Surface current variability in the Keum River Estuary (South Korea) during summer 2002 as observed by high-frequency radar and coastal monitoring buoy

Young-Tae Son\textsuperscript{a}, Sang-Ho Lee\textsuperscript{a,*}, Chang-Soo Kim\textsuperscript{a}, Jae Chul Lee\textsuperscript{b}, Gwang-Hee Lee\textsuperscript{a}

\textsuperscript{a}Department of Ocean Information Science, SERC, Kunsan National University, Kunsan 573-701, South Korea
\textsuperscript{b}Korea Inter-University of Ocean Science, Pukyong National University, Pusan 608-737, South Korea

Received 29 January 2005; received in revised form 2 August 2006; accepted 30 August 2006
Available online 30 October 2006

Abstract

High-frequency (HF) radar observations of surface currents were conducted for 3 months during summer 2002 in the Keum River estuary. A comparison between HF radar-derived currents and directly measured ones form a buoy showed that the regression slope is close to 1 and the correlation coefficient greater than 0.86, with an RMS difference less than 13 cm/s which is less than 17% of the tidal current. This fairly good agreement allows us to use HF radar observation in investigating the surface flow and circulation in this tidal-current-dominant coastal-plume area. To examine the spatial variation in tidal current characteristics, as well as currents associated with non-tidal forcing, the HF radar-derived currents were separated into tidal and sub-tidal frequency currents. The overall pattern of M\textsubscript{2}-current ellipse distribution in the study area showed a counterclockwise rotation, with the offshore maximum current direction to the northeast. Eccentricity, the direction of maximum current, and the phase of net motion of the ellipse changed near the estuary mouth and near the gap of the Saemangeum reclamation tide dyke due to the complex coastal geometry and the out-flowing jet during the ebb period.

The Eulerian mean current field in July was similar to the circulation patterns suggested in the previous studies using the CTD data and numerical models, implying that the region of northwestward flow may have developed by the rivers discharges. The short-term variation in the surface sub-tidal flow field was governed primarily by that of wind forcing and was responsible for the changes in the hydrographic conditions in the surface layer off the Keum River estuary mouth. The spatially averaged current, which is calculated after extracting the Eulerian mean currents from the sub-tidal flow, flowed almost to the right of wind during 22 days for an observer looking down-wind-stream, with the mean angle of 33°, indicating predominant Ekman drift. The sub-tidal current observed at the buoy showed that there is an almost unidirectional, persistent current irrespective of the variable wind forcing, producing strong Eulerian mean jet from the northern dyke gap. This current could be formed due to firstly the residual tidal currents generated by the open edges of the dyke and secondly the offshore discharge of the diluted water through the gap. However, when the daily river discharge increased greatly, the sub-tidal current speed at the buoy increased as much as 21 cm/s under the very strong southerly wind condition. This event is interpreted by relaxation process of the trapped coastal water by wind and the large river discharge.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: HF radar; Tidal current; Sub-tidal current; Ebb-jet; Wind effects; River plume; Effect of reclamation tide dyke

*Corresponding author. Tel.: +82 63 469 4603; fax: +82 63 469 4990.
E-mail address: sghlee@kunsan.ac.kr (S.-H Lee).

0278-4343/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.csr.2006.08.008
1. Introduction

In the eastern part of the Yellow Sea (Fig. 1), tide propagates northward along the Korean coast like a Kelvin-type wave, with increasing tidal range from the west to the east (Ogura, 1933; Choi, 1980; Lee and Beardsley, 1999 and Kang et al., 2002). Tidal ranges intensifies as well along the coast toward the Kyounggi Bay where spring tidal range reaches up to 8 m. Semi-diurnal tides are dominant in this area and the coastal water is always subjected to a strong tidal current produced by large sea level changes. The counterclockwise circulation has been accepted generally as basic features of summer surface circulation in the Yellow Sea (Beardsley et al., 1992; Lie, 1999; Lee and Beardsley, 1999).

The Keum River estuary is located on the southwest coast of South Korea (Fig. 1). Two small rivers, the Mankyung and Dongjin, are situated to the south of the Keum River. The bottom topography off the river mouths is shallow and gently deepening to the west. A group of islands, Gogunsan-gundo, is located off the estuaries, separating, naturally, the coastal area into northern and southern regions and affecting current fields in the area. The Keum River supplies a part of freshwater to the coastal area, annually about $6 \times 10^9$ m$^3$, while the Mankyung and Dongjin Rivers supply about 1/6 and 1/10 of the Keum River runoff, respectively. The runoff from these rivers influences salinity patterns in the coastal region, mainly during the summer rainy period, during which as much as the two-thirds of the total annual discharge could occur. Many artificial structures have been built around the study area. In the Keum River estuary, a river dyke, controlling runoff to preserve freshwater, prevents tidal propagation and upstream salt diffusion. Since 1992, the 33 km long Saemangeum tide dyke has been under construction to reclaim the wide tidal flats (40,100 ha) of the Mankyung and Dongjin River estuaries. The tide dyke involved the construction of three openings that had been significantly narrowed since 2000, while the opening in the northern dyke,

![Fig. 1. Map of study area with depth contours in meters. Site 1 (Yeun-do) and site 2 (Bieung-do) indicate the locations of HF radar antenna. Winds were measured by AWS in Mal-do (closed star); currents and winds by a coastal-monitoring buoy system (COMBS, closed circle) and the sea elevations by a tidal station at Kunsan tide station (closed triangle). S.P., O.P. and K.B. in inserted figure denote Shandong and Ongjin Peninsula and Kyunggi Bay, respectively.](image-url)
connecting Gogunsan-gundo and the mouth of the Keum River estuary, was entirely closed on June 7, 2003. In this paper, we focus on surface current variability observed in the northern area of Gogunsan-gundo during summer 2002, when the northern gap was still open in a width of about 4 km.

Before the northern gap was closed, the river plume extension and local summertime circulation were studied using a CTD survey and current data from anchored stations (Lee et al., 1995; Choi et al., 1999; Lee and Kwon, 1999). The results indicated that in summer tongue-shaped river plumes extended northward as far as 60 km from the Keum River estuary mouth. Through a three-dimensional numerical model with tidal motion, Shin et al. (2002) demonstrated tidal mixing and geostrophic balance along the plume front is responsible for the northwardly extension of the plume. Analyzing CTD data obtained in summer 1999, Lee et al. (2003) suggested that low salinity water due to the runoff from the Mankyung and Dongjin Rivers flows out through the gap in the northern tide dyke and merges into the Keum River plume. After 2000, this gap was significantly narrowed, a strong ebb-jet flowing out from the inner estuary region of the Mankyung and Dongjin Rivers was observed at a long-term monitoring buoy (Lee, 2003). Using a numerical model simulation, Choi and Lee (2003) predicted the local changes in tidal regime and the developments of water flow through the gaps during the sequential construction stages of the dyke. Kang (2002) and Choi (2001) predicted that the distributions of the M₂-tide harmonic constant would be changed significantly within 100 km radius from the dyke, i.e., amplitude reduction up to 10 cm and phase decrease up to 6 min near the dyke, if the tide dyke is entirely constructed. However, the effects of the large tide dyke construction on the offshore tidal current fields, i.e., spatial changes in tidal current characteristics, were not studied.

The study area is under the significant influence of Asian monsoons, with mean southerly wind in summer and northerly in winter. Wind stress is an important factor of coastal current variation (Bowden, 1983), but the effects of wind force have not considered in previous studies because the reaction of coastal water to transitionally varying winds in this area is not easily examined due to the constraint of shallow water depth, the complex coastal geography and the water stratification by runoff.

To investigate the effects of wind forcing on both the local circulation and plume behavior, observations of high spatial and temporal resolutions are necessary. One promising method of efficiently measuring temporally evolving current fields over a broad spatial area is high-frequency (HF) radar, though current observations from anchored buoys are also helpful in understanding local time variations of coastal flow.

HF radar systems have been used in the United States and United Kingdom to measure surface currents (Barrick, 1977; Prandle, 1987) and are being used increasingly to map surface currents in other parts of the world. This system is particularly useful for investigating currents associated with complex horizontal structures, such as oceanic fronts, variable river plume extensions or a residual current field around complex coastal geometry (Knight and Howarth, 1999; Haus et al., 2000, 2004; Hisaki et al., 2001; Kovačević et al., 2004). During summer 2002, when the gap in the northern dyke was not fully closed, we operated two HF radar antenna (Codar Ocean Sensors) sites and a coastal monitoring buoy system (COMBS) around the Keum River estuary to investigate variability and spatial patterns of sea-surface current fields. The object of this study was, initially, to examine the applicability of HF radar observations to a tidal-current-dominant coastal-plume area and, secondly, to undertake a preliminary analysis into tidal, sub-tidal frequency and mean current characteristics including the effects of coastal geometry, wind and runoff on the temporal and spatial variability of the flow field in this area.

2. Data collection and analysis

2.1. HF radar

Surface currents off the Keum River estuary were measured using a HF radar system (CODAR, 25 MHz frequency), covering a radial distance of 30 km with a spacing of 1 km radial and of 5° azimuthal resolutions from the two remote sites of Bieung-do (site 2) and Yeun-do (site 1), which are separated by about 15 km (see Fig. 1 for locations). HF radar recognizes sea-surface currents and waves by analyzing the backscattered signals from the HF radio waves radiated over the sea. When the radar signal hits ocean waves, the returned HF radar signal exhibits a Doppler-frequency shift which includes the information of the ‘Bragg wave’ speed plus the
influence of the underlying ocean current on the wave velocity in a radial path (Paduan and Rosenfeld, 1996). In depth description on the HF radar system can be found at the producer's home page (http://www.codaros.com:intro_hf_radar.htm). Once the known 'Bragg wave' speed is subtracted from the Doppler information, a radial velocity component of surface currents is determined. Using the software provided by the manufacturer, every 10 min radials were used in determining the radial velocities, providing bearing, range and speed. The radial data from two stations were then combined to produce hourly maps of current vectors (HF-radar-derived currents, here after HF currents) within a regular grid, using manufacture’s software program.

HF radar operated for the period from July 7, 2002 to October 5, 2002 (Fig. 2). Due to frequent power failure at the remote sites, the maximum data return was about 55%. The longest data set, without a loss gap longer than 3 h, was obtained from July 8 to August 1 (23.8 days), and this data set was mainly used for analysis of tidal and sub-tidal currents. Two sets of 1-week data were obtained from September 9–15 and from September 29 to October 4. The data gaps less than 3 h were filled by linearly interpolation from time series of current components. In August, power failures were very frequent in the site 1 where we had to go by a ship, and a long-term data set without loss gaps could not be obtained.

The system was operated in ideal mode in antenna signal pattern. The standard accuracy of current vectors is less than 7 cm/s in magnitude and less than 10° in direction, as specified by the producer. HF currents are produced in 2 km interval grid points because the resolution of arc distance by 5° angular resolution became about 2.1 km if we assume a creditable radial distance is 25 km from one antenna. We used the radials within ±75° sector with respect to the aim line of receive antenna in a remote site directing to the sea for the current vector computations, so as to reduce radial velocity uncertainties beyond that sector (Lipa and Barrick, 1983). Moreover, we selected grid points within an area where the intersection angles of the radials measured in two remote sites were between 30° and 150° in order to resolve the current vector better, as suggested by Paduan and Graber (1997).

2.2. Current meter

We have deployed a COMBS equipped with an Aanderaa Doppler current sensor (DCS) in January 2001 about 6 km to the west of the gap in the northern tidal dyke (see Fig. 1 for location). The water depth at the monitoring site is 10 m at low tide. The DCS, located 1.8 m below the sea surface, transmits acoustic waves to the side of the sensor, recording water velocity. The primary goal of the COMBS was to monitor the effects of the tide dyke construction on tidal current fields, e.g. tidal jets through the gap in the dyke. The data from the COMBS-measured current (here after COMBS current) were also used in examining local tidal and sub-tidal frequency currents and for valuation of the HF current measurements. Data were recorded at 10 min interval since June 5, 2002, and were retrieved in real time using a CDMA mobile phone. The COMBS current was not operated for a 2-week-long period from 26 August to 8 September for repair.

In 1986 and 1987, National Oceanographic Research Institute of South Korea (formerly known as South Korean Office of Hydrographic Affairs) had made short-term current measurements (here after NORI currents) of about during 1 lunar day long at several ten anchor stations around the study area to produce the tidal current chart. Most of NORI currents were observed at 5 m depth level during the period of spring tides, i.e., moon’s age of observation period was 14–18 or 0–3 lunar day, with time interval of 30 min. We analyzed these current data to estimate the distributions of the $M_2$-current characteristics before the dyke constructions.

2.3. Wind, river discharge and hydrographic survey

Hourly wind speeds, recorded at Mal-do AWS 30 m above the sea surface by the South Korean Meteorological Agency (Fig. 2a) as well as those observed at COMBS 2.5 m above the sea surface in 10 min interval were used. Wind directions are presented as the same manner as the current, which increases clockwise from the north. When the Mal-do and COMBS winds were compared, they agree well for the strong wind incidents though during the periods of weak winds they were differ notably probably because the observation heights were very different. Overall, the low-passed winds of both observation were very close (Fig. 2b). When the low-frequency variations of COMBS and HF current were examined we used the low-pass filtered COMBS wind.

During the experimental period, the daily discharge of freshwater at the Keum River dyke was
measured. Large runoff events occurred in early August 2002 and September 2002 (Fig. 2a). In July, the runoff was small but increased a little during July 22–23, 2002. The river discharge was well correlated with the precipitations measured in Kunsan meteorological station (not shown here). Hydrographic surveys using CTD were undertaken on the 9th and 13th of September, 2002. Hourly sea level variations, measured at the Government tide station in the outer port of Kunsan (here after TKS, see Fig. 1 for the location), were referred to in the tidal and sub-tidal currents analysis after inverse barometric atmospheric pressure corrections.

2.4. Data filtering and tidal analysis

The location and time-interval measurements of COMBS currents do not coincide with the spatial grid points and time-intervals of HF currents. We applied spatial bi-cubic spline interpolation using the nearest four grid-point values to the HF currents to obtain values at the buoy site. To construct an hourly COMBS current time series, we applied a running mean over a 1-h period to COMBS currents of 10-min interval, while making the central time of the running mean coincide with the observation time of HF currents. Hourly HF, COMBS currents

Fig. 2. (a) Daily discharge, sub-tidal frequency sea level and hourly wind vectors measured at the Keum River dyke, Kunsan tide station (TKS) and Mal-Do AWS from July to September 2002. Bold arrows denote the times of the CTD surveys and horizontal bars the period of available HF current measurement. (b) Comparison of sub-tidal frequency wind speed and direction observed at Mal-do AWS and COMBS. Bold arrows denote the selected wind conditions regarding sub-tidal flow field examination in Fig. 9.
and sea level data were decomposed into tidal and sub-tidal components using a low-pass filter with cut-off frequency at 40 h.

Tidal frequency currents, which remain after the removal of the sub-tidal frequency motion, were used for tidal harmonic analysis with the least square method (Easton, 1977). We used the tidal frequency HF currents over 14.5 days, from July 10, 2002, to analyze harmonic constants. The $M_2$ constant was stable because the data can resolve the beating of $M_2$ and $S_2$ constituents. The other major constituent constants were unstable owing to their small amplitude and ‘contamination’ by constituents of similar frequencies, $K_1$ by $P_1$, $S_2$ by $K_2$ and $T_2$, when a half month long data was used (Schureman, 1941, Lie et al., 2002). Even with the correction process suggested by Lie et al. (2002) to diurnal constituents, the contamination was not to be removed successfully.

For NORI currents analysis, the raw data were at first demeaned and interpolated into the lunar-hourly interval by applying the spline and splint method. The reference time of the interpolation was the moon’s transition time at $135^\circ$E (local time zone) within the observation period. According to the Rayleigh criteria, $\Delta T/T > 1$, where $\Delta f$ is frequency difference between any two harmonics and $T$ a time span of observation, diurnal and semidiurnal currents can be separated from a data of a lunar day span. We expressed amplitude and phase of semidiurnal current by the $M_2$ frequency using Fourier transformation of the interpolated current component. The phase was corrected by applying the difference between the start time of interpolated current and the moon’s transition time at $135^\circ$E, to obtain the phase referenced to the moon’s transition. However, the $M_2$-current amplitude and phase obtained from this step would be also modulated by the ‘contamination’ of other main constituents like as the $S_2$ and $N_2$ owing to short data length (Lie et al., 2002).

To estimate the usability of NORI current we tested consistency of characteristics of the current ellipse using COMBS current. We segmented the 58-day-long COMBS data into 25 h long data sets and applied the above process to the segments. The current rotation from segmented data was not changed though eccentricity of the $M_2$ ellipse, magnitude and direction of major axis and phase of the net motion, varied mainly during spring–neap cycle (e.g., Lie et al., 2002). However, the change in the direction of the major axis is very small ($< \pm 5^\circ$) during the period of spring tide, i.e., moon’s age of 16.5±2 and 1.5±2, and the eccentricity increases by 0.03 at the most compared with that from 58-day-long data. With these preliminary test results, by comparing the ellipses from HF and NOR current, we can examine at least the change in major axis direction and eccentricity of the $M_2$ ellipse before and after the dyke construction because the most of the NORI current was fortunately observed for spring tide period.

3. Current characteristics

3.1. Observed currents

Fig. 3 shows examples of the HF current field during ebb period. The blank region, without the current arrows connecting the two remote HF radar sites, denotes the undetectable zone of velocity vectors. During the early stage of the ebb period the offshore tidal current was weak, but a strong jet flowing to the west developed from the gap in the northern dyke, about 10 km to the west of the COMBS. The jet radiated from its axis. Two hours later, the offshore ebb current flowed strongly in a southwestward direction, indicating the current rotated counterclockwise, while the current speed and direction varied near the coast and around the islands. It is noticeable that the HF currents resolved the strong jet particularly well. The current field around the COMBS showed a large gradient or convergence of tidal currents, suggesting that significant spatial differences in current speed and directions occurred.

The COMBS was designed to detect the ebbing jet from the gap of the tide dyke, as mentioned previously. Tidal current characteristics around the COMBS during June and October 2002 can be seen in Fig. 4 (after Lee, 2003), which also appeared in July. The ebb current measured in the COMBS showed a two-stage directional flow. The early ebb current flowed in a WSW direction but, after the mid-ebb stage the direction changes to a SW direction, implying a counterclockwise rotation. These two steps appeared in the split of the ebb currents in a scatter plot. Moreover, it was evident from the change in current direction that the ebb current shifted direction suddenly to due-west just before mid-ebb stage, flowing for a short period of about 1 h. The ebb current reached a maximum speed when it flowed to due-west. This ebb current shift continued until
spring 2003 (data not shown). The reversal of the tidal current rotation to clockwise for about 1 h during the maximum ebb period is possible only if there is very strong jet directed towards the west (as shown in Fig. 3), which is the normal direction of tide dyke gap. This pattern is first described by Lee (2003), who reasoned that the maximum ebb current indicated that the ebb-jet extended to the COMBS location from the gap of tide dyke.

Fig. 3. Examples of HF-radar-derived flow fields observed on 24 July 2002 during an ebb period, which is 4 days before the spring tide at TKS indicated by an arrow in the mid-upper figure.
The harmonic constants of the major constituents of tide and tidal current at the TKS and COMBS are listed in Table 1. The Eulerian mean current during 58 days at the COMBS was 13.2 cm/s, flowing to the west. The amplitude of the most dominant constituent $M_2$ is as large as the sum of the other major constituent, and represents a half of the mean tidal range in this coastal area. The amplitudes of the $S_2$ and $N_2$, which are about 37% and 19% of the $M_2$, are larger than those of the $O_1$ and $K_1$. Mean spring tidal range ($2M_2 + 2S_2$) is greater than 6.0 m and the tide form number $(O_1 + K_1)/(M_2 + S_2)$, is 0.2, indicating semidiurnal type tide. The annual variation of sea level ($S_a$: period of 364.96 days), the sixth major variation, is 20.7 cm and larger than those of the $P_1$ and $M_4$, implying the importance of seasonal forcing.

### 3.2. Comparison of currents

The scatter diagrams in Fig. 5 with 573 samples over 23.8 days long period show the relationship between the east–west (U) and north–south (V) components of the HF and COMBS currents.
The slope of the regression lines are very close to 1 for both components, and the biases in the scatter-plots are less than 0.3 cm/s. The correlation coefficients between the two are greater than 0.86 for both components with RMS differences less than 13 cm/s. If we assume that the radial velocities and the errors for HF currents are independent, and the RMS values of the errors of the radial velocities for the two remote radar sites are equal, then the RMS error of the current vectors is amplified by a factor $1/|\sin \theta|$ (Graber et al., 1977), where $\theta$ is the intersectional angle between the radial lines of the two radar sites. The value of $1/|\sin \theta|$ at the COMBS location was 1.22, which contributes to the RMS difference. Since the observed maximum current speed was larger than 75 cm/s, the RMS of current component was acceptable.

Comparisons of the correlation coefficients and the slope of regression lines also show very good agreement, indicating that we could use HF radar observations to examine the surface current field in the study area. Part of the deviation may be due to the difference in the levels at which the two measurements were taken. RMS errors could be caused by ‘contamination’ of the strong ebbing jets (see Figs. 3and 4). The HF currents were weight-averaged values of currents in the radial illuminated cell, while the COMBS currents were at point values. If there is large shear around the COMBS site, as shown in Fig. 3, a discrepancy may occur statistically. The sudden change in ebb current direction with maximum current speed for a short period around the COMBS location (shown in Fig. 4) could be another potential source of error in current-component comparisons between the two different measurements, while the use of running mean of the COMBS current at 1-h intervals to produce the comparison current might smoothen this time-varying jet. Even though a comparison of current location was influenced by the strong ebb jet produced from the tide dyke gap, the statistical relationship of slope and correlation coefficient of the regression indicate that the HF radar captured well the real current variation around the COMBS location.

4. M$_2$-tidal currents

The distributions of the M$_2$-current ellipses and their characteristics obtained from HF currents are presented in Fig. 6. The tidal ellipses from the NORI current are also shown in Fig. 6a. Rotation of the M$_2$ current was counterclockwise both in the HF and NORI current ellipses over the entire observation area. This indicated that the dyke construction did not change the rotation of M$_2$ current even though the northern tide dyke modifies tidal current. The eccentricity of current ellipses obtained from the HF current (Fig. 6b) was relatively small in the northern and western part of the observation area and increases to the south and toward the Keum River estuary mouth, indicating a rectilinear increasing trend in the tidal current. This trend also appears in the NORI current ellipses. However, the eccentricities of the HF current ellipse south of the Keum River estuary mouth do not correspondent to this trend, i.e. significant decrease near the gap of the tide dyke.
compared to the offshore ellipses. The local decrease of eccentricity near Yeon-do (site 1) looks local effect on the tidal current around a small island, where the current speed can be reduced or the current direction can be diverted in front side coast. When the M$_{2}$ ellipses of HF and NORI current in Fig. 6a are compared, we can see that the eccentricity changed significantly near Gogunsan-gundo and in the northwestern area of the Keum River estuary mouth.

The direction of the maximum HF M$_{2}$ current, the maximum flood current direction (Fig. 6c) measured counterclockwise from the east, appears as a nearly uniform value of about 50° in the offshore region. The maximum current direction decreases near Gogunsan-gundo and the gap of the dyke, indicating that both the island group and the geometry of the dyke gap imposed the current flow in the east–west direction. Compared with the NORI current ellipses in Fig. 6a, the direction of the maximum HF current increased generally in the eastern part of the line connecting Mal-do and Yeon-do. The difference between the two directions becomes as large as 20° near Gogunsan-gundo and around the Keum River estuary mouth. However, the maximum current direction at the center of the dyke gap was not altered by the dyke construction.

The phase ($\phi$) of the net motion of the M$_{2}$ ellipse obtained from the HF current is about 35° over the central part of the observation area (Fig. 6d), and the maximum current flowing to the northeast occurs initially at time $t = \phi \times M_{2}$ period/360. Therefore over the central region the maximum flood current occurs almost concurrently. The phase decreases to 10° near the mouth of the Keum River estuary and to 0° near the gap of the tide dyke. The maximum currents in these regions occur more than 1 h earlier (phase difference of about 30°) compared to that in the central region. This earlier occurrence of the maximum current, shown in the distribution of the net motion phases around the gap, is due to the ebb-jet current, which acquires the maximum before the mid-ebb stage, as shown in Fig. 4a.

![Fig. 6. Distributions of (a) the M$_{2}$-current ellipse, analyzed using HF-radar-derived current data (solid line) and NORI current data (dashed line), (b) the eccentricity of current ellipse, (c) the direction of maximum current in degrees counterclockwise from the east, (d) the phase of the net motion.](image-url)
5. Sub-tidal currents

5.1. Eulerian mean current field

The Eulerian mean current (EMC) of the HF current, average over 23 days from July, is displayed in Fig. 7. Although the surface flow field was complex, there are three regions of well-developed mean current. Around the gap in northern dyke and to the north of Gogunsan-gundo, west to northwest flows larger than 10 cm/s are found. The westward flow near the COMBS location is correspondent with the mean current obtained by the 58 days COMBS current (Table 1). Over the area around the Keum River estuary mouth, a divergent flow system consisted of westward and northwestward flows are found. The third is the western part of observation area, around Sybiedongpa-do, where the EMC flows counterclockwise. Note that the strong westward flow from the gap turns north-westward to join the westward flow from the Keum River estuary.

The wind factor, defined as the ratio of the surface current to the wind speed measured at the standard height, has been known as about 3% (Bowden, 1983; Pond and Pickard, 1978). Because the time mean of the Mal-do and COMBS wind was southeasterly less than 0.5 m/s, maximum current speed driven by the mean wind would be less than 2 cm/s if we accept the wind factor. The energy of mean wind was not enough to produce the observed EMC larger than 10 cm/s around the gap and the Keum River mouth.

The EMC from the HF current (Fig. 7) was similar to the circulation patterns suggested by Lee et al. (2003) who analyzed the merging of river plumes using hydrographic survey and those by Shin et al. (2002) from the numerical modeling on the northwestward extension of the Keum River plume. From the similarity of the circulation patterns, we could argue that the region of northwestward flow must be due to the Keum River discharge and discharge of the Mankyung and Dongjin Rivers diluted water through the dyke gap. However, it needs an explanation why the current from the northern dyke gap was stronger than that around the Keum River estuary mouth although the discharge of the Keum River is greater than that of the Mankyung and Dongjin Rivers.

5.2. Response of sub-tidal flow to variable wind

To examine the temporal response of the sub-tidal flow to the variable wind we remove at first the EMC from the sub-tidal frequency HF current based on the assumption that the EMC was not

---

![Fig. 7](image-url) Fig. 7. Distributions of the Eulerian mean current (EMC) field of HF current in July 2002. The mean vector of Mal-do AWS wind during about 23 days is plotted in the left uppermost.
produced by the wind as discussed in previous section. Next, we calculate the spatially averaged current (hereafter SAC) in 1 h interval to obtain the representative of the area. The results are shown in Fig. 8 along with the sea level, the COMBS wind and its stress. Here, the wind stress \( \tau = \rho_a C_d |W| \frac{W}{|W|} \), where \( \rho_a \) is the air density, \( C_d = 1.4 \times 10^{-3} \) is the drag coefficient, \( W \) is the low-passed wind vector after time mean removed. The SAC flows to the right for an observer looking the down-wind-stream and the mean difference between the directions of the wind (wind stress) and the SAC is 33°. The Mal-do AWS wind produced similar results. This mean difference, which is smaller than 45° by the theoretical Ekman drift current at sea surface, is acceptable if we consider the effects of bottom friction in this shallow study area, summer stratification and coastal boundary (Madsen, 1977; Bowden, 1983). The mean speeds of the wind and the SAC are 2.5 m/s and 6.2 cm/s, respectively, resulting in the wind factor of 2.5%. These relationships between the SAC and the wind indicate the importance of the Ekman drift current on the temporal variability of surface flow in this coastal region. Though the sea level shows a variation with 4–5-days period, we need a long data length to find any relationship between the SAC, the wind and the sea level.

To examine the spatial response of the sub-tidal flow to the temporal wind, we selected two wind incidents when a southerly wind did not change its direction during two days from July 22 and the wind changed slowly from northerly in July 25 to southerly in July 29 (see arrows in Fig. 2b). We selected sub-tidal HF current fields, with considering the local inertial period (20h) for the spin-up time of surface flow development by wind (Allen, 1973). When the wind was southerly (Fig. 9a and b), a current flowing to the northwest on the shore-side of the observation area was observed. A relatively enhanced outward flow was formed around the estuary mouth and the dyke gap, indicating the effect of river discharges. These patterns of the surface flow imply that southerly winds help the plume extension northwestward during summer in the study area. However, the current in the dyke gap was stronger than that in the estuary mouth, and extended farther westward. Furthermore, a convergence of the surface flow occurred apparently to the north of Gogunsan-gundo (Fig. 9a). This convergence seems to be generated by both the coastal geometry effect on lee-side of the southerly wind and the westward extending flow.

When a northerly wind of up to 5 m/s blew for more than a day from July 25 (see Fig. 2 and 8), a uniform southwestward sub-tidal current due to the surface Ekman-drift current was observed (Fig. 9c). The current in the southeastern corner of the observation area shows a leakage of the surface water into the gaps between islands and the dyke. Two days later, the wind weakened while changing the direction to the west, but the sub-tidal current
did not change significantly (Fig. 9d). This suggests that the strong surface current field does not respond instantaneously to the weakening of wind forcing because of the current inertia. Note, however, that the flows are westward in the COMBS site when the wind speed was reduced.

5.3. Sub-tidal COMBS current

Sub-tidal frequency current at the COMBS is displayed in Fig. 10. The mean speeds of east and northward current components over 80 days from June 7 to August 25 were $-13.0$ and $-5.1$ cm/s with standard deviations of $3.5$ and $4.4$ cm/s, respectively, resulting in the EMC of $14$ cm/s, flowing to $248^\circ$ (WSW). It is noticeable that the current direction varied less than $\pm 25^\circ$, except for two events in early July and August. Thus, the sub-tidal frequency current at the COMBS is almost unidirectional during summer season irrespective of the variations in the wind and river runoff. In fact, when the current variation was compared with the discharge of the Keum River (see Fig. 2a) there was no meaningful relationship between the two except in early August. The vector-averaged wind velocity over 80 days was $0.48$ m/s blowing to $88^\circ$N. Therefore this strong persistent current was not generated by the local wind, as described in Section 5.1, but by another process. The mechanism for this current generation will be discussed later.

On the other hand, we see that the speed of the sub-tidal current responded to the change in the wind direction. The current intensified with northerly wind (including northwesterly to northeasterly) and weakened with southwesterly wind as displayed in Fig. 10. The current direction shows also a tendency responding to the wind direction, i.e., clockwise (counterclockwise) turning from the mean current direction by southerly (northerly) wind. To examine statistically the local current variations with the wind, we sorted both the wind vector and the current vector deviation from the EMC into a directional bin (Fig. 11). Here, the current deviation indicates the current remained after subtracting the
constant EMC (14 cm/s, flowing to 248°) from the sub-tidal COMBS current. The wind directions and the current deviations are divided up into the bins of 10° interval, and each bin contains the data separated by their speed intervals of 2 m/s and 4 cm/s, respectively. The percentages in each bin are the relative frequencies showing the numbers of the observations. It is apparent that the dominant directions of strong winds (>6 m/s) were southerly and northeasterly. Northwesterly winds were observed most frequently but the velocities were rather low (<4 m/s). The large current deviation (>8 cm/s) from the EMC occurred mainly in the northeastward and southwestward directional bins, highly suggesting it might be caused by the strong southerly (northeasterly) winds. However, the relative frequency of the current deviation between southeastward and southwestward was small in spite of the dominant northwesterly winds. The effect of coastal boundary with ‘J’ shape, formed with both the dyke and Gogumsan-gundo near the COMBS seems to block the current deviation from the EMC toward between these directions.

It is a remarkable phenomenon that the current speed at the COMBS increased as much as 21 cm/s under the very strong southerly wind condition from August 5 to August 9 (Fig. 10) during which the northward current of 3 cm/s changed into the westward one of 24 cm/s. The sharp increase of current speed coincided with the sudden decrease of wind speed in August 8. When we compared the current to the river discharge in Fig. 2a this current change happened concurrently with the large discharge in the Keum River dyke, implying that this variation of the current be related to both effects of the sudden changes of the wind stress and the river runoff. The moderate southwesterly wind blown during a week from July 30 reduced the current speed to 3 cm/s. In August 5 when the wind changed into strong southerly the current flowed to the north. However, we can see there was no daily discharge of the Keum River water till August 4 from July 27, but the discharge increased greatly up to $2.6 \times 10^8$ tone from August 6 to August 8 (Fig. 2a). We believe the discharge of the Mankyung and Dongjin River increased also very largely in this time because the rainfall of 150 mm during these 3 days was recorded at Kunsan meteorological station. This runoff could force the current direction changed from the northward to northwestward, with current speed increasing up to 14 cm/s, while Ekman transport with southerly wind enforces the waters trapped to the coast, preventing the westward current development. In August 8 when the southerly wind became weak suddenly, the current speed increased largely up to 24 cm/s, flowing to the west. This pattern of current variation suggests that the trapped water was relaxed dramatically by both the large river discharges and the concurrently happened wind stress reduction.

The sea level increase from August 4–7 in Fig. 2a was associated with the trapping of coastal water by
both the Ekman transport with southerly wind and the discharged water, and temporal drop of sea level in August 8 was responsible to the relaxation of the trapped waters. The sea level dropped largely in July 6 but recovered sharply in July 7. For this sea level variation, the strong northeasterly wind in July 6 (Fig. 10) leads the southwestward current at the COMBS, which might induce the sea level drop at the coast, and the strong southerly wind in July 7 reduces the current speed but changes the current direction to the northwest, which is responsible for the sharp recovery of the sea level. The similar cases with this sharp drop and recovery of sea level happened in September 1 and September 13.

5.4. Hydrographic conditions with the change in subtidal flow

We conducted two CTD surveys, on September 9 and September 13, to examine the response of hydrographic condition to the change in the subtidal flow field. The runoff of the Keum River was very large before the first survey (Fig. 2a). Two days before the first survey, winds were strong northeasterly but moderated to weak westerly during the survey. Winds were strong northwesterly before the second survey and moderated to mild one during the survey.

We overlapped the surface temperature and salinity distributions with the sub-tidal current fields to examine their inter-relationship (Fig. 12) while the resolved area of HF current was reduced during the CTD surveys. In the first survey on September 9, the observed pattern of surface current and parameters was very complicated (Fig. 12a and b). Sub-tidal flow was weak, but divergent, in the central part of the observation area under the mild westerly wind. A strong temperature and salinity front was established near the estuary mouth. Low salinity water was ubiquitous over the survey area, while salinity and temperature in the middle part was slightly high, separating surface water into a western and eastern part. In the second survey (Fig. 12c and d), the effect of wind on subtidal flow is more apparent. The sub-tidal currents, flowing to the southwest, developed over the observation area with northerly wind, which was similar to the case with strong northerly winds, shown in Fig. 9c. Compared with the first survey, low salinity water (<29‰) extended significantly from the mouth of the Keum River estuary to the southwest. The sub-tidal flow field, developed by wind, corresponded with the changes in surface hydrographic conditions between the first and second survey. In 10 m depth, however, we can see that high salinity water moved to the estuary mouth from the southwest region of survey area when the second survey are compared with the first survey (Fig. 13). This high salinity water advection in the low layer is an opposite direction to the low salinity surface water extension.

We postulate that the pattern in the first survey is transient, i.e. low salinity water, in the western area, is the remains of an extended river plume caused by very large runoff before this CTD survey, which spread over the survey area under the influence of
strong northeasterly winds as similar with Fig. 9c and d, and the salinity front was formed farther west of the survey area. However, the strong northeasterly wind ceased and moderated to mild westerly during the survey-day. Therefore, the westerly wind is not enough to allow the development of the significant drift current, but does contribute by confining the Keum River runoff (low salinity water, < 29%) near the estuary mouth, prohibiting the estuarine plume extension and separating the new plume from the old one. The weak divergence in the sub-tidal flow pattern, associated with the separation of plume development, can be explained by this scenario. However, the relationship between current changes and hydrographic conditions in surface layer, from the first to the second survey, indicates that the sub-tidal surface current, produced by significant wind forcing, is the major factor in temperature and salinity distribution variations off the mouth of the Keum River estuary during a short 4-day period.

On the other hand, farther offshore region in the second survey, surface temperature and salinity increased as much as 1°C and 1% compared to those in the first survey. We suspect that the increase of temperature and salinity may be related to a large-scale circulation system outside the study area during the 4-day period, perhaps associated with the plume front movement, while these increases could not be explained directly by the effect of wind-drift current change because of the small observation area. However, the salinity increase in the low layer between two surveys looks to be related to this offshore surface salinity increase. It could be an indirect evidence for the temporally compensating counter-flow occurrence. Discussions for this counter-flow occurrence will be given in later.

6. Discussions

The basin scale tidal structure determines basically the characteristics of tidal current, i.e., rotation, eccentricity and major axis direction etc., in the Yellow Sea. Fang et al. (1991) solved the Taylor problem with both linear bottom friction and partial opening in the bay head and applied their solution to the Yellow Sea. They pointed out that the Poincare mode produced from the closed end of the bay (Shandong and Ongjin peninsula in the case of the Yellow Sea, see Fig. 1) causes rotation of the $M_2$ current to be counterclockwise near the bay head. We can interpret that counterclockwise rotation of the $M_2$-current ellipses in our study area is the result of this basin scale current
structure. Fang et al. (1991, Figs. 2 and 6) also showed the distributions of major and minor axes of tidal currents solved in Taylor problem, where the eccentricities decrease offshore owing to the contribution of the Poincare waves generated from the corner of the closed head of bay. The decreasing trend of eccentricity of the current ellipse to the northern and western part of our observation area (Fig. 6b) is consistent with the Fang’s solutions and also to the results of numerical model current ellipse in local domain by Choi and Lee (2003, Fig. 15 and 16a) and Shin et al. (2002, Fig. 7).

The fact that maximum $M_2$-current direction is changed counterclockwise in the eastern area of the line connecting Mal-do and Yeon-do after the dyke construction (Fig. 6a) implies that the local tidal wave propagation changes partially into the direction of the dyke geometry. Under the conditions of oscillating tidal volume transport between the offshore and the estuary of the Mankyung and Dongjin Rivers (Choi, and Lee, 2003), the constructed dyke partly blocked the tidal current, reducing the volume transport between inner and outer regions. Compared with before the dyke construction, the reduction of the volume transport due to the dyke would cause the maximum current direction around the dyke to turn counterclockwise in order to redistribute the tidal volume influx from offshore. Using numerical model, Kang (2002) predicted that co-phase lines of the $M_2$ tide turned counterclockwise with the progress of the dyke construction, which is correspondent with our comparison result of maximum current direction.

The gap in the tide dyke is a narrowed zone between inner and outer regions, where large sea-level differences (hydraulic jumps) occur. The two-step change in ebb current direction and the strong ebb jet to due-west of the COMBS current, shown in Fig. 4, can be explained by the hydraulic jump in the gap. During the ebb period the offshore ebb current rotates basically counterclockwise from the west to the south. The hydraulic jump will start to develop the ebb-jet from the gap after the high tide (Choi and Lee, 2003). The jet reaches to the COMBS location before mid-ebb stage, being in maximum extension for a while, and imposes the local effect on tidal stream, which can rotate the ebb current direction clockwise from WSW to W as in Fig. 4a. When the ebb stage progresses with the increase of the offshore current speed, the ebb-jet would merge into the offshore current and then the current in the COMBS location flows in SW direction owing to the basic counterclockwise
rotation. This temporally contribution of the ebb-jet causes the scatter diagram of the COMBS current to appear in two-step of the ebb current.

The decrease in eccentricity of the HF current near the northern part off the gap in Fig. 6b, where the eccentricity of the NORI current was also small in Fig. 6a, can be also explained by the geometry of coastline and the contribution of the jet. The coast line connecting the dyke and the mouth of the Keum River estuary slanted with angle of about 45° with respect to offshore maximum current direction. It can be postulated that the real current is consisted by two kinds: the radiating component of the ebb jet from the gap (see Fig. 3a), and the background ebb tidal current flowing mainly to the southwest. The radiating jet contributes to the scatter of the background current differently in the north and south of the jet axis due to the angle between both currents during ebb period. In the north of the jet axis, both currents make almost the right angle between them, which result in the increase of the minor axis of the M₂ ellipses, decreasing the eccentricity. In the south of the jet axis, however, both currents make a small acute angle between them, which contribute to the increase of the major axis.

The variability of sub-tidal frequency current in the study area was mainly correspondent to Ekman drift current induced by the variable wind forcing, as shown in Fig. 8, 9, 11 and 12. However, we suggested that the strong persistent, almost unidirectional current is needed to explain the distribution of the EMC off the gap of the northern tide dyke shown in Figs. 7 and 10. We can introduce two possibilities for the generation of this locally enhanced current. The first is the formation of residual tidal current vortices. When we calculated the residual M₂-tidal current using fine-grid numerical model without river discharge, strong vortices pair of residual current was formed in both side of the gap (not shown here), which is very similar to those around tidal inlet and narrow short strait between basins, described by Imasato (1983) and Awaji et al. (1980). Because the gap of about 4-km wide is smaller than a tidal excursion distance, the vortices pair produces a strong residual tidal current jet larger than 13 cm/s along the normal line of the gap center. The counter flow in both sides of the EMC jet around the gap (Fig. 7) reflects the formation of these residual tidal current vortices. The second one is the out-flowing discharge of the diluted water through the gap of the northern dyke.

Lee et al. (2003) suggested the inflow through the two gaps in the southern dykes into the Seaman-geum reclamation area and the outflow through the gap of northern dyke as a summer circulation pattern. While the discharge of the Mankyung and Dongjin Rivers is relatively small compared with the Keum River, the net-outflow should increase if river discharges merge with the net-inflowing seawater from the southern gaps. We however need further studies for the compartment ratio between the residual tidal current and the net-outflow from the gap.

Meanwhile, we argue that the salinity increase in the low layer compared to that from the first hydrographic survey (Fig. 13) may be accompanied with the transiently compensating counter flow. This low layer high salinity water advection is possible when Ekman drift current with northerly wind was predominant in our study area. Because the coastal geometry effect with ‘ʃ’ shape, formed with both the dyke and Gogunsan-gundo, contributes to the offshore pile-up of coastal water under the northerly winds pushed the coastal water to the offshore through Ekman transport. We can expect the compensating flow toward the coast in these periods. Sea level rises in July 27, and in September 1, 6, 9, 14 and 20–22, implying that the northerly wind during 2 days before the second hydrographic survey was sufficient to develop the counter flow. This surface slope could be a generating force of high salinity water advection through the low layer under condition of summer stratification, as a similar manner with under-current formation in coastal Ekman upwelling area.

Sub-tidal frequency sea level variation at TKS in Fig. 2a shows large drops when northerly winds were very strong in July 6 and July 25 and in September 1, 6, 9, 14 and 20–22, implying that the northerly winds pushed the coastal water to the offshore through Ekman transport. We can expect the compensating flow toward the coast in these periods. Sea level rises in July 27, and in September 2, 7, 11 and 18, can be explained if we take into account of the possibility of the sea level recovery with over-shooting after drops due to northerly-wind-induced Ekman transport even though the wind was not so favorable for direct trapping of
waters to the coast at those times. We, however, needs more close examination because sub-tidal frequency sea level variations could be affected by many processes such as the relaxation process of transported water, low-frequency wave propagation from the outside area and the discharge of river waters as well.

Regarding the relationship between the sub-tidal current and the extension of the low salinity water around the mouth of the Keum River estuary, our results imply that the surface drift current due to the local wind is a more dominant factor on the short-term changes of surface sub-tidal flow and hydrographic conditions than the geostrophic current associated with light water from the estuaries. For the long-term fate of the plume extension, we believe, however, that the light water around the estuary mouth could produce the northwestwardly surface flow through a geostrophic balance, as suggested by Lee et al. (2003) and Shin et al. (2002), because the mean work of the wind stress was negligible during summer season. Long-term radar surveillance, combined with a hydrographic survey, is required in future for a more quantitative explanation of the shallow coastal phenomena, such as low salinity river plume variability, the development of surface flow convergence, and the effects of coastal geometry and topography on the variation of the surface Ekman drift currents, and seasonal variations of the local circulation, etc. The mechanism of plume extension including variable wind forcing is also the future subject of our study.

7. Concluding remarks

Off the Keum River estuary, surface current fields were observed, using HF radar, over a 3-month period during the summer of 2002. A comparison of HF and COMBS currents showed good agreement. As a result of preliminary examinations of the $M_2$-current characteristics and sub-tidal flow fields from HF currents, and the relationships between sub-tidal flow fields, winds, freshwater runoff and hydrographic conditions, we concluded that the current measured by the HF radar can be used for the investigation of tidal current fields and surface circulations in this tidal-current-dominant coastal-plume area. In the HF radar observation area, the $M_2$-tidal current ellipse rotates counterclockwise. The eccentricity of the ellipse increases toward the coastline, but decreases around the gap in the Saemangeum reclamation tidal dyke, with a change in maximum current direction and phase of the net motion. Compared with NORI current observed before the dyke construction, this change in the $M_2$-current characteristics can be explained by the dyke that blocks tidal current and an out-flowing tidal current jet during the ebb period from the gap.

Strong northerly winds generated a uniform sub-tidal flow. Southerly and southeasterly winds, combined with a large river discharge in summer, contributed to the development of northwesterly sub-tidal flow fields off the Keum River estuary, with a transient convergence of surface flow on the lee-side of Gogunsan-gundo. Surface temperature and salinity distributions, observed twice within 4 days intervals in September 2002, corresponded to the sub-tidal flow field, which developed from the change in wind direction from weak westerly to strong northeasterly. This implies that the short-term variation in the surface sub-tidal flow field is governed by the change in wind forcing, and that the wind drift current is primarily responsible for the changes in hydrographic conditions in surface layer off the Keum River estuary mouth. The variation of SAC of HF current, which was calculated after extracting the Eulerian residual current (EMC) during 22 days, shows that the SAC flowed almost to the right of wind for an observer looking down-wind-stream, with the mean angle difference of $33^\circ$, indicating the mechanism of Ekman drift current was predominant. The wind factor was 2.5% for the SAC.

Meanwhile, when the daily river discharge increased greatly from August 5 to August 9, the sub-tidal current speed at the COMBS increased as much as 21 cm/s under the strong southerly wind condition, with flow direction change from northward to westward. We interpreted that this event was produced by the trapping of coastal and discharged water under the southerly wind and the relaxation of trapped waters with sudden reduction of wind stress. The sub-tidal frequency sea level variation associated partly with those trapping and relaxation of coastal waters. The distribution of the EMC of HF current in July was similar to the circulation patterns suggested by Lee et al. (2003) and Shin et al. (2002). Based on the circulation pattern similarity, we could interpret that the region of northwestward flow may have developed by both the Keum River discharges and the discharge of the Mankyung and Dongjin River diluted water in the dyke gap. The almost unidirectional strong EMC from the northern dyke’s gap observed at the
COMBS. We suggest that this persistent current, which resists to variable wind forcing, could be formed with firstly the residual tidal currents generated by the edges of the dyke in the gap and secondly the out-flowing discharge of the diluted water of the Mankyung and Dongjin River through the gap.

Acknowledgments

The authors thank the NORI and KMA, Korea for kindly providing the short-term current and 1-year tide data, and the Mal-do AWS wind and precipitation data. This study is supported by SERC in Kunsan National University, a regional research center supported by KOSEF, ITEP, MOST and MOCIE of South Korea. Chang-Soo Kim received a support from the Ministry of Education, Korea through the second stage of the BK21 Program. Thanks to Dr. Y.G. Park of the KORDI for careful reading of our manuscript and to the reviewers for helpful comments to improve our analysis and interpretations.

References


