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Tidal deformation and inundation characteristics within mangrove swamps

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Abstract: Based on the field measurement of tidal elevation in mangrove areas and estimated astronomical tides in open sea, the tidal deformation in mangrove swamps was formulated quantitatively. Furthermore, considering that the physiology and ecology of biota in mangrove swamps are influenced by the water inundation with tidal periods through many decades, the statistical tidal characteristics in the swamp were analyzed, based on the above formulation.

It was found that the frequency of tidal inundation, tidal inundation duration and exposure duration in mangrove swamps vary seasonally over a wide range, corresponding to the seasonal changes in tidal condition and the mean sea level in the adjacent open sea. And, the field measurement showed that the tidal level in mangrove swamps deforms greatly from that in the adjacent open sea. The magnitude of the deformation was formulated using the parameters, the distance from the creek bank, the water depth at high tide and the vegetation condition. Based on these data analyses, it was shown that the tidal inundation duration needs to be modified significantly from that in a case without deformation. Further, it is noted that the deformation characteristics in mangrove swamps varies considerably between regions and between topographies of swamps.

Keywords: Mangrove, Tidal deformation, Statistics, Inundation duration

1. Introduction

Mangrove ecosystems are established as a result of feedback processes between coastal landform, water flow, atmosphere and biota itself through many decades (Snedaker and Snedaker, 1984; Vannucci, 1989). The total and partial feedback processes between these individual factors are schematically represented in Fig.1. For example, biota such as trees, benthos and algae in mangrove forests receive salt water, nutrients and dissolved oxygen through tidal inundation; in other words, the growth of biota in mangrove forests is stimulated and restricted by tidal inundation. On the other hand, the tidal inundation and flushing are controlled or strongly influenced by the drag and viscous forces of thickly vegetated mangrove trees/roots (Mazda *et al.*, 1997; Mazda *et al.*, 2005) and by the permeability of animal burrows under the ground (Ridd, 1996; Mazda and Ikeda, 2006), which vary with vegetation/population density. Change in density of mangrove trees causes the change in magnitude of tidal inundation. The chang in tidal inundation feeds back to the change in density of mangrove trees. However, the physiology and ecology of biota cannot respond instantly to the tidal change, which repeats with a period of one year in a statistical sense, but follow the statistical tidal inundation characteristics gradually through many decades.

Watson (1928) recognized a correlation between tidal inundation and the species zonation of mangroves in Malaysia. And he developed a zonation model composed of the site elevation and the tidal height. Snedaker (1989; further, personal communication) has also pointed out the importance of the statistical tidal information such as the frequency of tidal inundation, the tidal prism volume, the inundation duration and salinity for the growth of mangrove forests. Lewis (2005) has also recently described the importance of these same factors in controlling mangrove zonation and attempts to restore mangroves. Dr. Otto Dalhaus (personal communication) lasts laboratory examination about the dependence of the growth of mangrove seedlings on the inundation duration and salinity.

However, these relationships have not been quantitatively formulated, resulting in that the Watson ' s model has not been in practical use. In order to develop their ideas for practical use, at first, the tidal inundation characteristics in mangrove forests should be quantitatively understood.

In this article, we analyze particularly the characteristics of tidal inundation duration in mangrove forests, based on our field measurement in a mangrove forest and statistical features of the tidal elevation in open sea as an input into mangrove forest.

2. Sea level change in open sea as an input into mangrove swamp

2.1 Tidal and seasonal changes in sea level in various regions

Though the tidal water inundating mangrove swamps

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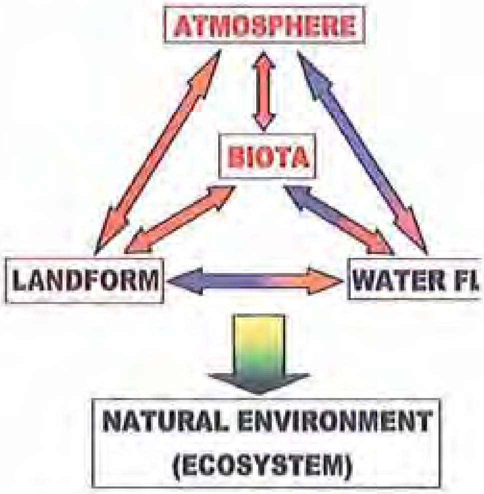

Fig.1. Feedback process in mangrove ecosystem.

from open sea is deformed due to drag and viscous forces of mangrove vegetation and landform or local topography (Mazda *et al.*, 2005), at first we need to understand the original feature of tidal motion in open sea as an input.

Figure 2 shows different tidal conditions in three coastal water areas, the mouth of Aira Gawa, Iriomote Island, southernmost Japan (Fig.2a), the mouth of Chone River, middle Ecuador (Fig.2b), and the offshore area of Can Gio, Vietnam (Fig.2c), adjacent to mangrove swamps, respectively. These time series plots of tidal level are estimations calculated using harmonic tidal constants. The seawater moves with tidal periods vertically as a tidal elevation and horizontally as a tidal current.

Due to astronomical force and latitudinal- topographical conditions the tidal motion has several periods of ca. 24 hours (K_1=23.93 hours; O_1=25.82 hours; P_1=24.07 hours; Q_1=26.87 hours; S_1=24.00 hours) and ca. 12 hours (M_2=12.42 hours; S_2=12.00 hours; N_2=12.66 hours; K_2=11.97 hours). Among these components, K_1, O_1, M_2 and S_2 are called the dominant tidal components. Both the amplitude and phase of each tidal component are different between locations of observation sites.

Generally, due to the characteristics of the dominant tidal components, both the high and low tide levels change tide by tide (see Fig.5a), resulting in that the duration of flood phase is different from that of ebb phase, which is called the tidal inequality, furthermore the timing of the high tide shifts by ca. 50 minutes every day (Ippen, 1966). In mangrove areas, it is usual that the tidal flow stagnates at high and low tides, and commences inundation into swamps around at middle of flood tide, as seen in Fig.5b. Though these tidal oscillations are roughly symmetrical between flood and ebb tides in offshore areas, they are modified asymmetrically in mangrove swamps due to the presence of mangrove vegetation and local topography, as discussed after. Particularly, the modification is great for a time before the bottom substrate dries up at ebb tide, as seen in Fig.5b.

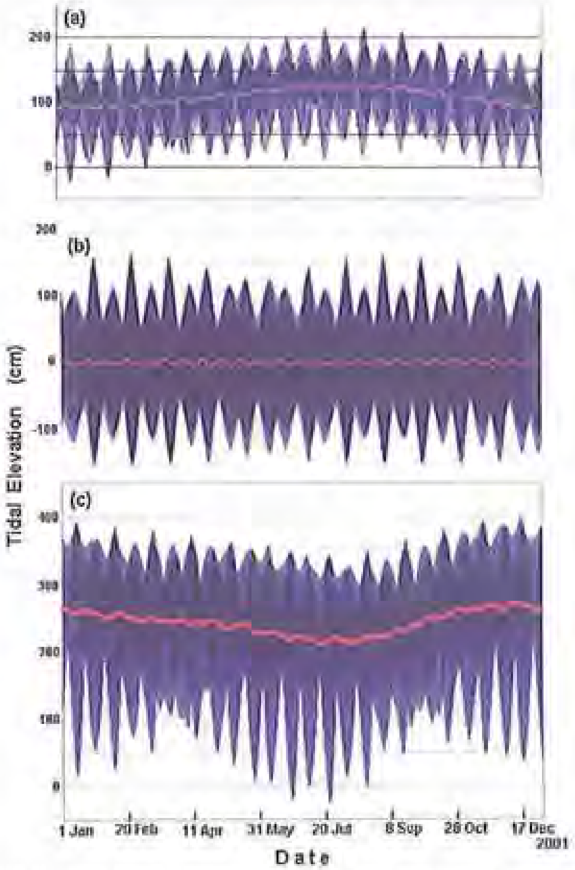

Fig.2. Sea level change and mean sea level (red line) in open sea in 2001.

(a) The mouth of the Aira Gawa mangrove area, Iriomote Island, southernmost Japan.

(b) The mouth of Chone River, middle Ecuador.

(c) The offshore area of Can Gio, Vietnam.

In Figs.2a and 2c the seasonal change in water level, particularly in mean sea level, can be appeared, while it is not obvious in Fig.2b. The seasonal change in mean sea level is caused by water temperature that controls the expansion of water, atmospheric pressure, seasonal wind such as monsoon and river runoff due to rain (Kjerfve, 1990). For example, in Fig.2c at the Can-Gio coast, Vietnam, the range of mean sea level change is ca. 60 cm with the lowest in summer and the highest in winter, while it is negligible at the mouth of Chone River (Fig.2b), middle Ecuador. Kjerfve (1990) has also stated that the semiannual changes in mean sea level can occur as a result of runoff events or variability in the wide scale ocean circulation. We can see, further, the semiannual change in tidal range, which is particular salient in Fig.2c. Thus, it is noted that some mangrove swamps may continue to dry through a few months, and their ecosystems depend strongly on these seasonal changes.

Due to astronomical forces, which form the change in new moon to full moon, the tidal range changes fortnightly with spring and neap tides as seen in Fig.2. The volume of water that inundates and is trapped in mangrove swamps changes greatly during this spring-neap cycle (Mazda *et al.*, 1995). The tidal inundation in some innermost parts of mangrove swamps is particularly affected by this cycle. As a result, innermost parts of mangrove swamps may continue to dry through a few days during neap tide. The magnitude of groundwater flux is also greatly different between the spring and neap tides (Mazda and Ikeda, 2006).

2.2 Statistical feature of sea level change

As mentioned above, in water areas there are various water motions horizontally and vertically with different periods. However, given that the movement of celestial bodies causing tidal motion and the atmospheric condition repeat with one year, the sea level behaves statistically with a period of one year, though it has a little dispersion.

For example, Fig.3 shows the statistical information for tidal inundation at a site in a mangrove swamp (Stn. E in Aira Gawa; see Fig.4), based on Fig.2a. Fig.3 was calculated on the assumption that the tide inundates the swamp without deformation from the open sea. The frequency of tidal inundation (*f*) is defined as the number of inundation times per a month (30 days). The inundation duration (*TI*) and the drought duration (*TD*) are defined as the average length of time that the site lasts to be submerged and dried up per a month, respectively. It is obviously seen from Fig.3 that these statistical values have wide seasonal variation. The relations between the inundation frequency per a month (*f*), the inundation duration (*TI*) and the drought duration (*TD*) are as follows.

$$(T_I + T_D)f = 24(hours)\times 30(days)..........(1)$$

Since the value of *f* varies with month, the value of *TI+TD* is not constant through months as seen in Fig.3. It is noted that these values depend on the site elevation.

These characteristics should influence the physiology and ecology of biota in the swamp. However, these results should be modified when mangrove trees are thickly vegetated in the swamp, because the tidal inundation is deformed due to the drag and viscous forces of mangrove trees and roots emerged from the substrate. In order to evaluate the significance of this deformation, the magnitude of this modification is estimated and discussed in the following section, based on our field observation.

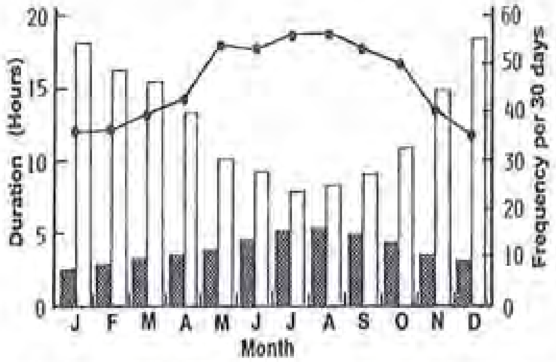

Fig.3. Statistical characteristics of sea level change in the Aira Gawa mangrove forest in a case without tidal deformation. Line graph represents the frequency of tidal inundation per a month (30 days). Bar graphs hatched and without hatching represent the inundation duration and the exposure duration, respectively.

3. Tidal measurement in a mangrove swamp

3.1 Study site

Figure 4 shows the observation sites in the Aira Gawa mangrove area on Iriomote Island, southernmost Japan. *Bruguiera gymnorrhiza* is the dominant species. In the tidal creek (Stn.A) and the mangrove swamp (Stns.B-E) water level gauges (Pressure memory-type RMD; Rigosha Co. Ltd.) recorded the surface water level at 1-min intervals from 19 to 23 April 2004.

Around these sites the bottom slope in a direction perpendicular to the creek is ca. 2/1000. Detailed local topography and vegetation distribution are described by Kobashi (2001) and Kamiyama (2005).

3.2 Results

Figure 5 shows the water levels measured at Stns.A to E. The sea level in the creek (Stn.A) is the same as that in open sea, except at low water level (Mazda *et al.*, 1995). Particularly, due to a sill at the mouth of the creek the water level at Stn.A in the creek was not able to descend below the sill level (ca.50cm; see Fig.5a). An enlargement of the record on 22 April is shown in Fig.5b. Around high tide the water levels in the swamp (Stns.B-E) changed in accordance with that in the creek (Stn.A), except when the tide is very small (Stn.E at midnight on 22 April).

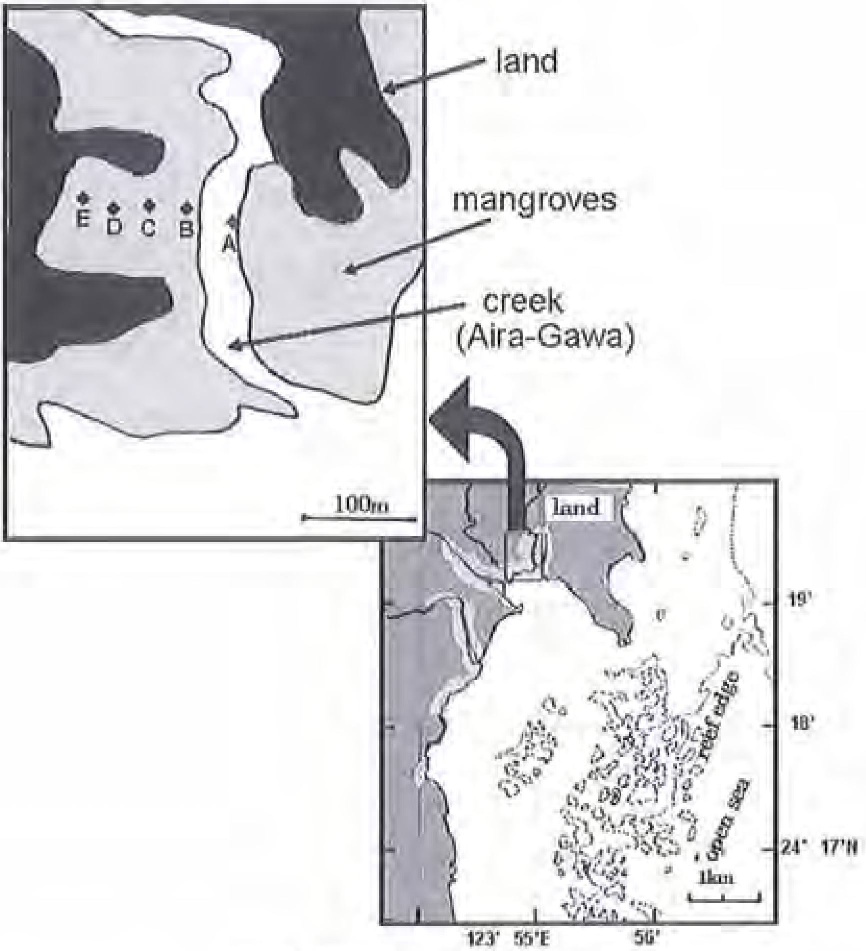

Fig.4. Map of observation sites, Stns.A-E

However, at the beginning of tidal inundation ($S1$ in Fig.5b) and for a time before the swamp surface was exposed ($S2$ in Fig.5b), the water levels in the swamp diverged from that in the creek. It is noted that according to this deformation the inundation duration increases a few hours, while the hatched area $S1$ is negligible compared to that of $S2$. After the water level fell below the soil surface, the descent speed of the groundwater level slowed and was approximately constant until the subsequent flood tide covered the swamp (Mazda and Ikeda, 2006).

4. Data analyses and discussion

4.1 Quantification of tidal level deformation in mangrove swamps

At the beginning of tidal inundation and for a time before the swamp surface was exposed, the water level in the swamp diverged from that in the creek or open sea. This deformation of tidal level in the swamp from that in the creek ($S1$ and $S2$ hatched in Fig.5b) is caused mainly by the drag and viscous forces of submerged mangrove vegetation. Here we define a value $S = S2 - S1$. As the value S means the net deformation toward the tide in open sea, we call hereafter this value S as the deformation fraction.

The relationship between the deformation fraction (S) and the water depth at high tide (H in Fig.5b) at each site is shown in Fig.6a. Obvious relationships can be seen between S and H in each site (Stns.B-E). The larger the tide, the deeper the tidal water inundates the recesses of the swamp. Drag and viscous forces due to mangrove trees and roots increase with inundation area, resulting in the conspicuous deformation. As the value of S should converge to 0 for the value of H going to 0, regression lines through the origin are shown in Fig.6a as a first-order estimation, which is represented as follows.

$$S = \alpha H \quad \text{........(2)}$$

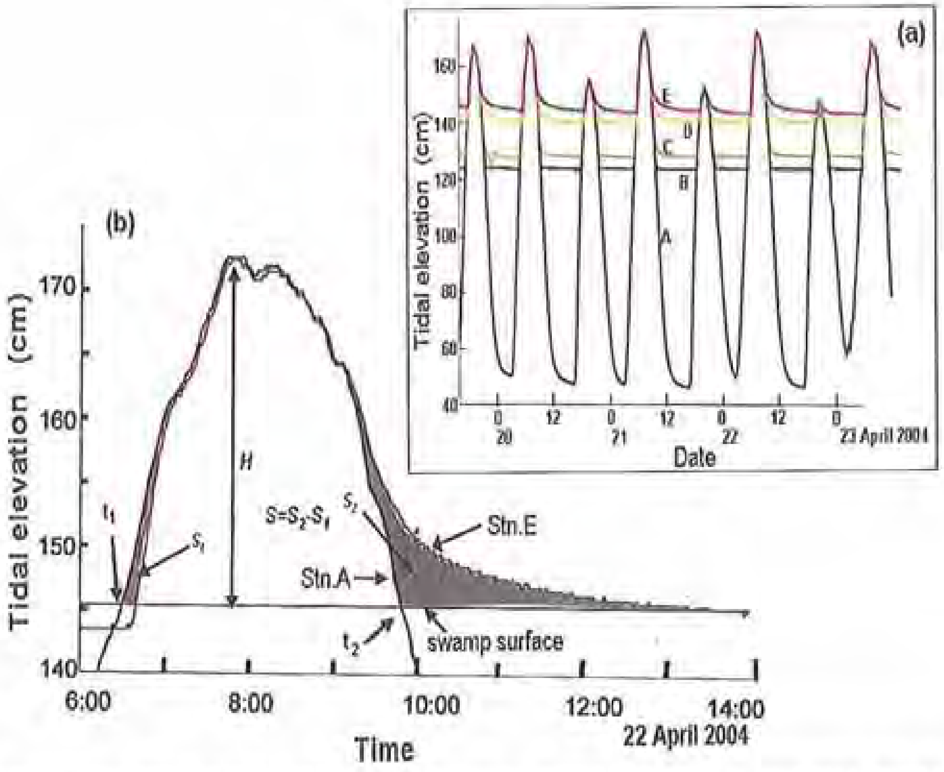

Fig.5. Time series plots of tidal level (a) during the period from 19 to 23 April 2004, and (b) the enlargement on 22 April. In Fig.5b, the definition of the deformation fraction (*S*) is represented as *S2-S1*.

where α is the gradient of the regression line, which is varies with sites. The relationship between the gradient (α) of the regression line and the distance of the site from the bank of the creek (*L*) is shown in Fig.6b. An obvious linear relationship can be seen between *L* and α , which is represented as follows.

$$\alpha = \beta L..........(3)$$

Where β is the coefficient of proportionality. In Eq.(3) the distance from the creek bank (*L*) can be replaced by the elevation of the soil surface at the site. Substituting Eq.(3) to Eq.(2),

$$S = \beta HL........(4)$$

In conclusion, the deformation fraction or the deformation of tidal level in mangrove swamps depends on both the distance from the creek bank and the water depth at high tide (or the tidal range). Further, it is suspected that the magnitude of β varies with the condition of mangrove vegetation such as mangrove species and the vegetation density.

4.2 Definition of the equivalent correction time of the inundation duration

As mentioned previously, the physiology and ecology of biota in mangrove swamps are influenced by the statistical factors such as the frequency of tidal inundation, the inundation duration and the water depth due to tidal inundation. If the deformation fraction (*S*) influences significantly the physiology and ecology of biota, the statistical values estimated in Fig.3 has to be corrected.

In areas such as mangrove swamps that reiterate water inundation and exposure with tidal period, it is suspected that the physiology of biota is exposed to more or less stress or is encouraged at a given water depth, i.e. the threshold depth. The intensity of the influence, i.e. the amount of stress, depends on form of biota which is under consideration. For example, mangrove trees are stressed at high water depth, while the physiology of small mud crabs living near the soil surface is influenced even at shallow depth such as a few cm. Once the target biota is selected, the magnitude of the threshold depth can be decided. In this paper this threshold depth shall be called the ecological control depth (*HE*). For example, the magnitude of *HE* for mud crabs is determined by the

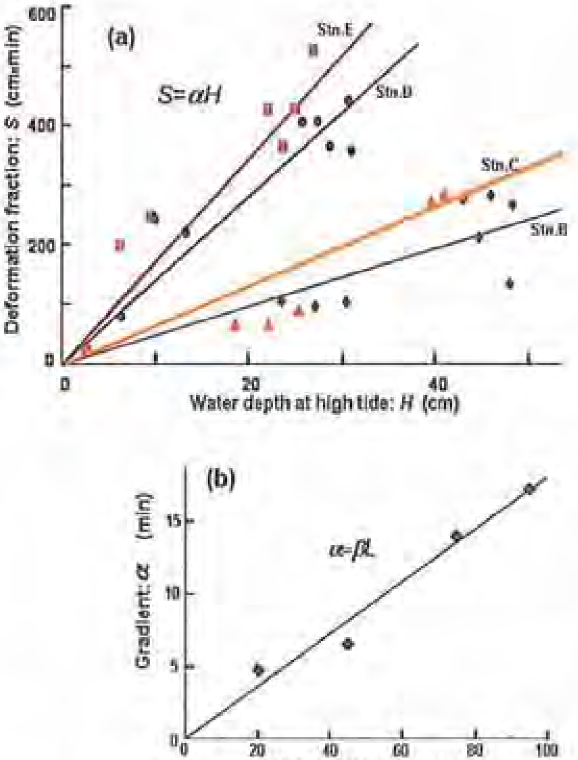

Fig.6. (a) Relationship between the deformation fraction *S* and the water depth at high tide at each site *H*, and (b) the relationship between the gradient α of the regression line in (a) and the distance of sites from the creek bank *L*.

water depth that mud crabs cannot survive at over a long period of time, which may be a few cm. However, the water depth larger or smaller than *HE* also influences the physiology of the target biota with different weight. Applying the idea of the ecological control depth (*HE*) to the deformation fraction (*S*), we discuss the correction of the inundation duration shown in Fig.3, as follows.

Considering that, as seen in Fig.5b, the water depth shallows gradually during a period of the deformation, furthermore the deformation fraction (*S*) has dimensions of the product of the depth and the time, we replace *S* as follows.

$$S = H_E T_E \text{ ....(5)}$$

Eq.(5) means that the deformation fraction (*S*), which is formed by the water depth gradually shallowing with time, is equivalently transformed into a situation that the ecological control depth (*HE*) continues with constant value during a period of *TE*. Since the water depths deeper and shallower than *HE* also influence weightedly the physiology of the objective biota, *TE* can be called the equivalent correction time of the inundation duration for the target biota. Substituting Eq.(5) into Eq.(4),

$$T_E = \beta \frac{HL}{H_E} \text{ ....(6)}$$

Once the target biota is selected (or *HE* is decided) at a given site (or *L* is decided), the magnitude of *TE* can be calculated corresponding each high tide (*H*), based on Eq.(6).

4.3 Correction of the inundation duration by the equivalent correction time

As mentioned previously, tidal condition changes seasonally, though it has a period of one year in statistical sense. It is difficult to measure the tidal level in mangrove swamps continuously during one year, because the hydraulic and hydrologic conditions in mangrove swamps are severe for tide gauges to measure through the long term. Here we discuss the seasonal characteristics of inundation duration, based on modifying the inundation duration shown in Fig.3, which is calculated from the data available for adjacent open ocean waters.

First, once the site (*L*) is selected, the inundation duration in a case without deformation from the open sea (*TO*: t_2-t_1 shown in Fig.5b) for each tide in a year is calculated in the same manner as calculated in Fig.3. Next, if the ecological control depth (*HE*) is selected, the correction time (*TE*) is calculated from Eq.(5) for each tide (*H*) in a year. Last, the corrected inundation duration (*TC=TO+TE*) is averaged during each month. Figure 7a shows examples for *HE*=3cm, 5cm 10cm and 15cm at Stn.E (*L*=96m).

In the figure the inundation duration in a case without deformation from the open sea is referred. Further, the rate of *TC* to *TO* at each site is also added in Fig.7a. The ecological control depth *HE*=3cm or 5cm may correspond to the height of mud crabs. And *HE*=15cm may correspond to the height of aerial roots of *Bruguiera* sp. (Mazda *et al.*, 1997). It is noted that the magnitude of correction is not negligible particularly for small biota. For example, the correction up to 170% is needed for *HE*=3cm. Further, the magnitude of correction, i.e. the increasing rate, is not constant through a year, but varies seasonally.

4.4 Regional change in tidal inundation

As shown in Fig.2, tidal condition is very different from region to region. Thus, the tidal nundation characteristics are suspected to be also different from region to region. Figures 7b and 7c exemplify the corrected inundation

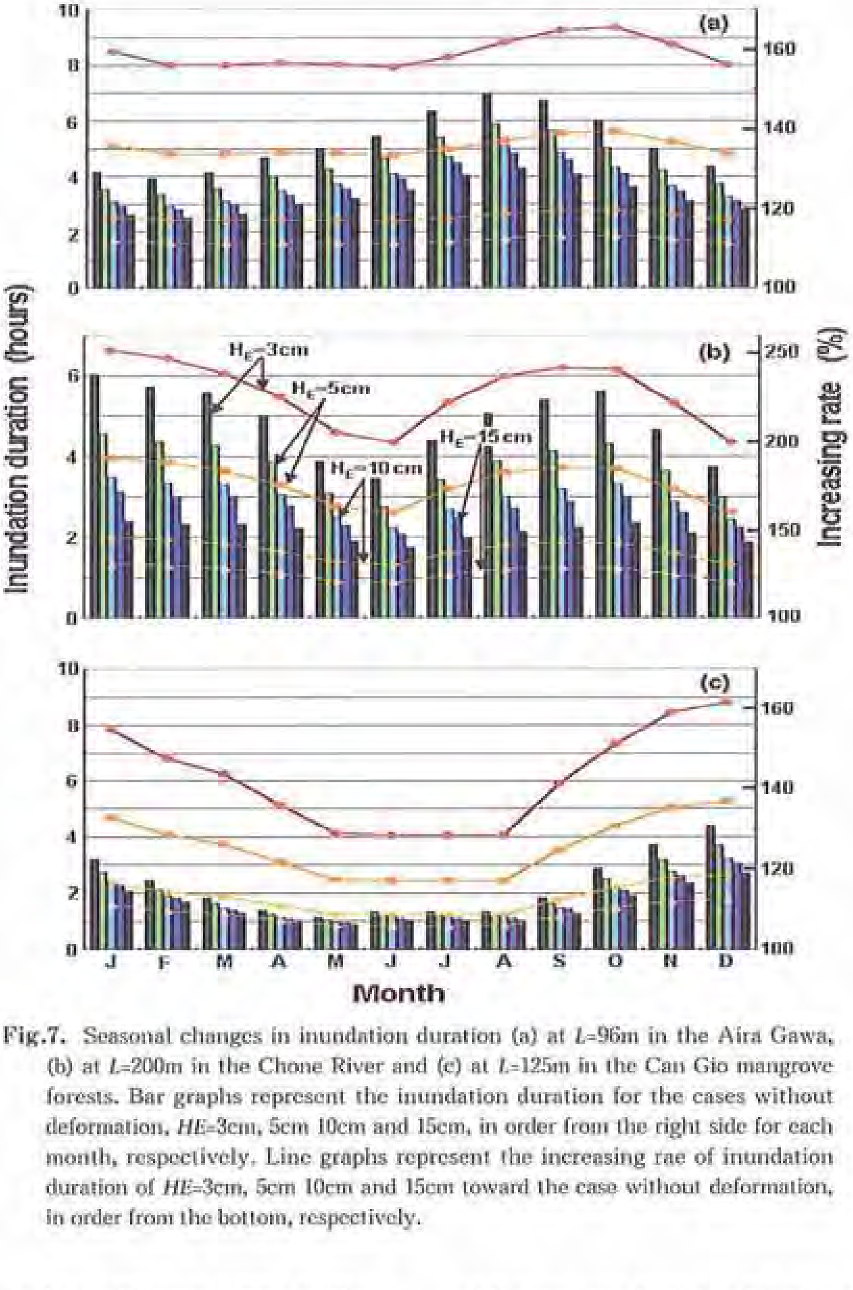

Fig.7. Seasonal changes in inundation duration (a) at L=96m in the Aira Gawa, (b) at L=200m in the Chone River and (c) at L=125m in the Can Gio mangrove forests. Bar graphs represent the inundation duration for the cases without deformation, HE=3cm, 5cm 10cm and 15cm, in order from the right side for each month, respectively. Line graphs represent the increasing rae of inundation duration of HE=3cm, 5cm 10cm and 15cm toward the case without deformation, in order from the bottom, respectively.

durations for various tidal conditions at L=200m in Chone River and at L=125m in Can Gio, respectively shown in Fig.2, but with the same value of β as that in Aira Gawa. As the magnitude of β varies with region, local topography of mangrove areas and vegetation condition, these results shown in Figs.7b and 7c are only model illustration, which emphasize the difference due to tidal condition. It is noticed that in Fig.7b the correction increases up to 240%. In Fig.7c both the inundation duration and the increasing rate change greatly through a year, as reasonably understood from the seasonal changes in tidal condition and the mean sea level (see Fig.2c). Also in Fig.7b the seasonal changes are remarkable, notwithstanding that in Fig.2b the seasonal change is not obvious, especially in the mean sea level. It should be noted that the seasonal change in Fig.7b is caused by the seasonal change in tidal range.

Fig.7: Seasonal changes in inundation duration (a) at L=96m in the Aira Gawa, (b) at L=200m in the Chone River and (c) at L=125m in the Can Gio mangrove forests. Bar graphs represent the inundation duration for the cases without deformation, HE=3cm, 5cm 10cm and 15cm,

in order from the right side for each month, respectively. Line graphs represent the increasing rae of inundation duration of *HE*=3cm, 5cm 10cm and 15cm toward the case without deformation, in order from the bottom, respectively.

4.5 Change in ecosystem through feedback processes

Mangrove ecosystems change very gradually and establish stabilized situation through feedback processes between coastal landform, water flow, atmosphere and biota itself (Fig.1) over many decades. Mazda *et al.* (1999) introduced the idea of transitional process that artificially-deforested mangrove colonies stabilize through the feedback system, based on their numerical model. Mazda *et al.* (2002) have pointed out that the transition of mangrove environment in the above mentioned Can Gio, Vietnam, which was caused by the artificial deforestation and the following reforestation, lasts during 80 years. When mangrove areas are artificially deforested or reforested, the quantitative result obtained in this paper cannot be adopted directly. It should be noted that the observational results shown in Fig.5 represent the situation stabilized after many decades through the above feedback processes. As mentioned previously, Dr. Otto Dalhaus and his collaborators are directly examining in their laboratory how the physiology of mangrove seedlings is influenced by the inundation duration, as same as salinity. Their study and our present results will help the quantitative development of Watson's inundation class model and Snedaker's idea mentioned previously, as basic findings.

5. Conclusion and remarks

The statistical tidal condition in mangrove swamps such as the frequency of tidal inundation, the inundation duration and the water depth due to tidal inundation, which influence the physiology and ecology of biota in mangrove swamps, has not been understood quantitatively. In this article, we analyzed particularly the characteristics of the tidal inundation duration, based on our field measurement in the Aira Gawa mangrove area in Iriomote Island, Japan and statistical features of the tidal elevation in open sea as an input of tidal inundation into the mangrove swamp.

It was noted that all of the frequency of tidal inundation, the tidal inundation duration and the exposure duration in the mangrove swamp varies over a wide range, corresponding to the seasonal change in tidal condition and the mean sea level in the open sea. It was shown that as tidal condition is very different from region to region, their tidal inundation characteristics are also different.

It was found that the tidal level in the mangrove swamp deforms greatly from that in the adjacent open sea. The magnitude of the deformation was formulated quantitatively with parameters, the distance from the creek bank, the depth at high tide and the vegetation condition near the soil surface. Based on this formulation and the ecological control depth, which is defined as the depth influencing the physiology and ecology of each sort of biota, the tidal inundation duration was corrected. Compared with the inundation duration in a case without deformation from the open sea, the magnitude of correction varied with the ecological control depth and seasonally.

As Snedaker has pointed out, the frequency of tidal inundation, the tidal prism volume (or the tidal inundation height) and the inundation duration are suspected to be important factors that influence the physiology and ecology of biota in mangrove swamps. Based on the consideration that the intensity of the influence is different between sorts of biota, we introduced a simple parameter, i.e. the ecological control depth as mentioned above. The significance of this parameter need to be discussed in detail, in collaboration with ecologists in this area.

In this paper we focused on the inundation duration. We acknowledge that other factors are important too, viz, the frequency of tidal inundation and the tidal inundation height. When the tide is very small, the water level at high tide in mangrove swamps cannot reach that in open sea because of drag and viscous forces due to mangrove roots particularly strong near the soil surface (Mazda *et al.*, 1999). For example, as seen in midnight on 22 April (Fig.5a), when the water depth at high tide is ca. 5cm, the water level is ca. 2cm lower than that at open sea. Accordingly, the above two statistical factors, i.e. the frequency of tidal inundation and the water depth due to tidal inundation also need to be modified from Fig.3.

In order to preserve and utilize the mangrove ecosystems, the feedback processes between coastal landform, water flow, atmosphere and biota itself through many decades must be studied quantitatively. Our present results were obtained in a steady state, in which the ecosystem was established through feedback processes during many decades. Based on these findings, the transitional processes, in which these factors are feeding back each other, should be studied.

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