The influence of alongshore and cross-shore wave energy flux on large- and small-scale coastal erosion patterns

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Received 25 February 2010; Revised 19 November 2010; Accepted 23 November 2010

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ABSTRACT: A strong low-pressure system traveled along the Japanese main island Honshu in October 2006. High waves and storm surge attacked the Kashima Coast resulting in huge erosion over the area. Airborne laser data measured in October 2005 and November 2006 were analyzed to estimate cross-sectional changes within the subaerial zone. The results of the alongshore distribution of the changes of cross-sectional area indicate that the amount of erosion of the 38 km-long northern and 15 km-long southern parts decreased toward the south in each part and that the amount of erosion was smaller in protected areas with artificial headlands than in unprotected areas. The local alongshore variation of the erosion and accretion patterns showed wavy fluctuations of several hundreds of meters. The total amounts of the estimated eroded volume of the subaerial zone over the northern and southern parts were 620 000 m³ and 600 000 m³, respectively. The Simulating Waves Nearshore (SWAN) wave model was applied to estimate wave conditions along the coast during the storm. The computational results were verified, and then the alongshore distribution of wave energies, expressed as the alongshore and cross-shore components of the wave energy flux, was compared with the alongshore distribution of cross-sectional change. The results show that the distribution of energy flux explains the distribution of erosion well: The alongshore variability in the cross-shore energy flux is responsible for the large-scale variability in erosion, and shorter-scale variability is due to gradients in the alongshore energy fluxes, especially for the areas without coastal works. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: airborne laser survey; erosion; storm surge; SWAN; wave energy flux

Introduction

Quantification of storm-induced beach erosion and understanding of the large-scale, spatially-variable beach response to storms is vital for developing a predictive assessment of the vulnerability of our coasts. This type of information is required by coastal planners and emergency managers for locating future development sites, protecting vulnerable infrastructure, planning storm evacuation routes, and taking preventative measures to avoid continued loss of life and property.

Within the storm-impact zone, some areas may experience severe dune erosion and overwash, while adjacent areas remain virtually unaffected. Previous studies have found that shoreline response to storms is highly variable along the shore (Stockdon et al., 2002; Robertson et al., 2005; Zhang et al., 2005). Also, the shoreline change is considered a good proxy or representative of volume change when data do not include major storm events (Farris and List, 2007; Robertson et al., 2007). Ruessink and Jeuken (2002) showed that the alongshore variability in dune erosion does not necessarily reflect differences in dune height but could also reflect alongshore variability in beach width, while Wetzell et al. (2003) found that the alongshore variation in storm impacts is consistent with the variation in dune height and the storm impact scale suggested by Sallenger (2000). Observations of the large-scale response of beaches to storms have shown that significant spatial variability is superimposed upon a general mean response (Stockdon et al., 2003). A qualitative assessment of hurricane impact along Santa Rosa Island in Florida concluded that dune survival is controlled by the characteristics of the storm and dune morphology (Claudio-Sales et al., 2008). However, the authors do not explain why the island response exhibited considerable variability in the alongshore direction. Recently, the alongshore-variable coastal response to hurricanes has been examined within the framework of a storm-impact scaling model that defines four levels of coastal response based on the relative elevations of storm-induced water levels and those of the dune or berm (Stockdon et al., 2007). The results support the predictive capabilities of the storm scaling model and illustrate that the impact regimes provide a framework for explaining the alongshore-variable coastal response to hurricanes.

To accurately predict the large- and small-scale coastal responses to hurricanes and storms, an understanding of the processes responsible for these observed patterns is required. Previous studies have suggested a number of possible reasons for the alongshore-variable storm response. Some researchers have explored its relation to wave run-ups (Sallenger, 2000;
Stockdon et al., 2007). Their results indicated that areas with steeper slopes had correspondingly higher run-up elevations and experienced more shoreline change during the hurricanes. Prasad et al. (2009) found that higher wave energies associated with higher wave run-ups caused severe erosion along the wave convergence zones.

Another possible explanation for the variance observed in a beach’s response to storms is the combined effects of alongshore morphology and fluid forcing. Dail et al. (2000) found that there was a high consistency between the beach volume and volume flux. Regnauld et al. (2004) used a numerical model to address the influence of storms along the French coast. The authors concluded that the French coast is highly varied in its response to storms because of variations in wave amplitude and direction during the events and storm strength. They showed bathymetric complexities exercise significant controls on wave refraction patterns during the storms and result in significant variability in coastal response. Furthermore, they suggested that the variability of the alongshore component of wave energy flux can be considered as a good measure to understand the variability of the morphological impacts of storm waves on the beach as the variability of mechanical impact of the wave is a function of the wave height and wave direction. Recently, Miner et al. (2009) used the computed alongshore transport rates where storm wave energy was concentrated to explain the hurricane-induced erosion.

The objectives of this study are (1) to assess the beach erosion induced by the 2006 autumn storm on the Kashima Coast, Ibaraki, Japan, using airborne laser data measured before and after the storm event, and (2) to compare the results of the erosion assessment with the generated wave energies, i.e. the alongshore and cross-shore components of the wave energy fluxes, during the storm event estimated with the Simulating Waves Nearshore (SWAN) wave model (Booij et al., 1999). In this paper, we try to explain the alongshore variability of the observed erosion patterns with the SWAN results.

After providing background information regarding the study site, in the next section, and the description of the sea state, in the third section, in the fourth section we estimate the alongshore distributions of the beach erosion using the airborne laser data. Comparisons between the distributions of the erosion and wave energies estimated with the SWAN wave model are shown in the fifth section and the conclusions of this work are given in the last section.

Study Area

The study area of this research is the northern and southern parts of the Kashima Coast, Ibaraki, Japan, facing the Pacific Ocean (Figure 1). Kashima Coast is located on a shelf whose edge in this area is at a depth of 160 to 170 m and the width is approximately 25 km (Saito, 1989). The well-developed sandy shorelines of these coasts had been preserved as nearly natural until the early 1960s. The construction of the Kashima industrial port, approximately 80 km east of Tokyo, began in the late 1960s on the nearly middle part of Kashima Coast. With the completion of Kashima Port in the beginning of the 1970s, the Kashima Coast was divided into 38 km-long northern and 15 km-long southern parts with respect to littoral sediments since the main breakwater of the port extends to a depth of 20 m. Coastal erosion has been a serious problem since the 1980s. Oarai Port at the north end and the Hasaki Fishery Port at the south end of the coast were extended in the 1980s and trapped sediments in their vicinities. To protect...
and to stabilize the coast, the construction of 40 artificial headlands (HLS), jetty-like rubble mound structures, along the coast at intervals of approximately 1 km was begun in 1985. Thirty-three of them had been completed by 2006.

Wave data collected offshore of Kashima Port show that high energy waves are incident in winter from the north, whereas relatively low-energy waves with a long duration are predominant in summer from the south. Waves and winds are relatively weak in summer except during typhoons, but strong in winter due to low pressure systems. The mean significant waves (fair-weather waves) at Kashima Port are approximately 1-4 m in wave height and 7-6 seconds in wave period.

Figure 1 shows the details of the study area: The northern part of the coast is 38 km long and bordered by Oarai Port at the north and Kashima Port at the south, while the southern part is 15 km long and bordered by Kashima Port at the north and the Tone River at the south. Triangles show the locations of the HLS installed by 2006. There are unprotected sections within the southern and northern parts of the study area expressed by rectangles: Zones I and II, respectively. The erosion due to the port construction within these areas was not so severe compared to the other areas protected with the HLS.

Sea State

From October 5–9 and October 24–26, 2006, two strong low-pressure systems traveled along the Japanese main island Honshu. High waves and storm surges caused by falling pressure and strong winds affected the Kashima Coast, resulting in huge erosion over the area. The minimum atmospheric pressure measured in Choshi was 983 hPa and the storm surge occurred for over three days during the first storm. Figure 2a shows the variations of tide levels measured by the Japanese Meteorological Agency at Choshi Fishery Port for each hour, while Figures, 2b–2d show the variations of significant offshore wave height $H_s$, wave period $T_s$, and wave incidence angle $\theta_s$, respectively, measured every two hours at the Nationwide Ocean Wave Information Network for Ports and Harbors (NOWPHAS; http://nowphas.mlit.go.jp/eng.html) station at Kashima Port, where the mean water depth is approximately 24 m.

In this study, we concentrate on the storm event which occurred from October 5–9, 2006. The measurements show that offshore wave height exceeded 7-0 m on October 6, 2006, and the maximum tide level deviation from the astronomical tide observed on the same day was 0·94 m, which was the highest on record measured at the Choshi Fishery Port in the period of 1981–2007. Some missed wave data at the Kashima wave station were estimated by linear interpolation from Hitachinaka wave station data. Circles in Figure 1 show the locations of the NOPHAS wave stations.

The most frequent tide level observed at the Choshi Fishery Port is approximately T.P. 0-1 m, and the mean high water level is approximately T.P. 0-6 m (T.P. designate the mean sea level of Tokyo Bay, Tokyo Peil). During the storm event in October 2006, a maximum water level of T.P. 1-51 m was observed on October 7 at 3:00 Japan Standard Time (JST).

Erosion of the Foreshore

In this section, the foreshore erosion resulting from the 2006 storm is estimated for the northern and southern Kashima Coast from two airborne laser data sets measured before and after the passage of the low-pressure system (Table I). Before proceeding to the analyses of the whole coast, erosion observed at the HORS research pier of the Port and Airport Research Institute is introduced briefly.

Erosion observed at research pier HORS

Beach profiles are measured along the HORS research pier on week days, which is located on the southern Kashima Coast at $x=0$ m in Figure 1 (Kuriyama et al., 2008). The mean water level at this location is approximately T.P. 0.0 m.

Figure 3a shows the variations of significant wave height and tide level within the period between the two aerial laser surveys. The record indicates that there had been a combination of high waves and storm surge only in October 2006. Storm surge occurred for over three days and the offshore wave height exceeded 7-0 m on October 6, 2006.

Table I. Dates of the aerial laser surveys

<table>
<thead>
<tr>
<th>Time and date</th>
<th>Tide level observed at the Choshi Fishery Port (T.P. m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 20, 2005, 9:00–12:00 JST</td>
<td>0.04–0.20</td>
</tr>
<tr>
<td>October 23, 2005, 12:00–15:00 JST</td>
<td>0.30–0.47</td>
</tr>
<tr>
<td>November 8, 2006, 10:00–12:00 JST</td>
<td>0.00–0.05</td>
</tr>
</tbody>
</table>
Figure 3b shows the time histories of the cross-shore locations of bottom elevations (T.P. 0, 1·0, 2·0, 3·0, 4·0, and 5·0 m) measured along the HORS pier. An example of the beach profile is shown in Figure 4. The results show abrupt landwards migrations of iso-lines for T.P. 1·0 m and 2·0 m occurred during the storm, which were not observed for other erosive events. The portion of the beach between T.P. 1·0 m and T.P. 2·0 m corresponds to the backshore and foot of the coastal dune.

Finally, Figure 3c shows the variation of the cross-sectional area of the beach between the elevations T.P. 0·5 m and T.P. 5·0 m. The results also show huge erosion resulted from the attack of the October 6, 2006, storm.

From the results, we may conclude that the storm event on October 6, 2006, is responsible for the major erosion that occurred over the area although there were high-wave events in the 12 months between the two laser surveys.

### Processing of the airborne laser data

Two aerial laser survey data sets measured in the autumns of 2005 and 2006 are analyzed in this study as shown in Table I. Digital elevation models (DEMs) have been processed above the mean sea water level at a 2-m resolution in the horizontal plane (grid size of the DEMs). Elevation data of the foreshore, backshore, and coastal dunes have been assembled.

Alongshore baselines along the coast are defined for the northern and southern part to estimate the amount of erosion. A polynomial baseline for the northern part is regressed from the T.P. 0·5 m elevations. A straight baseline is employed for the southern part, whose origin coincides with the origin of HORS research pier. Cross-shore profiles were processed along the coast at 10 m intervals perpendicular to the baseline. Bottom elevations at 5 m intervals in the cross-shore are compared to estimate cross-sectional changes along the shore.

Figure 5 shows the baseline for the northern Kashima Coast. The result of aerial laser surveys are verified with the bottom elevation surveyed along the HORS research pier. Figure 4 shows the comparison for 2006, demonstrating that the aerial laser survey matches well with the collected elevations of the beach profile above the water level. Random errors (standard deviations) of the aerial laser surveys above the water level are ±0·20 m for 2005 measurements and ±0·29 m for 2006. These precisions allow the aerial survey to be used to estimate the alongshore distributions of the foreshore erosion.

### Cross-shore profile variation in the alongshore

Two representative examples of cross-shore sectional variations observed in the unprotected sections (Zones I and II) are shown in Figure 6. Erosion extends up to a height of...
**Figure 5.** An aerial photograph of the northern Kashima Coast with details of the artificial HLs and the coordinate system.

**Figure 6.** Variations of cross-shore sections at unprotected beaches of (a) Northern Kashima Coast ($x = -33730$ m), and (b) Southern Kashima Coast ($x = 1760$ m).
approximately T.P. 5.0 m, which is far beyond the maximum tide elevation T.P. 1.51 m observed at the Choshi Fishery Port on October 7, 2006. This may be caused by wave setup induced by wave breaking, wind surge, run-ups of wind waves, low frequency waves, and other processes; however, the detailed erosion process and contributions of the hydrodynamical processes are not known. Cross-sectional change between the elevations T.P. 0.5 m and 5.0 m is indicated in Figure 6 as estimated from the differences of the elevations measured in 2005 and 2006 at each transect.

Cross-sectional changes between the elevations T.P. 0.5 m and 5.0 m (the subaerial zone, defined here as the zone measured between the dune toe and the shoreline for each respective data set) were estimated for the northern and southern parts. Figures 7a and 7b show the alongshore distributions of the changes of cross-sectional area, which is defined here as dA, for the northern and southern Kashima Coast, respectively. Negative values indicate that the subaerial zone was eroded, and the squares indicate the locations of the HLs. The length of the northern Kashima Coast is approximately 38 km and the southern is 15 km.

The total amount of the eroded volume of the subaerial zone over the northern and southern parts, estimated by summing up the cross-sectional change in the region from T.P. 0.5 m to variable upper limit, were estimated at 620 000 m³ and 600 000 m³, respectively. The probable error in the eroded volume estimation is in the order of 2000 m³, which is estimated from the standard deviation shown earlier and number of the points in the subarial zone of the DEM. The fate of the eroded sediments is not known at present.

In general, erosion dominates over accretion and decreases from north to south in both parts. The local variations of the erosion and accretion patterns show remarkable quasi-periodic fluctuations of several hundreds of meters. The main reasons influencing these features are discussed later by estimating the wave energies along the coast.

The amount of erosion in protected areas with the HLs is generally less than that in the unprotected area. The HLs seem to induce a saw-shaped pattern, i.e. less erosion (or even accumulation at some locations) is observed at the northern faces of the HLs than at the southern faces. This maybe induced by the prevailing wave incidences from the northern and southwards alongshore current, which is discussed later.

**Estimation of the Wave Field and its Relationship to Cross-sectional Change**

A combination of the variability in the pre-existing beach morphology (beach elevation, slope, or width) and the offshore fluid forcing (waves and storm surge) is considered one of the possible reasons for the spatial variability of storm-induced coastal response (Dail et al., 2000; Backstrom et al., 2008; Prasad et al., 2009). Therefore, the main goal of this section is to estimate the wave field using the SWAN wave model (Booij et al., 1999) to explain the alongshore variability of erosion patterns estimated in the previous section. The waves of the storm during October 5–9, 2006, will be estimated, since we think the influence of this storm on the resulting erosion was dominating as discussed earlier. Wave setup from storm surge and wind-induced current are estimated by Nobuoka and Kato (2008). Their results show that the alongshore distributions of wind driven current and water level rise due to low pressure

![Figure 7](image-url). Alongshore distributions of cross-sectional changes of (a) Northern Kashima Coast and (b) Southern Kashima Coast. Squares indicate the locations of the artificial HLs.
and wind setup were almost uniform along the coast, so we concentrate on the estimation of the alongshore distribution of wave energies.

The SWAN wave model (Booij et al., 1999) was applied using wave data observed during the passage of the first storm at the wave station at Kashima Port and provided wave field estimates. The computational results are verified, and then the alongshore distribution of wave energies expressed as the alongshore and cross-shore components of the wave power are compared with the alongshore distribution of the cross-sectional change dA.

Bathymetric and wave data

The bathymetric data of the study area are assembled in a rectangular format with grid squares of length 96 m covering an area of approximately 100 km alongshore and 56·8 km cross-shore, from north to south and east to west, respectively. Figure 8 displays the depth contours at intervals of 20 m in deeper areas and 5 m in shallower areas. The locations of the NOWPHAS wave stations at Kashima Port (depth approximately 24 m) and Hitachinaka Port (depth approximately 30 m) are displayed as white circles in Figure 8. The bathymetric data show that the deeper areas are characterized by relatively smooth contours, while the contours of the shallower areas, in the depths from 30 to 20 m, are characterized by the presence of many ridges which may affect the wave propagation. Angles between the ridge crests and the coastline directions are 50° to 70°. Ridge intervals are approximately 2 km, ranging from 1 to 3 km, and ridge height is 6 to 10 m (Saito, 1989).

Model setup

SWAN is a phase-average spectral wave model that calculates the change in wave spectra over complex nearshore bathymetry while maintaining computational efficiency. For further explanation regarding the formulations used in SWAN the reader is referred to Booij et al. (1999) and Ris et al. (1999).

The storm waves are computed with the SWAN wave model in stationary modes. Here, we made several assumptions and exclusion of hydrodynamic effects: (1) the sea state can be represented by a transition of steady states of every two hours; (2) the variations of mean water level due to astronomic tide, surges from pressure decreases, and wind setup can be ignored; (3) wind driven current can be excluded; (4) the growth of the waves due to the wind can be neglected; and (5) the effects of the HLs and breakwaters are excluded from the wave computations.

Computations were undertaken for a grid system which covers an area of approximately 84·1 km alongshore and 50·1 km cross-shore as shown within the bold dotted box of Figure 8. Dissipation of the wave energy is characterized by three source terms: (1) wave–wave interaction, (2) bottom
friction, and (3) depth-induced breaking. Table II shows the SWAN model controls and options used in the computations. Before starting the full computation, several intermediate steps were processed to set the boundary wave data, as shown in Figure 9. First, a backward propagation starting with the wave record at Kashima Port towards the deep water conditions was made by refraction computations to provide tentative values along the offshore boundary (y = 31 299 m). Next, a forward propagation computation was done with the SWAN wave model for the side boundaries (x = –71 329 m, 12 767 m) (Serra Ribas, 2005). Finally, full computations over the full domain were done. The results were verified at the wave stations, and modifications of the offshore boundary conditions were repeated until certain accuracy-of-fit criteria were satisfied. The details of the procedure are described in the following.

Backward propagation
To get a first estimate of the offshore boundary condition at y = 31 289 m, a backward refraction computation from a point at the Kashima Port wave station towards the offshore was done. Wave directions and heights varied in the backward computation whereas the wave period remained constant.

Table II. SWAN model options and controls used in computations

<table>
<thead>
<tr>
<th>Geographic grid</th>
<th>Size (km)</th>
<th>50·112 (east-west)×84·096 (north-south)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution (m)</td>
<td>192×192</td>
<td></td>
</tr>
<tr>
<td>Spectral grid</td>
<td>Range in f (Hz)</td>
<td>0·05 – 1·0</td>
</tr>
<tr>
<td></td>
<td>Range in θ (deg)</td>
<td>0°–360°</td>
</tr>
<tr>
<td></td>
<td>Resolution (Hz)</td>
<td>Δf =0·1f, Δθ=10°</td>
</tr>
<tr>
<td>Mode</td>
<td>Third generation (stationary mode)</td>
<td></td>
</tr>
<tr>
<td>Bottom friction</td>
<td>Yes, SWAN default (IONSWAP)</td>
<td></td>
</tr>
<tr>
<td>Breaking</td>
<td>Yes, SWAN default</td>
<td></td>
</tr>
<tr>
<td>Triad</td>
<td>Yes, SWAN default</td>
<td></td>
</tr>
<tr>
<td>Wind growth</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>White capping</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

Offshore boundary data

<table>
<thead>
<tr>
<th>Wave data measured by Kashima station [Hc, Tc, θc]</th>
<th>Backward propagation by refraction computation</th>
<th>Offshore boundary data [Hc, Tc, θc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correction for the new offshore boundary data Hc(new) = Hc*(Hc/Hsc) θc(new) = θc*(θc/θsc) Tc(new) = Tc*(Tc/Tsc)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comparison with measured wave data. Inspection criteria [Hc, Tc] &lt; 0·05 m [Tc, Tc] &lt; 0·5 sec</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>1-D SWAN runs for side (north and south) boundaries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-D SWAN Global run</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Wave field during the storm

Results of the wave computation at the locations of the Kashima and Hitachinaka wave stations are shown in Figure 10. There are some results which do not precisely satisfy the tolerance requirements; however, the overall storm passage is reproduced well.

During the storm, the significant wave height Hs at Kashima and Hitachinaka reached a maximum in the middle of the storm duration. The variation of the significant wave direction θs suggests that the waves were initially incident from the south relatively to the shore, whereas they turned northern incidences during later periods of the storm. The wave period Ts increased gradually during the storm.

Figure 11a shows the significant wave height distribution over the full domain at the peak of the storm on October 6, at
22:00 JST, while Figure 11b shows the wave rays processed from the results of wave angle distribution. Figures 11a and 11b indicate that the significant wave height distribution was affected by the presence of the ridges within the shallow water area, causing a variation of the wave height along the coast due to wave ray convergences and divergences.

**Alongshore distributions of wave energy flux components**

In this section we try to estimate the storm wave effects on erosion during October 6–7, 2006, by estimating the alongshore and cross-shore components of wave energy fluxes as indicators for the driving forces of the alongshore and cross-shore sediment transport. We applied the wave energy flux formula at the outer edge of the breaker zone, and we defined the breaking point by the maximum location of the wave energy dissipation along each cross-shore distribution.

The alongshore and cross-shore components of wave energy flux $P_l$ and $C_l$ are estimated using Equations 1 and 2, respectively (Dean and Dalrymple, 2002; Komar and Inman, 1970).

\[
P_l(x, t) = \frac{\rho_w g H_b^2(x, t)}{8} \sqrt{g d_b(x, t) \sin \alpha_b(x, t) \cos \alpha_b(x, t)}
\]

\[
C_l(x, t) = \frac{\rho_w g H_b^2(x, t)}{8} \sqrt{g d_b(x, t) \cos^2 \alpha_b(x, t)}
\]

where $x$ is the alongshore location, $t$ is time, $g$ is the gravity acceleration, and $\rho_w$ is the mass density of water ($1025$ kg m$^{-3}$). The values of $H_b$, $\alpha_b$, and $d_b$ are the breaking wave height, breaker wave angle relative to the local shoreline, and the breaking water depth, respectively.

The main panels of Figures 12a and 12b show the time-space distributions of $P_l$ and $C_l$, respectively. A positive (negative) $P_l$ indicates that sediments may be transported toward the south (north). The lower panels of Figures 12a and 12b display the time history of $P_{ls}$ and $C_{ls}$, which are averages of $P_l$ and $C_l$ in space, as:

\[
P_{ls}(t) = \frac{1}{L_C} \int P_l(x, t) \, dx
\]

\[
C_{ls}(t) = \frac{1}{L_C} \int C_l(x, t) \, dx
\]

where $L_C$ is the length of the coast. The variation of $P_{ls}$ indicates that sediments might be transported toward the south at the beginning of the storm and afterwards to the north. The variation of $P_{ls}$ and $C_{ls}$ indicates that the maximum sediment transport should have occurred in the middle of the storm.

Figure 10. Comparison between computed wave data and observed wave data at Kashima and Hitachinaka wave stations. (a) Significant wave height, (b) significant wave period, and (c) significant wave direction.
The left panel of Figure 12 displays \( P_b(x) \), which is an average of \( P_l \) in time, while the right panel displays \( C_b \), which is an average of \( C_l \) in time, as:

\[
P_b(x) = \frac{1}{T_{\text{storm}}} \int P_l(x, t) dt
\]

(5)

\[
C_b(x) = \frac{1}{T_{\text{storm}}} \int C_l(x, t) dt
\]

(6)

where \( T_{\text{storm}} \) is the duration of the storm. The distribution of \( P_b \) shows that the majority of sediments may have been transported toward the south. In some portion of the coast, e.g., Zone I within the southern Kashima part, the sediments may have been directed to the north. We suppose that this is induced by the sudden change of bathymetry in this area, as shown in the enlargement in Figure 8. The depth contour-line of 30 m locates closer to the shore at the south of Kashima Port compared to the north. This sudden change in beach profile bent wave rays along the slope when the waves were incident from the north as shown in Figure 11b.

Generally, \( C_b \) is considered as a measure of the intensity of cross-shore processes, such as wave breaking, wave setup, infragravity waves, undertow, etc. A larger \( C_b \) causes these processes to be more intense, which could result in a larger cross-shore transport from the upper beach to the surf zone. In other words, one would expect that the relation between \( C_b \) and amount of erosion is in phase. On the other side, \( P_l \) can be considered as a proxy for alongshore sediment transport. Changes of local beach volume and gradient of \( P_l \) are frequently related to understand coastal behaviors. The values of \( P_b \) and \( C_b \) will be used here as indicators or proxies to explain the alongshore variability of erosion patterns observed in the survey results.

Alongshore variation of wave energy flux components and cross-sectional change

In this section, the alongshore distributions of the time-averaged wave energy flux components \( P_b \) and \( C_b \) are compared with the alongshore distribution of cross-sectional change \( dA \). In the comparison, the results are decomposed into spatial mean and fluctuations, \( P_b = P_b^\prime + P_b^\prime \) and \( dA = dA^\prime + dA^\prime \), where \( P_b^\prime \) and \( dA^\prime \) are the spatial means of \( P_b \) and \( dA \), which are processed by applying a 3000 m moving average filter, and \( P_b^\prime \) and \( dA^\prime \) are the fluctuations from the spatial means \( P_b^\prime \) and \( dA^\prime \). Figures 13a–13c display the alongshore distributions of \( P_b \) and \( dA \), \( P_b^\prime \) and \( dA^\prime \), and \( P_b^\prime \) and \( dA^\prime \), receptively. Cross-shore component of wave energy flux \( C_b \) and the amount of erosion \( dA \) are compared in the same manner. Figures 14a–14c display the alongshore distributions of \( C_l \) and \( dA \), \( C_l^\prime \) and \( dA^\prime \), and \( C_l^\prime \) and \( dA^\prime \), respectively. The distributions of large-scale erosion \( dA \) and short-scale erosion \( dA^\prime \) have amplitudes of the same order. The results of \( P_b \) and \( C_b \) show that although the waves were obliquely incident for most hours of the storm, the magnitudes of the cross-shore energy flux were roughly 10 times larger compared to the alongshore energy flux. The overall distribution of the cross-sectional change \( dA \) is mostly accordant with the distributions of \( C_l \) along the coast; the amount of erosion decreased toward the south in both parts with decreasing wave energies as shown in Figure 14b. These indicate that the alongshore variability of the cross-shore energy flux \( C_l \) is responsible for the large-scale variability in erosion, and the large-scale distribution of energy flux is controlled by the concave mean sea bottom bathymetry.

The results of the alongshore distributions of \( P_l^\prime \), \( C_l^\prime \), and \( dA^\prime \) displayed in Figures 13c and 14c indicate that the highly eroded areas observed in the alongshore distributions of \( dA^\prime \) might be affected by the concentration of wave energies, especially in unprotected sections in Zones I and II. Indicated

Figure 11. Computed wave field at the storm peak time on October 6, 2006, at 22:00 JST. (a) Significant wave height distribution, and (b) wave rays estimated from the wave angle distribution. This figure is available in colour online at wileyonlinelibrary.com.
Figure 12. Alongshore distributions of (a) $P_l$ and (b) $C_l$. Main panels of (a) and (b) show the timespace distributions of $P_l$ and $C_l$. Panels at the bottom show $P_{ls}$ and $C_{ls}$, respectively. Right panel shows $C_{ls}$ and left panel shows $P_{ls}$. Panel at the top shows the definition of $P_l$. This figure is available in colour online at wileyonlinelibrary.com.

Figure 13. Alongshore distributions of (a) $P_h$ and $dA$, (b) $P_{ls}$ and $dA$, and (c) $P_{ls}'$ and $dA'$. The squares indicate the locations of the artificial HLs.
by rectangles in Figure 1). The response should be close to that of an undisturbed beach.

Figure 15 focuses on the results of the unprotected sections, Zones I and II. Figure 15a displays the relationship between the alongshore distributions of $P_{lt}'$ and $dA'$ for Zone I, while Figure 15b displays the auto-correlations of $P_{lt}'$ and $dA'$, and cross-correlation between these. Correlations are estimated by using half of the data estimated at the unprotected section. A

![Figure 15](image_url)

Figure 15. Alongshore distributions of $P_{lt}'$ and $dA'$ for (a) Zone I and (c) Zone II. The auto-correlations and cross-correlation between these variables are displayed for (b) Zone I and (d) Zone II.
clear periodic structure is obvious in $P'_h$ and $dA'$, and their wave lengths are approximately 2200 m estimated from auto-correlations. Figure 15a shows that the phase difference of the fluctuations is almost fixed, and we observe that most of the local peaks of $P'_h$ are located at the zero crossings of $dA'$. It can be also confirmed from cross-correlation shown in Figure 15b that there exists a systematic phase shift between $P'_h$ and $dA'$. Figures 15c and 15d display results of the same analyses for Zone II. Here, the wave length is 2800 m and existence of systematic phase shift between $P'_h$ and $dA'$ is confirmed again. The results shown here supports the concept of one-line modeling, in which convergence and divergence of sediment flux will induce the alongshore variation of erosion and accretion along the coast, and thus the shorter-scale variability of erosion is due to gradients in the alongshore energy flux. We argue the alongshore variability of $P'_h$ is induced by the presence of the ridges within the shallow areas between the depth of 20 m and 30 m, which is explained in Figures 8 and 11. Similar indications on the importance of distribution of the alongshore wave energy flux for the alongshore variability of beach erosion are given by Regnauld et al. (2004).

Figure 16a displays the alongshore distributions of $C'_h$ and $dA'$ and Figure 16b the auto-correlations and cross-correlation between these variables for Zone I. Correlations are estimated by using half of the data estimated at the unprotected section. Same items for Zone II are shown in Figures 16c and d. The distributions of the fluctuations $C'_h$ and $dA'$ show that the wave length of $C'_h$ is shorter than that of $dA'$, and the phases are not locked consistently.

The main conclusions of the computational results are summarized as follows: (1) the alongshore variability of the cross-shore energy flux $C'_h$ is responsible for the large-scale variability in erosion, and (2) shorter-scale variability for the unprotected sections can be explained by the distribution of alongshore energy flux $P'_h$. Beside these, the computational results show that wave energies along the area protected by the HLs were smaller compared to the rest of the area. The survey results also showed that the erosion of this area was smaller compared to that in the other sections. The computation does not incorporate the effect of the HLs, so it is difficult to discuss whether the HLs or the distribution of wave energies is the main reason in reducing the amount of erosion.

**Conclusions**

A strong low-pressure system traveled along the Japanese main island Honshu in October 2006, giving rise to high waves and storm surge along the Kashima Coast and, consequently, to huge erosion over the area. The erosion was estimated by using two airborne laser data sets measured before and after the passage of the low-pressure system. The results showed that the total amounts of the eroded volume of the subaerial zone of the northern part was 620 000 m$^3$ and southern part was 600 000 m$^3$. The general trend of the erosion distribution was decreasing from north to south along both stretches and the amount of erosion was generally less in areas protected by the artificial HLs than in the unprotected areas.
The SWAN wave model was applied to estimate the wave conditions along the coast during the storm hours. The computed longshore and cross-shore components of the wave energy flux were compared with the alongshore distribution of cross-sectional change. The results indicate that the overall distribution of the cross-sectional change is in accordance with the distributions of the alongshore and cross-shore components of wave energy flux $P_L$ and $C_R$ along the coast. The large-scale variability of erosion observed along the coast is related to the large-scale alongshore variability of the cross-shore energy flux, which is controlled by the concave mean sea bottom bathymetry. However, the short-scale variability of cross-sectional change $dA$ for the areas without coastal works showed a systematic correlation with the distribution of the short-scale alongshore energy flux, which is induced by the presence of the ridges within the shallow areas between the depth of 20 and 30 m.

Acknowledgements—The authors are grateful to the members of the Littoral Drift Division, Port and Airport Research Institute, who provided wave measurements and results of the depth surveys. The authors also acknowledge the financial support by the Grants-in-Aid from Kajima Foundation.

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