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A Note on Water Masses and General Circulation in the Yellow Sea (Hwanghae)

Heung-Jae Lie

Korea Ocean Research & Development Inst., P.O. Box 17, Yeongdong, Seoul

黃海水塊와 循環에 관한 考察

李　　興　　宰

海洋研究所

서울영동우체국사서함 17호

Abstracc: Water masses and circulation in the Yellow Sea (Hwanghae) were briefly reviewed and synthesized. Water masses were classified into four types: Hwanghae Cold Water, Hwanghai Warm Current Water, Coastal Waters and Changjiang River Diluted Water. The Hwanghae Cold Water can be defined to have a salinity of 32.0~33.0‰ and a temperature below 10°C, based on long-term hydrographic data and recent CTD casts (KORDI, 1984). Concerning circulation, there exists a cyclonic gyre throughout the year in the southern part. In winter, the coastal current along the Chinese coast is very strong due to northerly or northwesterly winds and the Hwanghae Warm Current becomes weak as can be expected from a surface to bottom thermohaline front west of Cheju-do. Meanwhile in summer, the Changjiang River Diluted Water flows northeastward toward Cheju-do and the coastal current in the western part is greatly reduced. The northward current during summer in the southeastern Hwanghae has been accepted to be the Hwanghae Warm Current until now, but it is more reasonable to define the flow as a density current along the boundary between coastal waters and the Hwanghae Cold Water in the central deep area, not a continuation of the Hwanghae Warm Current.

要約：黃海에서 水塊와 循環에 대해 간략히 檢討, 討議하였다. 水塊는 黃海冷水, 黃海暖流水, 沿岸水, 揚子江 稀釋水 네가지로 分類된다. 黃海冷水는 長期 海洋觀測資料와 最近 CTD로資料부터 32.0~33.0‰의 鹽分, 10°C이하의 水溫을 갖고 있는 것으로 定義할 수 있다. 海水循環은 南部海域에서 年中 反時計方向의 海水循環이 存在한다. 겨울철에는 中國沿岸을 따라 南向하는 沿岸流流가 北風, 北西風으르 인해 强하게 나타나며 濟州島 西部海域에 强한 水溫·鹽分前線이 잘 보여주듯 黃海暖流는 弱해진다. 반면에 여름철에는 揚子江稀釋水가 濟州島 쪽을 향해 北東쪽으로 擴張하며 中國沿岸流가 상당히 減少하게 된다. 지금까지 여름철 東南黃海에서 北向流를 黃海暖流로 分類하였으나 暖流의 延長이 아니라 沿岸水와 黃海冷水사이 境界面을 따라 形成되는 密度流로 보는 것이 더욱 妥當하다.

GENERAL FEATURES AND TOPOGRAPHY

The Hwanghae (or often called the Yellow Sea) is a marginal sea partially surrounded by the China Continent and the Korea Peninsula, which is connected south to the East China Sea. According to the convention of the International Hydrographic Bureau, the southern boundary of the Hwanghae (HH) is taken as a line extending from the mouth of the Changjiang River to Cheju-do off the south coast of Korea (Uda, 1966). However, the boundary between the

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south coast of Korea and Cheju-do is not definite until now. For a convenience of discussion the boundary will be chosen as a line along 126° 10′E. The innermost part of the HH is called the Gulf of Bohai limited by a line between Lia-Tung Peninsula and Shan-Tung Peninsula.

The Hwanghae proper and the Gulf of Bohai are semi-enclosed embayments enclosed by the northern part of the China Continent and the west coast of Korea Peninsula. The total area and water volume are 0.487×10^6 km² and 0.194×10^5 km³. The mean depths of the HH proper and the Gulf of Bohai are 44m and 21m (Uda, 1966). Thus the Yellow Sea forms a wide and shallow basin with an approximately rectangular form.

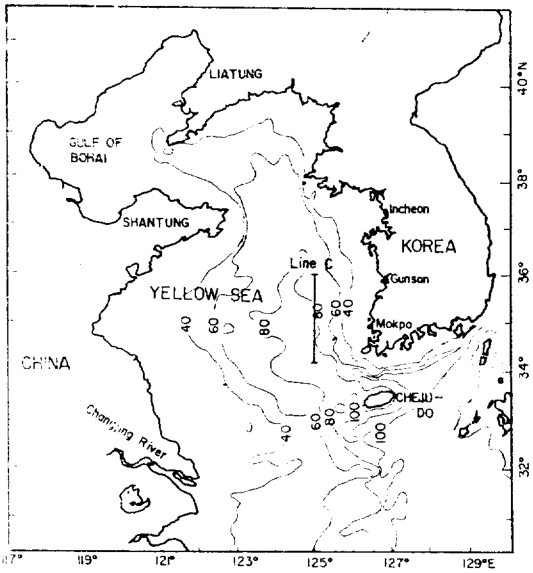

Fig. 1. Bottom topography of the Yellow Sea (Hwanghae). Depths are in meters.

As seen in Fig. 1, the regional bathymetric chart shows that the sea is composed of two parts; deeper central area having depths of more than 60m elongated from south to north and shallow coastal area where there are a lot of small channels. The west coastal area is very large compared to the east coastal area, especially near the mouth of the Changjiang River. The widest shallow area extends towards Cheju-do along the boundary between the HH and East China Sea.

METEOROLOGICAL CONDITIONS

The typical pattern of climate over the monsoon which is driven by the seasonal variation of polar continental air masses and tropical maritime air masses. During the winter monsoon from late November to late March, the polar front advances southward followed by the cold, dry air masses. Therefore a strong northerly wind prevails. During the summer season, the polar front moves landward into the Asian continent and the warm air masses of high humidity migrate northward. The dominant direction of wind is southeasterly. Typhoons occur frequently in summer. During transit periods, the wind is very variable and intermediate.

Air temperature in the HH has a zonal distribution showing a slow decrease in temperature from south to north (see Naval Oceanography and Meteorology, 1977).

Air temperature varies seasonally due to the winter and summer monsoon; generally, mini-

Table 1. Monthly air temperature for 1951~1980 (data from CMO, 1982) (°C)

Stations	Month	1	2	3	4	5	6	7	8	9	10	11	12	Mean
Incheon	37°29′N 126°38′E	−3.2	−1.2	3.6	10.2	15.7	19.7	23.7	24.8	20.5	14.3	7.1	0.0	11.3
Gunsan	36°59′N 126°42′E	−0.4	0.4	4.2	11.0	16.1	20.6	24.7	25.5	21.1	14.9	8.1	2.1	12.4
Mokpo	34°47′N 126°23′E	1.3	2.3	5.9	11.8	16.9	20.7	24.8	26.2	22.0	16.5	10.2	4.3	13.6
Cheju	33°31′N 126°32′E	5.2	5.6	8.4	13.0	16.9	20.7	25.5	26.4	22.4	17.4	12.3	7.7	15.1

Table 2. Monthly precipitation for 1951~1980 (data from CMO, 1982) (mm)

Stations	1	2	3	4	5	6	7	8	9	10	11	12	Total
Incheon	18. 1	25. 4	45. 3	96. 8	73. 2	120. 4	287. 6	236. 2	136. 4	45. 5	42. 3	23. 5	1, 150. 7
Gunsan	35. 5	38. 9	50. 8	107. 2	98. 2	134. 5	231. 9	219. 6	131. 1	53. 8	48. 3	36. 4	1, 186. 3
Mokpo	35. 6	46. 6	57. 9	108. 1	102. 5	151. 0	190. 6	170. 1	125. 5	52. 2	52. 4	34. 8	1, 127. 2
Cheju	67. 8	74. 6	65. 1	100. 5	94. 3	179. 6	212. 2	241. 6	202. 7	66. 1	80. 6	54. 9	1, 440. 0

Table 3. Monthly relative humidity for 1951~1980 (data from CMO, 1982) (%)

Stations	1	2	3	4	5	6	7	8	9	10	11	12	Mean
Incheon	66	66	68	70	71	79	85	82	75	69	67	67	72
Gunsan	74	72	72	73	75	81	84	81	78	73	74	75	76
Mokpo	71	71	71	74	75	81	85	81	77	70	70	70	75
Cheju	69	70	69	73	76	80	82	80	78	72	70	69	74

mum in January and maximum in August. Temperature ranges between summer and winter seasons reach 21°C at Cheju-do near the southern boundary and more than 30°C in the northern part (Table 1; Kim, 1973).

The annual rainfall decreases from north to south. Most of precipitation occurs in summer (June-September) due to the advance of thermal front toward the north. The amount of annual precipitation ranges from 500mm in the northern part to 1500mm in the southern part as shown in Table 2 and Kim (1973). Relative humidity is low during the winter monsoon and high during the summer monsoon (Table 3).

WATER MAESSES

Representative water masses of the HH are the Hwanghae Cold Water, the Hwanghae Warm Current Water, the Coastal Waters and the Changjiang River Diluted Water. The Coastal Waters can be divided into two types according to the regions: the Coastal Water of the China Continent and the Korean Coastal Water. The Changjiang River Diluted Water is a mixed water between the Coastal Water of the China Continent off the mouth of Changjiang River and waters originated from the Taiwan Warm Current Water.

Hwanghae Cold Water

The Hwanghae Cold Water (HCW) is the most important water which occupies the bottom layer of the central HH even during spring to fall. The formation of the cold water is thought to be due to cooling of surface water by a cold and dry wind during the winter monsoon. Consequently, the water column becomes vertically homogeneous in winter by vertical convection and wind stirring (Ho et al., 1959; Nakao, 1977; Lacombe et al., 1981) Meanwhile, as the surface water is heated in spring-fall, the strong thermocline separates the warm and relatively fresh surface water from the cold and salty water. The water has been broadly accepted to have a temperature below 10°C and a salinity range of 32. 0-32. 5‰. Referring to recent CTD observations conducted in mid-summer 1983 by Korea Ocean Research & Development Institute (1984), the cold bottom water is found to have a salinity higher than the range of 32. 0-32. 5‰. Lie (1984a) has proposed that it is more reasonable to define the salinity of the HCW as 32. 0-33. 0‰ as shown in Fig. 2. Furthermore, preliminary results of CTD casts in mid-August 1984 also showed the HCW have the same range of salinity (not shown here).

Hwanghae Warm Current Water

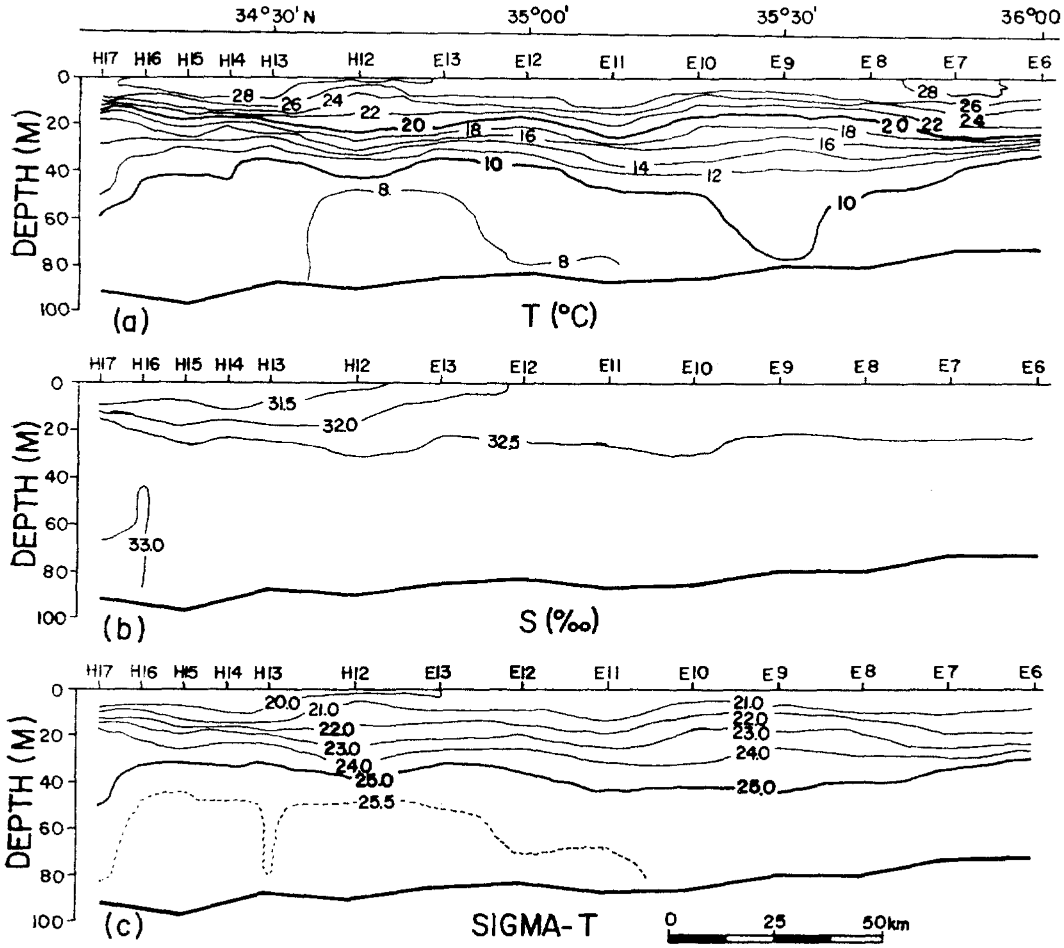

Fig. 2. Vertical sections of temperature, salinity and sigma-t along 125°05′E in August (line C in Fig. 1).

The Tsushima Warm Current (TWC) has a branch west of Kyusyu which flows to the northwest. The branch, known as the Hwanghae Warm Current (HWC), carries waters of high salinity and temperature, partly affected by the Kuroshio. Therefore, the HWC influences greatly oceanographic conditions in the southeastern Hwanghae. In winter, the northern limit of the water is marked clearly by an east-west strong thermohaline front parallel to the line of latitude 34°N (Kang, 1971; Lie, 1984b) as shown in Fig. 3. Meanwhile, in summer the water has its characteristics largely modified compared to those in winter since the TWC is originated from mixed water between the Kuroshio and fresh waters on the continental shelf in the East China Sea (Sawara and Hanzawa, 1979). The water in the mid-winter is characterized by temperature of 11-15°C and salinity of 34.0-35.0‰. based on a long-term hydrographic data (Lie, 1984b).

Changjiang River Diluted Water

The Changjiang River Diluted Water (CRDW) is formed by mixiing between the Changjiang River discharge and waters from the Taiwan Current (Limeburner et al., 1983). In winter, the CRDW flows southward in a narrow band confined to the coast and its effect on the hydrography in the HH is so weak to be negligible. But in summer when the river is flooding, the surface

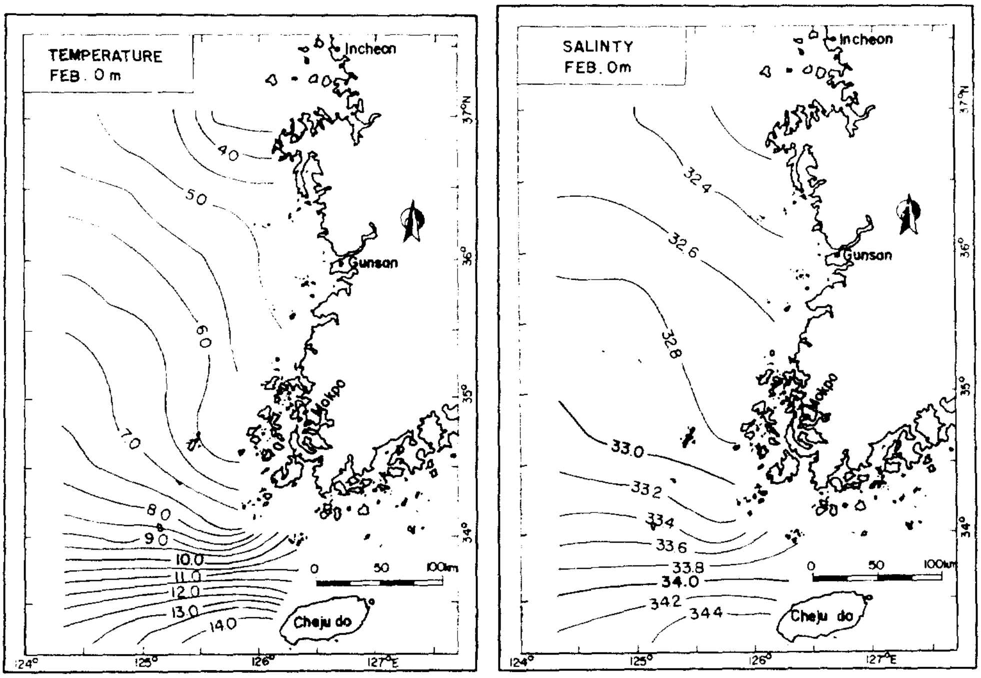

Fig. 3. Mean surface temperature and salinity in February over 1961~1980.

tongue-like plume points to the northeast in the direction of Cheju-do (Beardsely et al., 1983; Le, 1983; Uda, 1936) Thus, the CRDW is an important water mass only in summer along the southern boundary of the HH. The CRDW defined by salinity less than 30‰ has a relatively small volume and mixes mainly with the Taiwan Warm Current Water (Limeburner et al., 1983).

Coastal Waters

Coastal Waters along the coast have generally a relatively low temperature and a low salinity. During the summer season the salinity of coastal waters decreases greatly due to heavy precipitation and river run-off, especially near the mouths of rivers. The boundary between coastal waters and offshore waters can be easily detected by front formed parallel to the coastline which can be observed by infrared satellite images (cf. Hue, 1982) or hydrographic data (KORDI, 1983; 1984). In winter when rainfall and river discharge are very small in quantity, it is difficult to distinguish coastal waters from offshore waters since the front seen in summer, maybe induced by tidal mixing (Pingree and Griffiths, 1978; Simpson *et al.*, 1978), disappears. For a convenience, coastal waters along the Chinese and Korean coasts are frequently called Coastal Waters of the China Continent (CWCC) and Korean Ceastal Waters(KCW), respectively.

GENERAL CIRCULATION

The general circlation pattern is known to be dependant upon season because the monsoon climate influences physical properties of sea water and generates seasonally different currents. Inwinter the whole water column is homogeneous because of convectional mixing and wind stirring. Meanwhile, in summer the surface water is warmed by the absorption of solar radiation and diluted due to precipitation and fresh water discharge. Consequently, in the central part of the HH where tidal mixing is not so important to make water column homogeneous, seasonal thermocline is developed. Of course, water properties is variable from place to place. It has to be mentioned that in spring and fall, when wind field is very variable in space and in time, the circulation pattern seems to be much more complex than those in summer and winter.

Winter Circulation

In general sea surface temperature (SST) is reported to have a characteristic feature such that the cold coastal water extends southward in the western part of the sea, while relatively warm and saline water is found off the west coast of Cheju-do. The southward extension of the cold water and the apparent northward HWC form an anticlockwise circulation in the southern part of the HH (Asaoka and Moriyasu, 1966; Niino and Emery, 1961). Numerical models explain qualitatively the formation of a cyclonic circulation in the southern part of the sea under the condition of northerly or northwesterly steady and uniform winds (Choi, 1982; Yuan *et al.*, 1982). However, Lie (1984b) has reported on the basis of long-term hydrographic data that a strong surface to bottom thermohaline front is formed in the western area off Cheju-do, running from west to east. The persistent front during winter reflects that the HWC could not always flow northward beyond the front. This is a different point from the conventional concept of the HWC.

Summer Circulation

Due to solar heating, SST is high with a develpment of thermocline. In addition, fresh water dischage is increased. The complexity of temperature and salinity distributions makes it difficult to derive a schematic pattern of general circulation. In general, coastal waters are uniform from surface to bottom due to active tidal mixing, but in a deeper offshore area vertical stratification is very stable. The CRDW is found to flow northeastward to Cheju-do along the boundary between the HH and the East China Sea. The HWC might be intensified with a rich supply of saline water from the south, mainly due to the southerly monsoon, while the southward coastal current along the Chinese coast becomes very weak (Guan and Mao, 1982; Le, 1983; Yu *et al*, 1983). The three different currents consist of a cyclonic circulation in the southern part of the HH. Such a schematic pattern is apparently coincident with results estimated from the dynamic method (Nakao, 1977; Uda, 1934, 1936) and drift bottle experiments (Lee, 1970). However, numerical models presented different types of circulations because they depend on the computation scheme, the boundary conditions, the stratification and wind fields, etc (Choi, 1982; Yuan *et al.*, 1982; Yuan and Su, 1983).

DISCUSSIONS AND CONCLUSIONS

We briefly reviewed and summarized water masses and general circulations in the Hwanghae, together with meteorological conditions. On the basis of literature and supplementary data, it is convenient to classify water masses into four types in spite of shortage of data and informations: Hwanghae Cold Water, Hwanghae Warm Water, Coastal Waters and Changjiang River Diluted Water. The HCW is a representative water mass formed in the HH during winter, persistent all the year round, while the CRDW exists only in summer along the boundary between the HH and the East China Sea. In particular, the HCW is found to have a salinity range of 32.0~33.0‰ from the long-term hydrographic data and recent surveys of KORDI (1983, 1984). It is worth saying that studies on the HCW, such as its formation, southward extension in summer, mixing with coastal and surface water, are a key to understand major structures of hydrography and circulation in the HH.

Though several schematic patterns of circulation have been proposed (Asaoka and Moriyasu, 1966; Choi, 1982; Guan and Mao, 1982; Niino and Emery, 1961; NOM, 1977; Uda, 1934, 1936; Yuan *et al.*, 1982; Yuan and Su, 1983), the models are thought not to successfully describe circulation because of various reasons; a) limits of geostrophic estimation in the shallow sea, b) difficulty of eliminating wind effect on drift bottles, c) poor data and information gathered only during special cruises and periods, d) some constraints in numerical models. For instance, the HWC was estimated to have a northward component of about 14 cm/s from the geostrophic calculation west of Gunsan (Nakao, 1977), but the relatively long-term moorings did not show such a strong current (KORDI, 1983; 1984). Most of models porposed existence of a cyclonic gyre in the southern part, though there are large discrepancies between models, especially in the coastal area and the northern part.

The northward current, observed during summer in the southeastern Hwanghae, have been broadly accepted as a continuation of the HWC from temperature distribution. Although the isotherms running from south to north might indicate a northward flow, waters carried by the HWC have to be warm and saline. However, hydrographic observations rather showed avery narrow band of warm and saline waters located close to the west and north coast of Cheju-do (Kim and Lee, 1982). In addition, according to results of recent CTD casts in summer 1983 (KORDI, 1984), it is found that the HCW has the lowest salinity in the east-west section along 34°N between 124°30′E and 126°E. The northward flow in the southeastern Hwanghae may be a density current along the boundary formed between coastal water and the HCW in the central deep area.

Our present understanding on general circulation and water masses is very poor and primitive. In order to get a more comprehensive and concrete picture, we should carry out systematic field surveys covering the whole area under a close cooperation in future between countries of great concerns and synthesize carefully all available hydrographic and current data.

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