Journal of the Korean Society of Remote Sensing, Vol.15, No.2, 1999, pp.175~181

Communication

A Recurring Eddy off the Korean Northeast Coast Captured on Satellite Ocean Color and Sea Surface Temperature Imagery

Young-Sang Suh*, B. G. Mitchell, and Kyuen-Sik Lim*****

Remote Sensing Lab. NFRDI*, Scripps Institution of Oceanography, USA**, and R.O.K. Naval Academy***

위성의 해색 영상과 해수면온도 영상을 활용한 재발생 와동류에 관한 연구

서영상* · B. G. Mitchell** · 임근식***

국립수산진흥원 원격탐사실*, 미국 스크립스 해양연구소**, 해군사관학교***

Abstract : A recurring eddy which located at the terminal end of the Korean East Warm Current was captured on ocean color and sea surface temperature imagery from satellite in spring and autumn. During late April, 1997 thermal infrared imagery from the NOAA AVHRR sensor and ocean color data from the Japanese ADEOS-I OCTS sensor, revealed this feature. The cold core had elevated chlorophyll concentrations, based on OCTS estimates, of greater than 3 mg/m^3 while the warmer surrounding waters had chlorophyll concentrations of 1 mg/m^3 or less. The elevated chlorophyll associated with this eddy has not been previously described. The eddy is also evident in SST images from autumn, but the SST in the core is warmer than in spring, and the warm jet flowing to the west of the eddy is also warmer in autumn compared to spring. A reccuring eddy and the high chlorophyll_a concentration area which surround around the eddy show on NOAA and SeaWiFS images in March 2, 1998.

The eddy forms at the northern extent of the Korean East Warm Current as those waters collide with the cold, south-flowing Liman Current over a topographic shelf about 1500 m deep. This region of the eddy formation appears to have a strong connection with the dynamics of the western part of the polar front eddy field that dominates surface mesoscale structure in the central East (Japan) Sea. Interaction of the eddy with ARGOS tracked drifters, and evidence for its persistence are discussed.

Key Words : eddy, satellite remote sensing, chlorophyll, SST, ARGOS drifter

요 약 : 동한 난류의 북상 끝부분 해역에서 재발생하는 와동류는 봄철과 가을철에 위성이 관측한 해수면 온도 영상에 나타났다.

이러한 재발생 와동류는 1997년 9월 하순 NOAA 위성에 탑재된 AVHRR의 열적외선 영상과 일

Received 15 March 1999 ; Accepted 18 April 1999.

본 ADEOS 위성에 탑재된 OCTS의 클로로필 영상에도 나타났다. 와동류의 중심은 주변보다 온도가 낮으며, OCTS 위성자료에서 3mg/m^3 이상의 클로로필 농도가 나타났다. 반면, 와동류를 이루는 주변의 더운물에서는 클로로필 농도가 1mg/m^3 이하로 나타났다.

와동류는 가을철 표면수온영상에도 나타났으며 봄에 나타난 것보다 와동류 중심핵의 찬물 온도가 높게 나타났다. 또한 와동류 중심에서 서쪽축의 더운물 온도가 봄에 나타난 것보다 가을에 더 높게 나타났다.

1998년 3월 NOAA위성과 SeaWiFS 위성 영상자료에서도 재발생되는 와동류와 클로로필량의 농도가 높은 물이 와동류 주변으로 포획되는 장면이 포착되었다.

동한난류의 북쪽 확장 선두와 약 1500m 수심의 대륙붕 위로 남하하는 리만한류가 만나 충돌하는 해역에서 와동류가 형성되는 것으로 사료된다. 와동류가 형성되는 이 해역은 동해 중앙부 해수면에서 우세하게 나타나는 극전선역에서 중규모 구조의 와동류가 극전선 서쪽해역의 역학적인 해양현상과 강한 연관성이 있음을 나타내었다. ARGOS 위성추적 표류부이와 와동류의 상호연관성 및 와동류의 지속성에 관한 증거가 토론되었다.

주요어 : 와동류, 위성원격탐사, 클로로필, 해수면 온도, 위성 추적 부이

1. Introduction

The Korean East Warm Current flows north on the eastern coast of Korea and eventually collides with the colder Liman Current that flows south along the Russian coast. Along 40° N, there is a prominent frontal boundary between the southern warm masses and the northern sub-polar waters. This zonal boundary spans the entire East Japan Sea and is populated with numerous meso-scale eddies that have general west to east flow, but with significant basin scale variance in trajectories.

A every year recurring cold-core anti-cyclonic eddy feature centered at approximately 39° N and 129° E frequently is evident in satellite sea surface temperature (SST) images collected from the NOAA AVHRR polar orbiter satellite series. The colder interior water has higher pigment concentrations, as evidenced by the ADEOS-I OCTS and the Orbview-2 SeaWiFS satellite ocean color sensors. This eddy has been noted in previous hydrographic (Lie et al., 1995; Tomczak, and Godfrey, 1994, Yurasov and Yarichin, 1991), satellite (Huh, 1982) and modeling (Kim, 1995) reports.

A study of the September-October-November 1997 mean SST composite of SST from NOAA 12/14 clearly illustrates the main basin scale aspect of the sub-polar front, but most of the mid-basin mesoscale structure is smoothed due to the time-variance of the location of maximum and minimum temperatures at this scale. However, the eddy that we focus on has a persistent representation at approximately the same spatial scale as it is noted in single image. The persistent nature of this eddy, and its obvious influence on the water mass circulation at the western end of the basins eddy field leads us to postulate that this eddy has a significant influence on circulation of the western Japan/East Sea Basin. We refer to this quasi-stationary eddy as the Korea Coastal Cold Eddy (KCCE).

2. Data and Method

The several satellite data from ADEOS-I OCTS, Orbview-2 SeaWiFS and NOAA-12/14 were used for analyzing a recurring eddy in the Korean East Warm Current. In addition, NOAA satellite tracked ARGOS drifter data from September to November, 1997 was used for characteristic of eddies.

The equations computed chlorophyll-a are as follows:

In Orbview-2 SeaWiFS data, we use seabam (SeaWiFS Bio-optical Mini-workshop) algorithm(McClain, 1997).

$$\text{chlorophyll-a} = CH1 + CH2 \times r35 + CH3 \times r35 \times r35 + CH4 \times r35 \times r35 \times r35 \quad (1)$$

where CH0 through CH4 are the coef-ficents (CH0 = -0.0929, CH1 = 0.2974, CH2 = -2.2429, CH3 = 0.8358, CH4 = -0.0077) and r35 = log 10 (rrs[2] / rrs[4]), r35 is the ratio of remote sensing reflectances of seawifs channels 2 & 4, where rrs is the remote sensing reflectance.

In ADEOS-I OCTS data, following equation comput chlorophyll-a(ADEOS reference manual, 1995).

$$\text{chlorophyll\_a} = 10^{(-2.0+0.015 \times DN)} \quad (2)$$

where DN is digital number

Sea Sufrace Temperaute data was obtained with following equation from NOAA Infrared channels using linear Multi-Channel Sea Surface Temperature(MCSST) algorithm(Bernstein, 1982)

$$SST = A \times T_4 + B \times (T_4 - T_5) + C \times (T_4 - T_5) \times (SEC(sza)-1) + D \times (SEC(sza)-1) + E \quad (3)$$

where T_4 and T_5 are NOAA channel 4 and 5 infrared temperature, A through E are the coefficients to calculate MCSST using satellite data(A=1.029088, B=2.275385, c=0.752567, D=0.000 and E=-1.145). and sza means satellite zenith angle.

3. Results

Figure 1 illustrates the location and structure of a cold core eddy off the eastern coast of Korea on April 25, October 20 and November 10, 1997, respectively. The center of rotation, size and basic structure of the eddy are similar on three images. Based on calibrated NOAA MCSST analysis using the most updated calibrations as applied by the TeraScan software, the average SST of 4 × 4 pixels centered at 39°N and 129°E is estimated to be

Fig. 1. NOAA-14 AVHRR Sea Surface Temperature(SST) structure off the east coast of Korea. A) April 25, 1997. B) November 10, 1997. C) Argos-tracked surface current drifter track for the period September 8(S8) - November 5 (N5),1997. The drift track is superimposed on the SST image for October 20, 1997. The warm jet west of the KCCE on October 20, (1C) strengthened in late October and eventually surrounded the KCCE by November 11 (1B). (symbol × represents the center of eddy)

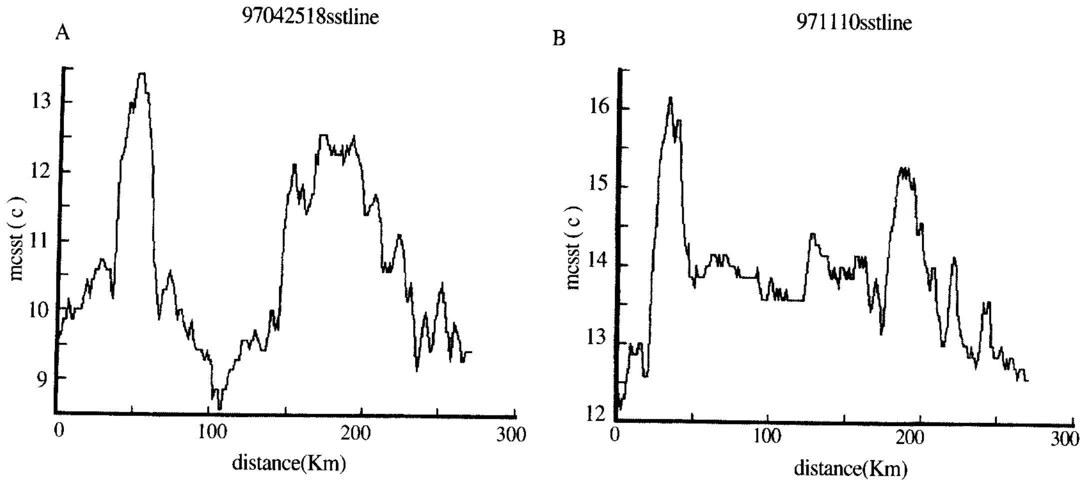

Fig. 2. The MCSST profile on the a-a' (A) and b-b' (B) line in Fig.1 A and B.

8.6°C and 13.6°C for the spring (Figure 1a) and autumn (Figure 1b) images, respectively(Figure 2). Mean temperatures were determined for a 4 × 4 pixel box in the warmest part of the warm jet at 39°N on each date. These mean MCSST temperatures were 13.4°C and 15.9°C for the spring and autumn dates.

Figure 1c illustrates the interaction of an ARGOS-tracked surface current drifter. From early September to mid October, the drifter followed the East Korean Warm Current moving off shore in early October as it interacted with a warm eddy north of Ulleung Island. However, a rapid reversal of direction of this drifter occurred from October 13 - November 5. The drift track is superimposed on the SST image of October 20, 1997, a time when the warm jet on the west of the KCCE accelerated rapidly. Note that from October 20 (Figure 1c) to November 11 (Figure 1b), the warm jet continued to strengthen, eventually surrounding the entire eddy by November 11. Figure 3 shows OCTS image from April 24, 1997. Higher surface chlorophyll is presumably due to higher nutrients present in the cold core of the eddy compared to the warm, nutrient depleted sub-tropical waters. The cold core had elevated chlorophyll concentrations, based on OCTS estimates, of greater than 3 mg/m^3 while the warmer surrounding waters had chlorophyll concentrations of 1 mg/m^3 or less.

The relatively high chlorophyll_a concentration

Fig. 3. Surface chlorophyll distributions off the east coast of Korea on April 24, 1997 determined with the ADEOS-I OCTS sensor. The KCCE has elevated chlorophyll in the cold core. Generally higher chlorophyll is observed in the colder waters to the northeast, and lower chlorophyll is observed in the warmer waters to the southeast.

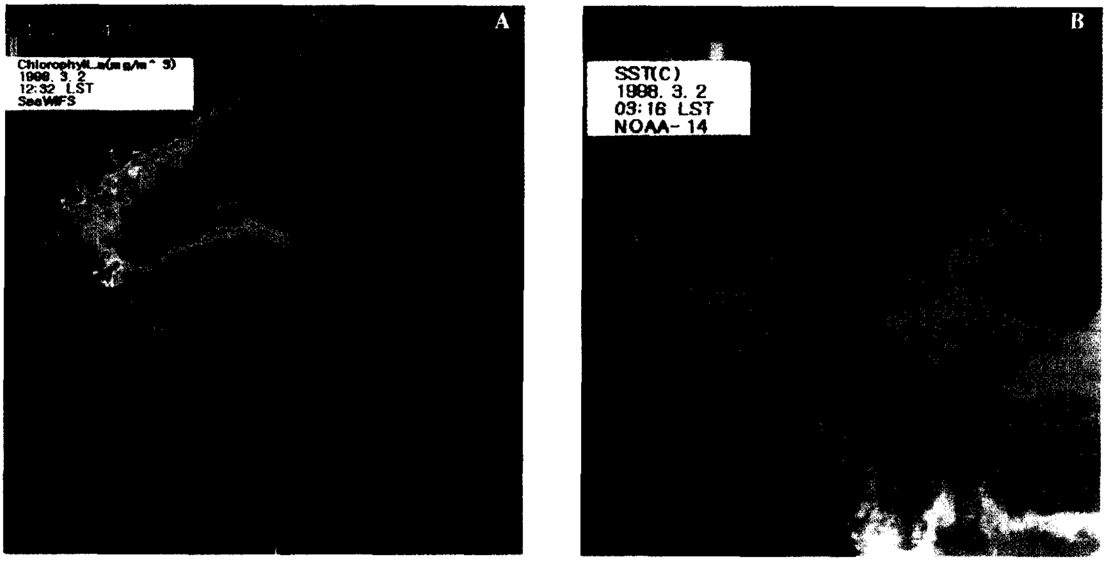

Fig. 4. Surface chlorophyll distributions determined with the Orview-2 SeaWiFS sensor(A) and NOAA AVHRR SST distribution(B) off the east coast of Korea on Mar. 2, 1998.

area which surround around the eddy in SeaWiFS image show a good agreement with higher SST distribution in NOAA image on March 2, 1998 when it was almost onset of reccuring eddies(Fig. 4).

The autumn (September-October-November) composite MCSST from NOAA-12/14 for most of the East (Japan) Sea is shown in Figure 5. Superimposed on the image are drift tracks of three separate drifters deployed in the region in early September, 1997. The Korean coastal drifter is the same as illustrated in Figure 1c. The drifter in the southeast of East Sea indicates meandering flow in the Tsuchima Current with a clear trajectory toward the northeast along the west coast of Japan. Along the northern boundary of the sub-polar front the drift track also meanders but has a clear west to east trajectory. As discussed above, the Korean coastal drifter flows north until it exhibits strong interaction with the warm eddy north of Ulleung Island and then the strengthening of the warm jet west of the KCCE. It is important to note that the mesoscale eddies

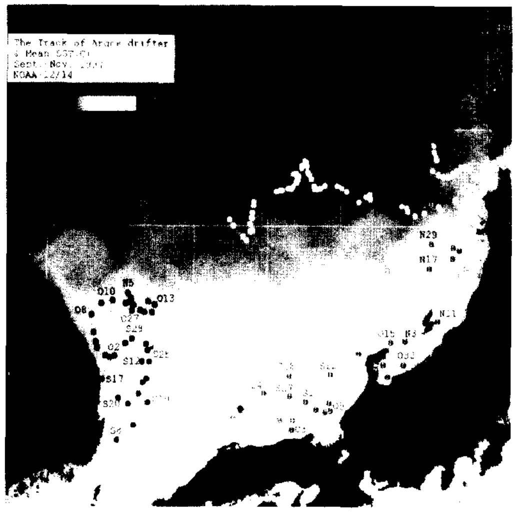

Fig. 5. NOAA-12 and NOAA-14 composite SST for autumn (S-September, O-October, N-November) in 1997 for the East (Japan) sea. ARGOS-tracked drift buoys for the same time period revealed how surface currents follow the SST structure observed from satellites. The large scale structure of the subpolar front is evident, but meso-scale structure of the frontal zone is lost through averaging. However, the Korean Cold Core Eddy has a well defined, permanent structure.

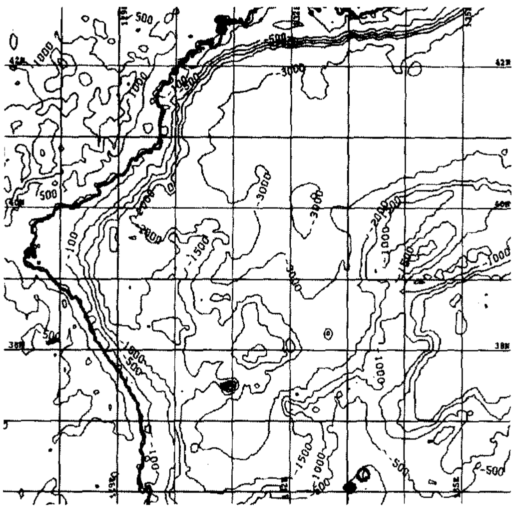

Fig. 6. Ocean basin topography of adjacent regions of the East (Japan) Sea. A shelf of approximately 1500 m depth is centered at 39° 15′ N and 129° 15′ E.

evident in Figures 1 and 3 for the central basin are mostly smeared in the composite indicating that the mesoscale variance is large enough at the seasonal time scale to smooth over the smaller scale features. However, the eddys cold core is evident, even at the seasonal composite scale. This strongly supports our hypothesis that this is a recurring eddy with a relatively fixed location and size, and with relatively predictable structure as it steers the East Korea Warm Current along the northern Korea coast into the Liman current.

Figure 6 shows the ocean bottom topography for East Sea and adjacent waters. There is a relatively large shelf located at approximately 1500 m depth centered about 39° 15 N and 129° 15 E. The 2000 m isobath at about 39° 45 N and 129° 45 E on the northeast border of this shelf defines the location of the northeast wall of the warm jet as it recirculates to the southeast around the eddy (Figure 1). The persistence of the eddy in the same location, with a length scale similar to the 1500 m shelf near the cold-core center, implies a significant influence of bottom topography in

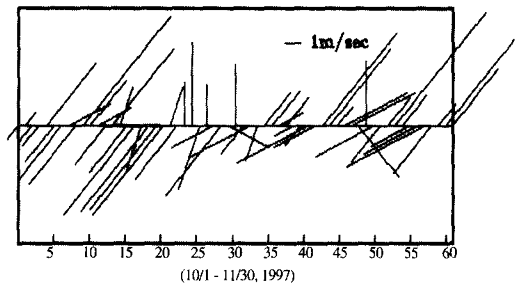

Fig. 7. Wind strength and directional vectors for October 1 - November 30, 1997, at Ulleung Island. Southwestly winds dominated from mid October through mid November at a time when the warm jet bordering the KCCE exhibited

defining the location and the size of the eddy (Lie et al., 1995).

The wind speed and direction vectors for October through November 1997 are shown in Figure 7 for Ulleung Island. A strong pulse of southwesterly wind occurred from October 13 - 20 at the time the drifter had a rapid reversal of direction along the southern boundary of the KCCE. Southwest winds continued to dominate from 25 October through 10 November, but were weaker, with some wind reversals occurring. Southwesterly winds are upwelling favorable for the Korean coastline between 39 30' and 41 N latitude. A time series of SST in the region indicated simultaneous development of a strong warm jet on the western side of the KCCE, and cold, upwelling water along the Korean coast between 39 30' and 41 N (Figure 1B and 1C).

4. Conclusions

The persistent nature of (KCCE) appears to exert a strong influence on the water mass circulation at the western end of the basins eddy field. The warm jet that forms on the western boundary of the eddy typically represents the warmest surface water that is propagated along the northern Korea coast into the southward flow of the Liman current. The KCCE deserves considerable focus as a recurring and energetic feature that may influence the dynamics of the mesoscale eddy field of the central (Japan) Sea along 38-40°N through the secondary structure that spins off its eastern border. The eddy may be topographically trapped and strength of its rotation may be partially controlled by wind forcing.

Acknowledgements

This work was supported by the Korean National Fisheries Research and Development Institute. BGM was supported by the U.S. Office of Naval Research grant number N00014-98-1-0247.

References

ADEOS reference manual. 1995. Level-3 SMI, pp.63

Bernstein, R. L. 1982. Sea surface temperature estimation using th NOAA-6 advanced very high resolution radiometer, *J. Geophys. Res. 97*, pp. 9455-9465

Huh, O.K. 1982. Spring seasons flow of Tsuschima Current and its separation from Kuroshio: satellite evidence. *J. Geophysical Research* **87** pp. 9687-9693.

Kim, S.Y. 1995. Numerical experiments on the generation of the mesoscale eddies off the east coast of Korea. *Ph.D. thesis. National Fisheries University of Pusan.*, pp. 128.

Lie, H.-J., S.-K. Byun, I. Bang and C.-H. Cho. 1995. Physical structure of eddies in the southwestern East Sea, *Journal Korean Society of Oceanography* **30(3)** pp. 170-183.

McClain, C. R., 1997. SeaWiFS Bio-Optical Mini-Workshop(SeaBAM) Overview.

Tomczak, M. and J.S. Godfrey. 1994. Regional Oceanography: An Introduction. Pergamon, Oxford.

Yurasov, G.I. and V.G. Yarichin. 1991. Techeniya Yaponskogo Morye (Currents of the Japan Sea). *Far East Branch of the Russian Academy of Sciences.* 176 pp. (in Russian).