The Journal of the Oceanological Society of Korea
Vol. 16, No. 2, p. 49~56, December 1981

ON THE VARIATION OF THE MIXED LAYER DEPTH AND THE HEAT FLUX IN THE SEA OF JAPAN

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ABSTRACT

Annual variation of the surface mixed layer depth (MLD) in the southern part of the Sea of Japan is investigated based upon the oceanographic and meteorological data taken during 1971~1975 by the Fisheries Research and Development Agency and the Central Meteorological Office of Korea. It is found that the variation of the MLD is strongly correlated with the heat exchange between the atmosphere and sea. The MLD and heat flux vary within ranges comparable to those in the Kuroshio region found by Bathen (1972) and Wyrtki (1965).

I. INTRODUCTION

Mixed layers have been observed at various parts of the world ocean and temporal and spatial variations of these layers have been a subject of intensive phenomenological and dynamical studies (Ekman, 1905; Munk and Anderson, 1948; Kraus and Turner, 1967; Kondo, Sasano and Ishii, 1979). The surface MLD is important not only as a physical process at the boundary between the sea and atmosphere, but in relation to such as the productivity of the plankton population (Sverdrup, 1953) and the sound wave propagation in the sea (Clay and Medwin, 1977).

The present study is concerned with the annual variation of the MLD in the Sea of Japan. As a deep, marginal basin with three straits opening to the North Pacific Ocean the Sea of Japan is characterized by a large annual change of sea surface temperature with a range of 15°C in the southern part to 20°C in the northern part (Nakayama, 1951). An active heat exchange is expected particularly in winter as cold and dry arctic air blows from the Siberia over a warm water flowing into this area through the Korea Strait (see Fig. 1).

Previously Wyrtki (1965) found the loss of heat in the study area in his calculation of the average annual heat balance of the North Pacific Ocean. Examining the annual variation of the MLD in the North Pacific Ocean Bathen (1972) found that in the Sea of Japan the variation deviated from the general pattern. Therefore it will be worthwhile to look into the annual variation of the MLD in the Sea of Japan in details. Bathen (1972) also suggested that the summer heating is the cause for the very shallow MLD during summer months. However, the deep MLD found in the Sea of Japan in winter deserves good physical

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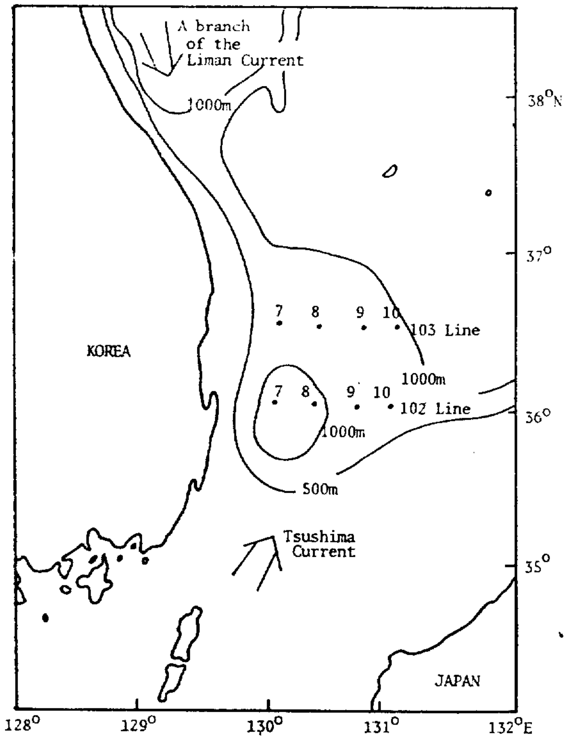

Fig. 1. Study area and oceanographic conditions

explanation as well.

The aim of the present study is to verify the correlation between variations of the MLD and heat flux. For our interest good data coverage is important and it is necessary to limit the study area to the southern part of the Sea of Japan.

II. DATA ANALYSIS

1. Oceanographic and Meteorological Data

East of the Korean Peninsula hydrographic stations have been taken regularly by the Fisheries Research and Development Agency of Korea. The data for the present study are taken from 1971 through 1975 and reported in the Annual Report of the Oceanographic Observations Volume 20~24. The data have been collected even months of year at standard depths (0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250, 300 meters, etc.). Accordingly only the annual variation will be considered in the present study. The meteorological data are from the Monthly Weather Report published by the Central Meteorological Office of Korea for the same period.

In order to minimize effects of land and bottom topography the rectangular area between 36°−37°N and 130°−131°E has been chosen as the study area, which includes the stations 7, 8, 9 and 10 of lines 102 and 103 as shown in Figure 1. Usually the observations along these lines have been completed within two days.

2. Annual Variation of the MLD

After considering numerous definitions of the MLD (e.g., Bathen, 1972; Camp and Elsberry, 1978; Kondo, et. al., 1979), the following procedure has been taken to determine the MLD for each hydrographic station; the mixed layer is defined as a layer within which the temperature varies no greater than 0.3°C from the sea surface temperature. Figure 2 shows some examples of vertical temperature profiles. Discrete sampling depths introduce an error in determing the MLD as when temperature change between sampling depths is large.

Table 1 shows the MLD data as determined

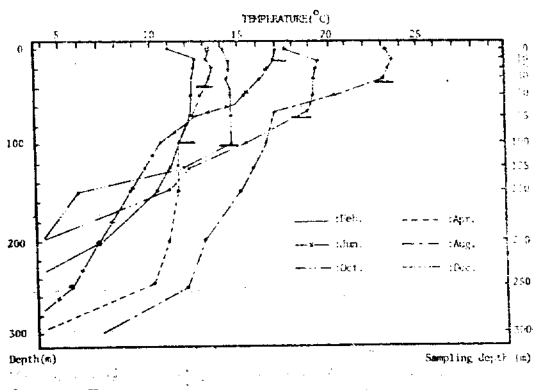

Fig. 2. Typical temperature profiles with the MLD indicated by '—'.

on the basis of the above criteria. Since its variation from one station to another in each month is probably due to some high frequency process other than the seasonal one or discrete sampling depths, an average is taken in order to minimize the error. Averaging is also needed for the comparison with heat flux since presumably the latter varies over a large spatial scale.

The time series of the average MLD during 1971~1975 shown in Figure 3 are dominated by the annual variation. The layer is as shallow as less than 10 meters in summer and as deep as 170 meters in winter. This large range of variation is satisfactorily comparable to Bathen's (1972) work. It is interesting to note that in winter the MLD in the study area is about twice deeper than what can be observed in the Korea Strait. This seems to be a result of an active heat exchange occurring between the atmosphere and sea as a warm and saline current (The Tsushima Current) flows into the Sea of Japan.

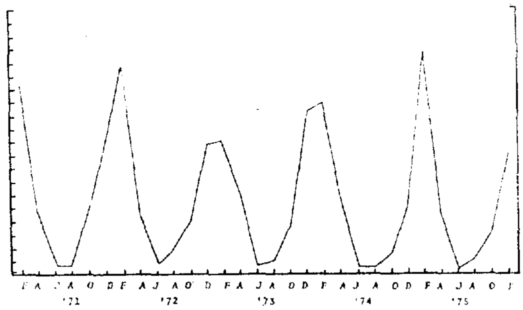

Fig. 3. Time series of the MLD during 1971-1975

Ⅲ. CALCULATION OF THE HEAT FLUX

The heat flux across the sea surface can be calculated as follows.

$$Q = Q_i - Q_b - Q_e - Q_s \quad \cdots\cdots\cdots\cdots (1)$$

where

Q_i; incoming solar radiation,

Q_b; effective back radiation,

Q_e; the heat used for evaporation,

Q_s; sensible heat exchange.

Table 1. Complete MLD data. *; no data +; discarded

YEAR		1971				1972				1973				1974				1975			
PT.		7	8	9	10	7	8	9	10	7	8	9	10	7	8	9	10	7	8	9	10
MON	LINE																				
2	102	175	*	100	*	100	200	250	150	100	+	125	+	200	125	125	+	150	100	75	150
	103	125	*	150	*	150	100	+	150	75	100	+	75	+	100	75	+	150	250	250	200
4	102	50	*	20	*	30	75	50	30	*	*	*	*	+	75	+	75	50	50	30	50
	103	75	*	100	*	50	30	50	30	50	50	50	*	30	50	+	+	30	50	75	50
6	102	0	*	10	*	0	10	0	0	10	0	10	10	0	0	10	10	0	10	0	0
	103	0	10	0	*	10	20	0	0	0	0	0	20	0	0	0	0	0	0	0	0
8	102	10	*	0	*	0	5	30	20	0	0	10	10	0	0	10	10	10	0	10	10
	103	0	*	10	*	10	20	20	30	10	10	10	20	0	0	0	0	10	20	10	10
10	102	30	*	75	30	30	30	20	20	30	20	30	30	10	10	10	20	30	30	30	30
	103	50	50	50	50	50	30	20	30	30	50	50	30	0	10	20	20	30	+	20	30
12	102	100	75	125	75	75	100	75	100	75	150	125	125	50	50	30	50	100	75	75	75
	103	125	100	125	75	100	125	50	100	125	125	125	50	30	50	50	50	50	75	100	125

Ⅳ. STATISTICAL ANALYSIS AND DISCUSSION

From the comparison of time series of both the MLD and net heat flux one can see a close relationship. Each year the MLD becomes deepest in winter as the heat loss for the sea reaches its maximum. In summer the MLD exists nearly nil as the heat gain reaches its maximum. In order to examine this relationship in detail scatter diagrams are constructed for the complete data after dividing them into three groups by month. Also the correlation between the MLD and the heat flux has been found by using the least square method. Linear regression lines relating the MLD (Y_i) to the heat flux (X_i) and the correlation coefficient, r, are defined as follows (Harnett and Murphy, 1975) and Table 3 summarizes results.

$$Y=\overline{Y}+b'\ (X-\overline{X})$$

$$r=\frac{S_{xy}}{\sqrt{S_{xx}\ S_{yy}}}$$

where

$$\overline{Y}=\frac{1}{n}\sum_i Y_i$$

$$\overline{X}=\frac{1}{n}\sum_i X_i$$

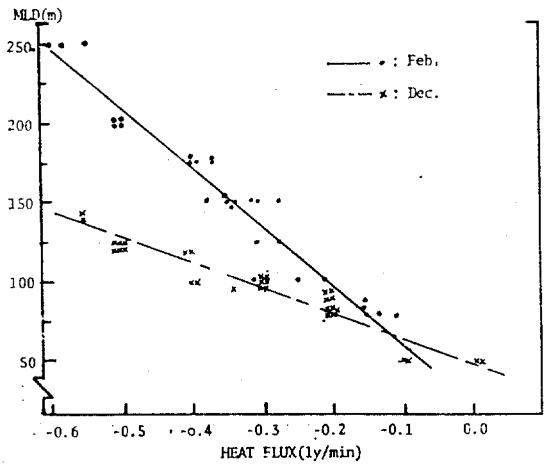

Fig. 5-a. Scatter diagram for February and December.

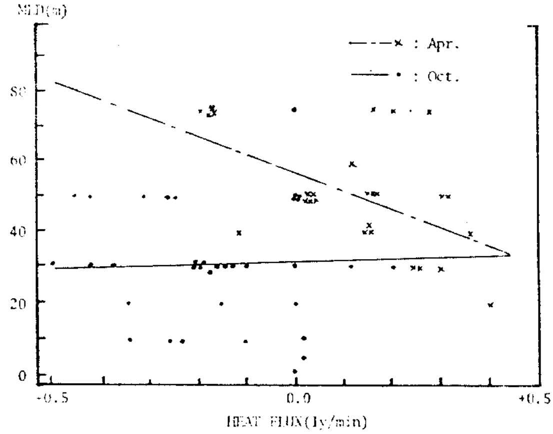

Fig. 5-b. Scatter diagram for April and October.

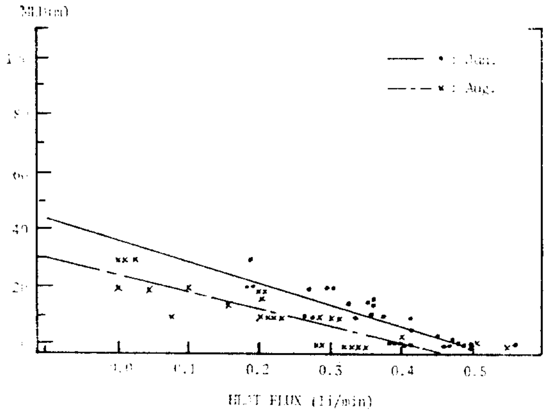

Fig. 5-c. Scatter diagram for June and August.

$$b'=\frac{S_{xy}}{S_{xx}}$$

$$S_{xy}=\sum_i X_iY_i-\frac{(\sum_i X_i)(\sum_i Y_i)}{n}$$

$$S_{xx}=\sum_i X_i^2-\frac{(\sum_i X_i)^2}{n}$$

$$S_{yy}=\sum_i Y_i^2-\frac{(\sum_i Y_i)^2}{n}$$

n: Sample Size

In Fig. 5a tight correlations are notable for February and December with a remarkably high correlation coefficient of 0.97. For the same negative heat flux the MLD in February is deeper than one in December without an exception. This means that as winter progresses the MLD deepens. It is interestiug that the MLD can be deeper in December than in Feb-

Table 3. Regression curve between the MLD(Y) and heat flux (X) and correlction coefficient.

Month	Least square regression curve	Correlation coeff.
Feb.	$Y=-387.8X+21.2$	−0.97
Apr.	$Y=-49.5X+57.6$	−0.53
Jun.	$Y=-76.2X+36.5$	−0.83
Aug.	$Y=-58.7X+24.5$	−0.83
Oct.	$Y=6.2X+32.7$	0.06
Dec.	$Y=-165.8X+45.7$	−0.96

ruary if the negative heat flux is sufficiently large. Therefore the linear relationships imply that the MLD in winter varies with two temporal scales, seasonal scale and some short scale of several days.

In April and October a lot of scatters can be seen in Fig. 5b and particularly nearly no correlation exists for October. Both of positive and negative values are present in heat flux indicating that in terms of the heat exchange between the atmosphere and sea these months belong to transient periods. It is clear that some process other than heat exchange determines the MLD. According to the Annual Weather Report of the Central Meteorological Office cyclones and anticyclones pass very frequently over the study area. For a time scale of a day Pollard, Rhines and Thompson (1972) showed theoretically that the wind stress can dominate the deepening process of the MLD. It is speculated that the wind stress is the main cause for the short term variation of the MLD, but at present the lack of reliable wind data makes it impossible to pursue this matter further.

High negative correlation is also found for summer months. The MLD disappears completely as the net heat gain to the sea increases above 0.5 ly/min. The regression line for August lies below one for June, which again reflects the annual evolution of the MLD.

V. CONCLUSION

In the southern part of the Sea of Japan both of the MLD and heat flux across the sea surface vary with an annual cycle. The ranges of the variations are 0 to 160 meters for the MLD and −0.35 ly/min to 0.38 ly/min for the heat flux, which are very comparable to those which occur in the Kuroshio region. As an annual average both regions lose heat as much as 0.11 ly/min.

During both of the active cooling and heating seasons the MLD and heat flux variations are tightly correlated with the coefficient such as −0.95 and −0.83. It is evident that the heat flux plays a major role in changing the MLD on a seasonal time scale. Meanwhile the variation of the MLD during the transient period between cooling and heating seasons is poorly correlated with the heat flux, suggesting that the wind effect is as importent as the heat exchange.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge Drs. Jong Wha Lee and Jung Yul Na for their support and members of the department of oceanography at the Chinhae Machine Depot for their assistance.

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