Diurnal Shelf Waves off Hamada on San’in Coast

Y. ISODA1 and T. MURAYAMA2

1Department of Civil and Ocean Engineering, Ehime University, Matsuyama 790, Japan
2Shimane Prefectural Fisheries Experimental Station, Setogashima, Hamada 697, Japan

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The tidal current data observed off Hamada on San’in coast have shown the diurnal tidal currents to be larger than the semidiurnal ones by a factor of 5–8, although the ratio \((K_1+O_1)/(M_2+S_2)\) for the tidal heights at Hamada is 1.3. Furthermore, the diurnal currents are found to be more remarkable on the shelf slope than on the shelf. We consider such diurnal current features as being due to the vertical mode waves, and show that the broad shelf and steep shelf slope off San’in coast allow 1st-mode interior shelf waves (ISWs) at a diurnal-period. Using a simple shelf model, it is shown that ISWs occur in response to the seaward component of diurnal tidal oscillations on the shelf and their propagation originates from the western entrance of the Tsushima Straits.

1. Introduction

The Japan Sea is a semi-enclosed sea surrounded by the Asian Continent and the islands of Japan, and connected with other seas by three major straits; Tsushima, Tsugaru, and Soya Straits. Odamaki (1989b) showed that tides in the Japan Sea could be reproduced with the co-oscillating tide forcing at each strait. These straits are so narrow and shallow that tidal amplitudes are smaller than those in the adjacent seas. Therefore, until now considerably less attention has been given to the tidally forced phenomena over the shelf in the Japan Sea. Our observed results in current off San’in coast, however, showed the abrupt increase in the diurnal currents on the shelf slope region. Such a unique feature of tidal currents was unknown in the previous studies in the Japan Sea. This paper describes the nature of these currents, showing that their behavior on the shelf slope agrees well with the predicted behavior of diurnal shelf waves.

Before the analysis, we review the distributions of tide off San’in coast. Figure 1 shows the cotidal and corange charts for semidiurnal \((M_2)\) and diurnal \((K_1)\) tides in the shelf region off San’in coast (Odamaki, 1989a, b). It is found that the tidal range for both waves is very small, less than 10 cm off Hamada. The cotidal chart of semidiurnal tide indicates that the wave rotates counter-clockwise around the amphidromic point found on the shelf break off Hamada. For the diurnal tide, the amphidromic point is found very close to the Korean coast and its phase and amplitude are almost uniform in the Japan Sea. Odamaki (1989b) concluded that the composite of co-oscillating tides by three straits resulted in such a large shifting of the diurnal amphidromic point by using an one-dimensional model. His results agreed with the observations for the tides, but not so well for the tidal currents. In particular, a comparison with the tidal current phase around the Tsushima Straits is less satisfactory. We consider that diurnal tidal waves will be severely distorted over the shelf topography near the Tsushima Straits, whose topographic effects could not be accurately included in his model.

In the present study, first, a brief description of the cross-shelf current structures for the semidiurnal and the diurnal tides off San’in coast is presented. Second, we discuss the physical
Fig. 1. Cotidal (solid lines) and corange (dotted or dashed lines) charts off San'in coast for the M₂ and K₁ tides (Odamaki, 1989a, b). The open circles off Hamada indicate the locations of tidal current observations in 1989 and 1990.

interpretation for each tidal wave. In particular, we will try to explain the selective predominance in the diurnal currents using a simple shelf model.

2. Observations

The tidal currents and water temperatures discussed in this paper were observed from 20 June to 6 August 1990 at two moorings seaward of Hamada on San'in coast (Fig. 2). This mooring array is as referred to Line A. Each of the moorings, at Stn. H1 on the shelf and Stn. H2 on the shelf slope, consists of two Aanderaa current meters. They were separated by about 40 km. The upper current meters were positioned 50 m below the sea surface. We also set the lower current meters at the depths of 140 m at Stn. H1 and 170 m at Stn. H2. Although the sampling interval is 10 minutes, one-hour averaged data are used for the present analysis. The hourly mean sea-
level data at Hamada over the current observation period are also used.

The CTD observations along the Line A were carried out on 30 July 1990. Figure 3 shows the vertical sections of temperature and salinity. High-salinity waters more than 34.3 psu spread horizontally at the middle layer between the seasonal thermocline at the depth of 30–40 m and the permanent thermocline at the depth of 100–130 m. The ocean has a three-layer structure, which is known as a typical structure off San’in coast in summer (Moriwaki and Ogawa, 1988). The upper current meters are located below the seasonal thermocline and the lower ones below the permanent thermocline. It is noteworthy that the shelf waters near the sea bottom vary with time depending on the evolution of cold water with a period of several weeks, which is called the “Bottom Cold Water” (e.g. Isoda and Oomura, 1992). Our CTD observation exhibits a large evolution of the “Bottom Cold Water”, namely a permanent thermocline with about 10°C isotherm extends onto the shelf and intersects the nearshore.

3. Results

Figure 4 shows the time series of sea-level at Hamada, eastward (VE) and northward (VN) current velocities, and water temperatures at Stns. H1 and H2. The tidal current oscillations are the most dominated and their maximum currents are of order 30–40 cm s⁻¹ at Stn. H2. It is also seen that tidal currents are superimposed on the low frequency current which flows eastward and
is of order 10–20 cm s$^{-1}$. This low frequency current is called the Tsushima Current and flows from the Tsushima Straits along San’ in coast. Water temperatures at the upper levels are nearly constant throughout the observations, while those at the lower levels are dominant in the tidal-period variations. To examine the relation between currents and water temperatures for the tidal-period, the cross-correlation analysis is carried out. Table 1 shows the coherence squared and phase difference at two peaks of 25 and 12.5 hour-periods. High coherence more than 0.8 can be seen only at the lower levels in a diurnal-period, where the phase difference between offshore current (VN) and increase of water temperature is about 90°. This relationship is probably due to the lateral or vertical displacements of the permanent thermocline forced by the on-offshore lateral advection.
Fig. 4. Time series of hourly-mean adjusted sea-level at Hamada (top), the eastward (VE) and northward (VN) current velocities and water temperature (from second to bottom) at the depth of 50 m and 140 m at Stn. H1, and at the depth of 50 m and 170 m at Stn. H2.
Table 1. Coherence squared and phase difference (in parenthesis) at 25 and 12.5 hour-periods between eastward (VE) (or northward (VN)) velocity component and water temperature.

<table>
<thead>
<tr>
<th>Period (hour)</th>
<th>25.0</th>
<th>12.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 (50 m)</td>
<td>VN 0.26</td>
<td>(154.5)</td>
</tr>
<tr>
<td></td>
<td>VE 0.56</td>
<td>(−164.6)</td>
</tr>
<tr>
<td>H1 (140 m)</td>
<td>VN 0.93</td>
<td>(−84.4)</td>
</tr>
<tr>
<td></td>
<td>VE 0.97</td>
<td>(−21.3)</td>
</tr>
<tr>
<td>H2 (50 m)</td>
<td>VN 0.62</td>
<td>(164.0)</td>
</tr>
<tr>
<td></td>
<td>VE 0.58</td>
<td>(−128.6)</td>
</tr>
<tr>
<td>H2 (170 m)</td>
<td>VN 0.83</td>
<td>(−92.0)</td>
</tr>
<tr>
<td></td>
<td>VE 0.80</td>
<td>(−11.4)</td>
</tr>
</tbody>
</table>

To investigate the characteristics of tidal currents in more detail, tidal current ellipses are calculated for the four major constituents ($M_2$, $S_2$, $K_1$, and $O_1$). Figure 5 shows the cross-shelf distributions of ellipses along the Line A. The ellipses at 35°00' N and 35°30' N which are calculated using the current data in summer 1989 (Isoda et al., 1992) are added to this figure. The arrow on each ellipse indicates the direction of rotation and its position is at the time of meridian passage of a tide-generating body at the Japanese standard longitude (135°E). First, it is clear that the amplitudes of diurnal tidal currents are too large comparable to the semidiurnal ones by a factor of 5–8. Although such energetic diurnal currents are larger in the lower levels than in the upper levels, the phase variations of current ellipses at both levels are almost the same.

For the semidiurnal currents, although their direction of rotation and phase are somewhat unstable, the principal axes of ellipses are elongated north to south, i.e. almost perpendicular to the isobaths. Its maximum speed is about 2–4 cm s⁻¹. Such orientation of tidal ellipses suggests the seaward propagation of waves off Hamada and also agrees with propagating direction of semidiurnal tidal wave inferred from the cotidal chart in Fig. 1.

For the diurnal currents, some distinctive and unique features are as follows: (1) The current vector stably rotates clockwise at all ellipses. (2) The tidal current amplitudes increase rapidly seaward and major axes have maximum speed of 10–15 cm s⁻¹ at lower levels on the shelf slope. (3) The ellipticity (minor axis/major axis) increases seaward from 0.1 to 0.8, namely the ellipses on the shelf slope are almost circular. (4) The major axes of tidal current ellipses orient perpendicular to the isobaths in the seaward directions.

Next, the stability in time for the diurnal current ellipses is examined. Figure 6 shows the daily variations of diurnal tidal current ellipses at Stns. H1 and H2, and of phase differences between Stn. H1 (140 m) and Stn. H2 (170 m). Assuming a sinusoidal function with a 25 hour-period, each ellipse is calculated by applying the least-squares method to the data for each day. The phase for the principal axis is the lag angle measured from midnight of the day. The orientation and shape of the tidal current ellipses at the lower levels are relatively stable. During the decrease in the tidal current amplitude, the phase of tidal current at Stn. H1 (nearshore) tends to lead that at Stn. H2 (offshore), although its phase difference is variable from 45° to 180°. On the other hand, during the increase in the tidal current amplitude, the phase difference between
Fig. 5. Tidal current ellipses for M₂, S₂, K₁, and O₁ tides on the shelf off Hamada. Ellipses at 35°00' N and 35°30' N are calculated using the current data obtained from the observations in 1989 (Isoda et al., 1992).
Fig. 6. Daily variations of diurnal tidal current ellipses at the depths of 50 m and 140 m at Stn. H1 and at the depths of 50 m and 170 m at Stn. H2. Time series of phase differences in the diurnal tidal current velocity between Stn. H1 (140 m) and Stn. H2 (170 m).

both lower levels tends to be zero, namely the phase is almost uniform from the shelf to the shelf slope. This suggests that such cross-shelf distribution is controlled by some form of cross-shelf modal structure, when the diurnal current amplitudes is large.

4. Discussions for the Diurnal Tides

Previous studies of sea-level along the Japanese coast suggested that both diurnal and semidiurnal barotropic tides propagate northeastward along San’in coast, mainly as Kelvin
waves (Ogura, 1933; Odamaki, 1989a). These waves belong to the gravity waves, possessing relatively large surface displacements and weak currents. For the semidiurnal tide, it is suggested that its dynamics can be interpreted as familiar standing waves with a pair of Kelvin waves traveling in opposite directions on the shelf off San’in coast. In the same way, if the Kelvin waves may cause large diurnal currents on the shelf off Hamada, the associated tidal heights should also increase. However, the ratio \((K_1+O_1)/(M_2+S_2)\) for the tidal heights at Hamada is 1.3 and the expected intensive increase of the diurnal tidal height is not observed. Therefore, it is considered that the majority of the energy in diurnal tidal currents resides in horizontal kinetic energy rather than in potential energy associated with the surface displacement.

Recently, there have been a number of reports on internal tidal wave observations in the shelf regions around the world (e.g. Sandstrom and Elliott, 1984). These studies suggest that observed large amplitude of the diurnal currents might be caused by the seiche of internal tide on the shelf or internal waves trapped on the shelf break. However, since internal Rossby radius deformation is only about 20 km off San’in coast, it is difficult that the tidal phenomena which spreads over the shelf with 50–100 km width may be explained by trapped-mode internal waves. In addition, since the inertial period 20.4 hours at the latitude of our moorings is less than a diurnal-period, no inertial-gravity waves can be considered to propagate across the shelf and constructive interference also cannot occur. Then, there may be following two candidates for the mechanism of the predominance of the diurnal tidal currents off San’in coast: one is due to the “diurnal external forcing” and the other is due to the existence of “diurnal shelf waves”.

4.1 Diurnal external forcing

We can think of two external forcings associated with a local wind-forcing: a resonance with the land-sea breeze and a resonance with the inertial oscillations after a strong wind-forcing stops. The former resonance will occur in the nearshore region, namely several tens of kilometers from the coast. However, the observed results exhibit the predominant currents only in the seaward regions.

Figure 7 shows the power spectra for eastward (VE) and northward (VN) current velocity and water temperature at each lower level. If the latter resonance occurs, the broad-band peaks from the inertial period (20.4 hours) to the diurnal period (about 25 hours) should be expected. However, such broad-band peak cannot be seen and there are only two peaks, about 25 and 12.5 hours, which are associated with the semidiurnal and the diurnal variations. Thus, the predominancy of the diurnal currents cannot be interpreted as a resonant phenomena due to the local wind-forcing.

4.2 Diurnal shelf waves

We consider the predominancy of the diurnal tidal currents as being due to the vortical mode waves, i.e. shelf waves, because these waves are characterized by relatively large currents and small heights of sea-level. Then, larger energetic tidal current fluctuations might be expected around the shelf break owing to the large topographic \(\beta\)-effect. Furthermore, there is no obvious obstacle to the propagation of shelf waves only at a diurnal-period, since the inertial period is less than a diurnal-period and larger than a semidiurnal-period.

Studies of diurnal shelf waves have been done elsewhere around the world: off western Scotland by Cartwright (1969); off the coast of Vancouver Island by Thomson and Crawford (1982) and Crawford and Thomson (1984); in the Weddell Sea by Middleton et al. (1987); on the east Australian continental shelf by Freeland (1988). These waves were trapped on the coast
and could only exist poleward of midlatitudes with a steep bottom slope. Then, we consider that tidal fluctuations around the shelf break off Hamada are caused by “interior shelf waves” (referred to as ISWs), which can be trapped on the shelf slope region. The theoretical model of ISWs has been already discussed by Buchwald and Adams (1968). Their theory shows that the 1st-mode wave has a high-frequency cutoff at the inertial period and such cutoff occurs as wavelength and phase approach infinity. In contrast, higher modes of ISWs have a very long wavelength when motions of very low frequency are restricted.

4.2.1 Dispersion relations and on-offshore current structures of the ISWs

The physical property of shelf waves gradually changes to the bottom trapped mode according to the development of stratification. Actually, our observed results also exhibit the bottom trapped mode. First, we discuss the influence of stratification on the wave solutions. This effect is generally characterized by the parameter $S = NH/fL$, where $N$ is Brunt-Vaisala frequency, $H$ is the mean depth around the shelf break, $f$ is Coriolis parameter, and $L$ is the width of shelf plus shelf slope. For small value of $S$, motion takes the form of barotropic shelf waves. Parameter for the Line A off Hamada give an indication of size of $S$: typically $H = 200$ m, $L = 100$ km, $f = 8.5 \times 10^{-5}$ s$^{-1}$ and $N = 1.0 \times 10^{-2}$ s$^{-1}$ whereby $S = 0.24$ and stratification can be expected to have a moderately weak influence on the shelf wave in the shelf break region. Thus, we expect the influence of stratification on the basic horizontal structure of ISWs and their generation to be insignificant. Therefore, in our first approach, we adopt a barotropic model with a simplified bottom topography off San’in coast.

The Buchwald-Adams’s theory is adopted for the case of the broad shelf and steep shelf slope off Hamada. An idealized shelf profile used to simulate the real bottom topography is shown in Fig. 8. That is,
Fig. 8. Bathymetric profile (solid line) along Line A (Fig. 2) together with model topography (dashed line). The model topography consists of an exponential shelf slope connecting to the shelf and open ocean with constant depths of 150 m and 2000 m, respectively.

\[ \begin{align*}
\text{Region 1} & \quad y \leq 0 & h &= h_1, \\
\text{Region 2} & \quad 0 < y \leq \lambda & h &= h_1 e^{2by}, \\
\text{Region 3} & \quad \lambda < y & h &= h_1 e^{2bh_2} = h_2.
\end{align*} \tag{1} \]

Here \( h_1 \) and \( h_2 \) are the depths on the continental shelf and open ocean, respectively, and \( \lambda \) is the horizontal scale of the shelf slope region. The solution of stream function \( \psi_j = \phi_j(y) e^{ikx + i\omega t} \) (where, \( j = 1, 2, 3 \) is the region number, \( k \) is the wavenumber, and \( \omega \) is the angular frequency) in each region, which is assumed the shelf slope trapped-mode, is as follows:

\[ \begin{align*}
\phi_1 &= A_1 e^{ky}, \\
\phi_2 &= e^{by} (A_2 \sinhy + A_3 \cosh) \\
\phi_3 &= A_4 e^{-kh(y-\lambda)}.
\end{align*} \tag{2} \]

and

\[ \phi_j = \phi_{j+1}, \quad \partial \phi_j / \partial y = \partial \phi_{j+1} / \partial y \quad (j = 1, 2) \quad \text{at} \quad y = 0, \lambda \tag{3} \]

The boundary conditions requiring to be continuous as

and these conditions applied to the above solutions yields the dispersion relation
\[ m^2 + k^2 + b^2 + 2bk / \omega = 0, \]

and

\[ \tan \lambda m = \frac{2mk}{m^2 + b^2 - k^2}. \tag{4} \]

This dispersion relation has been calculated as a function of wavenumber for the first three modes using the following parameters: \( h_1 = 150 \text{ m}, h_2 = 2000 \text{ m}, \) and \( \lambda = 56 \text{ km}, \) and these are presented in Fig. 9. We are certain that the 1st-mode ISW over the shelf off San’in coast exists in a range of a diurnal-period. The theoretical wavelengths of \( K_1 \) and \( O_1 \) tides are 160 km and 141 km, respectively, and their phase velocities are 1.9 m s\(^{-1}\) and 1.5 m s\(^{-1}\). These waves have a very slow propagation speed with the coast on the right-hand side and occur with relatively short alongshore scales comparable to that of the Kelvin waves (10\(^3\) km). Their group velocities \(-2.8 \text{ m s}^{-1}\) have the opposite sign of the phase velocities, so that the decay of the eastward propagating wave is more likely to be due to wave dispersion effect. The amplitudes of current components \( u \) and \( v \) are also shown for the 1st-mode, \( \omega / f = 0.79 \) (a case of the \( O_1 \) constituent) in Fig. 10. Over a constant depth, i.e. on the shelf and open oceans, the alongshore velocities \( u \) have amplitudes comparable to the offshore velocities \( v \). Since \( u \) and \( v \) have opposite signs and \( v \) lags \( u \) by \( \pi / 2 \), the velocity vector rotates clockwise in the horizontal plane. Therefore, the theoretical ellipses over the shelf may be circular and are qualitatively similar to the observed ones in Fig. 5.

### 4.2.2 Generation mechanism of the ISWs

We next consider the generation mechanism of the ISWs. Thomson and Crawford (1982) first proposed the following generation mechanism of diurnal shelf waves; shelf wave currents

![Dispersion curves for the lowest three modes of ISWs.](image)

Fig. 9. Dispersion curves for the lowest three modes of ISWs.
Fig. 10. The distributions of amplitudes of offshore velocity component \((v)\) and alongshore velocity component \((u)\) of ISWs with O\(1\) tidal frequency.

are indirectly forced through an offshore mass flux within a time-dependent bottom turbulent boundary layer produced by the tidal currents. However, adoption of the above mechanism is limited to the case of coastal trapped shelf waves.

Because the axis of the Tsushima Straits is roughly perpendicular to the shelf slope off San’in coast, it is possible that the currents at the entrance to the straits co-oscillate with motions over the shelf. Then, it is expected that the vortex will be directly supplied by the on-offshore displacements of the water column over the shelf/slope topography and lead to a regional amplification of diurnal currents. Presumably, the entrance to the straits may prove to be a source of diurnal wave energy.

To confirm quantitatively the above generation process, numerical experiments are performed using a barotropic model with a simplified coast configuration and shelf topography. A schematic view of this barotropic model is shown in Fig. 11. The opening at southern lateral boundary corresponds to the Tsushima Straits. The other lateral boundaries are represented by artificial vertical walls in our model. The distance between the western (the Korean peninsula) and eastern (the Oki islands) lateral boundaries is about 300 km. At these artificial walls, the normal component of velocity to the wall is zero, and for the tangential component the slippery condition is adopted. A slope running east-west in the model basin represents the shelf slope off San’in coast. It has a simple form of the exponential depth profile shown in Fig. 8. Thus, the model configuration of Fig. 11 is a high simplification of those in Fig. 2, because we are mainly concerned with the dynamics of the generation of the diurnal ISWs rather than simulating realistic tidal flow patterns. A rectangular coordinate system on \(f\)-plane is used with \(x\) alongshore and \(y\) offshore. The positive \(y\) direction is northward. Under the hydrostatic approximation, the linearized momentum equation and the continuity equation are
Here \( u = (u, v) \) with \( u \) and \( v \) being the depth-averaged components of velocity in the \( x \) and \( y \) directions, respectively; \( \nabla \) is the horizontal differential operator; \( k \) is the locally vertical unit vector; \( g \) is the gravitational acceleration; \( \eta \) is the elevation; \( H(x, y) \) is the undisturbed water depth; \( t \) is time; \( f \) is the Coriolis parameter; \( \nu \) is the coefficient of the horizontal eddy viscosity \( (10^6 \text{ cm}^2 \text{ s}^{-1}) \). The dotted enclosed region is a buffer region where higher viscosity \( (10^8 \text{ cm}^2 \text{ s}^{-1}) \) is set. The ocean is initially at rest. The model ocean is forced at the southern lateral boundary \((y = 0)\), such that

\[
\frac{\partial u}{\partial t} + f k \times u = -g \nabla \eta + \nu \nabla^2 u, \tag{5}
\]

\[
\frac{\partial \eta}{\partial t} + \nabla (Hu) = 0. \tag{6}
\]

where \( \omega = 2\pi/25 \text{ hours} \) for the case of diurnal tide and \( \omega = 2\pi/12 \text{ hours} \) for the case of semidiurnal tide. In both cases, \( v_0 = 20 \text{ cm s}^{-1} \) is assumed, which is the typical value for the tidal current in the Tsushima Straits (Odamaki, 1989a).

Figure 12 shows the distributions of current ellipses for the simulated semidiurnal tide (12 hour-period; a) and diurnal tide (25 hour-period; b). Figure 13 shows the space-time \((x-t)\) diagrams along the shelf edge (Line L–L' in Fig. 11) for seaward (or northward) velocity component \((v)\), with the periods of 12 hours (a) and 25 hours (b). The semidiurnal currents show that onshore current is dominant on the shelf and its amplitude gradually decreases seaward. The
Fig. 12. Distributions of current ellipses for semidiurnal tide (12 hour-period; a) and diurnal tide (25 hour-period; b).
fluctuations on the shelf slope propagate eastward at about 40 m s$^{-1}$, which corresponds to the phase speed of the Kelvin waves. On the other hand, the diurnal tidal currents have maximum amplitude on the shelf slope in the western part of the model ocean basin where the shape of ellipses becomes circular. From Fig. 13, it is found that the diurnal waves are generated near the western side wall and start propagating eastward slowly. This eastward propagation speed is about 2 m s$^{-1}$ as indicated by a solid line. These simulated feature is similar to that of the theoretical 1st-mode ISWs. The eastern part of the model ocean has been gradually affected by the reflected ISWs, although there is a buffer region connected to the eastern wall.

As mentioned above, the propagation of ISWs originates from the western end of model ocean basin, corresponding to the cross-point between the shelf slope off San’in coast and the Korean peninsula in the actual topography. We note the abrupt beginning of waves near the western entrance of the Tsushima Straits where the diurnal amphidromic point found very close to the Korean coast exists.

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Fig. 13. Space-time $(x-t)$ diagrams along the shelf break (Line L–L' in Fig. 11) for the offshore velocity component ($v$), with the periods of 12 hours (a) and 25 hours (b). Contour interval is 5 cm s$^{-1}$ and positive (negative) values are shown by solid (broken) lines.
5. Conclusion

The variability of tidal currents found in the data from current meters deployed at two moorings around the shelf break off San’in coast was described. Data have shown that the diurnal tidal currents were larger than the semidiurnal tidal currents and the predominant diurnal tidal currents had higher-energy levels on the shelf slope than on the shelf. Then, we proposed the existence of ISWs as the possible cause of the predominant diurnal tidal currents.

An analysis of current data in a diurnal-period indicates that the cross-shelf current field is fitted well by the theoretical 1st-mode ISWs. Furthermore, it is inferred from a simple model experiment that tidal current forcing in the Tsushima Straits may be generating the ISWs on the shelf slope, because of direct vortex stretching of the water columns across the shelf/slope topography. It is also suggested that diurnal ISWs generated along the shelf slope consist of the waves with group velocity in the opposite direction of phase velocity. Such forcing mechanism exists everywhere there are significant diurnal currents in the seaward direction, whereas the response is limited to sections of a topography having sufficiently broad shelf and steep shelf slope to support ISWs oscillations. The wave propagating along the actual shelf slope off San’in coast, however, will encounter a narrow shelf region near the Oki islands (see in Fig. 2) beyond which the topography will no longer support the diurnal ISWs. From these reasons, the diurnal currents associated with ISWs will be expected to prevail only on the western part of the shelf region off San’in coast. A full description of how the ISW is affected by the alongshore variation in depth depends on our future study.

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References