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Diurnal tidal currents attributed to free baroclinic coastal-trapped waves on the Pacific shelf off the southeastern coast of Hokkaido, Japan

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ABSTRACT

To understand the properties of tides and tidal currents on the Pacific shelf off the southeastern coast of Hokkaido, Japan, we analyzed time series of 9 current meters that were moored on the shelf for 1 month to 2 years. Diurnal tidal currents such as the K_1 and O_1 constituents were more dominant than semi-diurnal ones by an order of magnitude. The diurnal tidal currents clearly propagated westward along the coast with a typical phase velocity of $2\,m\,s^{-1}$ and wavelength of 200 km. Moreover, the shape and phase of the diurnal currents measured by a bottom-mounted ADCP were vertically homogeneous, except in the vicinity of the bottom boundary layer. These features were very consistent with theoretically estimated properties of free baroclinic coastal-trapped waves of the first mode. An annual (semi-annual) variation was apparent for the phase (amplitude) of the O_1 tidal current, which was correlated with density stratification (intensity of an along-shelf current called the Coastal Oyashio). These possible causes are discussed in terms of the propagation and generation of coastal-trapped waves.

1. Introduction

Tides and tidal currents are among the most basic oceanographic variations. To understand their properties and precisely predict them are essential issues not only for oceanography but also for some practical-use fields such as fisheries. Regarding the 8 major tidal constituents (i.e., K_1, O_1, P_1, Q_1, M_2, S_2, K_2, and N_2), barotropic tides with a large basin-scale wavelength propagate like Kelvin waves trapped against the coasts of the Kuril, Four, Hokkaido, and Japan Islands in the Northwestern Pacific (e.g., Fig. 1a), and dominate tidal elevations on the Pacific shelf of Japan (Nishida, 1980). Generally, such barotropic tides interact with irregular coastline or bottom topography, modifying the barotropic wave properties (e.g., Osborne et al., 2011; Zhang and Yankovsky, 2016) or causing a strong vertical velocity that results in the generation of smaller-scale waves such as internal waves (e.g., Tanaka et al., 2007, 2010). At latitudes poleward of 30°, the diurnal tide occurs at a frequency below the inertial frequency, and even weak density stratification makes it easy for the diurnal tide to excite coastal-trapped waves (CTW) (e.g., Brink, 1991; Huthnance, 1978). In fact, representative studies of coastal-trapped waves with a diurnal period were intensively carried out for the shelf off the west coast of Vancouver Island north of 48°N (Crawford and Thomson, 1984; Flather, 1988; Foreman and Thomson, 1997; Cummins et al., 2000), where the irregular coastline of the Juan de Fuca Strait, which is associated with anomalously large diurnal tidal currents, generated the diurnal CTWs.

Hokkaido is located north of 41°N and is surrounded by the Northwestern Pacific, Japan Sea, and Okhotsk Sea (Fig. 1). Strong diurnal tidal currents are induced by differences in tidal elevation between these 3 regions and are observed near the straits connecting them, i.e., Tsugaru Strait (Kuroda et al., 2004; Luu et al., 2011; Odamaki, 1984), Soya Strait (Aota and Matsuyama, 1987), and plural straits around the Four and Kuril Islands (Kovalev and Rabinovich, 1980; Kowalik and Polyakov, 1998; Nakamura et al., 2000; Ohshima et al., 2002; Rabinovich and Thomson, 2001; Yefimov and Rabinovich, 1980). It is expected that energetic diurnal tidal currents near the straits excite CTWs on the shelves, which then propagate along the coast of Hokkaido, but all of the features of the CTWs have not been understood, except for what has been reported in a few articles.

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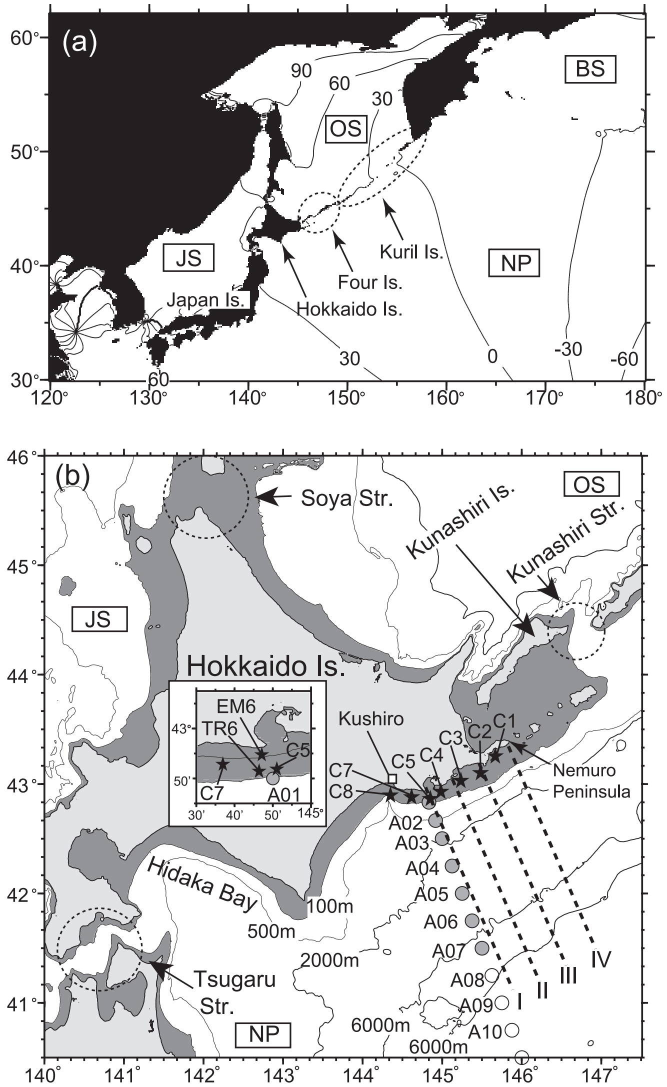

Fig. 1. (a) Co-tidal chart of the K_1 tide based on FES2004 (Lyard et al., 2006) using Greenwich phase (degrees). The Kuril and Four Islands are surrounded by dashed ellipses. (b) Bathymetry around Hokkaido. Shallow shelves with water depths less than 100 m are emphasized by gray shade. Closed gray and open circles represent hydrographic stations of the regular monitoring line called the "A-line". In this study we analyzed CTD data from 7 stations (i.e., Stns. A01–A07) corresponding to the closed gray circles. Locations of current measurements are denoted by black stars. The bathymetry and measurement positions around Stn. C5 are expanded and illustrated in a separate panel. The location of the Kushiro tidal gauge is indicated by an open square. The following abbreviations are used in (a) and (b): BS (Bering Sea), NP (Northwestern Pacific), OS (Okhotsk Sea), and JS (Japan Sea).

Odamaki (1994) reported that diurnal tidal currents dominant near Soya Strait propagate southeastward as barotropic CTWs (i.e., shelf waves) along the Okhotsk coast off the northeastern coast of Hokkaido (Fig. 1b). Kuroda et al. (2008) discovered that diurnal tidal currents, particularly the O_1 currents, were much more dominant than semidiurnal ones on the shelf in Hidaka Bay off the southwestern coast of Hokkaido (Fig. 1b), and they attributed them to free baroclinic CTWs of the first mode. The observed diurnal tidal currents were highly variable in time; their amplitude and phase changed substantially with time. However, possible causes of this high variability have not been identified. To explore these points, it is instructive to understand the features of diurnal tidal currents in the upstream region of Hidaka Bay, because diurnal CTWs can propagate along the coast from the outside to the inside of the bay.

This study examined properties of tides and tidal currents on the Pacific shelf off the southeastern coast of Hokkaido, which is located upstream of Hidaka Bay and to the southwest/downstream of the Four and Kuril Islands (Fig. 1). We moored 2 current meters on the Pacific shelf off the Hokkaido coast and analyzed them by adding time series of 7 current meters that were also moored along the shelf during summer by the Japan Coast Guard. The purpose of this study was to describe the nearly steady state features of tides and tidal currents and discuss the seasonal variation of diurnal tides and tidal currents.

2. Material and methods

2.1. Data

We analyzed time series of 9 mooring current meters as summarized in Table 1. Current data from 7 of the stations (Stns. C1, C2, C3, C4, C5, C7, and C8) were collected from the Japan Oceanographic Data Center. The number in each station name roughly indicates the mooring location by ascending order from east to west. The measurements were conducted by the Japan Coast Guard on the Pacific shelf at water depths of 34–83 m off the southeastern coast of Hokkaido (Fig. 1b). The current meters were moored at a depth of 10 m below the sea surface. The mooring periods were about 1 month during June–August. The sampling intervals were 15 or 60 min.

Hokkaido University and the Japan Fisheries Research and Education Agency (FRA) conducted a mooring current measurement at Stn. EM6 during May–December in 2002. A compact electromagnetic current meter, "Compact-EM", manufactured by JFE Alec electronics, was moored 17 m below the surface. The sampling interval was 60 min. Moreover, the FRA carried out a long-term current measurement at Stn. TR6 with a water depth of 82 m for about 2 years from July 2003 to July 2005 using a bottom-mounted, 300-kHz acoustic Doppler current profiler (ADCP) (Workhorse Sentinel, RD Instruments) (Kusaka et al., 2009, 2016). In this study, the original station name of Stn. AK1 (Kusaka et al., 2016) was changed to Stn. TR6. The sampling interval was 15 min. We analyzed high-quality ADCP data, with percent good more than 80%, from the depths of 76–12 m below the sea surface at vertical intervals of 4 m.

Conductivity-temperature-depth (CTD) measurements have been regularly carried out along a transect called the "A-line" off the southeastern coast of Hokkaido by the FRA (e.g., Kuroda et al., 2015, 2017) (Fig. 1b). CTD were basically lowered to a pressure level of 3100 dbar or the vicinity of the sea bottom at stations with a water depth $<$ 3100 dbar. In this regard, there were some CTD measurements deeper than 3100 dbar. This study used CTD data from Stns. A01–A07 on the shelf-slope region: Stn. A01 was located on the shelf at a water depth of 99 m, and Stn. A07 was in the vicinity of the Kuril-Kamchatka Trench at a water depth of 7150 m. We used CTD data from 14 cruises that corresponded to the 2-year period of bottom-mounted ADCP measurements: July, September, and October in 2003; January, February, March, April, May, July, August, and October in 2004; and January, March, and May in 2005. Additionally, to understand the variations of the Oyashio transport on the continental slope off Stn. TR6 during the 2-year period, we used time series of daily estimated transports that were generated by combining satellite altimetry and CTD data on the A-line (Kuroda et al., 2017).

Hourly coastal sea level data at Kushiro (Fig. 1b) were collected from the Japan Oceanographic Data Center from July 2003 to July 2005, which corresponds to the 2-year period of the bottom-mounted ADCP measurements. The sea level data were originally measured by the Japan Meteorological Agency.

2.2. Harmonic analysis

To estimate harmonic constants (i.e., amplitude and phase), 3 kinds of harmonic analyses based on the least squares method were adopted because the precise estimation of tidal constituents strongly depends on