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Tidal-scale hydrodynamics within mangrove swamps

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Abstract

Both the drag force and the horizontal eddy viscosity play a dominant role in the tidal-scale hydrodynamics in mangrove wetlands. Using field observations and basic fluid mechanics laws, the drag coefficient and the coefficient of dynamic eddy viscosity are found to be predictable as a function of the Reynolds Number based on the characteristic length scale of the vegetation. The characteristic length scale of the vegetation varies greatly with vegetation species, vegetation density and tidal elevation. Both these coefficients decrease with increasing values of the Reynolds Number. At the low range of the Reynolds Number both these coefficients reach much higher values than those typical of vegetation-poor estuaries and rivers. Consequently, the tidal flow within mangrove areas depends to a large degree upon the submerged vegetation density that varies with the tidal stage. These findings may be applied also in other vegetated tidal wetlands, including salt marshes.

Introduction

The mangrove ecosystem was constructed over a long span of time through feedback processes including the biotic activity, landform evolution, and water flows (Wolanski et al. 1980; Boto and Bunt 1981; Thom 1982; Woodroffe 1985; Mazda et al. 1990, 1999, 2004; Wolanski 1992). Boto and Bunt (1981) first recognized that the nutrient exchange between a mangrove swamp and the adjacent coastal waters depends on the magnitude of the tidal force and the elevation of the substrate relative to the tides. Wolanski (1992) suggested that the occurrence of the tidal flow asymmetry in mangrove-fringed tidal creeks depends on the magnitude of the tidal inundation into the fringing mangrove swamp; this asymmetry maintains the depth in the tidal creek, resulting in enhancing the water exchange between a mangrove swamp and the adjacent coastal waters. Further, Mazda et al. (1999) pointed out the importance of the interaction between the water flow and the biotic activity. They found that the dispersion of mangrove seeds, that is the process that controls the formation and preservation of mangrove forests, depends on the magnitude of the tidal inundation into the swamp, while the hydraulic resistance due to the vegetation density in the mangroves controls the tidal inundation. However, the quantitative information of the water flow in mangrove swamps is particularly sparse compared to those of the biotic activity and the landform, and the hydrodynamics have not been clearly recognized and quantified as the physical mechanism which helps maintain the ecosystem health.

The biological importance of the flow through vegetation has been recognized for the case of air blowing through and above plant canopies (e.g., Wilson and Shaw 1977; Raupach and Thom 1981). For water the biological importance of flow through vegetation has received less attention. Kouwen et al. (1969) and Shimizu et al. (1992) have studied the hydrodynamics of open channels with vegetation-covered beds; this was found to control the riverine natural environment. In these studies, it was suggested that both the form drag and the viscous drag of the flow control the flow field around the complex arrays of leaves and branches of a canopy or submerged grass. In this study it is shown that similar processes prevail in mangrove swamps although the spatial and time scales are different.

The water flow in mangrove areas varies with periods of diurnal tides and sea waves, while flows in river and air are steady or quasi-steady. Further, the behavior of tidal flow that has a diurnal or semi-diurnal time scale is very different from that of sea waves with periods less than ca. 20 s. The latter has been studied by Furukawa et al. (1997), Mazda et al. (1997a) and Massel et al. (1999). An unifying theory of tidal scale hydrodynamics in mangrove swamps is proposed in this paper by quantifying the relative importance of the drag force and the horizontal eddy viscosity as a function of the characteristic length scale of vegetation.

Basic concept of hydrodynamics in mangrove swamps

The water flowing within mangrove swamps is resisted by the drag force due to mangrove trees and their roots, by the bottom friction on the uneven mud floor, and by the eddy viscosity due to turbulent motions of water through narrow openings between trees/roots. The mechanisms of the drag force in mangrove swamps that include the effect of the bottom friction have been analyzed quantitatively by Mazda et al. (1997b) and Magi (2000), while Mazda (2003), Kobashi and Mazda (2005), Mazda et al. (2004) and Okada (2004) have studied the eddy viscosity in mangrove swamps theoretically and in field observations. However, at present, no unifying theory has been proposed to quantify the relative importance of these forces.

The schematic view of the control volume in a mangrove swamp is shown in Figure 1. The volume V (a hatched rectangular element in Figure 1a) with a horizontal area $S\,(\Delta x\,\Delta y)$ and a depth H is divided into two parts as

$$V = V_{\mathrm{M}} + V_{\mathrm{W}}, \quad (1)$$

where V_{M} is the total volume of obstacles including submerged tree trunks and roots over the substrate, and V_{W} is the volume of water in V. Following the concept of Raupach and Thom (1981) and Shimizu et al. (1992) who modeled the drag force and the eddy viscosity separately, the momentum equations are:

$$\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right)V_{\mathrm{W}} = -g\frac{\partial \zeta}{\partial x}V_{\mathrm{W}} + F_{\mathrm{D},x} + (F_{\mathrm{T},x1} + F_{\mathrm{T},x2}) + F_{\mathrm{B},x} \quad (2)$$

$$\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right)V_{\mathrm{W}} = -g\frac{\partial \zeta}{\partial y}V_{\mathrm{W}} + F_{\mathrm{D},y} + (F_{\mathrm{T},y1} + F_{\mathrm{T},y2}) + F_{\mathrm{B},y}, \quad (3)$$

where x and y are the horizontal axes (Figure 1b), t is the time, u and v are the depth-averaged velocities in the x- and y-directions, respectively, ζ is the water surface elevation, g is the acceleration of gravity, $F_{\mathrm{D},x}$ and $F_{\mathrm{D},y}$ are the x- and y-components of the drag force due to submerged mangrove trees/roots, $F_{\mathrm{T},x1}$ and $F_{\mathrm{T},x2}$ are the shear stresses (eddy viscosities) on two vertical planes along x-axis, $F_{\mathrm{T},y1}$ and $F_{\mathrm{T},y2}$ are the shear stresses (eddy viscosities) on two vertical planes along y-axis, and $F_{\mathrm{B},x}$ and $F_{\mathrm{B},y}$ are the x- and y-components of the bottom friction.

The shear stress on the water surface can be ignored because of calm conditions under the mangrove canopy. F_{D}, F_{T} and F_{B} are assumed to depend on both the vegetation density and the bottom roughness. Further, F_{D} and F_{T} may vary with the tidal stage because the submerged portion of mangrove vegetation varies with the tidal stage. Consequently, each of these terms has to be formulated with the vegetation condition and tidal condition.

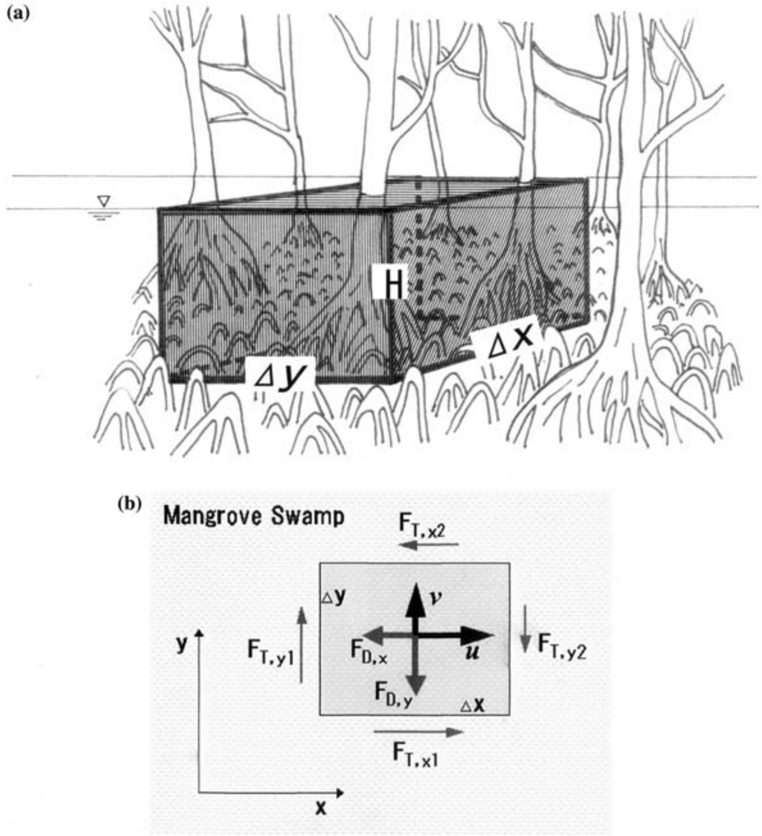

Figure 1. (a) A sketch of the control volume in a mangrove swamp and (b) a schematic plan view of the hydrodynamics.

Quantification of the drag force

First, a formulation is found for $F_{D,x}$ and $F_{D,y}$ in Eqs. (2) and (3), respectively, i.e. the drag force in mangrove swamps. Eqs. (2) and (3) can be simplified as follows, focusing on physical properties of the riverine type mangrove area (R-type mangal; Cintron and Novelli 1984). The R-type mangal is composed of long tidal creeks and wide, flat, heavily vegetated mangrove swamps.

The x-axis is oriented along the creek pointing upstream, the y-axis in the direction perpendicular to the creek. Since the tidal wavelength (typically several tens of km) is much longer than the length of a creek (typically 5 km), the water flow in the swamp is predominantly in the y-direction everywhere except in a small transition area near the banks (Wolanski et al. 1980; Mazda et al. 1997b). The second term on the left side in Eq. (3) can then be neglected, because the velocity gradient in the direction along the x-axis is negligible. The third and fourth terms on the right side in Eq. (3) cancel each other because of the same reason. Further, the third term on the left side can be neglected, because in the inner portion of the swamp the velocity gradient along the y-axis is negligible. In addition, since the tidal flow varies at periods of 6 (or 12) h, the first term on the left side is also negligible. Thus Eq. (3) becomes:

$$g\frac{\partial \zeta}{\partial y}V_{\mathrm{W}} = F_{\mathrm{D},y} + F_{\mathrm{B},y} \tag{4}$$

Eq. (4) shows that the pressure gradient due to water surface slope is balanced by the sum of the drag force and the bottom friction force (Figure 2). Wolanski et al. (1992) suggested that the magnitude of the bottom friction is too small to balance the water surface slope. Consequently, at zero-order the water surface slope is mainly balanced by the drag force. Thus, including the bottom friction conveniently in the drag force, Eq. (4) reduces to

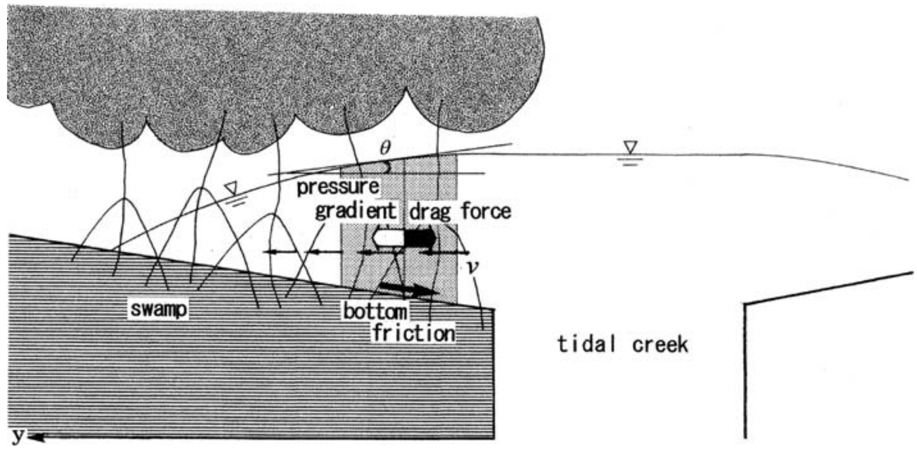

Figure 2. A schematic cross-section in an inner portion of a mangrove swamp of the R-type mangal.

$$g\frac{\partial\zeta}{\partial y}V_{\mathrm{W}} = F_{\mathrm{D},y} \qquad (5)$$

The validity of Eq. (5) and the significance of the above assumptions have been confirmed by the field observations of Mazda et al. (1997b) and Magi (2000) (see also Table 1).

From the engineering literature, the drag force can be parameterized as a function of vegetation density, following Wilson and Shaw (1977) and Raupach and Thom (1981):

$$F_{\mathrm{D},y} = -\frac{1}{2}C_{\mathrm{D}}Av|v|, \qquad (6)$$

where A is the total projected area of the obstacles to the flow in the control volume V and C_{D} is the drag coefficient. Substituting Eq. (6) into Eq. (5), the drag coefficient C_D is represented as

$$C_{\mathrm{D}} = -2g\frac{\partial\zeta}{\partial y}\frac{L}{v|v|}, \qquad (7)$$

where L is defined by

$$L = \frac{V_{\mathrm{W}}}{A} \qquad (8)$$

Eq. (8) shows that L has a dimension of length, and includes information about the spacing between vegetations such as mangrove trunks and roots in the swamp. Mazda et al. (1997b) suggested that L varies greatly with vegetation species, vegetation density, and tidal elevation. A few examples of L that varies with tidal level are shown in Figure 3. The method for calculation of L is explained by Mazda et al. (1997b). According to these considerations, L is termed the representative length of the vegetation.

Table 1. Observation sites, durations of observations, and vegetation species used for calculation of the drag coefficient.

Observation site	Duration	Vegetation
Coral Creek(1) (Australia)	July/1989 (3 tides)	*Rhizophora* sp.
Nakama-Gawa(1) (Japan)	September/1990 (9 tides)	*Bruguiera* sp.
Nakama-Gawa(2) (Japan)	September/1991 (9 tides)	*Bruguiera* sp.
Nakama-Gawa(3) (Japan)	April/1992 (4 tides)	*Bruguiera* sp.
Coral Creek(2) (Australia)	May–June/1992 (4 tides)	*Rhizophora* sp.
Nakama-Gawa(4) (Japan)	June/1994 (14 tides)	*Bruguiera* sp.
Shiira-Gawa (Japan)	July/1995 (14 tides)	*Rhizophora* sp.
Maera-Gawa (Japan)	May–June/1996 (18 tides)	*Rhizophora* sp.
Funaura-Bay (Japan)	July/1996 (1 tide)	*Rhizophora* sp.
Can-Gio (Vietnam)	September/1997 (7 tides)	*Rhizophora* sp.

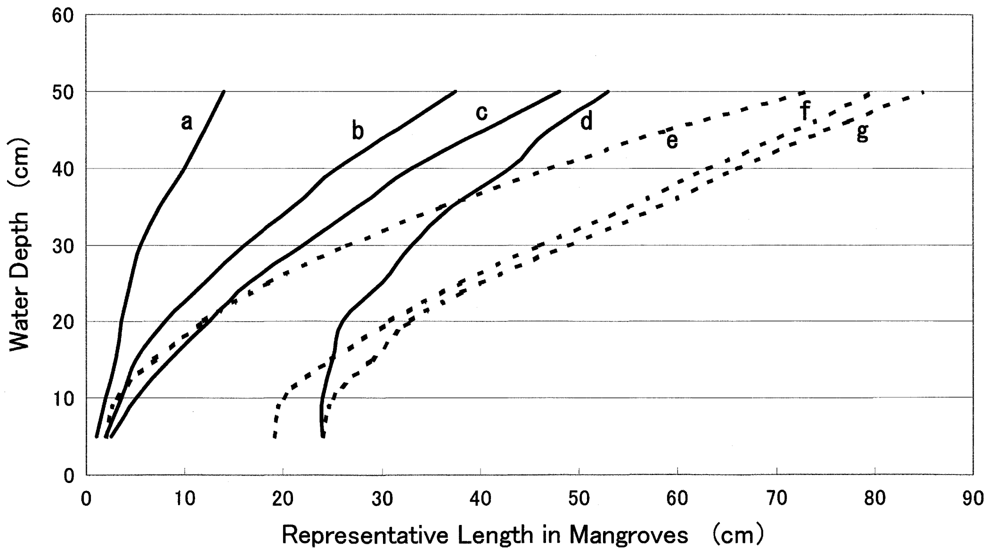

Figure 3. The dependence of L on the water depth. a: Coral Creek, Hinchinbrook Island, Australia (*Rhizophora* sp.) b: Can-Gio, Ho-Chi-Minh, Vietnam (*Rhizophora* sp.) c: Maera-Gawa, Iriomote Island, Japan (*Rhizophora* sp.) d: Rio-Chone, Manabi, Ecuador (*Rhizophora* sp.) e: Aira-Gawa, Iriomote Island, Japan (*Bruguiera* sp.) f: Nakama-Gawa, Iriomote Island, Japan (*Bruguiera* sp.) g: Maera-Gawa, Iriomote Island, Japan (*Bruguiera* sp.).

Mazda et al. (1997b) and Magi (2000) have calculated the drag coefficient C_D using Eq. (7), based on field observations that include different sites, different mangrove species, and different tidal conditions (Table 1). The drag coefficient that they calculated is plotted in Figure 4 against the Reynolds Number Re defined using the representative length of the vegetation L,

$$Re = \frac{vL}{\nu}, \tag{9}$$

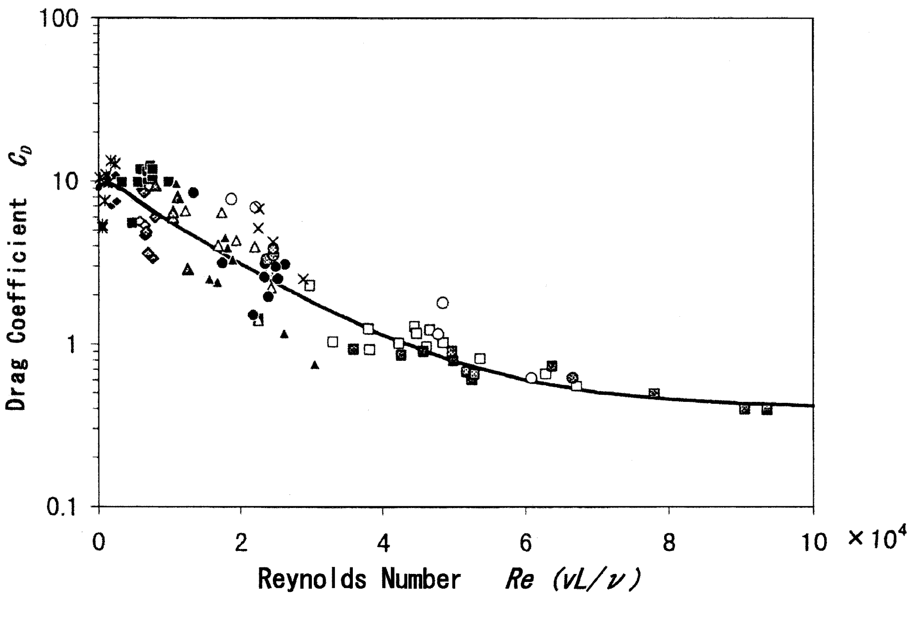

Figure 4. The relationship between the drag coefficient C_D and the Reynolds Number Re. The marks show the different observation sites (see Table 1).

where v is the kinematic viscosity. Figure 4 shows a unique relationship between C_D and Re. The magnitude of C_D decreases with increasing values of Re. At the low range of Re, the value of C_D reaches a value as high as 10, which is very large (e.g., Batchelor 1967). This relationship is qualitatively similar to the result by Kouwen et al. (1969), which was obtained in an open channel with grass beds.

Thus, the drag coefficient in mangrove swamps in tidal time scale depends not only on the current velocity, but also on the submerged vegetation and on the tidal stage.

The relationship shown in Figure 4 has been measured in an inner portion of R-type mangal and from Eq. (3) in a direction perpendicular to the creek. However, the result can be adapted to any other area in different type mangals (Cintron and Novelli 1984) and to any other direction, because the horizontal distribution of mangrove vegetation is isotropic and the physical mechanism of C_D is universal in natural mangrove vegetations. Thus, $F_{D,x}$ in Eq. (2) will also follow the same relationship as shown in Figure 4.

Quantification of the eddy viscosity

The flow field depends not only on the form drag mentioned above, but also on the viscous drag due to vegetation distribution. In field observations of R-type mangals, i.e. Coral Creek in Australia (Wolanski et al. 1980), Aira-Gawa in Iriomote Island, Japan (Kobashi and Mazda 2005), and Rio-Chone in Ecuador (Okada 2004), the tidal flow in a swamp near a creek is predominantly parallel to the creek. This suggests that the horizontal eddy viscosity, i.e. the lateral shear stress, is important in the hydrodynamics of mangrove swamps (Figure 5). Following Mazda et al. (2004), the horizontal eddy viscosity, F_T in Eqs. (2) and (3), can be parameterized using Newton's law of viscosity (e.g., Lamb 1932; Raupach and Thom 1981). Consequently, Eq. (2) is rearranged as,

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial \zeta}{\partial x} - \frac{C_D u|u|}{2L} + f\frac{\partial^2 u}{\partial y^2}, \quad (10)$$

where the third term on the right side is the eddy viscosity, and f is the (still unknown) coefficient of dynamic eddy viscosity.

For the same reasons as in the above section, the three terms on the left side and the first term on the right side in Eq. (10) can be ignored (for details, see Kobashi and Mazda 2004). Thus Eq. (10) reduces to

$$0 = -\frac{C_D u|u|}{2L} + f\frac{\partial^2 u}{\partial y^2} \quad (11)$$

Eq. (11) implies that at zero-order the drag force balances with the eddy viscosity force. Thus, in a swamp near a creek, the energy supplied through

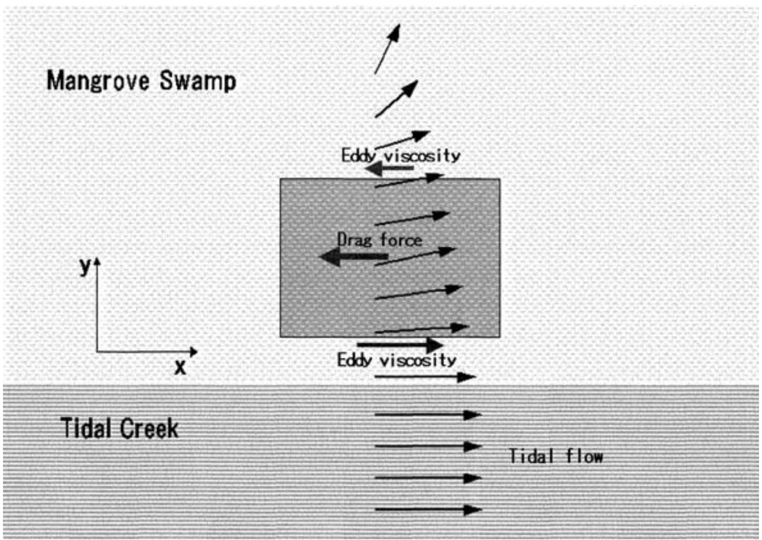

Figure 5. A schematic plan view of the hydrodynamics in a mangrove swamp near the tidal creek.

the shear stress due to the tidal flow in the creek is dissipated by the drag force due to mangrove vegetations. From Eq. (11) the coefficient of dynamic eddy viscosity f is represented as

$$f = \frac{C_D u|u|}{2L}\left(\frac{\partial^2 u}{\partial y^2}\right)^{-1} \quad (12)$$

Equation (12) can be used to calculate the magnitude of f, based on field observations, because the magnitudes of C_D and L in Eq. (12) can be determined using Figure 3 and 4, respectively. Okada (2004) has calculated values of f, based on five observations in Aira-Gawa in Japan, Rio-Chone in Ecuador and Maera-Gawa in Japan, which include various mangrove species and various tidal conditions (Table 2). These values are plotted in Figure 6 against the Reynolds Number *Re*. Figure 6 shows that the magnitude of f varies widely from an order of 10^3 cm^2 s^{-1} in the high range of *Re* to an order of 10^5 cm^2 s^{-1} in the low range of *Re*, which are values not experienced in vegetation-poor estuaries and rivers (Dyer 1973; Neumann and Pierson 1966). Figure 6 suggests that the mechanism of the eddy viscosity in mangrove swamps with many submerged obstacles is quite different from that in vegetation-poor rivers and estuaries.

Table 2. Observation sites, durations of observations and vegetation species used for calculation of the coefficient of dynamic eddy viscosity.

Observation site	Duration	Vegetation
Aira-Gawa(1) (Japan)	August/2001 (7 tides)	*Bruguiera* sp.
Aira-Gawa(2) (Japan)	May/2002 (6 tides)	*Bruguiera* sp.
Rio-Chone (Ecuador)	March/2003 (3 tides)	*Rhizophora* sp.
Maera-Gawa(1) (Japan)	August/2003 (11 tides)	*Bruguiera* sp.
Maera-Gawa(2) (Japan)	August/2003 (6 tides)	*Rhizophora* sp.

Conclusion and remarks

Both the drag force and the eddy viscosity play a dominant role in the tidal-scale hydrodynamics in mangrove swamps. The drag coefficient C_D can be expressed as a function of the Reynolds Number *Re* defined using the representative length of the vegetation L (Figure 4). The value of C_D includes the effect of the bottom resistance, but it does not include the effect of the eddy viscosity caused by the horizontal velocity shear. The coefficient of dynamic eddy viscosity f can also be formulated as a function of *Re* (Figure 6). It is emphasized that the characteristics of C_D in Figure 4 and f in Figure 6 are universal in any mangrove area and any tidal condition. Consequently, for any mangrove area the following, vertically-averaged, momentum equations can be simplified by using the parameters L, C_D, and f, the values of which can be readily found from Figures 3, 4 and 6.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial \zeta}{\partial x} - \frac{C_D u\sqrt{u^2+v^2}}{2L} + f\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \quad (13)$$

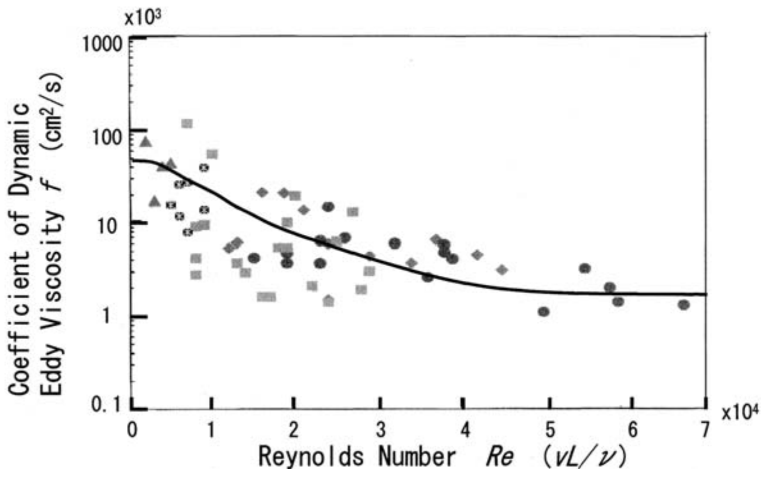

Figure 6. The relationship between the coefficient of dynamic eddy viscosity f and the Reynolds Number *Re*. The marks show the different observation sites (see Table 2).

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial \zeta}{\partial y}-\frac{C_D v\sqrt{u^2+v^2}}{2L}+f\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \quad (14)$$

The characteristics of the drag coefficient C_D and the coefficient of dynamic eddy viscosity f are summarized as follows:

(1) Both C_D and f are unique functions of the Reynolds Number Re defined using the representative length of the vegetation L which varies greatly not only with vegetation species and vegetation density but also with the tidal level.
(2) Both C_D and f decrease with increasing values of Re.
(3) At the low range of Re, C_D, and f have values much higher than those typical of vegetation-poor estuaries and rivers.

Additional data from more localities around the world should be collected to improve the accuracy of the formulation. Also further mathematical studies are needed of flow through vegetation to better quantify the dependences of both C_D and f upon Re.

These findings may be applied also in other vegetated tidal wetlands, including salt marshes. Such field and mathematical studies are needed to assess the environmental changes (e.g., eutrophication and siltation) in tidal creeks and vegetated tidal wetlands due to human actions; such actions can include dramatic ones as mangrove land reclamation (e.g., Mazda et al. 2002), less damaging activities as sustainable forestry (e.g., Mazda et al. 1999), and even reforestation of mangrove ecosystems for coastal protection against storms.

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