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RELATIONSHIPS BETWEEN OFFSHORE WAVES AND BEACH PROFILE CHANGES IN THE FORESHORE AND INNER TRANSITION ZONE

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Abstract

The relationships between the offshore wave energy flux and the beach profile changes in the foreshore and the inner transition zone, located seaward of the foreshore, on the Hasaki coast in Japan were investigated using 28-year datasets of offshore waves and beach profiles. The energy flux displayed two peaks at 6 and 12 months and had strong negative correlations with the beach profile changes in the foreshore and the shoreward part of the inner transition zone. Both the areas accreted when the energy flux was small and eroded when the energy flux was large. However, the foreshore eroded more from August to November than from February to April, whereas the shoreward part of the inner transition zone eroded almost equally during the two periods. In long-period variations, although the amplitude of the energy flux was relatively small, the inner transition zone eroded and accreted when the energy flux increased and decreased, respectively.

Key words: nearshore zone, surf zone, swash zone, morphodynamics, sandy beach, shoreline

1. Introduction

The nearshore zone of a sandy beach including the foreshore dissipates wave energy, offers attractive amenity to visitors and nurtures rich ecosystems, which makes the beach quite valuable from the viewpoints of disaster prevention, recreation, and environment. However, it is vulnerable to both sea level rise and the increase in tropical cyclone intensity caused by global warming. Understanding the mechanism driving morphological changes in the nearshore zone is crucial for the conservation of valuable sandy beaches.

The foreshore tends to erode under severe wave conditions and accrete under mild wave conditions. The morphological change in the foreshore was conceptually modelled with that in the bar-trough zone by many researchers such as Wright and Short (1984), Wright et al. (1987), Sunamura (1988), Lippmann and Holman (1990), Masselink and Short (1993), Short and Aagaard (1993), Ranasinghe et al. (2004), Castelle et al. (2007), Ortega-Sanchez et al. (2008), Senechal et al. (2009), Price and Ruessink (2011) and Scott et al. (2011).

Based on a 28-year beach profile dataset obtained on the Hasaki coast in Japan, Kuriyama and Yanagishima (2016) showed that the inner and outer transition zones are located between the foreshore and the bar-trough zone and had different morphological properties from the adjacent zones. However, the relationships between the beach profile changes in the transition zones and offshore waves, one of the influential driving forces of morphological change, were not well examined. In this study, we investigated the relationship in the inner transition zone as well as that in the foreshore using beach profile and offshore wave data at Hasaki.

2. Study Site

The Hasaki coast is located in eastern Japan facing the Pacific Ocean (Figure 1). At Hasaki, along the 427-m-long field observation pier of Hazaki Oceanographical Research Station (HORS), the beach profiles

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were measured at 5-m intervals using a rope with graduated depth-marking and a 5-kg lead from the pier and a level and a staff landward of the pier every workday from March 12, 1986 to March 31, 2011 and

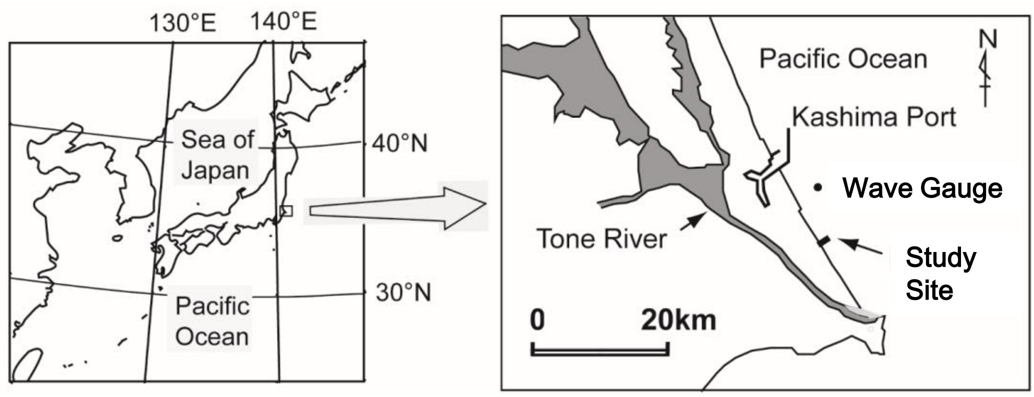

Figure 1. Study site.

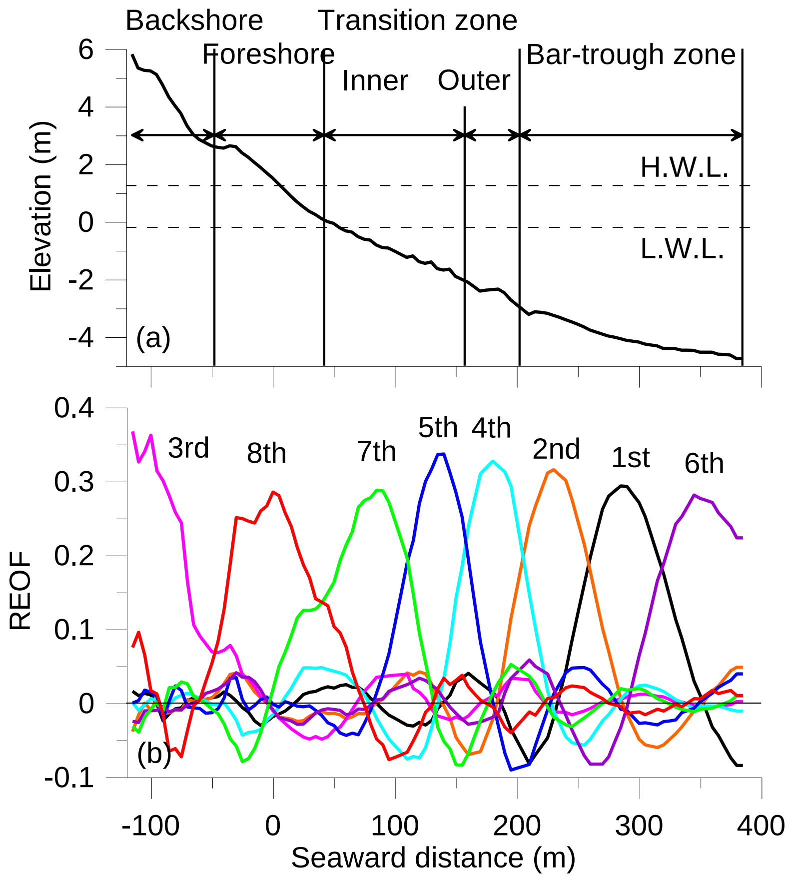

Figure 2. Mean beach profile (black solid line) and the locations of the zones detected by Rotated Empirical Orthogonal Function (REOF) analysis (a) and eight REOFs (b).

once a week, mostly on Mondays, from April 5, 2011 onwards.

The mean beach slope was approximately 1/25 at $z = 0$ m (z is the elevation) and 1/120 at the tip of the pier (Figure 2). The elevation is based on the datum level at Hasaki (Tokyo Peil –0.69 m) and defined to be positive in the upward direction. The median sediment diameter was 0.2 mm and remained almost uniform along the profile. However, it occasionally increased to 1.0 mm in troughs following severe storms (Katoh and Yanagishima, 1995). The high, mean, and low water levels were 1.25 m, 0.65 m and –0.20 m, respectively.

Alongshore uniformity of bathymetry near the pier was investigated by Kuriyama (2002). In addition to beach profile measurements taken along the pier, the bathymetry near the pier was surveyed once or twice a year in an area 600 m wide in the alongshore direction and about 700 m long in the cross-shore direction. Kuriyama (2002) applied Empirical Orthogonal Function (EOF) analysis to 17 bathymetric maps around the pier obtained from 1986 to 1998 and showed that the bathymetry adjacent to the pier was almost uniform alongshore and the influence of the pilings on the bathymetry appeared to be minimal.

Offshore waves were measured at a water depth of about 24 m with an ultrasonic wave gauge for 20 minutes every 2 hours (see location in Figure 1). The mean offshore significant wave height and period were 1.34 m and 8.00 s, respectively (Banno and Kuriyama, 2012). Waves were large from January to April owing to extratropical cyclones and from September to October owing to typhoons (tropical cyclones) (Kuriyama et al., 2012).

3. Data Description

Kuriyama and Yanagishima (2016) analyzed beach profile data obtained once a week from March 17, 1986 to November 3, 2014 using Rotated Empirical Orthogonal Function (REOF) analysis. REOF analysis, which is widely used in climate research, is a method in which Empirical Orthogonal Functions (EOFs) are transformed to a non-orthogonal linear basis (e.g., von Stork and Zwiers, 1999; Hannachi et al., 2007). REOF analysis is considered to be useful to detect localized behaviors, whereas EOF analysis tends to detect behaviors spanning the whole domain, which are sometimes difficult to interpret.

REOF analysis using the first eight EOFs at Hasaki showed that the beach profile changes in the backshore (x = –110 to –50 m, x is the seaward distance) and the foreshore (x = –45 to 40 m) were represented by the third and eighth modes, respectively (Figure 2). The sixth, first and second modes represented the profile changes in the bar-trough zone (x = 205 to 385 m). The area between the foreshore and the bar-trough zone had different morphological properties from the adjacent zones. Furthermore, the area was divided into shoreward and seaward areas, which were defined as the inner (represented by the seventh and fifth modes, x = 45 to 155 m) and outer (represented by the fourth mode, x = 160 to 200 m) transition zones, respectively.

In this study, to examine the relationships between offshore waves and the beach profile changes in the foreshore and the inner transition zone, we used temporal components (Rotated Principal Components, RPCs) of the fifth, seventh and eighth modes (Figure 3). Missing offshore wave data were corrected using values measured off Hitachinaka Port and Onahama Port 65 km and 120 km north of the study site, respectively.

4. Methods

First, cross-spectral analysis was applied to the time series of the offshore wave energy flux E_f, estimated by Equation (1), the fifth, seventh and eighth RPCs and the change rates of the three RPCs.

$$E_f = \frac{\rho g}{16} C_g H^2 \tag{1}$$

where ρ is the density of seawater, g is the gravitational acceleration, H_s is the offshore significant wave height and C_g is the group velocity corresponding to the offshore significant wave period.

Because the offshore waves and the beach profiles were measured every 2 hours and 1 week, respectively, the E_f values were averaged during a 1-week period between the times when a beach profile and the previous profile were obtained. In cross-spectral analysis, the data were tapered using the Boxcar window. The spectral densities were smoothed three times using a triangle filter and the degree of freedom was 9.

Second, to investigate the relationships between E_f and the three RPCs and those between E_f and their change rates in long and short periods, the components whose frequencies f were lower and higher than 0.0022 (cycle/day) (T = 455 days; T is the period) were reconstructed as in Kuriyama and Yanagishima (2016). The E_f components whose frequencies were lower than 0.000209 (cycle/day) (T = 4780 days) were also reconstructed. For short-period relationships, the monthly averaged values of the reconstructed short-period components were estimated.

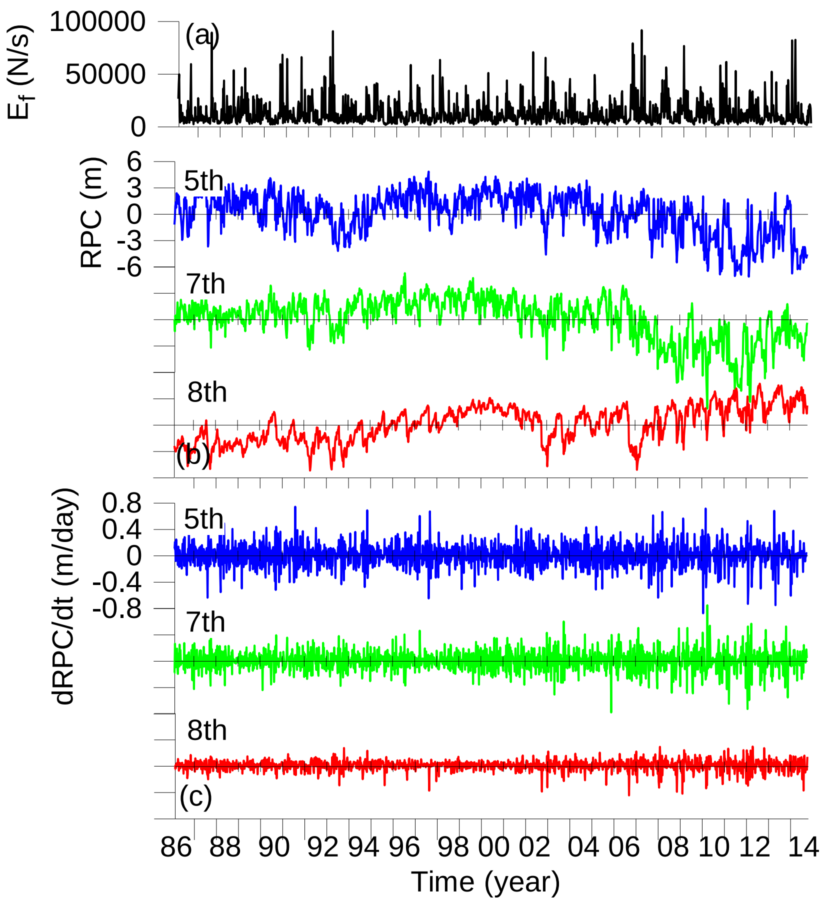

Figure 3. Time series of E_f (a), the fifth, seventh and eighth RPCs (b) and their change rates (c).

5. Results and Discussion

The E_f value showed two peaks at 6 and 12 months and the spectral densities at long periods (low frequencies) were relatively small (Figure 4a). However, the three RPCs had large spectral densities at long periods. At $T > 4780$ days ($f < 0.000209$ cycle/day), the fifth and seventh RPCs had high coherence with E_f, whereas the coherence between the eighth RPC and E_f was small (Figure 4b). The fifth and seventh RPCs were out of phase with E_f (Figure 4c).

Contrary to the RPCs, their change rates had large spectral densities at short periods (Figures 5a). The change rates of the seventh and eighth RPCs had strong correlations with E_f at 6 and 12 months, while that of the fifth RPC did not (Figures 5b).

The time series of the long-period components of E_f, the three RPCs and their change rates, shown in Figure 6, revealed that although the long-period components of E_f were relatively small in amplitude, they have weak negative correlations with the long-period components of the fifth and seventh RPCs as indicated by the results of cross-spectral analysis. However, E_f and the eighth RPC were not correlated.

The mean beach profiles in 1986, 1993, 2000, 2007 and 2014 (Figure 7) showed that overall the profiles in 1986 and 1993 were similar, while the inner transition zone slightly eroded and the foreshore accreted from 1986 to 1993. From 1993 to 2000, when E_f was relatively small and decreased in components longer than T = 4780 days (longer-period components), both the foreshore and the inner transition zone significantly accreted. However, from 2000 to 2007, when E_f increased and became large in the longer-period components, both eroded and returned to profiles similar to those in 1986 and 1993. Then, from 2007 to 2014, when E_f was still large but decreased in the longer-period components, the inner transition zone eroded more, but the foreshore accreted and almost reached the profile in 2000.

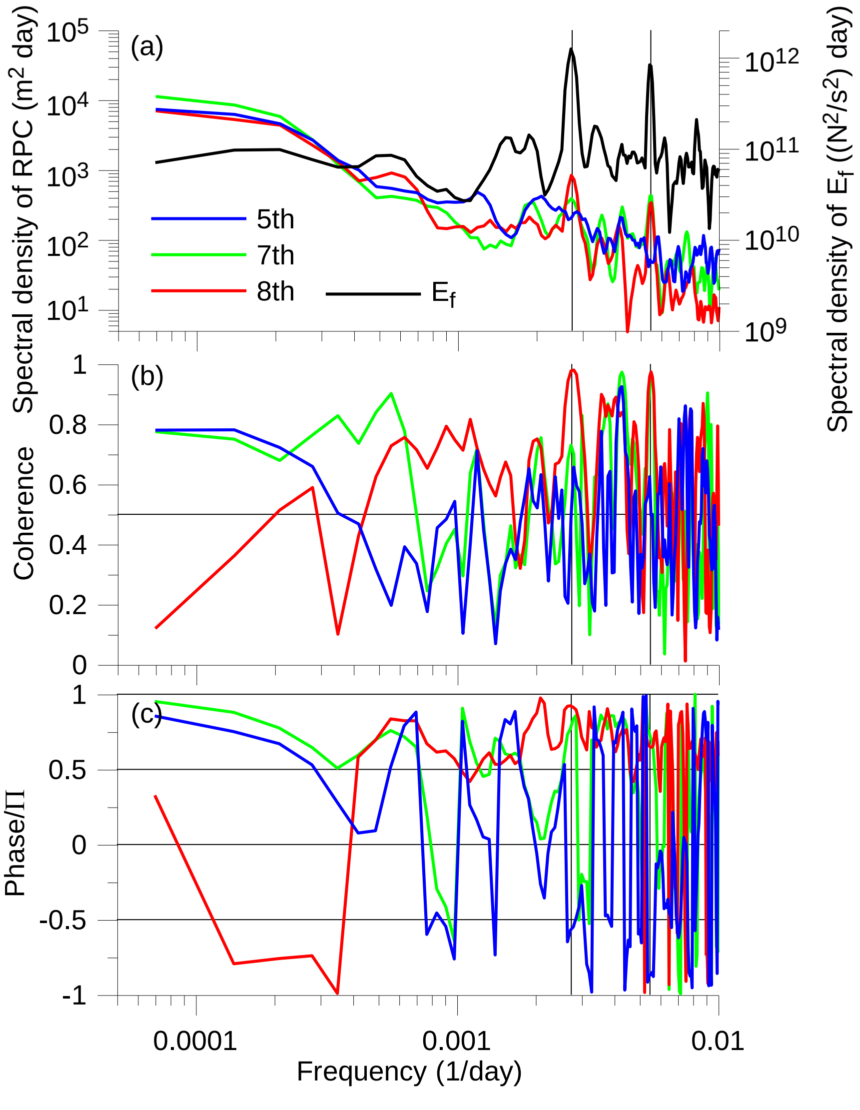

Figure 4. Spectral density (a), coherence (b) and phase (c) of E_f and the fifth, seventh and eighth RPCs. Coherence and phase are relevant to E_f. The thin vertical lines show T = 365 and 183 days (f = 0.00274 and 0.00546 Hz).

From 1986 to 2007, the foreshore and the inner transition zone changed in a similar way. However, from 2007 to 2014, they changed in the opposite direction. This is the reason why in long-period components, E_f had a weak correlation with the beach profiles in the inner transition zone, but not with those in the foreshore. The causes of the beach profile changes from 2007 to 2014 in the foreshore and the inner transition zone are not clear yet. As such, further investigation is required.

The monthly averaged values of the short-period components of E_f had two peaks and were large from January to March and from September to October (Figure 8). The change rates of the seventh and eighth

RPCs had strong negative correlations with E_f (Figures 5b, 5c and 8). The foreshore and the shoreward part of the inner transition zone accreted when E_f was small, from April to August, and eroded when E_f was large, from February to April and from August to November (Figure 9). However, the profile changes in the foreshore and the inner transition zone were slightly different. The foreshore eroded more from August to November than from February to April, whereas the shoreward part of the inner transition zone eroded almost equally during the two periods. This difference was due to the profile change from February to April. Although E_f was large and the shoreward part of the inner transition zone eroded, the profile change

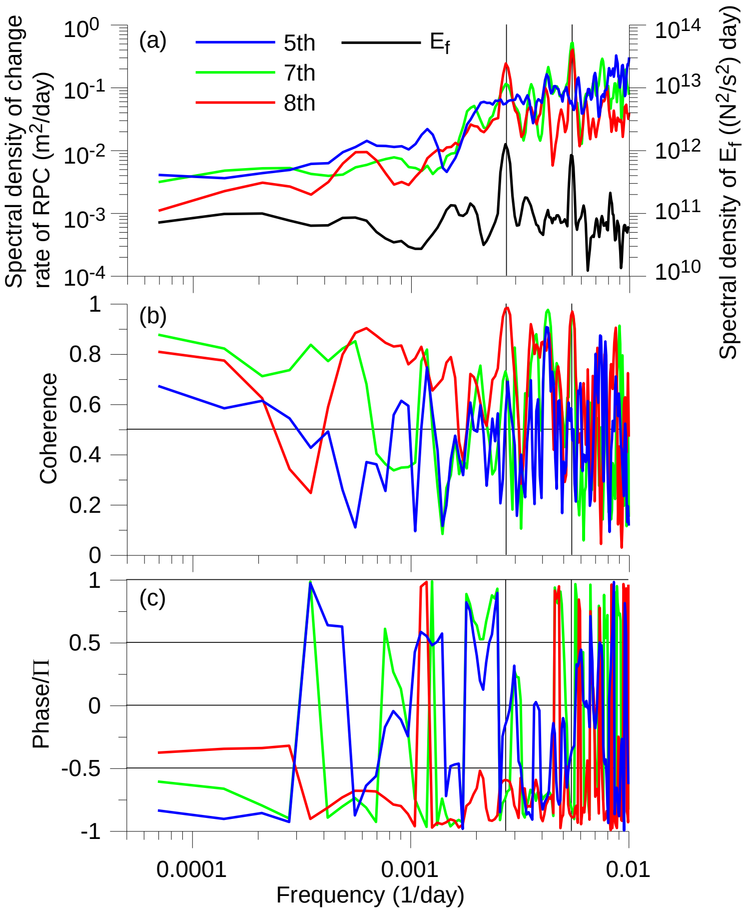

Figure 5. Spectral density (a), coherence (b) and phase (c) of E_f and the change rates of the fifth, seventh and eighth RPCs. Coherence and phase are relevant to E_f. The thin vertical lines show T = 365 and 183 days (f = 0.00274 and 0.00546 Hz).

in the foreshore was small. This might be partly because a negative morphological feedback system, in which the beach is more eroded when it has been accreted than when it has been eroded, would work more strongly in the foreshore than in the shoreward part of the inner transition zone. In other words, in November, which is the end of the other period with large E_f, the foreshore may have reached its equilibrium profile under severe wave conditions, but the shoreward part of the inner transition zone may not.

Compared with the short-period variations observed in the foreshore and the shoreward part of the inner transition zone, that of the seaward part of the inner transition zone, represented by the fifth RPC, was small.

Shepard (1950) and Winant et al. (1975) reported that the foreshore erosion induces the inner bar formation under severe wave conditions and the foreshore recovery is accompanied by the disappearance of the inner bar under mild wave conditions. However, the "seesaw type" beach profile change was not observed in the short-period variations (Figure 9). The foreshore erosion and formation may have been caused by the cross-shore sediment transport to and from a relatively wide area seaward of the foreshore.

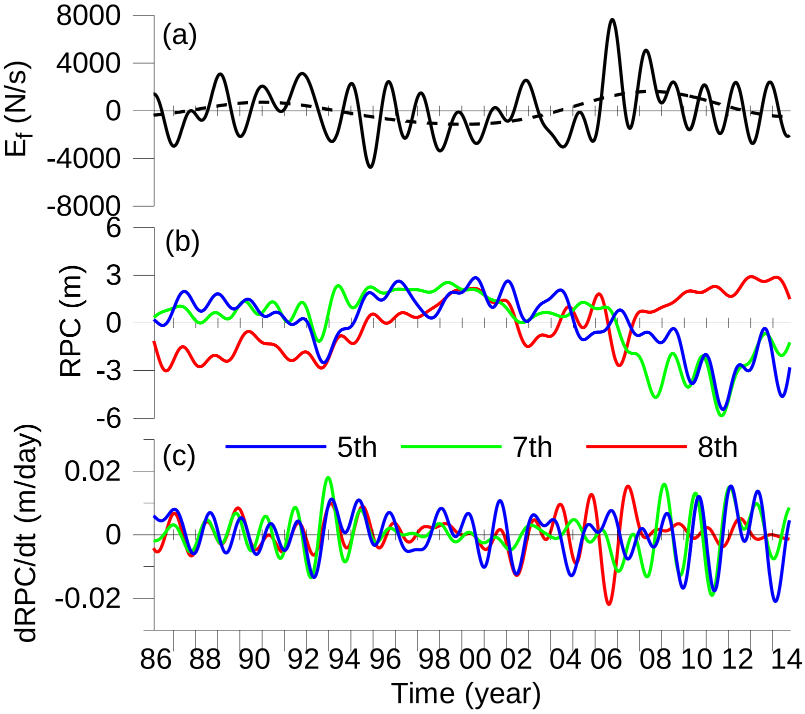

Figure 6. Time series of long-period components of E_f (a), the fifth, seventh and eighth RPCs (b) and their change rates (c). The black solid and broken lines in panel (a) show the time series of long-period and longer-period (T > 4780 days) components of E_f.

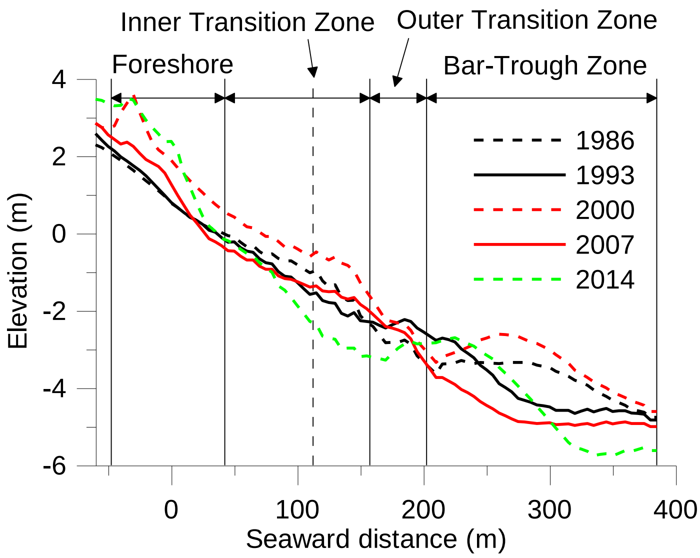

Figure 7. Mean beach profiles in 1986, 1993, 2000, 2007 and 2014. The vertical black broken line shows the boundary between the areas represented by the fifth and seventh modes.

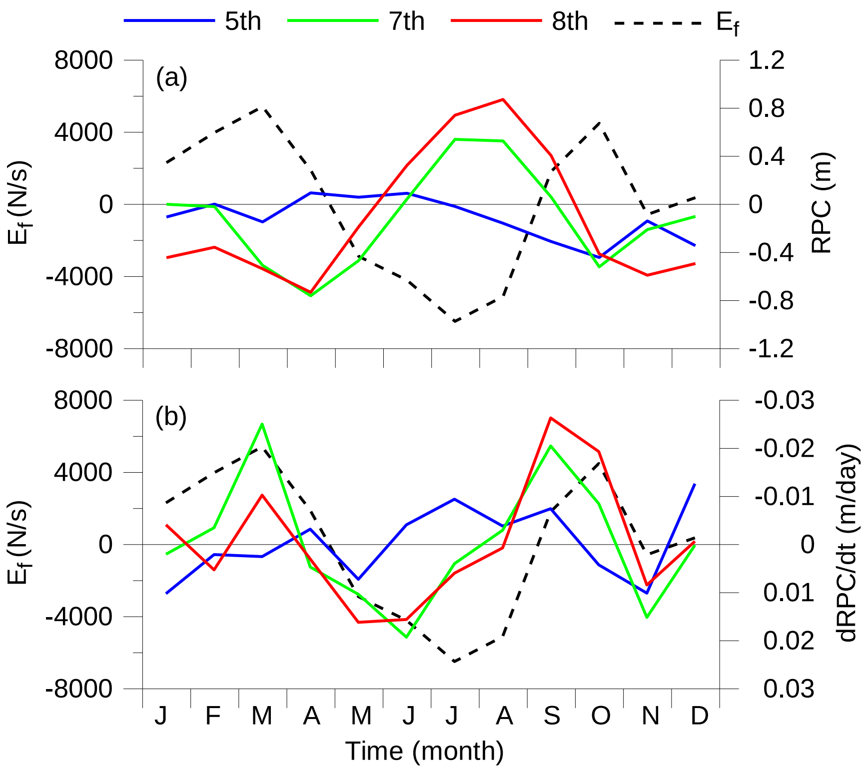

Figure 8. Monthly averaged values of the short-period components of E_f and the fifth, seventh and eighth RPCs (a) and those of E_f and their change rates (b). The axis for the change rates in panel (b) is reverse.

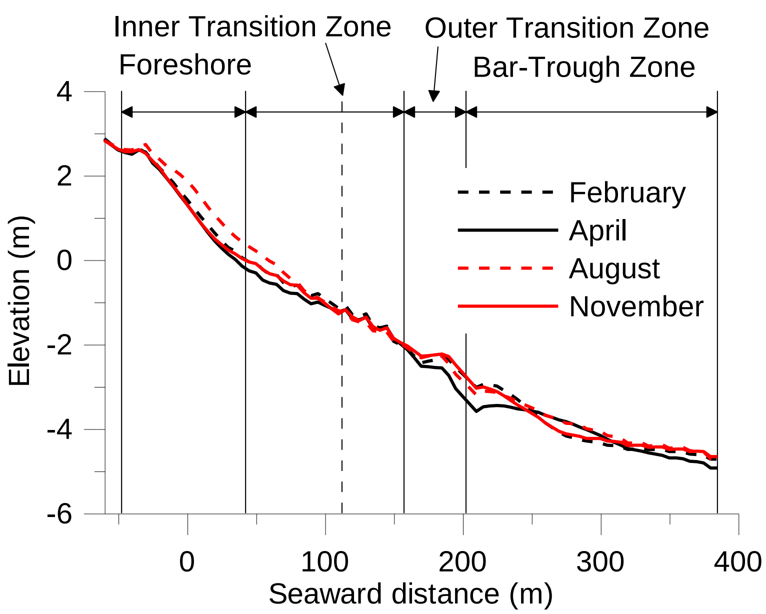

Figure 9. Mean beach profiles in February, April, August and November. The vertical black broken line shows the boundary between the areas represented by the fifth and seventh modes.

6. Conclusions

We investigated the relationships between the offshore wave energy flux and the beach profile changes in the foreshore and the inner transition zone on the Hasaki coast in Japan. The temporal components (Rotated Principal Components, RPCs) of the fifth, seventh and eighth modes of Rotated Empirical Orthogonal Function analysis were used as parameters representing the beach profiles. The eighth mode represents the profile changes in the foreshore, and the fifth and seventh modes represent those in the inner transition zone (Kuriyama and Yanagishima, 2016).

The E_f value had two peaks at 6 and 12 months and had strong negative correlations with the change rates of the seventh and eighth RPCs. The foreshore and the shoreward part of the inner transition zone accreted when E_f was small, from April to August, while they eroded when E_f was large, from February to April and from August to November (Figure 9). However, the profile changes in the foreshore and the inner transition zone were slightly different. The foreshore eroded more from August to November than from February to April, whereas the shoreward part of the inner transition zone eroded almost equally during the two periods. This might be partly because a negative morphological feedback system would work more strongly in the foreshore than in the shoreward part of the inner transition zone.

In the variations whose periods were longer than 455 days, although the amplitude of E_f was relatively small, E_f had weak negative correlations with the seventh and fifth RPCs but not with the eighth RPC. The foreshore and the inner transition zone significantly accreted during the period from 1993 to 2000, when E_f was relatively small and decreased, and eroded during the period from 2000 to 2007, when E_f increased and became large. However, during the period from 2007 to 2014, when E_f was still large but decreased, the inner transition zone eroded more, but the foreshore accreted and almost reached the mean profile in 2000. As a result, there was a correlation between E_f and the beach profiles in the inner transition zone, but not between E_f and the profiles in the foreshore.

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