NOTES AND CORRESPONDENCE

Observations of Ice–Ocean Eddy Streets in the Sea of Okhotsk off the Hokkaido Coast Using Radar Images

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ABSTRACT

This study examines the features of fairly regular ocean-wave motion in which some eddy streets or backward breaking waves are successfully visualized using sea ice floes as a tracer. These examinations are made using the time sequence of radar imagery data collected during the past 20 years, 1969–88; the correspondence of the radar images with the actual pattern is partially confirmed through aircraft observations. The ice–ocean eddy street or backward breaking wave pattern runs parallel to the coastline at a distance of about 20 km from the Hokkaido coast; the eddy street also corresponds to a boundary between the Soya Warm Current and colder, less saline offshore water. The wave motion is characterized by wavelengths of 40–55 km, phase velocities of 14–20 km day−1 and periods of 2.3–5.5 days. The regular ice–ocean wave motion pattern was observed when pack ice had a small ice concentration composed of uniform sized ice floes and weak winds. The sea ice floes serve as a highly effective flow indicator in the radar observations of the ice–ocean wave motion.

1. Introduction

The Sea of Okhotsk is located at the lowest latitude for a sea-ice covered region in the Northern Hemisphere. The sea ice cover first forms in Shantar Ski Bay in late November and then advances eastward. Part of it flows southward to the east of the Sakhalin, taking the form of a long, narrow belt and usually reaching the Hokkaido coast (mainly off the coast of Esashi-Ohmu) in early January. The sea ice cover with a thickness of the order of 0.3–1 m usually stays there for about 3–4 months though the ice content changes year to year. The patterns of the sea ice advance and retreat change remarkably depending upon atmospheric and oceanic conditions. Figure 1 shows the bathymetry off the Hokkaido coast in the Sea of Okhotsk. This region is characterized as a continental shelf sea, being for the most part relatively flat, shallower than a depth of 200 m, though there is a steep bottom slope in the eastern margin.

The Institute of Low Temperature Science, Hokkaido University, Japan, has maintained an ice-floe monitoring radar network on the northern coast of Hokkaido facing the Sea of Okhotsk since 1969. The network consists of three land-based radars and allows a continuous monitoring of real-time ice field scenery along a 250-km coastline to about 50 km offshore in the Sea of Okhotsk (Fig. 1). In the marginal sea ice zone off the Hokkaido coast, we have sometimes found patterns of ice–ocean eddies in the movie films made of 3-hour interval time-lapse radar images (e.g., Sonu and Aota 1985). Meanwhile from spring to fall, we also have observed a fairly regular wavelike pattern in the front of the Soya Warm Current, which flows southeastward off the Hokkaido coast having the characteristics of a coastal boundary current, through the satellite infrared imagery of the sea surface shown in Fig. 2.

Also, on 12 January 1987, a cyclonic ice–ocean eddy was observed from an aircraft about 20 km off Esashi-Ohmu of the Hokkaido coast in the Sea of Okhotsk (Fig. 3). At that time, the radar network also caught the images of the corresponding ice–ocean eddy. One of them is shown in Fig. 4. The ice–ocean eddy seems to be one of a vortex street. This aerial photography confirms the eddy patterns in the radar images. The correspondence of radar images with the actual eddy pattern prompted us to reexamine thoroughly the radar records collected during the past 20 years.

The existence of ice–ocean eddies in the Greenland Sea has been reported by several investigators. Five kinds of mechanisms for the formation of the ice–ocean eddies have been proposed: 1) barotropic instability (Johannessen et al. 1983), 2) baroclinic instability (Wadhams and Squire 1983), 3) topographic control (Smith et al. 1984), 4) wind effect (Hakkinen 1984), and 5) advection of open-ocean eddies towards the ice edge (Johannessen et al. 1987).
Fig. 1. Bathymetric map (contours in meters) off the Hokkaido coast in the Sea of Okhotsk; the whole geographical map of the Sea is inserted in the upper right side (SB, Shantarisky Bay). Five meteorological stations are located along the coastline facing the Sea: W: Wakkanai; E: Esashi; O: Ohmu; M: Mombetsu; A: Abashiri. Broken lines show the areas covered by the three land-based radars. The mark (x) shows the location of the 1987 ice–ocean eddy (Fig. 3).

In this paper, we present quantitative characteristics of an ice–ocean eddy street or backward breaking waves off the Hokkaido coast in the Sea of Okhotsk, obtained from the analyses of radar records during the period of 1969–88. In a separate paper (Ohshima and Watsatsuchi 1990), we also propose a mechanism for the formation of the ice–ocean eddy street derived from a numerical experiment on the basis of the observational results.

2. Aircraft observations

Several pictures of the ice–ocean eddy were taken from a variety of directions and altitudes. The cyclonic pattern of the ice–ocean eddy was drawn with ice bands that were radially concentrated in the center of the eddy as shown in Fig. 3. The ice bands were composed of uniform sized pancake ice floes with a dimension of about 10 m in diameter. The open water area between the ice bands was covered with rapidly forming new ice. No larger ice floes existed in the surrounding ice field. A large area of open water was found in a region between the coast of Esashi-Ohmu and the ice–ocean eddy. The dimension of the ice–ocean eddy was estimated to about 20 km in diameter. From the radar records, this estimate is approximately correct.

3. Analyses of radar images and oceanographic observation data

We examined all records, which were obtained through three land-based radars during the past 20 years, 1969 through 1988. We often observed a fairly regular wave-motion pattern, such as an eddy street or
backward breaking waves, distinguished from the background ice motion. Figure 5 shows the time sequence of the backward breaking wave-patterned ice edge as a typical example. This characteristic pattern mainly occurred at the front of advancing sea ice cover under an ice concentration of less than 60% generally recognized to have zero internal ice stress (Røed and O’Brien 1983). The field of flow velocity vectors of ice floes and leads identifiable in the sea ice cover (Fig. 5) also showed that the backward breaking wave-patterned ice motion actually occurred in the marginal ice zone and the waves propagated southeastward off the Hokkaido coast.

In the sea ice edge off the Hokkaido coast in which the backward breaking waves are visualized, an ice-ocean eddy street composed of two or three eddies with a dimension of 20–30 km in diameter also forms. It seems that part of the ice–ocean eddy street was taken as the isolated eddy as shown in Fig. 3. The northernmost eddy is mostly observed off the coast of Esashi-Ohmu, Hokkaido. The ice–ocean eddy street runs parallel to the coastline at a fixed distance of about 20 km. The life time of eddies traced by the sea ice floes ranged from 1 to 4 days. The ice–ocean eddy pattern eventually disappeared with the supply of additional ice floes from the north. Figure 6 shows the spatial distribution of flow velocity vectors for the 1979 ice–ocean eddies and the trajectories for 42 hours of two typical ice floes inside the eddy. Both ice floes made one counterclockwise rotation over a period of about 40 hours and the maximum orbital speed was about 0.7 m s\(^{-1}\). These observations show that a cyclonic eddy motion occurs.

The generation of oceanic eddies in a region with irregular bottom structure such as a depression or rise is explained with the concept of potential vorticity conservation (Smith et al. 1984). The topographic eddy generation does not occur over the continental shelf off the Hokkaido coast because no irregular topography exists there, as shown in Fig. 1. Ohshima (1987) theoretically suggested the possibility of barotropic instability as a mechanism for the formation of the wavelike pattern that occurs at the front of the Soya Warm Current in summer. Fortunately, oceanographic surveys off the Hokkaido coast were made by the Hokkaido Wakkani Fisheries Experimental Station in late April 1984 just after the pattern of the ice–ocean wave motion shown in Fig. 5 was disappeared. A distinct front also exists in a boundary between the Soya Warm Water and the colder, less saline offshore water in the early spring, as shown in Fig. 7a. Also, a cold water mass lies inside the Soya Warm Water, as shown in Fig. 7b. The water structure in this region is also characterized by the existence of a weak density stratification and no clear density front, though the distinct fronts of temperature and salinity exist. The cold water masses were also found in other oceanographic sections across the Soya Warm Current. According to observations with moored current meters (Aota and Kawamura 1978), the Soya Warm Current barotropically flows southeastward off the Hokkaido coast throughout the winter, having the characteristics of a coastal boundary current. The existence of cold water masses may be interpreted as a result of intrusion of the offshore water caused by the ocean-wave motion. These observations suggest that the wave motion that originated in the ocean actually may have existed in the front of the Soya Warm Current in the winter season and was successfully traced by the sea ice floes as a tracer (Fig. 5).

We next examine the wavelength, phase velocity and period of the ice–ocean wave motion from several different patterns as typically shown in Fig. 8. The results are summarized in Table 1. In winter and spring the
Fig. 3. A photograph of a cyclonic ice-ocean eddy observed off the coast of Esashi-Ohmu from an aircraft at altitude, 10 000 feet, 0700 LST 12 January 1987 (provided by the Asahishinbun Co.). The cyclonic eddy has a dimension of about 20 km in diameter and is marked by ice belts composed of homogeneous sized ice floes with a diameter of about 10 m.

Fig. 4. Radar images of Esashi (left) and Mombetsu (right) stations at 0600 LST 12 January 1987. The ice–ocean eddy off the Esashi coast, shown by a white arrow, corresponds to that shown in Fig. 3. Another eddy pattern is also found off the Mombetsu coast. Scales are shown by 3-mile interval circles.
Fig. 5. Radar images (left) and flow velocity vectors (right) at a half-day interval of ice-ocean wave pattern (backward breaking waves) off the Hokkaido coast on 14–16 April 1984.
waves in this region are characterized by wavelengths of 40–55 km, phase velocities of 14–20 km day\(^{-1}\) and periods of 2.3–3.5 days, though there is an example of a slower phase velocity of 10.2 km day\(^{-1}\) for April 1979. An inertial period off the Hokkaido coast is about 18 hours (Ono 1979). It is suggested from the above results that a wave motion with a period distinctly different from the inertial period occurs off the Hokkaido coast in winter and spring.

Figure 9 shows wavelengths of the wave motion as a function of distance from the Soya Strait. These results were obtained from the analysis of 35 examples that distinctly showed the patterns of ice–ocean eddy street or backward breaking waves in the radar imagery data collected during the past 20 years, and from the NOAA IR imagery data in the early spring (March through May). These waves were not concentrated in a fixed location though the regular eddy patterns were mostly observed off the coast of Esashi-Ohmu. The wave motion occurred anywhere along the coastline off the Hokkaido coast. As shown in the NOAA IR imagery data of Fig. 9, a similar wave motion also occurred when there is no sea ice cover. Therefore, it appears that the wave-patterned motion occurs independent of the existence of the sea ice cover; hence, its only role is as a tracer.

4. Discussion

The atmospheric surface pressure in the Sea of Okhotsk throughout the winter is characterized by high pressure to the west and low pressure to the east. Therefore, the prevailing wind off the Hokkaido coast in winter is from the northwest, though the wind directions often change with the passage of small scale cyclones through the region. Figure 10 shows the variations of wind direction and speed at several stations along the Okhotsk coast of Hokkaido before and after the 1984 ice–ocean eddy street event shown in Fig. 5. According to the radar records, the patterning of the 1984 ice–ocean eddy street off the coast of Esashi-Ohmu began at about 1500 local time 14 April. At that time, the wind direction dramatically changed from a northerly to a southerly direction, then wind speed markedly weakened, particularly at Esashi and Ohmu off which the ice–ocean eddy street was clearly observed (Fig. 10). Similar trends in the change of wind direction and the decrease of wind speed were also observed in the other eddy formation years (1979 and 1987). With weakening wind speed, the mean flow velocity of the advancing sea ice floes rapidly decreased, for example, in 1987 it decreased from 1.2 to 0.15 m s\(^{-1}\) during the period of 12 hours before the patterning of the ice–ocean eddy begins.

Meanwhile, the patterns of ice–ocean eddy street or backward breaking waves have never been observed when a strong wind was continuously blowing from the northwest; at that time the wind brought about the constant supply of pack ice from the north to the eddy region and the resultant wind-driven ice motion broke the patterns of ocean eddies on the surface. Moreover, the wind-induced Ekman transport under the ice for northerly winds will cause ice convergence and increased ice concentration (Røed and O’Brien 1983). Also, the eddy patterns have never been observed for a sea ice concentration higher than about 80% even under no or weak winds; the high ice concentration may cause attenuation of the ocean eddy velocity.

A theoretical examination of the interaction of isolated mesoscale ocean eddies with a marginal ice zone by Smith et al. (1988) also shows that the patterning of the ocean eddies with sea ice depends upon wind effect; in the absence of wind, the ice equilibrates rapidly to the ocean eddy velocity, resulting in radial ice motion, while under a strong wind, the ice responds...
largely to the wind, and the appearance of ocean eddy can be rapidly eroded by wind-driven ice motion.

To observe the patterns of such a regular ice–ocean wave motion as eddy street or backward breaking waves off the Hokkaido coast in the Sea of Okhotsk, therefore, some natural conditions must occur. First, a reasonable extent of pack ice as a tracer should advance from the north through a northwesterly wind having a small ice concentration. Second, the pack ice is needed to be composed of small, uniform sized sea ice floes, as shown in Fig. 3 because they have a minimum interaction with one another and act as a tracer of the existing ocean–eddy street or backward breaking waves. Finally, no wind or a weak southeasterly wind are required during the visualization of ice–ocean eddy street, as shown in Fig. 10, because the additional supply of pack ice from the north will cause active ice motion and destroy the regular pattern.

5. Concluding remarks

In a marginal sea ice zone off the Okhotsk coast of Hokkaido, we observed a fairly regular ocean-wave motion in which an eddy street or backward breaking waves were successfully visualized with sea ice floes as a tracer, through the radar imagery data collected during the past 20 years, 1969–88. The correspondence of the radar images with the actual phenomena was partially confirmed through aircraft observations. The wave motion, which is distinctly different from the inertia-period oscillation, occurred at the front of the Soya Warm Current which flows southeastward along the Hokkaido coastline, having the characteristics of

FIG. 7. (a) Horizontal distributions of temperature and salinity, and (b) temperature, salinity, and (c) sigma-τ sections along a line [dark arrow in (a)] off the Hokkaido coast in the Sea of Okhotsk just after the 1984 ice–ocean wave motion event shown in Fig. 5. Sea ice cover remains offshore.

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<td>48</td>
<td>15.4</td>
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FIG. 8. Radar images at a half-day interval of the ice–ocean eddy street off the Hokkaido coast on 15–17 April 1979.
Fig. 9. Wavelengths of the ice–ocean wave patterns as a function of distance from the Soya Strait. Data (+) are based on the records of radar images collected during the past 20 years, 1969–88. Data (●, ○) are based on the NOAA IR images in the spring (March through May). The dark dots indicate the case that no sea ice exists and the open dots the case that sea ice exists.

wavelengths, 40–55 km, phase velocities, 14–20 km day\(^{-1}\), and periods, 2.3–3.5 days.

The above observations showed that the pack ice acted well as a tracer of the ocean-wave motion pattern when some natural conditions were successfully completed; the pack ice must consist of small, uniform sized ice floes, there must be a small ice concentration over the eddy region, and no wind or weak wind is required to visualize the ice–ocean eddy. Under these circumstances, therefore, it is suggested that the existence of pack ice as a tracer is highly effective in examining the properties of oceanic phenomena with a radar network system.

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Fig. 10. Variations of wind directions and speeds at five stations (see Fig. 1) located in order from the north along the coastline of Hokkaido facing the Sea of Okhotsk. A white arrow shows a time when the 1984 ice–ocean eddy street began to appear off the coast of Esashi-Ohmu.
Ministry of Education, Science and Culture and completed while one of us (M.W.) stayed in the University of Washington as a visiting scientist.

REFERENCES


