for transport, as revealed by the amounts of a potential rim height deflation on the order of 28 mm (ca. 60% towards the lagoon). In spite of the lack of strong wave-driven currents and the observation that both the near-bed Stokes drift and wave streaming could be almost neglected compared to the orbital velocity and mean current, the intense oscillatory motions of the nonbreaking waves in combination with a moderate current condition can make a great contribution to the development and/or preservation of the >10m deep reef flats.

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Data Availability Statement

Datasets for this research are available on the website https://figshare.com/s/80e56a04149db78d3aa5.

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