An Intensive Field Survey of Physical Environments in a Mangrove Forest

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ABSTRACT

A field observation of physical environments in a mangrove forest was made in Fukido River with a surrounding mangrove swamp in Ishigaki Island, Okinawa, Japan. The characteristic flow structures are observed in creek and swamp and then found to be similar to hydraulic phenomenon in a compound meandering channel. The thermal environments in the creek and swamp are investigated by a heat budget analysis, indicating the significant importance of the heat transport by tidal current and the heat flux to swamp bottom. We also examine the sediment dynamics in detail by measuring a vertical turbulent flux of suspended sediments.

KEY WORDS: Mangroves; physical environments; flow structure; thermal environments; sediment dynamics; field measurement.

INTRODUCTION

Mangrove forests in tropical and subtropical estuaries have an important role as the basis of natural ecosystems in nearshore zone. Mangrove ecosystems have recently been exposed to large human-based environmental impacts mainly caused by the reclamation in land and coastal regions. To clarify these environmental influences on ecosystems and water environments in a mangrove forest, it is desirable to realize the detailed physical processes which control several key biological and chemical processes in mangrove regions. However we have poorly understood physical environments in mangrove estuaries compared to those in template estuaries, although field surveys on the hydrodynamics and water environments in mangrove forests have been conducted (*e.g.*, Wolanski et al., 1992; Furukawa et al., 1997). This is mainly why the mangrove estuaries are mostly located in tropical areas in less-developed countries with less research fund (Wolanski et al., 1992). Moreover the hydrodynamics and the material transports in mangrove regions are quite complex due to complicated local topography and high friction caused by densely vegetated mangrove roots. In the present study, we have attempted to conduct an intensive field observation in Fukido River with a meandering mangrove-fringed estuarine section in Ishigaki Island, Okinawa, Japan, to clarify the physical processes and water environments in a mangrove forest.

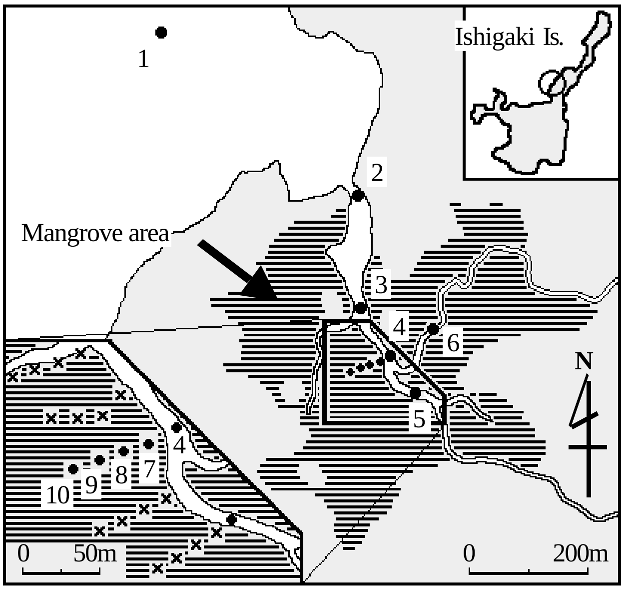


Fig. 1 Map of Fukido River with a surrounding mangrove swamp in Ishigaki Island, Okinawa, Japan, and locations of measuring stations.

FIELD MEASUREMENTS

We carried out an intensive filed survey on physical processes in a mangrove forest over about four successive tidal cycles from September 30 to October 2, 2000. The field site chosen for this study was Fukido River in the north-west part of the Ishigaki Island, Okinawa, Japan, as shown in **Fig. 1**. Fukido River drains an area of about 0.2km^2 of mangrove swamp and at its mouth the main channel is *c*. 55m wide and *c*. 1.1m deep. In this region the area in the swamp is about ten times as large as that in creeks. Major mangrove species are *Rhizophora stylosa* and *Buruguiera gymnorrhiza*.

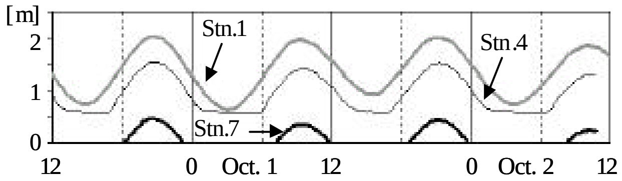
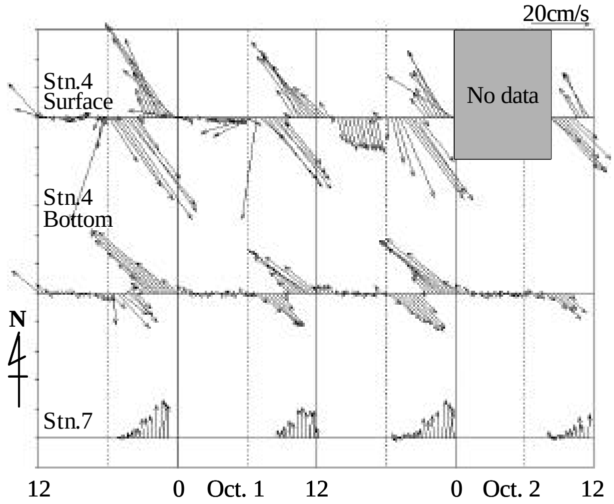
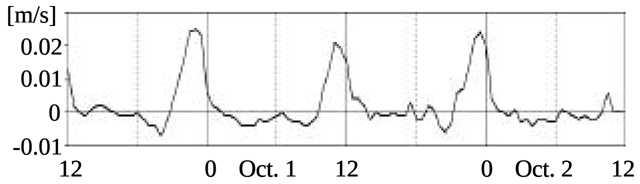


Fig. 2 Time variations of water elevation.



(a) Horizontal velocity vectors at Stns.4 and 7.



(b) Vertical near-bottom velocity at Stn.4

Fig. 3 Time series of currents in the creek and swamp.

In this field survey, we installed vertical instrument arrays at a measuring station in the reef (Stn.1), 5 stations in the creek (Stns.2~6) and 4 stations in the swamp (Stns.7~10), as shown in **Fig. 1**. The mean water depths at the measuring stations are 2.0m in the reef and about 0.8m in the creek, respectively. At all the measuring stations, we measured water temperature, salinity and water elevation. Turbidity sensors were deployed at these stations except for Stns.6 and 10. Currents were observed at Stns.1, 2, 4 and 7. In addition to these instruments, to understand the horizontal pattern of water temperature in the swamp, we also deployed 16 small thermometers in the swamp near Stns.7~10, as depicted by the crosses in **Fig. 1**. These data were recorded at 10 or 20 minutes interval.

To examine sediment dynamics in detail, we have attempted to measure a vertical turbulent flux of suspended sediments from the creek bottom and sedimentation rate in the creek and swamp. For measuring the sedimentation rate, we mounted a number of sediment traps with the diameter of 6.0cm on the bottom at Stns.1~10 and 16 stations in the swamp as the same locations of small thermometers.

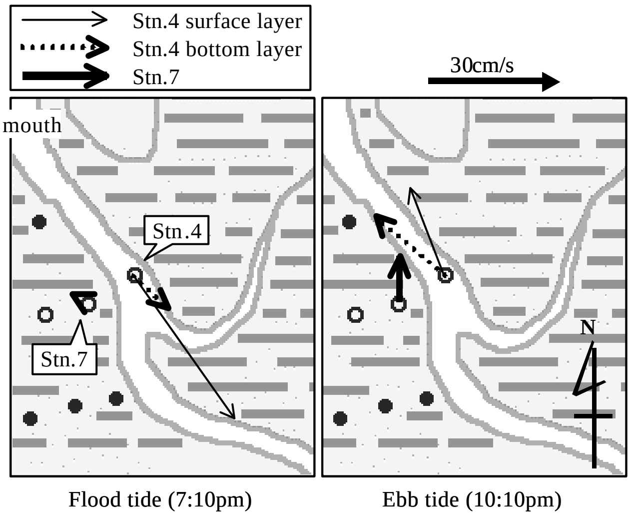


Fig.4 Horizontal distributions of currents in and around the creek (September 30, 2000).

To observe directly the vertical turbulent sediment flux, we deployed an acoustic doppler velocimeter (ADV) on the bottom at Stn.4 in the creek. The ADV measures instantaneous 3-dimentional velocities and, in addition, acoustic scattering intensities, which are known to have the potential for extracting information for suspended sediment concentration (SSC) (Hay, 1991), and hence can evaluate the vertical sediment transport by turbulence.

RESULTS AND DISCUSSIONS

Water-Elevation Fluctuations in Reef, Creek and Swamp

Figure 2 shows the time variations of water elevation at Stns.1, 4 and 7 in the reef, creek and swamp, respectively. While the water elevation at Stn.1 varied smoothly with the amplitude of about 75cm, the time variation of water elevation at Stn.4 was distorted appreciably and its value in low tides was nearly constant. This distortion of the water-elevation fluctuations was also observed at the other stations in the creek. At the low tides, there existed an exposed tidal flat, which is located between the reef and the mouth of the main creek near Stn.2. These facts indicate that the distortion of water-elevation fluctuations in the creek was caused by the disconnection between the reef and creek in low tides due to the existence of the tidal flat. The result of the water elevation at Stn.7 represents that the swamp bottom was exposed in low tides and was inundated only for several hours in high water levels. It is easy to see from **Fig. 2** that the high water level appeared almost simultaneously in the reef, creek and swamp.

Flow Structure

Figure 3(a) depicts the time series of horizontal velocity vectors in the surface and bottom layers at Stn.4 in the creek and of the horizontal near-bottom velocity at Stn.7 in the swamp. The horizontal near-bottom velocity at Stn.4 shows a well-known tidal asymmetry between the flood and ebb water velocities (Wolanski et al., 1980; 1992; Mazda et al, 1995) that the ebb current is stronger than the flood current. On the other hand, the near-surface velocity at Stn.4 indicates that the flood velocity was almost the same as the ebb velocity, revealing the characteristic vertical flow structures in the creek with appreciable differences in the flood and ebb tides. The temporal fluctuation of the vertical near-bottom velocity at Stn.4 is displayed in **Fig. 3(b)**, indicating that while the vertical velocity was nearly zero in the flood tides, the upwelling current occurred up to 2cm/s in the ebb tides. This strong upwelling motion may cause the vertical mixing process of creek water in the ebb tides.

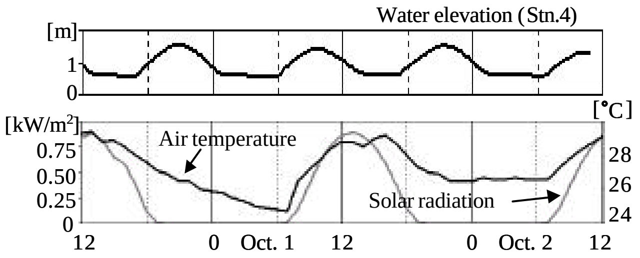
At Stn.7 in the swamp, the near-bottom velocity in the flood tides was quite different from that in the ebb tides; the velocity in the flood tides reached only 2cm/s and the flow went toward the interior of mangrove swamp. However, on the other hand, the ebb currents exceeded 10cm/s with the direction not normal but rather parallel to the creek around Stn.4.

To clarify the reason for appearance of the differences in the flood and ebb currents, we first examine the relationship between the horizontal distributions of currents in and around the creek and morphological features of the meandering creek. **Figure 4** illustrates the horizontal distributions of currents at the flood tide (7:10pm) and the ebb tide (10:10pm) in September 30, 2000 on the map of Fukido River with the surrounding mangrove swamp. The flood currents in both the layers and the near-bottom ebb current at Stn.4 went along the creek as shown in the above. However the principal direction of the near-surface ebb current at Stn.4 was different from that of the creek at Stn.4, actually corresponding to the direction to the river mouth, and moreover the main flow direction in the swamp was similar to that in the surface layer at Stn.4. It is also found from **Fig. 4** that the morphological features in the main creek around Stn.4 are meandering considerably and almost straight in the upstream and downstream, respectively. These facts demonstrate that the flow structure around the creek at the ebb tides is qualitatively consistent with that in a compound meandering channel (Muto et al., 1996; Fukuoka et al, 1997; Fukuoka, 2000). It should be also noted that since a secondary flow structure appears appreciably in a compound meandering channel in the previous study (Fukuoka et al, 1997), the strong vertical current at the ebb tides, as depicted in **Fig. 3(b)**, may be generated as a part of hydraulic phenomenon in a compound meandering channel.

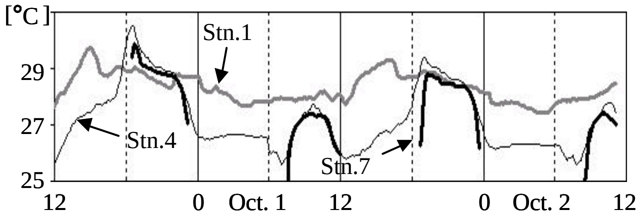
Thermal Environments

To investigate the overall characteristics on thermal environments in the mangrove area, the time series plot of the water temperatures in the reef (Stn.1), creek (Stn.4) and swamp (Stn.7) are shown in **Fig. 5** with those of air temperature and solar radiation measured at the meteorological station of Japan Meteorological Agency in Ishigaki Island. The water temperature in the reef was relatively higher than those in the creek and swamp and may be influenced appreciably by the solar radiation and tide; the highest water temperature in the reef appeared at low tides in the daytime, and then, in the subsequent flood tides, the abrupt decrease in the water temperature in the reef was caused due to the intrusion of outer sea water with lower temperature to the reef.

It is evident from **Fig. 5** that the fluctuations of the water temperature in the creek and swamp were closely related to those of tidal oscillation; at flood tide, the reef water with higher temperature causes the increase of the water temperature in the mangrove area. Comparison of the water temperatures in the creek and swamp indicates that the values of the water temperature in the creek were slightly higher than those in the swamp. The observed data of a number of thermometers deployed in the swamp revealed that the water temperature in the swamp decreased with a distance from the creek and the horizontal gradient of the water temperature reached about $0.5^\circ C/100m$ at high tide. These facts indicate that the seawater flowing into the mangrove area was cooled in the swamp and hence the water temperatures in the creek and reef were depressed in ebb tides.



(a) Meteorological state



(b) Water temperature

Fig. 5 Thermal environments in the reef, creek and swamp.

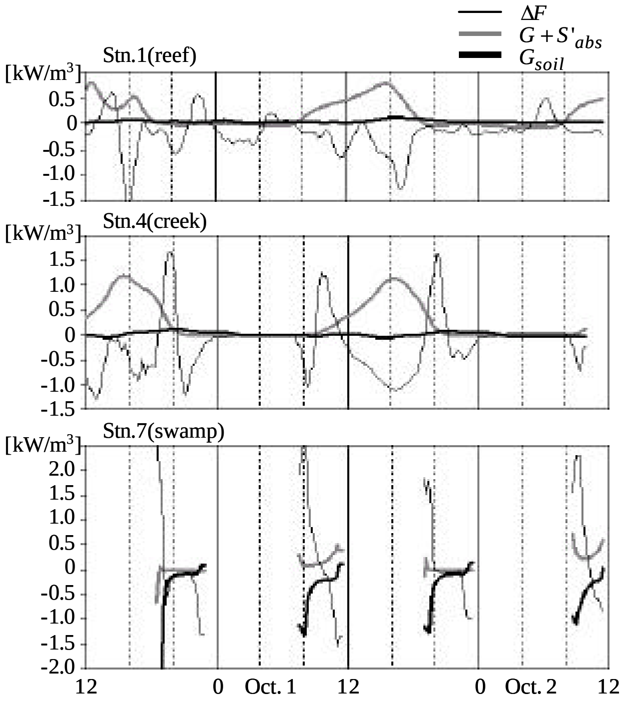


Fig. 6 Results of the heat budget analysis.

To clarify quantitatively the cause of the water temperature fluctuations in the reef, creek and swamp as described above, we have attempted to perform a heat budget analysis, in which the temporal change rate of heat storage in a water column with unit volume ΔQ equals to the summation of the heat fluxes through sea surface and sea bottom, G and G_{soil}, respectively, an advective horizontal heat flux ΔF and the gain of heat by radiative processes in the water column and the ground S'_{abs}, as given by

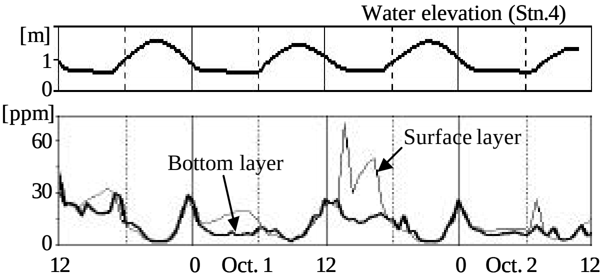


Fig. 7 Time variations of the turbidities in the creek (Stn.4).

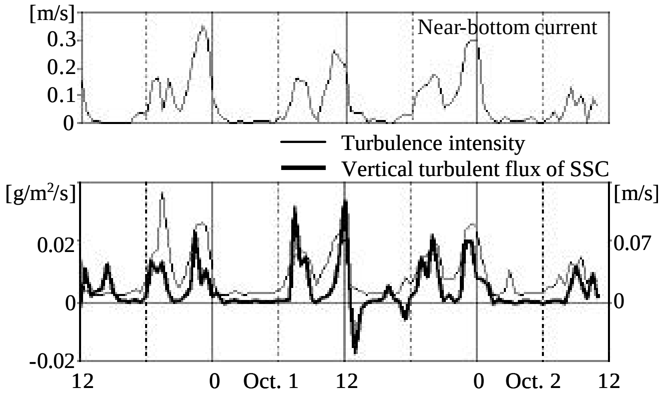


Fig. 8 Time histories of the vertical turbulent flux of SSC at Stn.4.

$$\Delta Q = G + \Delta F + G_{soil} + S'_{abs}\,. \tag{1}$$

We here incorporated the effects of radiative processes in the water and the heat flux to the ground into the heat budget analysis. In evaluating the radiation balance for the water column, the albedo on sea surface was chosen to be 0.06 as a standard value on water surface and the albedo on bottoms was given to be 0.25 for the reef and 0.14 for the creek and swamp, respectively. We also incorporated the effect of light attenuation in mangrove canopy into the heat budget analysis, in which the transmissivity of the shortwave and longwave radiations in the canopy layer was set at 0.10 in line with Clough (1992). For further detailed information in the heat budget analysis, one can refer to Nihei et al. (2002).

The results of the heat budget analysis are displayed in **Fig. 6**, where the summation of G and S'_{abs} as the total heat flux from atmosphere is depicted. In the reef, the atmospheric heat flux $G + S'_{abs}$ was prominent with the heat transport by current ΔF. In the case for creek water, these heat fluxes were also dominant but the horizontal advective heat flux ΔF varied remarkably with the larger amplitude more than 1.0KW/m^3. This is attribute to the tidal exchange between the reef with relatively higher temperature and the swamp with relatively lower temperature. Concerning the heat balance of swamp water, the horizontal advective heat flux appeared markedly and the atmospheric heat flux in the swamp was relatively smaller than that in the reef and creek. Furthermore the heat flux to the ground G_{soil} was mostly negative and lowered -1.0KW/m^3 just after the water inundated in the swamp. It is noteworthy that the heat flux to the swamp bottom plays a more important role for the cooling effect on the swamp water than the atmospheric heat flux through water surface. These results reveal that the water in the swamp was cooled considerably by the heat flux to the ground at the high tides and, in the subsequent ebb tides, the water temperatures in the creek and reef decreased due to the negative heat transport by tidal current.

Sedimentary Environments

Figure 7 shows the time variations of the turbidity fluctuations in the surface and bottom layers at Stn.4. The near-bottom turbidity at Stn.4 increased in flood and ebb tides with the current, and its maximum value in the ebb tide was rather larger than that in the flood tide. The fluctuation of the near-surface turbidity was almost similar to those of the near-bottom turbidity in the flood and ebb tides, indicating the appreciable vertical mixing in the creek. However, at low tide, the peak turbidity occurred frequently only in the surface layer, indicating the distinct vertical stratification at low tide, in which was also found in the vertical profiles of water temperature and salinity in the creek.

One of the above main results for the turbidity fluctuations in the creek is the difference of the turbidity fluctuations in flood and ebb tides, possibly relating to the vertical transport of suspended sediments due to turbulent processes and horizontal sediment transport by tidal current. For this purpose, we shall show the time histories of the vertical turbulent flux of SSC, measured by the bottom-mounted ADV in the creek, in **Fig.8**. The vertical turbulent flux of SSC was evaluated by multiplying the turbulent component of the vertical velocity by that of SSC. This figure represents that the vertical transport of SSC by turbulence increased with the near-bottom current and turbulence intensity and besides the maximum values of the vertical turbulent transport of SSC were almost comparable in the flood and ebb tides. This result, therefore, indicates that the difference of the near-bottom turbidity fluctuations in the flood and ebb tides may be closely related to the horizontal transport of suspended sediment due to the tidal current; while the horizontal transport of 'clear' reef water decreases the turbidity in the flood tide, the ebb turbidity increases due to 'turbid' water horizontally advected from the swamp and creek in the upstream.

CONCLUSIONS

To understand the overall characteristics of physical processes and water environments in a mangrove forest, we have conducted an intensive field observation in Fukido River with a surrounding mangrove swamp in the Ishigaki Island, Okinawa, Japan. The main conclusions in the present study are as follows:

(1) The observed results of flow structure in creek and swamp indicated the characteristic horizontal and vertical patterns of currents with the appreciable differences in flood and ebb tides. We found from these results that the flow structures in and around the creek are regarded as a kind of hydraulic phenomenon in a compound meandering channel.

(2) The results of the heat balance in the creek and swamp indicated that the water temperature fluctuations in the creek and swamp were considerably caused by the horizontal advective heat flux due to tidal current, and furthermore the swamp water was remarkably cooled by the heat flux to the ground.

(3) The turbidity fluctuations in the creek exhibited the evident differences of its peak values in flood and ebb tides. Since the vertical turbulent flux of suspended sediments from the creek bottom, measured by the bottom-mounted ADV, was comparable in the flood and ebb tides, the differences of the turbidity fluctuations may be subjected to the horizontal advective flux of suspended sediments in the flood and ebb tides.

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