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Variability of the Constant Flow in Ôsaka Bay*

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Abstract: Some current measurements were carried out in Ôsaka Bay to understand the characteristics and causes of fluctuations of the constant flow in the bay. It is shown that the major part of fluctuation of the constant flow in Ôsaka Bay is the wind-driven current. The direction of the wind-driven current in the near surface water deflects clockwise through 10 to 30 degrees from the wind direction while in the lower layer the current deflects counter-clockwise to that in the near surface water in the eastern half of Ôsaka bay. The speed of the wind-driven current in the near surface water is 0.5 to 1.5 % of the wind speed while that in the lower layer is smaller than that in the near surface water in this area.

1. Introduction

It is well known that constant flow plays a very important role in the dispersion of material in coastal seas (YANAGI, 1974). Here constant flow is defined as the velocity averaged over the diurnal tidal period of 24 hours 50 minutes which is thought to be caused by the wind, fresh water discharge, currents from the open sea and nonlinearity of tidal currents, etc. Hence it is not necessary that the constant flow be steady both in speed and in direction. In a semi-enclosed coastal sea such as the Seto Inland Sea, the constant flow is not influenced directly by the current from the open sea, and consequently the major parts of the constant flow are thought to be the tidal residual flow, the density current and the wind-driven current (YANAGI and HIGUCHI, 1979). Tidal residual flow is defined as the flow which is caused through the nonlinearity of tidal currents in relation to boundary geometry and bottom topography (YANAGI, 1976). As tidal current is nearly stable throughout the year though its amplitude changes from the sping tide to the neap tide, the tidal residual flow is thought to be fairly steady in coastal seas. The density current is thought to be steady on the time scale of several days except in the case of river flood, because it is caused mainly by warming or cooling at the sea surface and by river discharge. On the other hand, the wind-driven current in coastal seas is thought to play a role in the fluctuating component of the constant flow since there are no winds that prevail through out the year, such as trade winds or prevailing westerlies in coastal seas. Accordingly we may expect that the major part of the day to day fluctuation of the constant flow in coastal seas is due to the wind-driven current. OONISHI (1979) showed through numerical experiment that the steady components of the constant flow in Ôsaka bay are the tidal residual flow and the density current. In this paper I will try to clarify the quantitative relation between the wind and the wind-driven current using current observations in Ôsaka Bay.

2. Observations

Current measurements were carried out from March 17 to March 31 in 1978 (hereafter refered to as spring in this paper) and from August 31 to September 15 in 1978 (hereafter refered to as autumn). Locations of mooring stations are shown in Fig. 1. Aanderaa RCM-4 current meters were set 3 m below the low water surface (hereafter refered to as the near surface water), 3 m above the bottom (hereafter refered to as the near bottom water) and at half the total depth (hereafter refered to as the intermediate water) on a mooring line at each of the stations except Stns. S-5 and S-6. Current meters were not set in the intermediate water at Stns. S-5 and S-6 where the water depth is only about 10 m. The water depths of other stations are 16 to 20 m. In the case of the observations in spring current meters were not

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set at Stn. MT and in the intermediate water at Stns. S-3 and S-4. Water temperature, salinity, flow direction and flow speed were measured at five minute intervals. The data were not obtained in the near surface water at Stn. MT and in the near bottom water at Stns. S-1 and S-3 in autumn because of a malfunction of the current meter. Tidal levels around Ôsaka Bay, wave heights at Stn. MT, river discharges of the Yodo River and the Yamato River and wind speeds and wind directions at Stn. MT and Stn. C were also obtained.

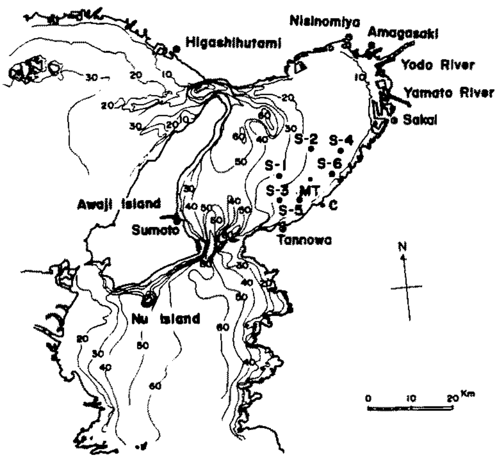

Fig. 1. Map showing the observation stations in Ôsaka Bay. Numerals show the depth in m. Current measurements were carried out at Stns. S-1, S-2, S-3, S-4, S-5, S-6 and MT. Tide levels were observed at Higashihutami, Nishinomiya, Sakai, Stn. MT, Tannowa, Sumoto and Nu Island. River discharges were observed at the mouth of the Yodo River and the Yamato River. Wave height was observed at Stn. MT. Wind was observed at Stn. MT and Stn. C.

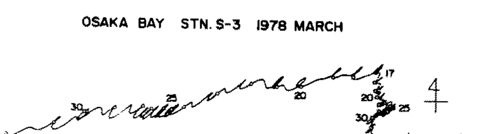

Fig. 2. The progressive vector diagrams of observed tidal currents at Stn. S-3 from March 17 to April 1, 1978. The solid line is for the near surface water and the broken line for the near bottom water. Numerals show the dates and open circle and open square show the position of the vector at midnight on each day.

3. Results

Water temperature and salinity were nearly the same from the surface to the bottom and their average values over 15 days were about

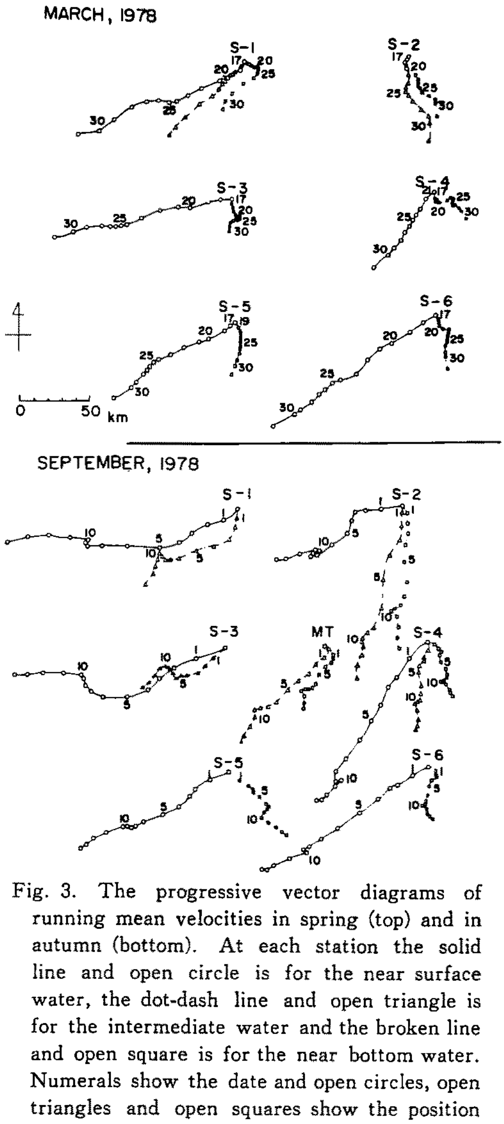

Fig. 3. The progressive vector diagrams of running mean velocities in spring (top) and in autumn (bottom). At each station the solid line and open circle is for the near surface water, the dot-dash line and open triangle is for the intermediate water and the broken line and open square is for the near bottom water. Numerals show the date and open circles, open triangles and open squares show the position of the vector at noon on each day. In spring the diagram in the near surface at Stn. S-4 begins on March 21 and that in the near bottom water at Stn. S-5 begins on March 19 because earlier data were unreliable. In autumn only the data at Stn. MT were obtained through August 30 to September 13. Note that a drift of 10 km day^{-1} is equivalent to a current of about 12 cm s^{-1}.

10°C and 32 ‰ respectively in spring. They were also the same from the surface to the bottom and average values over 15 days were about 26°C and 33 ‰ in autumn. It is thought that density stratification did not influence the velocity field in either season.

A progressive vector diagram of observed tidal current at Stn. S-3 in spring is shown in Fig. 2. Water particles in the near surface water flow towards the west-south-west due to the constant flow superimposed on the oscillating motion of the tidal current. Water particles in the near bottom water also flow towards the south with the same motion as in the near surface water. The speed averaged over 15 days is about 10 cm s^{-1} in the near surface water and about 2 cm s^{-1} in the near bottom water. It can be seen from this figure that constant flow plays a more important role than the tidal current in the long period transport of material in this sea.

The progressive vector diagram of constant flow, which is obtained from the 24 hour 50 minute running mean of observed velocity is shown in Fig. 3. The speed averaged over 15 days in the near surface water is about 7 to 10 cm s^{-1} in spring and about 8 to 14 cm s^{-1} in autumn. Those in the near bottom water are about 3 to 5 cm s^{-1} in spring and about 3 to 7 cm s^{-1} in autumn. The intermediate water flows in between the near surface water and the near bottom water. There is a strong resemblence between the fluctuations of constant flows at these stations through the whole water column, that is, constant flows change their speeds and directions characteristically on March 25 in spring and on September 10 in autumn as shown in Fig. 3. The fluctuating component of constant flow (hereafter denoted by FCCF in this paper) is obtained by subtracting the

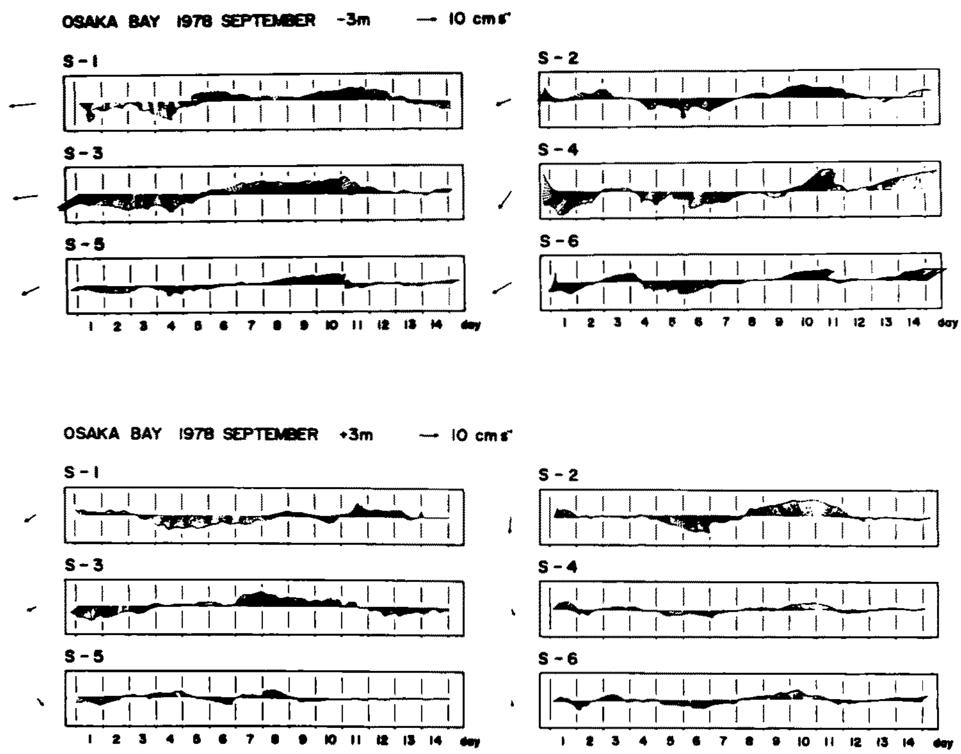

Fig. 4. Time series of hourly velocity of FCCF in the near surface water (top) and those in the near bottom water (bottom) in autumn. Each arrow indicates current vector. North is in the vertical upward direction. The data for the near bottom water at Stns. S-1 and S-3 are replaced by those for the intermediate water because of the lack of data. The vector on the left side shows the 15 day average velocity of constant flow.

mean value of constant flow averaged over 15 days from the above mentioned constant flow. The time series of FCCF in the near surface water and those in the near bottom water in autumn are shown in Fig. 4. The main components of the velocity averaged over 15 days shown on the left side of Fig. 4 is thought to be the tidal residual flow and the density current as described by OONISHI (1979). He showed that the tidal residual flow has the same speed from the surface to the bottom but the density current in the upper layer is stronger than that in the lower layer in this area. The fluctuating patterns of FCCF show a similar tendency in the near surface water at Stns. S-2, S-4, S-5 and S-6 and in the near bottom water at Stns. S-2, S-4 and S-6, that is, it shows a southward flow on September 1 to 2 and on September 6 and a northward flow on September 10 and 14. The maximum speed that FCCF attains is about 15 cm s^{-1} both in the near surface water and in the near bottom water.

4. Discussion

Tide and the fluctuation of mean sea level averaged over 25 hours around the observed area are examined to understand their relations to the fluctuation of FCCF. In the spring tide the semidiurnal tide whose amplitude is about 60 cm predominates. In the neap tide the diurnal tide whose amplitude is about 30 cm predominates. Mean sea levels around the observed area fluctuate with an amplitude of 4 to 5 cm and a period of 6 to 7 days. They do not have a direct relation to the fluctuation of FCCF which is shown in Fig. 4. The fluctuations of river discharges of the Yodo River and Yamato River are also examined. The river discharge of the Yamato River is about one tenth of that of the Yodo River. The usual river discharge of the Yodo River in this season is about 100 $m^3 s^{-1}$. That suddenly increased to 200 $m^3 s^{-1}$ on September 4, decreased to 150 $m^3 s^{-1}$ on September 5 and recovered to normal on September 6 as shown in Fig. 5. The strong southward flow of FCCF in the near surface water at Stns. S-2, S-4 and S-6 on September 5 to 6 may relate to this sudden increase of river discharge. However, overall the fluctuation of river discharge does not seem to account for the fluctuation of FCCF.

The variation of wind is examined (Fig. 6). Wind directions at Stn. MT on the sea are almost similar to those at Stn. C on the coast

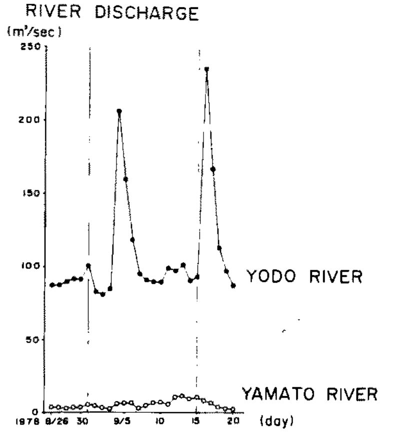

Fig. 5. Daily mean discharges of the Yodo River and the Yamato River.

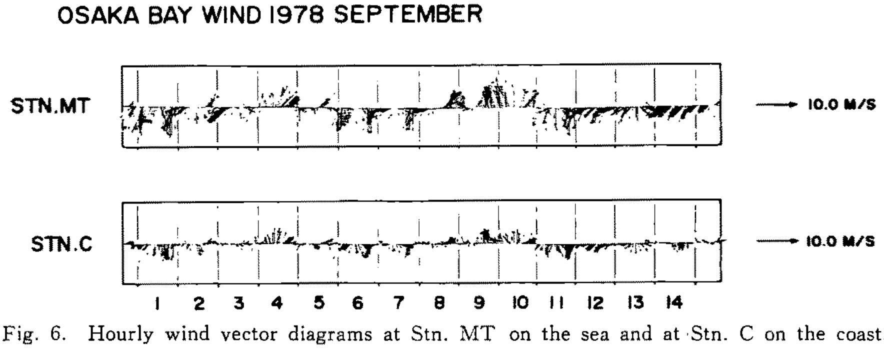

Fig. 6. Hourly wind vector diagrams at Stn. MT on the sea and at Stn. C on the coast. The data at Stn. MT was obtained 15 m above the mean sea surface and that at Stn. C 10 m above the ground.

and wind speeds at Stn. MT are 1.5 to 2.0 times those at Stn. C. A fairly regular variation with a period of 4 to 5 days seems to exist, with a strong north wind on September 1 and on September 6 and a strong south wind on September 4 and on September 9 to 10. This variation is due to the movements of the continental high pressure and low pressure areas. During this period the continental high pressure passed over Japan for a period of 4 to 5 days. By comparison of Fig. 6 with Fig. 4 it can be seen that the characteristic fluctuation of the wind correspond well to those of FCCF and the main cause of the fluctuation of the constant flow is thought to be the wind. Following the same procedure, it is seen that the constant flow fluctuates with a period of 2 to 3 days and an amplitude of 15 cm s^{-1} in spring and the main cause of this fluctuation is thought to be the wind. The horizontal and vertical distributions of FCCF are shown for the north wind and for the south wind at the top and the bottom of Fig. 7, respectively. The directions of FCCF in the near surface water deflect clockwise to the wind heading direction for both the north and south winds. The directions of FCCF in the lower layer deflect counterclockwise to those in the near surface water. According to Ekman theory the direction of the wind-driven current

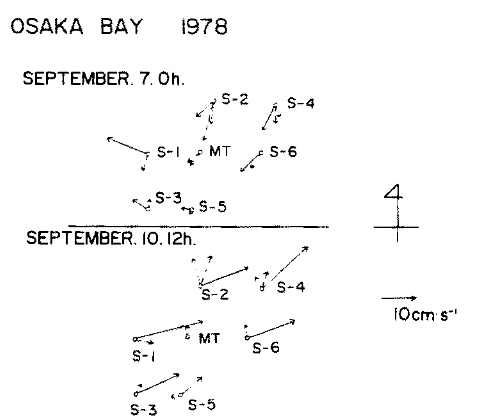

Fig. 7. Horizontal and vertical distributions of FCCF at midnight on September 7, when a north wind was blowing (top) and those at noon on September 10, when a south wind was blowing (bottom). The solid line vector shows FCCF in the near surface water, the dot-dash line vector is for the intermediate water and the broken line vector is for the near bottom water.

in the lower layer deflects clockwise from that in the upper layer in the open sea of the northern hemisphere. But the results of observations in the coastal sea sometimes do not coincide with that of Ekman theory. The reason for this may be attributed to the fact that the vertical distribution of wind-driven current directions depends on the coupling effect of the horizontal and vertical circulations induced by the wind. The major features of wind induced circulations in a bay are strongly controlled by the geomorphology of the area concerned, *i.e.* the configuration of the coast line and submarine topography, as well as the direction and speed of the wind. There may be a clockwise spiral of wind-driven current at some places in a bay and a counterclockwise spiral at other places in the same bay.

The simultaneous difference between the hourly direction of FCCF in the near surface water and that of wind heading direction is shown in Fig. 8. A positive value denotes that the direction of FCCF deflects counterclockwise to the wind direction. The mode of histogram seems to lie at -10 to -30 degrees, that is, the wind-driven current in the near surface water is deflected clockwise through about 10 to 30 degrees from the wind direction in this area. This result coincides with that of KIRWAN *et al.* (1979) in the open sea. In classical theory the wind-driven current is a function of the product of wind magnitude and the wind vector. In this theory the shear stress is continuous across the air-sea interface but the velocity is not. On the other hand, empirically the wind-

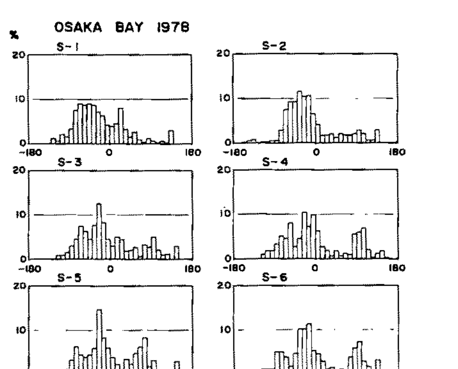

Fig. 8. Composite histogram of the difference of the wind direction minus the flow direction of FCCF in the near surface water in autumn.

driven current has been linearly related to the wind by NEUMANN and PIERSON (1966; pp. 208-211). Theoretically a linear relation can arise from matching turbulent boundary layers on either side of the interface (KIRWAN *et al.* 1979). If we devide the hourly speed of FCCF in the near surface water by the wind speed at Stn. MT without phase lag (Fig. 9a), the mode of histogram seems to lie at 0.5 to 1.5%. In comparison the histogram in the case of dividing by the square of wind speed (Fig. 9b) instead of wind speed is rather flat. The wind-driven current in the near surface water is linearly related to the wind and a wind-driven current of 5 to 15 cm s^{-1} is caused by winds of 10 m s^{-1} in this area.

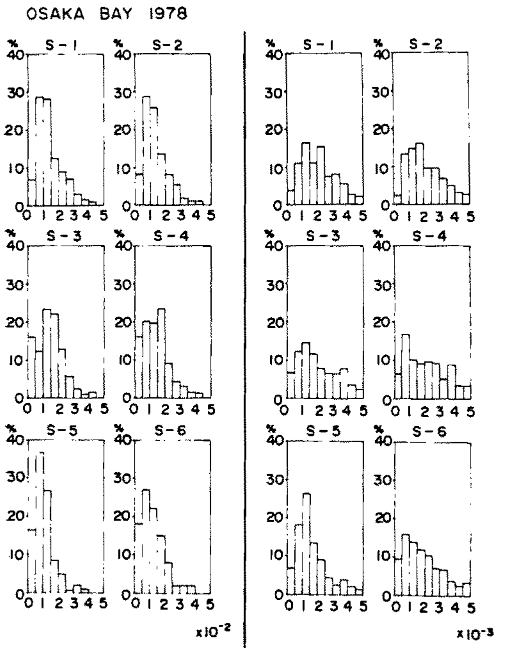

Fig. 9. Composite histogram of the flow speed of FCCF divided by the wind speed (a) and by the square of wind speed (b). Numerals on the abscissa in (a) must be multiplyed by 10^{-2} and those in (b) by 10^{-3} as indicated.

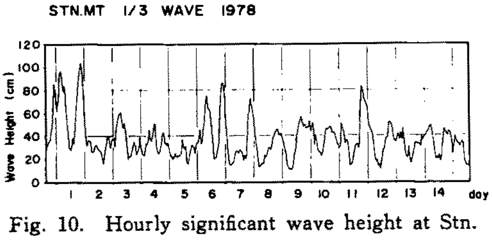

Fig. 10. Hourly significant wave height at Stn. MT.

The significant wave height at Stn. MT is shown in Fig. 10. The heigher waves occured on September 1, 6 and 11 due to north wind and did not occur on September 4, 9 and 10 when the wind was southerly. On the other hand, strong FCCF was caused by both the north and the south winds as shown in Fig. 4. These facts indicate that the wave height relates to the fetch of the wind but the wind-driven current does not relate to the fetch of the wind in this area.

5. Conclusion

Constant flow predominates in Ôsaka Bay. Its speed averaged over 15 days is about 10 cm s^{-1} and it flows to the west to west-south-west in the near surface water off the Senshû Coast. The speed of constant flow in the near bottom water is about 5 cm s^{-1} and it flows to the south to south-west. The main components of this constant flow are the tidal residual flow and the density current. The constant flow fluctuates with an amplitude of about 15 cm s^{-1} and a period of 4 to 5 days in autumn, and with a period of 2 to 3 days in spring. This fluctuation is mainly due to the variation of the wind. The direction of the wind-driven current in the near surface water deflects clockwise through 10 to 30 degrees from the wind direction and its speed is about 0.5 to 1.5% of the wind speed in this area. The directions of wind-driven current in the lower layer deflect counter-clockwise to that in the upper layer and current velocities observed are smaller than in the upper layer in this area of Ôsaka Bay.

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大阪湾の恒流の変動特性

柳　哲雄*

要旨: 大阪湾の恒流の変動特性を明らかにするため，湾の東南部において，流速観測を行なった．その結果，恒流変動の主成分は吹送流であることがわかった．観測海域の表層の吹送流向は風の吹き去る方向から10～30度，時計回りにずれ，その流速は風速の 0.5～1.5% であった．底層の吹送流向は表層のそれより反時計回りにずれ，流速は表層のそれより小さい．

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