# The Response of the Wave-driven Circulation at Ningaloo Reef, Western Australia, to a Rise in Mean Sea Level

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**Abstract**
Ningaloo Reef extends some 280 km along the western coast of Australia, and consists of a barrier reef ~1-6 km offshore with occasional gaps, backed by a shallow lagoon. The reef morphology thus has some similarities to submerged breakwaters, which largely attenuate wave energy by wave breaking over the reef flat. This wave breaking generates radiation stress gradients that produce setup and wave-driven mean currents across Ningaloo Reef. A section of reef at Sandy Bay was chosen as the focus of an intense 6-week field experiment and numerical modelling and wave modelling of the region was conducted using SWAN coupled to the 3D circulation model ROMS. The circulation model was forced by radiation stresses provided by SWAN, and was configured with a 50 m grid resolution that incorporated high-resolution hyperspectral bathymetry. The response of the reef currents to potential forcing mechanisms (wind stress, wave height and tidal level) was investigated with the field data and the modelling, which revealed the dominant role that wave breaking plays in driving the mean circulation and flushing of this reef system. The physics of nearshore processes such as wave breaking, wave setup and mean flow across the reef were investigated in detail by examining the various momentum balances established in the system. The magnitude of the terms in this balance were sensitive to changes in mean sea level, e.g. the wave forces decreased as the water depth increased (and hence wave breaking dissipation was reduced). This led to changes in the intensity of the circulation of the reef-lagoon system, thus highlighting the sensitivity of waves and currents over reefs in response to a potential rise in mean sea level.

*Keywords: nearshore circulation, mean sea level rise*

## 1. Introduction

Coral reefs morphologically function as protective barriers to many of the world's tropical coastlines, by buffering these coasts from offshore waves, extreme storm events (e.g. cyclones) and tsunamis [1]. They also contain much of the world's marine biodiversity, and are the source of many socio-economic benefits [2].

The hydrodynamics of coral reef systems have been increasingly investigated over the past decade, but these systems are still relatively poorly studied relative to other nearshore environments such as beaches. The circulation over coral reefs can be driven by a number of forcing mechanisms, including wave breaking, tides, winds and buoyancy effects [see review by 3]. With most Indo-pacific coral reef systems exposed to waves to some degree, many (or most) reef field studies have found the circulation to be dominantly driven by the effects of wave breaking [e.g., 4, 5-7].

Wave-driven flows on reefs are forced by the same mechanisms that occur in all nearshore environments. That is, wave dissipation (primarily due to wave breaking) in shallow water generates radiation stress gradients that impose forces on the water column [8]. However, the particular response to these wave forces can differ widely among nearshore systems as a result of differences in nearshore morphology [e.g., 9].

There is general agreement that two broad categories of stress are involved in coral reef decline or 'coral reef crisis': local scale impacts and global- scale climatic changes induced by production of greenhouse gases [2]. Local impacts on coral reefs stem from natural phenomena, such as storms, and from human populations in coastal areas, which are large and growing. The features of climate change affecting coral reefs are very broad. Whilst high sea-surface temperatures (coral bleaching) and ocean acidification have received most of the attention regarding the impacts of climate change on coral reefs, the hydrodynamic impact to coral reefs from predicted future rising sea level has only recently begun to be investigated in detail [10].

The rise in mean sea level which is the focus of this study is not only a threat to submerged reefs, but also to the coastlines which are currently protected by these natural barriers from destructive waves [e.g. Bruun rule in 11]. Most climate projections suggest that sea level may rise on the order of 0.5–1.0 m by 2100 [12] and it is not clear, what the hydrodynamics and beach response will be to an increase in mean sea-level rise. A number of recent studies pointed out that not only is the global sea level rising, but the rate of rise is increasing in response to global climate change, i.e. there is an acceleration of the global mean sea level rise [13]. The present study was undertaken to examine the effect of different mean sea level rise scenarios on a tropical fringing reef system in Western Australia. In particular the response of the hydrodynamics of the reef/lagoon system, such as wave breaking, wave setup and mean flow over the reef, and the wave height incident on the coastline in the lee of reef was investigated using a fully validated numerical model.

## 2. Site Description

Ningaloo Reef lies on the west coast of Australia, near the NW Cape, between 21° and 24° S latitude (Figure 1). Ningaloo is the longest fringing coral reef system in Australia (and one of the largest in the world), extending nearly 300 km along the coast. Its morphology consists of a shallow ~1-2 m depth barrier reef located ~1-6 km offshore, which is backed by a deeper sedimentary lagoon. The reefs are broken periodically by gaps (channels) in the reef, which have been estimated to occupy roughly 15% of the entire length of the reef tract [14].

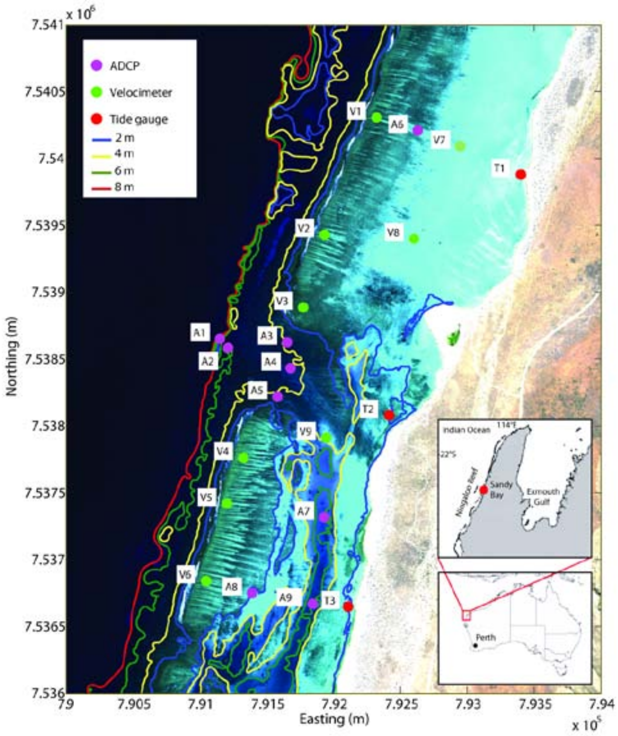


Figure 1 Map of the study area at Sandy Bay in Ningaloo Marine Park, located in the northwest of Australia (coordinates are based on UTM zone 49S). Isobaths between 2 and 8 m are superimposed to highlight the key features of the reef morphology. The locations of the moored instruments during the field experiment are also shown. The white bands visible along the reef crest show wave breaking, i.e., highlighting the narrow surf zone.

The present study focuses on a section of Ningaloo Reef near Sandy Bay, which was the focus of a major hydrodynamic field study detailed in Taebi et al. [7]. This site had been specifically chosen because it has a fairly typical morphology of the broader Ningaloo reef tract; as inferred from inspection of aerial photography; [7], i.e. in terms of both its reef and lagoon geometry. At Sandy Bay, the fore-reef slope (~1:30) rises to a shallow reef flat (mean depth ~1-2 m) with dense coral coverage [15]. Waves incident to the reef break on the leading edge of the reef flat (i.e. at the reef crest) located ~1 km from shore. The reef flat (~500 m wide) is separated from shore by a deeper lagoon, comprised mostly of sand and coral rubble. The northern lagoon is relatively shallow (mean depth ~2-3 m), whereas the southern lagoon is incised by a deep lagoon channel (mean depth ~8 m). The reef is broken at the centre of the study site by a relatively deep channel (mean depth ~5 m).

## 3. Methods

### 3.1. Numerical Modelling

The numerical modelling was based on recent nearshore developments (version 3) within the Regional Ocean Modeling System (ROMS). In particular, coupled wave-circulation modelling was conducted using the wave-current interaction routines implemented into the source code by [16]. The transformation of random, short-crested surface waves was simulated using the SWAN wave model [17]. SWAN solves the wave action balance with energy sources (e.g., wind-wave growth) and sinks (e.g., dissipation by wave breaking and bottom friction). The SWAN model is iteratively coupled to the circulation model ROMS [18-20], which solves the three-dimensional incompressible Reynolds averaged Navier-Stokes equations for conservation of mass and momentum on a horizontal orthogonal curvilinear grid with a stretched vertical s-coordinate system. Wave forces responsible for driving mean currents in ROMS are provided by the passing of radiation stress gradients (due to wave breaking) derived from SWAN, based on the wave-current interaction theory by Mellor [21, 22]. Other wave-current interaction processes are also incorporated in ROMS, such as the wave-enhancement to shear stresses and turbulent mixing. With its two-way coupling, ROMS then provides SWAN with water elevations and current fields (i.e. to account for possible current-induced wave refraction).

The model was configured with a 50 m grid resolution (interpolated from high-resolution hyper-spectral imagery based bathymetry with 3.5 m horizontal resolution) and forced by tides derived from a global tidal model and the observed wave and wind forcing. Both wave and circulation models were validated using an extensive data set collected over a 6-week period in 2006. The contribution of each forcing mechanism (wave, tides and wind) to the overall circulation was investigated by switching different forcing mechanisms on and off in the calibrated model. The results from the numerical model with complete forcing (waves, tides and winds) revealed that the dominant forcing of the currents in the reef system was driven by wave breaking with the effect of winds being negligible [23]. The model runs used to quantify the sensitivity of the results to a mean sea level rise (MSLR) were forced using the mean tidal range and a historical mean significant wave height of $H_S$=1 m and peak period $T_p$=13 s. The reef bathymetry was kept constant and several mean sea level rise scenarios were specified to examine the hydrodynamic changes (MSLR=0, 0.25, 0.5, 0.75, 1, 2, 3 m). It is recognised that MSL rise beyond 1 m is unlikely in the next 90 years, but the 2 and 3 MSL are included to examine extreme conditions.

### 3.2. Momentum Balance

To investigate the detailed dynamics controlling wave-driven flows at Ningaloo, the momentum balances established in the reef and lagoon were examined by comparing the magnitude of different terms in the nearshore momentum equation. The model was forced with steady wave forcing (the dominant forcing mechanism observed) and mean tides, with winds turned off due to their negligible influence [7]. The simulations were forced with the different MSLR scenarios described above. Thus, with steady wave forcing applied, each simulation was run for one day to achieve a quasi-steady state (this generally occurred after ~6 hours).

For these simulations, the model output was used to investigate spatial variability in the momentum balances established across the system. To achieve this, the results were decomposed based on the terms in the cross-shore (x) and along-shore (y) momentum equations, respectively [24, 25]. A detailed overview of Eq.1 and the extraction of the momentum terms is given in Taebi et al. [26]. This paper focuses on the response of the cross-shore momentum terms, i.e.

$$\underbrace{U\frac{\partial u}{\partial x}+V\frac{\partial u}{\partial y}}_{\text{advection}}+\underbrace{g\frac{\partial \bar{\eta}}{\partial x}}_{\text{pressure gradient}}+\underbrace{\frac{1}{\rho(\bar{\eta}+h)}\frac{\partial S_{xx}}{\partial x}+\frac{1}{\rho(\bar{\eta}+h)}\frac{\partial S_{xy}}{\partial y}}_{\text{radiation stress gradients}}+\underbrace{\frac{\bar{\tau}_x}{\rho(\bar{\eta}+h)}}_{\text{shear stress}}=0 \quad (1)$$

### 3.3. Wave Transmission

The transmission of incident waves across the reef under different MSLR conditions was investigated using a wave transmission coefficient. Wave energy is either dissipated by the reef, primarily by wave breaking or bottom friction, or returned to the ocean as reflected wave energy. The higher the wave transmission coefficient, the less the wave attenuation occurs. Wave transmission was quantified using a wave transmission coefficient $K_t$,

$$K_t=\frac{H_t}{H_i} \quad (2)$$

where $H_t$ is the height of the transmitted wave on the landward side of the reef, and $H_i$ is the height of the incident wave on the seaward side of the reef (offshore).

## 4. Results

For the typical incident wave condition ($H_s$=1 m), the predicted significant wave height field shows that the waves slightly attenuate on the forereef (primarily due to bottom friction dissipation) and then rapidly decrease near the seaward edge of the reef flat due to wave breaking in the surf zone, with some wave energy penetrating into the channels (Figure 2a). The wave forces increase the mean water level (wave setup) across the reef-lagoon system (Figure 2b). Wave setup is greater by a factor of ~2 in the northern half of the domain compared to the southern half of the domain. The resulting wave forces then drive mean flows across the shallow reef flats, with water primarily returning to the ocean through three major channels in the domain (Figure 2c). The waves, breaking at an angle to the reef, also generate a narrow band of alongshore currents within the surf zone located near the seaward edge of the reef flat (Figure 2c).

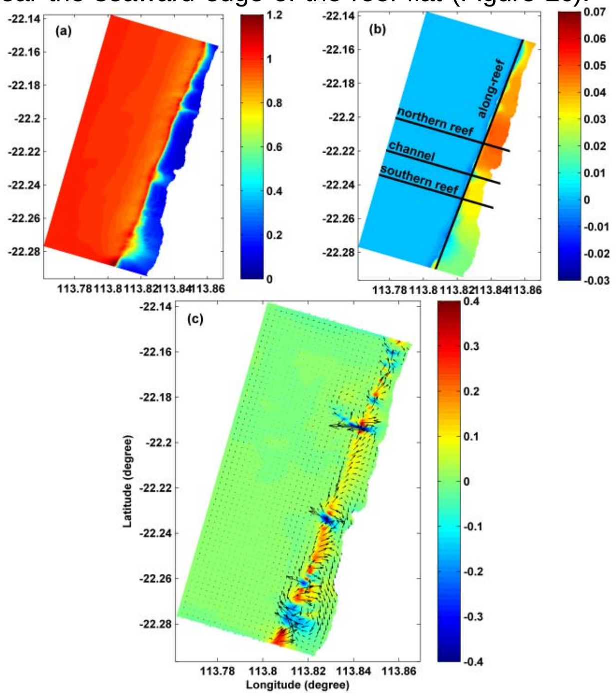


Figure 2 Spatial maps of (a) significant wave height (m), (b) wave setup (m) and (c) cross-reef depth-averaged current velocity (m $s^{-1}$) with current vectors (one out of every 5) superimposed forced by waves of $H_s$=1 m. In (b), the locations of the three cross-reef and along-reef transects used for the momentum calculations are shown.

To investigate sources of this spatial variability, the relative magnitude of the four terms in momentum equations (advection, pressure gradient, radiation stress gradients, and bottom shear stress) were quantified in the cross shore direction (Eq. 1). This analysis was conducted along three cross-reef transects (northern reef, channel, southern reef in Figure 3) and a single along-reef transect on the reef flat (Figure 4). Note that for this analysis, a coordinate system was introduced where x' represents the cross-shore distance (positive towards shore) from an origin (x'=0) chosen as the along-reef transect line. The alongshore origin (y'=0) was chosen as the location of the central Sandy Bay channel (positive towards the north).

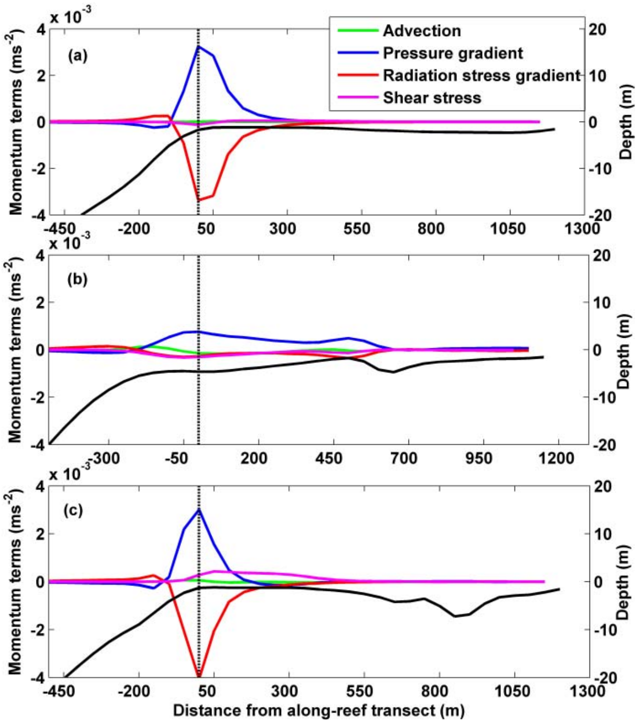


Figure 3 Cross-shore momentum terms for the cross-reef transects in Figure 2b. (a) northern reef (b) channel, and (c) southern reef.

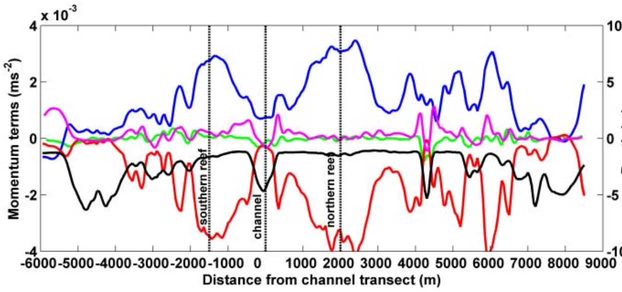


Figure 4 Cross-shore momentum terms for the along-reef transect shown in Figure 2b. Colour code is the same as Figure 3.

For the two cross-reef transects over the shallow reef ('northern reef', Figure 3a; 'southern reef', Figure 3c), the balance in the cross-shore (x) direction is between the radiation stress gradients (dominated by the $\partial S_{xx} / \partial x$ component) and a mean water level (pressure) gradient within a region extending from the forereef (x'≈ -200 m) to the back of the reef flat (x'≈ +200). It is important to emphasize that, although these radiation stress gradients are largely balanced by a pressure /setup gradient, the difference in these two large terms must strictly be non-zero to drive the wave-driven currents across this reef that are observed (Figure 2c), i.e. this small difference is balanced by the bottom stress term.

The cross-shore momentum balances of the along-reef transect oscillate in response to the presence of sections of reef broken by channels (Figure 2b). Within the longer sections of reef (i.e. centred at y'≈-1500, +2000, and +6000 m), the cross-shore momentum balances are dominated by the pressure gradient and radiation stress gradients terms. In areas within a channel (i.e. centred at y'≈ -4500, 0, +4500, and +8000 m), there is still a positive cross-shore pressure gradient (implying the mean water level is higher towards shore), yet the radiation stress gradients term becomes much smaller due to the reduced wave dissipation within the deeper channels. In the channel, the cross-shore pressure gradient is also balanced by the bottom shear stress term due to flow out the channel and the acceleration term.

The forcing parameter (wave height) and hydrodynamic response variables (wave setup and current velocity) were plotted for an extreme rise in mean sea level (3 m) in figure 5. Wave height and wave setup over reef flat for this scenario are respectively larger and smaller than the same parameters in Figure 2 (a and b). Although a similar pattern of cross-reef flow on the reef flat and offshore directed flow in the channel is maintained, the surf zone has moved toward the beach resulting in increased current speed in the lagoon.

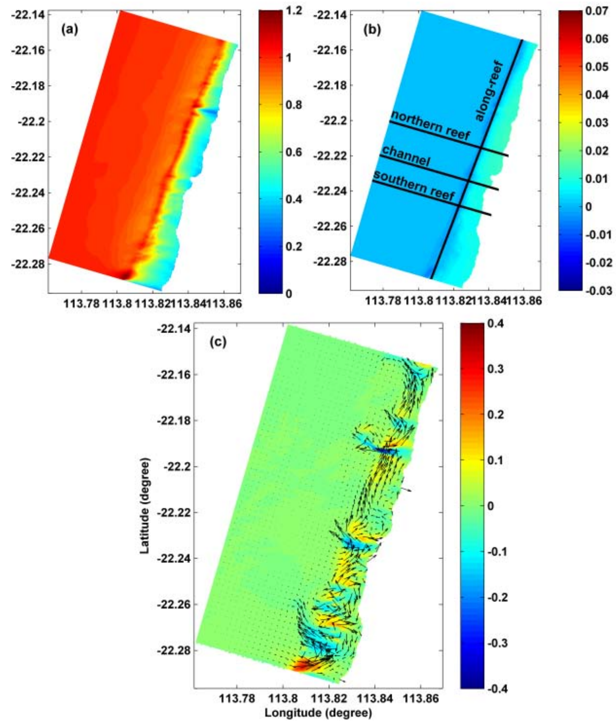


Figure 5 Spatial maps of (a) significant wave height (m), (b) wave setup (m) and (c) cross-reef depth-averaged current velocity (m s$^{-1}$) with current vectors (one out of every 5) superimposed, forced by waves of $H_S$=1 m for 3 m rise in mean sea level. In (b), the locations of the three cross-reef and along-reef transects used for the momentum calculations are shown.

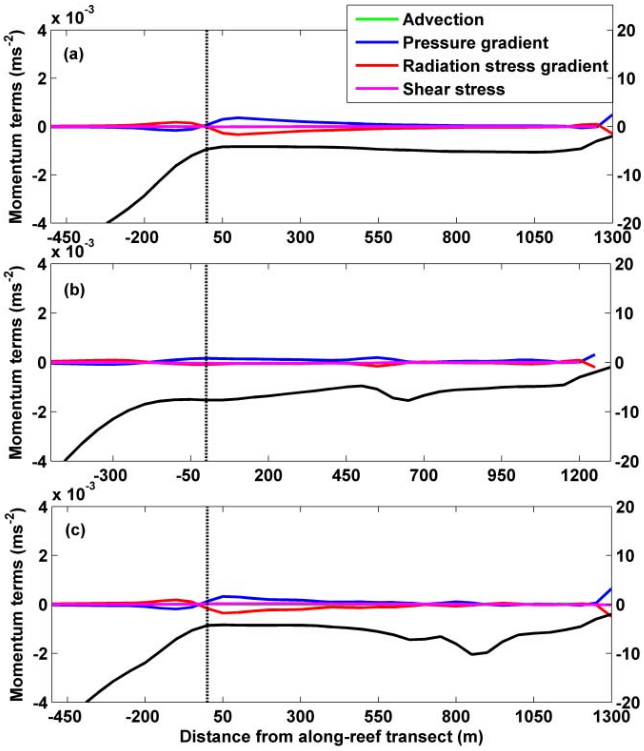


Figure 6 Cross-shore momentum terms for the cross-reef transects in Figure 5b with 3 m rise in mean sea level. (a) northern reef (b) channel, and (c) southern reef.

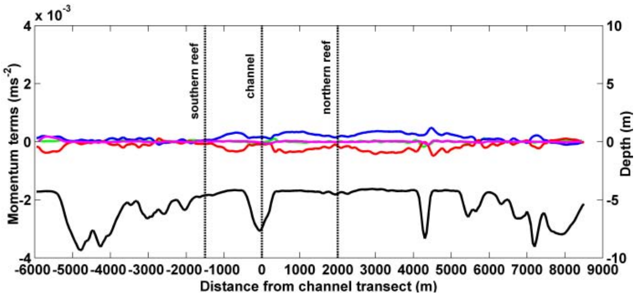


Figure 7 Cross-shore momentum terms for the along-reef transect shown in Figure 5b with 3 m rise in mean sea level. Colour code is the same as Figure 6.

While the dominant terms in the cross-shore momentum equation (pressure gradient and radiation stress gradients) decreased significantly on reef flat in both cross-reef and along-reef transects by a rise mean sea level, they increased on the beach in Figure 6 (x≈ 1300 m) where wave dissipation now mostly occurs.

## 5. Discussion

Wave transmission coefficients were calculated for a wide range of MSLRs (Figure 8). Whilst wave transmission by the reef was only 10% for present mean sea level, it increased with a near linear relationship up to 60% for a 3 m rise in mean sea level. Based on an expected 1 m rise in mean sea level by the end of the century (2100), the wave transmission coefficient was 30%, or almost 3 times greater than its present value. Such an increase in wave transmission coefficient means an even higher increase in wave power on the beach (Figure 8).

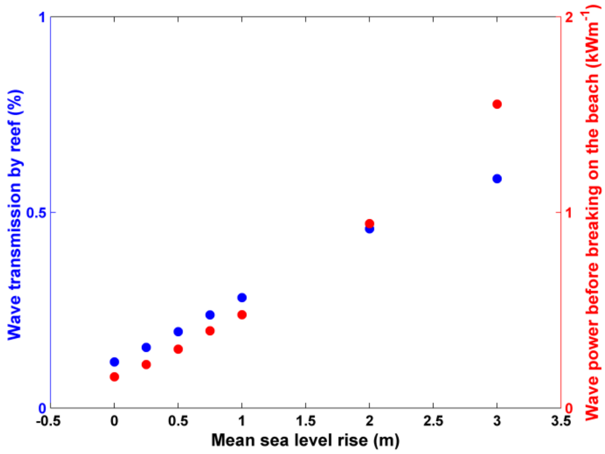


Figure 8 Wave transmission coefficient and wave power response to increases in mean sea level.

## 6. Conclusion

Hydrodynamic parameters and the momentum balances established in Sandy Bay, Ningaloo Reef, were investigated for a range of rises in mean sea level. Although the dominant momentum terms (pressure gradient and radiation stress gradients) dropped drastically by a MSLR over the reef flat, they increased slightly on the beach. Therefore, smaller wave breaking over reef flat allowed larger wave heights inside the lagoon. The study revealed the shift in the surf zone from offshore to nearshore resulted in a higher wave transmission coefficient by the reef and larger wave power in the lagoon. This will have an influence on the stability of the beach system through both a direct increase in mean sea level and an indirect effect of higher incident wave heights.

## 7. Acknowledgements

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