Vertical Temperature Profile in the Yellow Sea according to the Variations of Air Temperature*

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The vertical temperature profiles of the Yellow Sea in summer are investigated by means of the nine air temperature (AT) patterns which are classified with the AT of winter and summer.

The sea surface temperature (SST) is high when the AT of summer is high, and vice versa. The gradient of thermocline in the offshore region is higher than that in the coastal region and is not always favorable with the AT patterns. The relation between sea bottom temperature (SBT) and the AT of winter is favorable when the SBT is averaged in the coastal and offshore stations. In addition, the SST of coastal stations is higher than that of offshore stations because of the strong mixing by the tidal current in the coastal region.

The correlation between the AT and the SST of August is favorable ($r=0.44$ - 0.69), while the correlation between the AT of February and the SBT of August is not favorable except the stations, A2 ($r=0.57$) and B2 ($r=0.61$).

Introduction

The Yellow Sea is a semi—closed sea bounded by the continent of the China and the Korean peninsula, and is composed of the shallow continental shelf, 44*m* of mean depth. These characteristics make the sea very vulnerable to the meteorological conditions of the surroundings. In winter, all the sea is thermally homogenous, 2-8°C, by the cooling effect of the cold monsoon that originates in the Siberia. In summer, however, a strong stratification is formed between warm surface water and the cold bottom water formed during the previous winter. This stratification is destroyed in the coastal region by the turbulence made from tidal current, and then the typical tidal front is formed between the coastal water and offshore water.

The observation survey of the sea has been mainly conducted by the Korea Fisheries Experiment Station(the institute was renamed the National Fisheries Research and Development Agency in 1963). The coastal oceanographic observation was started in 1916 and the serial oceanographic observation was started in 1921. The data observed have been published in the form of weekly, monthly, and yearly reports. The Oceanographic handbook of the neighbouring seas of Korea compiling the observation data was published in 1956, 1964, and 1979, by the National Fisheries Research and Development Agency (NFRD).

The previous study on the Yellow Sea has been mainly concerned with the surface water. Gong (19

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68) showed that the yearly mean water temperature of the adjacent seas of Korea is higher than that of air temperature (AT), and the yearly variation of water temperature in the cold water zone was 8 – 22 ℃. Yi (1966) showed that the yearly mean sea surface temperature (SST) of the adjacent seas of Korea was 9 – 20℃, which are 0.7 – 3℃ higher than that of AT. Shim and Kim(1981) showed that heat flux greatly influences the mixed layer depth (MLD) as much as wind does in the East Sea. Han (1970a, 1970b) showed that the SST of the Yellow Sea have a period of 11 – 12 years.

As the patterns of AT are not the same every year, it is important to investigate the vertical temperature profiles according to the patterns of AT. In this study, we patterned the AT of winter and summer and then compared these patterns with SST, MLD, the gradient and thickness of thermocline, and sea bottom water (SBT) of August.

Data and method

In order to investigate the vertical temperature profiles of the Yellow Sea, the meteorological and oceanographic data were tabulated in Table 1. The oceanographic data are observed in the standard depth such as surface, 10*m*, 20*m*, 30*m*, 50*m*, and bottom. Fig. 1 shows selected stations for this study. The positions and stations number of the Annual Report of Oceanographic Observations of the National Fisheries Resesrch and Development Agency appear in Table 2. The selected stations are classified into coastal stations (A1, A2, A3) and offshore stations (B1, B2, B3) on the basis of this tidal front which appear in the Oceanographic handbook of the neighbouring seas of Korea (NFRD 1979, 3rd ed.). To see the difference of the temperature profiles to latitude variation, we classified the stations with north station (A1, B1), middle station (A2, B2), and south station (A3, B3), respectively.

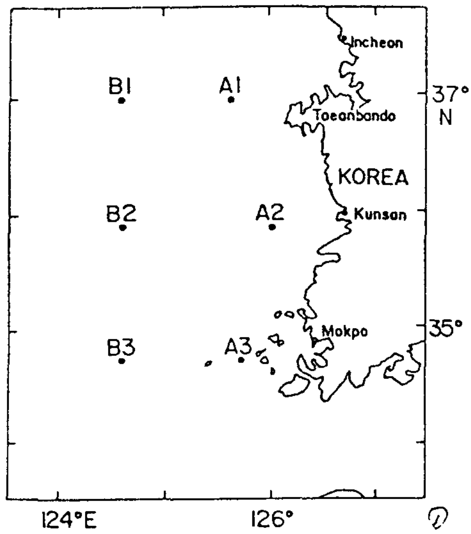

Fig. 1. Locations of stations.

Table 1. List of Oceanographic and weather observation data

Data source	Year	Institute of publication
Monthly Weather Report	1971 – 1984	Central Meterological Office of Korea
Annual Weather Report	1971 – 1984	Central Meterological Office of Korea
Climate Table of Korea	1981	Central Meterological Office of Korea
Annual Report of Oceanographic Observations	1971 – 1984 (Vol. 20 – 32)	Fisheries Research and Development Agency of Korea
Oceanographic Handbook of the Neighbouring Seas of Korea	1979 (3rd ed.)	Fisheries Research and Development Agency of Korea

Table 2. The position of stations and comparision of the stations in this study with the stations in Annual Report of Oceanographic Observations

	Station	Latitude (N)	Longitude (B)	St. name in Annual report of oceanographic stations*
Coastal	A1	36'55.5'	125'37.7'	307−04
	A2	35'51.3'	126'02.0'	309−02
	A3	34'43.0'	125'43.9'	311−04
Offshore	B1	36'55.5'	124'34.8'	307−09
	B2	35'51.3'	121'35.1'	309−09
	B3	34'43.0'	124'35.8'	311−09

* Annual Report of Oceanogrphic Observations (Fisheries Research and Development Agency of Korea)

To classify the patterns of AT, the 3 meteorological stations (Incheon, Kunsan, and Mokpo) are selected to be adjacent to the Yellow Sea and accessible AT data. The yearly AT anomalies of winter (December, January, February) and summer (June, July, August) are obtained by substracting the sum of three months from the arithmatic averaging of the sum of three months for 14 years (1971~1984). From these AT anomalies, we classify the anomalies into three types and mark those as H(high), N(normal), and L(low). The 9 AT patterns (HH, HL, HN, LH, LL, LN, NH, NL, NN) are made in the basis of one year. For example, the HL year of AT pattern means that the AT of winter is higher than that of normal but the AT of summer is lower than that of normal.

To clarify the relation between the 9 AT patterns and the vertical temperature profiles of the Yellow Sea, we select the 6 oceanographic stations of coastal and offshore region and then examine SST, MLD, the gradient and thickness of thermocline, and SBT. We also compute the correlation coefficient between the AT of February and August and the water temperature of surface and bottom of August.

Results and discussion

The patterning of AT

The Fig. 2 shows the time series of yearly winter and summer AT anomalies in Incheon, Kunsan, and Mokpo which are obtained by subtracting the arithmatic average from the AT sum of three months which are December, January, February in winter and June, July, August in summer. Table 3 shows the years classified with the 9 AT patterns and the 3 meteorological stations. We classify the AT into 3 types when the AT anomaly is 0.5℃

Table 3. The years classified with the patterns of air temperture and the three AT stations

Pattern	Incheon	Kunsan	Mokpo
HH	1973, 1978, 1979	1973, 1978	1973, 1978
HL	1972	1972	1972
HN	−	1979	1979
LH	1984	1984	1984
LL	1974	−	1974
LN	1977, 1981	1977, 1980, 1981	1977, 1981
NH	−	−	1975
NL	1976, 1980	1974, 1976, 1977, 1980	1976, 1980
NN	1971, 1975, 1982, 1983	1971, 1975, 1982, 1983	1971, 1982, 1983

* normal air temperature(N), higher air temperature(H), lower air temperature(L).

higher than that of normal, we mark it H (high), when the AT anomaly is 0.5℃ lower than that of normal, we mark it L (low), and when the AT anomaly is within −0.5℃, we mark it N (normal). The first capital of the 9 AT patterns means the AT of winter and the next capital means the AT of summer.

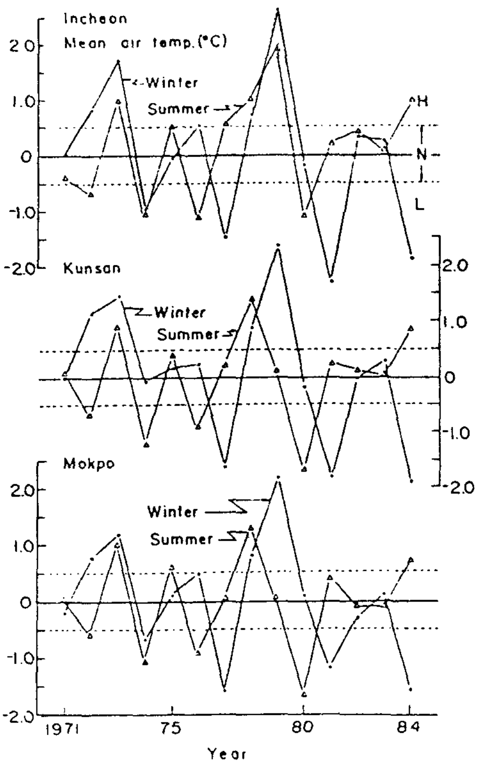

Fig. 2. The secular variations of air temperature anomalies of winter(December, January, February) and summer (June, July, August) in Incheon, Kunsan, and Mokpo.

From Fig. 2 and Table 3, the years of HH AT pattern which are high AT in both winter and summer were 1973, 1978. The others were that HL was in 1972, LH in 1984, LN in 1976 and 1980, and NN in 1971, 1982, and 1983. The patterns of HN appeared in Kunsan and Mokpo in 1979 and the pattern of LL in Incheon and Mokpo in 1974. The pattern of NH appeared in only Mokpo in 1975. In 1979, Incheon had HH pattern but Kunsan and Mokpo had HN pattern. In 1974, Incheon and Mokpo had LL pattern but Kunsan NL had pattern.

Vertical temperature profiles according to AT patterns

The Table 4 shows SST, SBT, the difference between SST and SBT(◁T), and the average of three stations(◁lT), and the gradient(◁T) and thickness of thermocline of coastal and offshore stations in summer according to the AT patterns. The Table 5 shows the average of SST, SBT, and the gradient and thickness of thermocline of coastal and offshore stations according to the AT patterns.

From Table 5, the SBT of the years (1972, 1973, 1979) which had a high winter AT was 16.68 − 18.64 ℃ (17.91℃ in average) in the coastal stations and 8.38 − 13.27℃ (10.84℃ in average) in the offshore stations. The SBT of the years (1974, 1977, 1984) which had a low winter AT was 15.42 − 17.76℃ (16.27℃ in average) in the coastal stations and 6.38 − 15.16℃ (9.98℃ in average) in the offshore stations. The SBT of the years (1975, 1980, 1983) which had a normal winter AT was 15.38 − 18.73℃ (16.71℃ in average) in the coastal stations and 8.15 − 11.99℃ (10.49℃) in the offshore stations. Form the Point of average of 3 stations, we can conclude that when the AT of winter was higher than normal, the SBT of summer is also higher than normal, and vice versa. This means that the AT of winter influences the SBT of summer in the average point of views. However, the relation between the AT of winter and the SBT of summer per each station was not always favorable.

The SST of the years (1973, 1975, 1984) which had high AT of summer was 25.92 − 26.42℃ (26.15℃ in the coastal stations and 27.07 − 28.17℃ (27.67℃ in average) in the offshore stations. The SST of the years (1972, 1974, 1980) which had low AT of summer was 21.57 − 25.19℃ (23.07℃ in average) in the coastal stations and 23.64 − 26.17℃ (24.67℃ in average) in the offshore stations. The SST of the years (1977, 1979, 1983) which and normal AT of summer was 23.71 − 25.67℃ (24.46℃ in average) in the coastal stations and 26.00 − 27.92℃ (26.77℃ in average) in the offshore stations. The relation between the AT and the SST of summer was very favorable.

From Table 4, the gradient of thermocline in the offshore stations was 0.695℃ /*m*, the highest value, at the station A2 in 1984 when the AT pattern was LH and 0.132℃/m, the lowest value, at the station A1 in 1973 when the AT pattern was HH. In 1972 (HL), the thermocline was not found at the station A1. The gradient of thermocline in the coastal stations was 0.844℃/m, the highest value, at the stations B1 in 1979 when the AT pattern was HN and 0.148℃/m, the lowest value, at the station B1 in 1973 when the AT pattern was HH.

From Table 5, the highest value of thermocline of the offshore station was 0.624 ℃/m in 1974 (LL) and the next was 0.518℃/m in 1975 (NH). In 1984 (LH), the gradient of thermocline was 0.420℃/m. The lowest value of thermocline was 0. 255℃/m in 1972 (HL). The highest value of thermocline of the coastal stations was 0.521℃/m in 1979 (HN) and the next was 0.510℃/m in 1984 (LH). The lowest value of thermocline was 0.327℃/m in 1972(HL). In general, the gradient of thermocline of coastal stations was higher than that of offshore stations, which is a typical phenomenon taking place in both sides of the tidal front. The relation between the

Table 4. Sea surface temperature (SST), sea bottom temperature (SBT), temperature difference between sea surface and bottom(△T) and its mean value(△T̄), and the gradient(▽) and thickness of thermocline in the summer (August) according to the patterns of air temperature

Pat-tern	Year	Offshore							Coastal						
		Sta.	SST (℃)	SBT (℃)	△T	△T̄	Thermocline ▽ (℃/m)	Thermocline thick (m)	Sta.	SST (℃)	SBT (℃)	△T	△T̄	Thermocline ▽ (℃/m)	Thermocline thick (m)
		A1	25.53	23.49	2.04		0.132	10	B1	28.00	20.05	7.95		0.148	40
HH	73	A2	27.40	12.67	14.73	7.14	0.512	20	B2	27.90	11.75	16.15	14.91	0.339	40
		A3	26.32	13.88	12.44		0.415	30	B3	28.62	8.00	20.62		0.710	10
		A1	20.52	20.12	0.40		–	–	B1	22.95	7.00	15.95		0.304	65
HL	72	A2	22.61	15.51	7.10	4.05	0.406	10	B2	22.97	6.55	16.42	15.26	0.281	50
		A3	24.25	19.60	4.65		0.358	10	B3	25.00	11.58	13.42		0.395	30
		A1	26.50	19.13	7.37		0.316	10	B1	26.30	8.27	18.03		0.844	20
HN	79	A2	26.27	17.20	9.07	7.03	0.660	10	B2	26.70	12.75	13.95	15.13	0.325	40
		A3	24.25	19.60	4.65		0.358	10	B3	25.00	11.58	13.42		0.395	30
		A1	24.24	18.35	5.89		0.241	20	B1	26.69	6.68	20.01		0.493	40
LH	84	A2	27.21	11.44	15.77	10.67	0.695	20	B2	26.93	6.00	20.93	20.69	0.519	40
		A3	26.84	16.48	10.36		0.324	32	B3	27.60	6.46	21.14		0.519	40
		A1	25.00	21.42	3.58		0.230	10	B1	26.21	14.38	11.83		0.547	20
LL	74	A2	26.31	16.62	9.69	7.42	0.291	30	B2	26.30	12.01	14.29	11.01	0.254	50
		A3	24.25	15.25	9.00		0.270	10	B3	26.00	19.10	6.90		0.525	10
		A1	22.50	18.09	4.41		0.202	10	B1	25.79	9.20	16.59		0.379	40
LN	77	A2	25.81	12.47	13.34	8.37	0.461	20	B2	27.09	7.50	19.59	18.00	0.510	30
		A3	23.71	16.35	7.36		0.245	30	B3	26.29	8.47	17.82		0.323	50
NH	75	A3	25.92	18.73	7.19	7.19	0.518	12	B3	27.77	8.15	19.62	19.62	0.366	40
		A1	22.59	13.65	8.94		0.279	32	B1	23.25	8.30	14.95		0.750	20
NL	80	A2	21.30	15.00	6.30	6.19	0.534	10	B2	23.55	10.70	12.85	14.45	0.300	40
		A3	20.81	17.49	3.32		0.280	10	B3	25.82	10.28	15.54		0.349	40
		A1	24.43	21.50	2.93		0.262	10	B1	27.80	18.18	9.62		0.318	30
NN	83	A2	26.65	13.41	13.24	6.33	0.436	30	B2	28.00	9.74	18.26	15.93	0.598	30
		A3	20.04	17.21	2.83		0.180	10	B3	27.96	8.06	19.90		0.449	40

AT patterns and the gradient of thermocline was not always favorable. So we can assume that there are some other factor affecting the gradient of ther mocline in the Yellow Sea.

Table 5. The mean values of three stations of sea surface($\overline{SST}$), sea bottom temperature($\overline{SBT}$), and the gradient(▽) and thickness of thermocline according to the patterns of air temperature

Pattern	Year	Offshore SBT (℃)	Offshore Thermocline ▽	Offshore Thermocline thick	Coastal SBT (℃)	Coastal Thermocline ▽	Coastal Thermocline thick	Pattern	Year	Offshore SST (℃)	Coastal SST (℃)
HH	1973	16.68	0.353	20	13.27	0.399	30	HH	1973	26.42	28.17
HL	1972	18.41	0.255	10	8.38	0.327	48.3	LH	1984	26.10	27.07
HN	1979	18.64	0.445	10	10.87	0.521	30	NH	1975	25.92	27.77
mean		17.91	0.393	13.3	10.84	0.416	36.1	mean		26.15	27.67
LH	1984	15.42	0.420	24	6.38	0.510	40	HL	1972	22.46	23.64
LL	1974	17.76	0.624	16.7	15.16	0.442	26.67	LL	1974	25.19	26.17
LN	1977	15.64	0.303	20	8.39	0.404	40	NL	1980	21.57	24.21
mean		16.27	0.329	20.2	9.98	0.452	35.56	mean		23.07	24.67
NH	1975	18.73	0.518	12	8.15	0.366	40	HN	1979	25.67	26.00
NL	1980	15.38	0.364	17.33	9.76	0.466	33.3	LN	1977	24.01	26.39
NN	1983	17.37	0.293	16.7	11.99	0.455	33.3	NN	1983	23.71	27.92
mean		16.71	0.356	16.30	10.49	0.447	34.29	mean		24.46	26.77

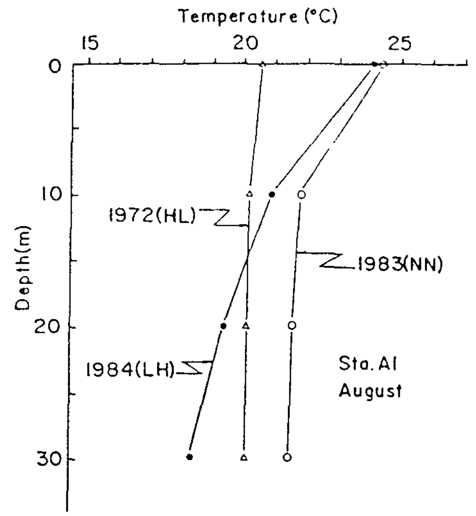

Fig. 3. Vertical temperature profiles of station A1 in the summer(August) according to the patterns of air temperature (HL, LH, NN).

In general, when the AT of winter was lower than that of normal, the SBT of summer (16.27℃ in the coastal stations and 9.98℃ in the offshore stations) was lower than that of the years having high AT of winter (17.91℃ in the coastal stations and 10.84℃ in the offshore stations). The SBT of the coastal stations was higher than that of the offshore stations. In coastal region of the Yellow Sea, the strong turbulence caused by the tidal current destroyed the seasonal thermocline and then mixed the bottom cold water with the warm surface water. So the SST of coastal water is lower than that of off shore water but the SBT of coastal water is higher than that of offshore water. The existence of this phenomenon coincide with the mechanism of tidal front explained by Cho et al. (1983) and Choo and Cho (1984)

In order to investigate vertical temperature profiles schematically according to the AT patterns, we select the 3 standard patterns (HL, LH, NN). The Fig. 3 shows the vertical temperature profiles of 1972 (HL), 1984 (LH), and 1983 (NN) in the station A1. The SST was 20.75℃ in 1972 which are lowest value and 24.43℃ in 1983 and 24.24℃ in 1984, respectively. The SBT was 18.35℃ in 1984, 20.12℃ in 1972, and 21.50℃ in 1983. The gradient of thermocline was in the order of LH and NN, but the thermocline of HL was not found. As former

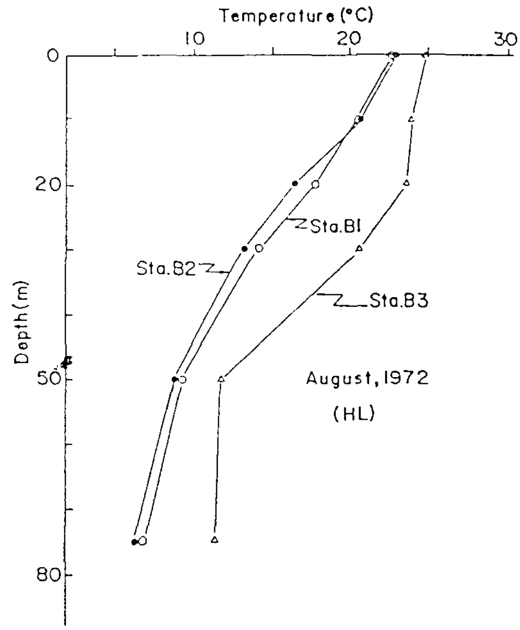

Fig. 4. Vertical temperature profiles of station B1, B2, and B3 in the summer(August, 1972) according to the HL patterns of air temperature.

explanation, this phenomenon is caused by the mixing effect of both the turbulences from bottom by tidal current (Fearnhead, 1975) and wind stirring from surface. The vertical temperature profiles of 1972 (HL), 1984 (LH), and 1983 (NN) in the offshore stations are shown in Fig. 4, Fig. 5, and Fig. 6, respectively. As we explain the stratification in Table 4 and Table 5, the stratification of 1984 when the AT was low in winter and high in summer was stronger than that of 1972 (HL) in Fig. 5 and 1983 (NN) in Fig. 6. In Fig. 6, the surface mixed layer was not found. This is assumed to be a temporal phenomenon caused because the observations were made during the daytime when the radiation of the sun is strong.

When we assume (generally accepted) that the cold water of winter of the Yellow Sea formed by the cold winter monsoon remains in the bottom layer of summer, the vertical temperature profiles of 1972, 1983, and 1984 is very favorable with the assumption. However, when we consider the relation between the 9 AT patterns and each profiles of the 6 stations, the vertical temperature profiles were not always favorable with the patterns.

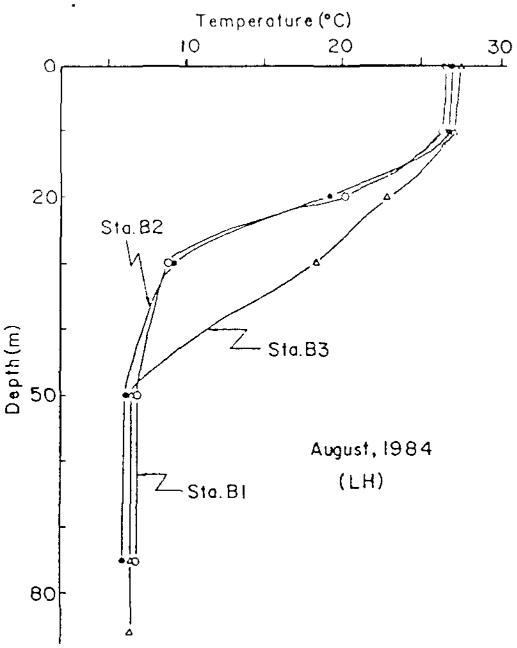

Fig. 5. Vertical temperature profiles of station B1, B2, and B3 in the summer (August, 1983) according to the LH patterns of air temperature.

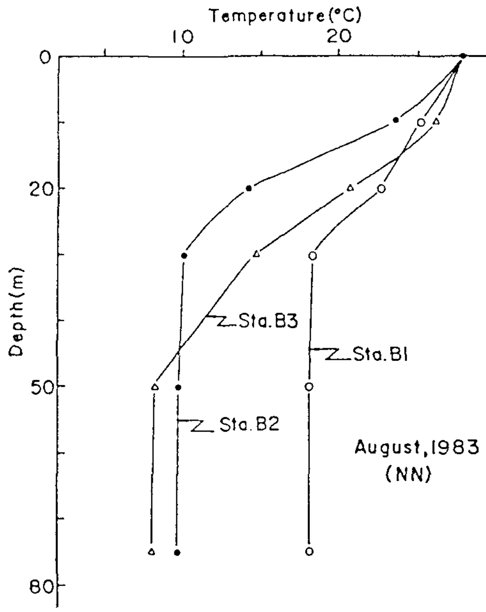

Fig. 6. Vertical temperature profiles of station B1, B2, and B3 in the summer (August, 1983) according to the NN pattern of air temperature.

The correlation between AT and water temperature (WT)

To investigate the relation between AT and WT, the time series of the AT anomalies of February and August in Incheon and the WT anomalies of the station A1 is shown in Fig. 7. And those AT anomalies and the WT anomalies of the staiton B1 in Fig. 8. In Fig. 7 and Fig. 8, all the layers but the bottom have similar WT anomalies in the coastal stations, but the upper and lower layer with the border of thermocline have similar WT anomalies in the offshore station. So we compared the AT anomalies with the WT anomalies of the surface and bottom in the coastal stations and suface and 50m in the offshore stations. Fig. 9 shows the WT anomalies of the surface and bottom of the station A2 (upper part) and the surface and 50m of the station B2 (lower part). We compared these with the AT anomalies of February and August of Kunsan. Fig. 10 shows the WT anomalies of surface and bottom of the station A3 (upper part) and the susface and 50m of the station B3 (lower part). We compared these with the AT anomalies of Fubruary and August of Mokpo.

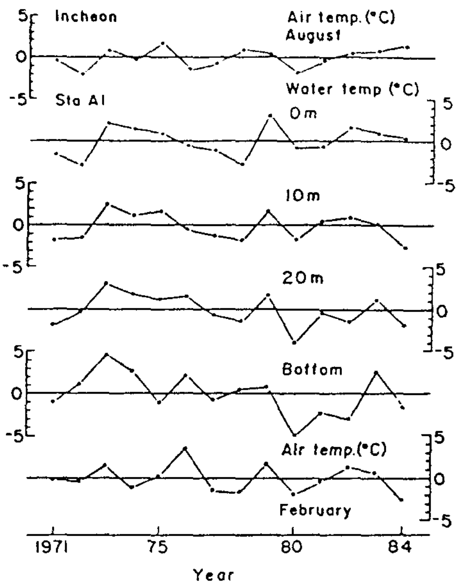

Fig. 7. Secular variations of air temperature anomalies of February and August at Incheon and water temperature anomalies of August at station A1.

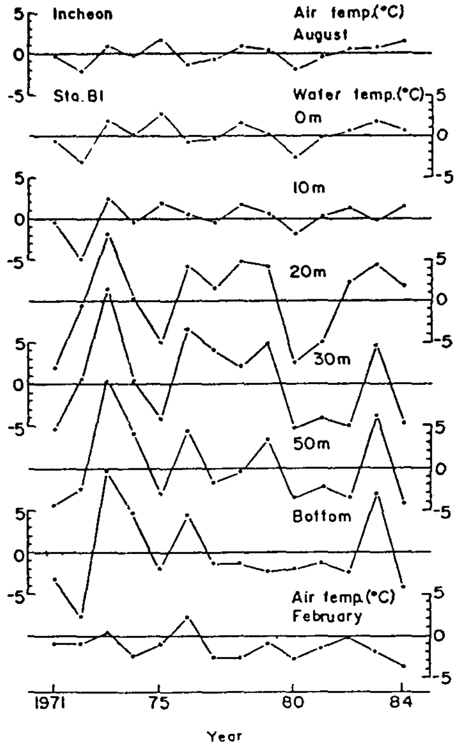

Fig. 8. Secular variations of air temperature anomalies of February and August at Incheon and water temperature anomalies of August at station B1.

Generally, the anomaly pattern of SST is similar with that of AT. The years (1973, 1975, 1978) which showed high SST were high AT but 1975 when the AT was normal. The year (1980) of low SST had low AT in all stations. However, when we compared the AT anomalies of February with the WT anomalies of bottom in the coastal stations and 50*m* in the offshore stations, the pattern between the AT and the WT was not favorable. The correlation coefficient between the AT of February and August and the WT of coastal and offshore stations is ap peared in Table 6. The correlation coefficient between the AT and the SST of August was 0.44~0.89 whose confidence level is less than 5%. In the stations of A1, A2, B1, B2, the confidence level is less than 1%. The correlation coefficient between the AT of February and the WT of 50*m* of August was less than 0.43 but the station A2 ($r=0.57$) and B2 ($r=0.61$).

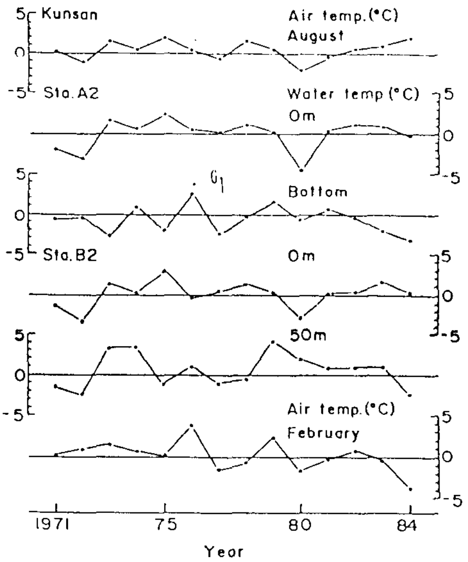

Fig. 9. Secular variations of air temperature anomalies of February and August at Kunsan and water temperature anomalies of sea surface at station A2 and sea surface and 50*m* at station B2 in August.

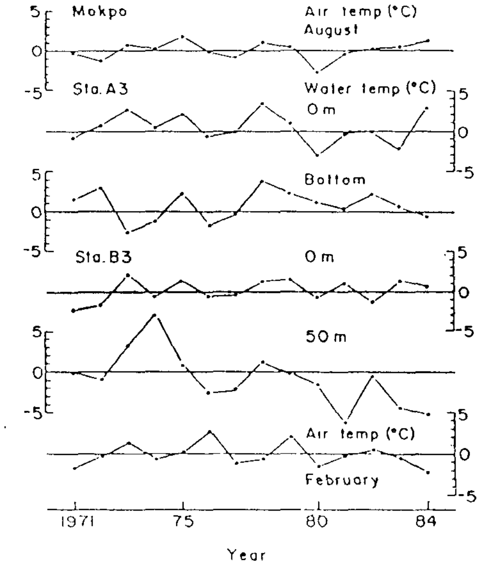

Fig. 10. Secular variations of air temperature anomalies of February and August at Mokpo and water temperature anomalies of sea surface and bottom at station A3 and sea surface and 50*m* at station B2 in August.

Conclusion

To investigate the vertical temperature profiles of the Yellow Sea according to the patterns of the air temperature (AT) of winter and summer, the patterns of AT are made with the AT of Incheon, Kunsan, and Mokpo, and are compared with sea surface temperature (SST), mixed layer depth

Table 6. Correlation coefficient (r) between air temperature (TA) and water temperature (TW)

Temp TA	TW	Depth (*m*) / Sta.	0	10	20	30	50	75
Feb.	Aug.	A1	0.30	0.43	0.54*	0.33		
		A2	0.11	0.05	0.04	0.40	0.57*	
		A3	−0.01	−0.13	0.03	−0.39		
		B1	0.17	0.40	0.26	0.28	0.30	0.27
		B2	−0.42	0.00	−0.05	0.33	0.61*	0.61*
		B3	0.07	0.12	0.13	−0.08	0.19	0.15
Feb.	Aug.	A1	0.53*	0.53*	0.37	0.20		
		A2	0.89**	0.70*	0.55*	0.19	−0.37	
		A3	0.68**	0.58*	0.59*	0.02		
		B1	0.87**	0.46	0.31	0.00	0.10	0.24
		B2	0.80**	0.80**	0.71**	0.43	0.24	−0.07
		B3	0.56*	0.44	0.39	0.25	0.11	−0.11

* confidence level 5%, ** confidence level 1%

(MLD), the gradient and thickness of thermocline, and sea bottom temperature (SBT).

In general, the SST of the patterns having high AT of summer (LH, HH, NH) is a little higher than that of normal (LN, HN, NN), and the SST of the patterns of low AT of summer (LL, HL, NL) is somewhat lower than normal. In the typical patterns of AT (LH, NN, HL), the gradient and thickness of thermocline in the offshore stations is 0.51°C/m and 20*m* in 1984 (LH), 0.455°*C*/*m* and 33*m* in 1983 (NN), and 0.370°*C*/*m* and 48*m* in 1972 (HL), respectively. But the gradient of thermocline is not always similar with AT patterns in the coastal stations by the tidal mixing. The SBT of summer is similar with AT patterns only when the SBT of coastal and offshore stations is averaged. The SST of the offshore stations is higher than that of coastal stations but the SBT of coastal stations is lower than that of offshore stations.

The correlation between the AT and the SST of August is favorable (r=0.44-0.89) but the correlation between the AT of February and the SBT of August is not favorable except the station A2 (r=0.57) and B2 (r=0.61).

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