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Annual Variation of Water Temperatures in the Upper 200m Off Southeast Coast of Korea

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韓國 南東海岸 外海 表層 200m 水温의 年變動

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Abstract

We studied the annual variation of water temperatures in the upper 200m off southeast coast of Korea by means of harmonic analysis of the temperatures at 10 standard depths of 51 stations. The distributions of the mean temperature in coastal zone are almost parallel to the coast, whereas those in offshore are almost zonal. With an increase of depth, the annual amplitude decreases nearly exponentially and the annual phase increases nearly linearly. The average e-folding depth for the annual amplitudes is 65 m, vertical change of the annual phase is 180° per 200 m, and the vertical eddy conductivity is 4 cm^2/sec. Annual variations of temperatures in the coastal zone of a few tens miles from the coast are considerably different from those in offshore area. The e-folding depths in coastal zone are shallower than those in offshore region, and the changes of phase with depths in coastal zone are smaller than those in offshore region.

요약 : 동해안 외해역 51개 정점의 표층 200m내 10개 표준 수심의 누년평균 수온자료에 대한 조화분석을 통하여 수온의 연변동을 구명하였다. 연안에 인접한 해역에서 연평균 수온의 등온선은 해안선에 거의 평행한 반면에, 외해에서는 등온선이 위도선에 거의 평행한다. 수심이 증가함에 따라 수온의 연진폭은 지수함수적으로 감소하고, 연위상은 거의 선형적으로 증가한다. 동해 남동해역에서의 평균적인 지수적 진폭 감소 수심(e-folding depth)은 65m이고, 수심증가 200m에 따른 연위상의 변동은 180°이며, 연직방향의 난류적 전도계수는 4 cm^2/sec이다. 해안으로부터 수십 해리 이내인 연안역의 수온 연변동은 외해의 수온 연변동과 상당히 다르다. 연안역 진폭의 지수적 감소 수심은 외해에서보다 얕으며, 수심에 따른 수온 연변동 위상의 증가는 연안쪽이 외해쪽보다 완만하다.

INTRODUCTION

Fluctuations of sea water temperatures in the upper layer of the oceans are dominated by annual variations due to annual variations of heat fluxes across the sea surface and heat advections by the ocean currents. Previous works on the annual variations of water temperature in coastal waters (Gong, 1968; Kim, 1983) and in the neighbouring seas of Korea (Kang and Jin, 1984) were limited to the investigations of the sea surface temperature (SST). Previous works on the interannual fluctuations of water temperature in the Korea Strait (Kang and Lee, 1984), in the Tsushima Current region (Kang and Choi, 1985) and in the southeastern Japan Sea (Gong and Kang, 1986) were also limited to the investigations of SST only, and fluctuations of water temperatures in the interior of the neighbouring seas of Korea were not studied in detail yet.

Kang (1985) reported that the spatio-temporal characteristics of seasonal variations of heat content in the southwestern Japan Sea are quite different from those of SST. In this work, we extend Kang's (1985) work by analyzing the annual variations of water temperatures in the upper 200 m layer by the harmonic method. The spatial distributions of the means, amplitudes and phases of annual temperature variations are presented in horizontal and vertical planes.

DATA AND METHOD

The data set used in this work is the bimonthly normals of sea water temperatures for 15 years (1961-1975) at 10 standard depths (0, 10, 20, 30, 50, 75, 100, 125, 150 and 200 m) in the upper 200 m layer off southeast coast of Korea. The data set was published by the Korea Ocean Research and Development Institute (1977), Hahn (1978), and the Fisheries Research and Development Agency (1979). The 51 oceanographic stations used in this work are shown in Fig. 1.

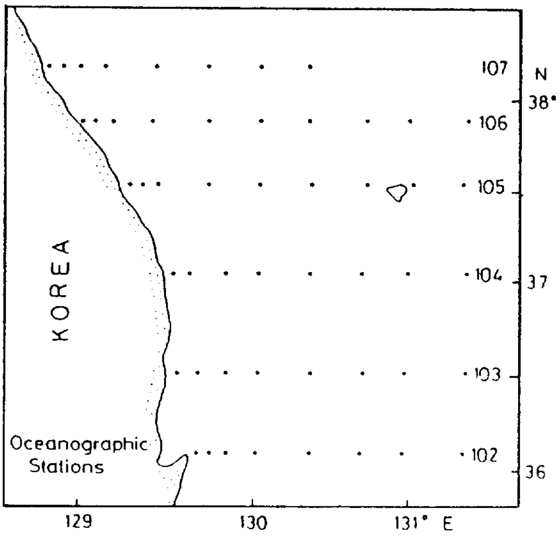

Fig. 1. Oceanographic stations in the southwestern East Sea.

The sea water temperature at a depth of each station is fitted to a harmonic function

$$T(t) = T_0 + T_1 \cos(\omega t - \phi_1) + T_2 \cos(2\omega t - \phi_2) \qquad (1)$$

where T(t) is the fitted temperature, t is the time from January 1, T_1 and T_2 are the annual and semi-annual amplitudes, respectively, ω is the angular frequency of the annual variation, and ϕ_1 and ϕ_2 are the annual and semi-annual phases, respectively. The 5 parameters (T_0, T_1, T_2, ϕ_1 and ϕ_2) at each depth and station are obtained by the least squares method discussed by Kang and Jin (1984). The harmonic constants for the annual variation are displayed in horizontal planes at 0, 50 and 100 m depths and also in vertical sections along the Lines 102, 104 and 106 (Fig. 1). The harmonic constants of the semi-annual variation are not presented, because the semi-annual amplitudes are much smaller than annual amplitudes, and semi-annual harmonic constants show irregular spatial fluctuations.

The e-folding depth for annual variation at each station is obtained by fitting the observed amplitudes at 7 standard depths (0, 10, 20, 30, 50, 75 and 100 m) in the upper 100 m layer to an exponential function

$$\mathrm{Amp}(z) = A \exp(-z/z_e), \qquad (2)$$

where A is a constant and z_e is the e-folding depth. The parameters A and z_e are obtained by the least squares method for the logarithm form of (2). Similarly, the vertical slope of phase is obtained by fitting the observed annual amplitudes in the upper 100 m layer to a linear function

$$\mathrm{Phase}(z) = C + Dz, \qquad (3)$$

where C and D are constants. We present the horizontal distributions of e-folding depths and also those of the depths with phase difference of one month from the phase at the sea surface.

RESULTS

The horizontal distributions of the means, amplitudes and phases of temperatures at 0, 50 and 100 m are shown in Figs. 2, 3 and 4, respectively. These figures show the followings. The mean temperatures are 14-17 °C at the sea surface, 7-14 °C at 50 m, and 4-11 °C at 100 m (Fig. 2). The isotherms are nearly parallel to the coast in coastal region and they are nearly zonal in offshore region. The extent of coastal region with isotherms parallel to the coast increase with depths.

The annual amplitudes of temperature decrease with depths (Fig. 3). They are 6-9 °C at the sea surface, 2-3.5 °C at 50 m, and 1-3 °C at 100 m. At the sea surface, the annual amplitudes in the northern part are larger than those in the southern part. In the subsurface layer (50 and 100 m), the annual amplitudes in the coastal region are smaller than those in offshore area.

Fig. 4 shows that the annual phase increases with depth. The horizontal differences of phase at the sea surface are small and those in subsurface layer are large. The annual phases at the sea surface are 230-236° and their horizontal differences are less than 6°. At 50 and 100 m, the annual amplitudes are 260-320° and 260-360°, respectively, and the horizontal differences of phase are up to 60° and 100°, respectively. At 50 and 100 m, there appear abrupt changes of the phase across about 130°E meridional.

Fig. 5 shows vertical distributions of the horizontally averaged annual amplitudes and phases. The annual amplitude decreases nearly exponentially with depths, and the annual phase increases nearly linearly with depths. The standard deviations of the amplitudes, which is a measure for horizontal inhomogeneity of the amplitudes, are about the same at each standard depth. However, the standard deviations of the annual phases have a tendency to increase with depths.

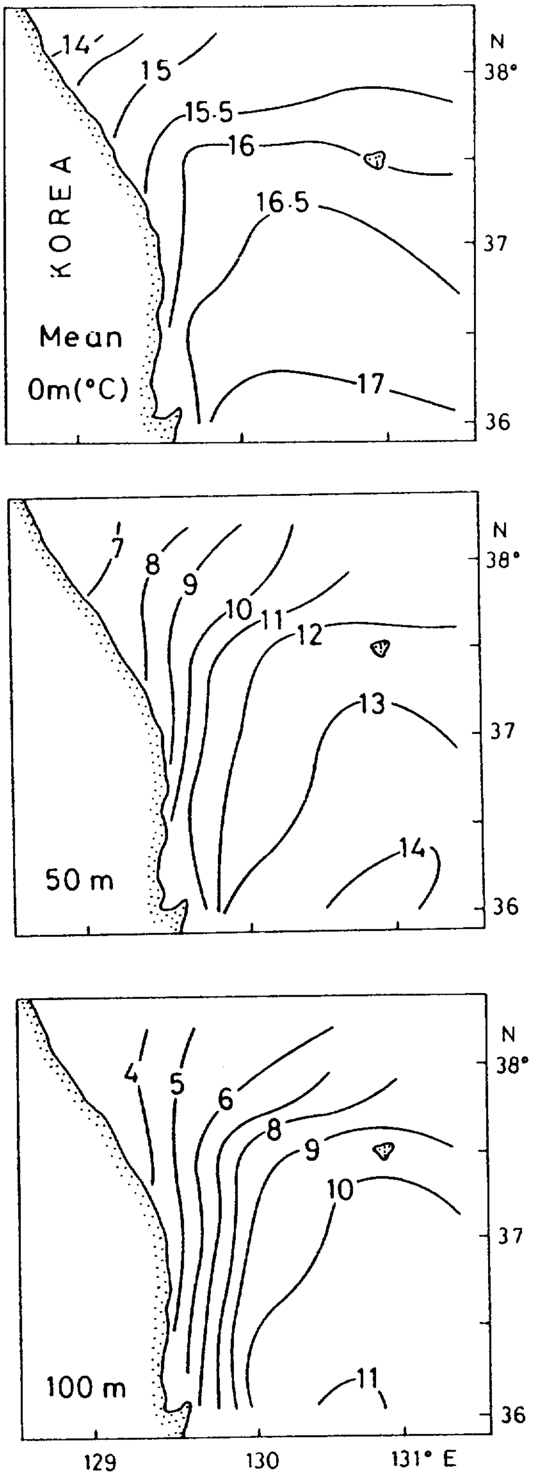

Fig. 2. Horizontal distributions of mean temperature (°C) at 0, 50 and 100 m.

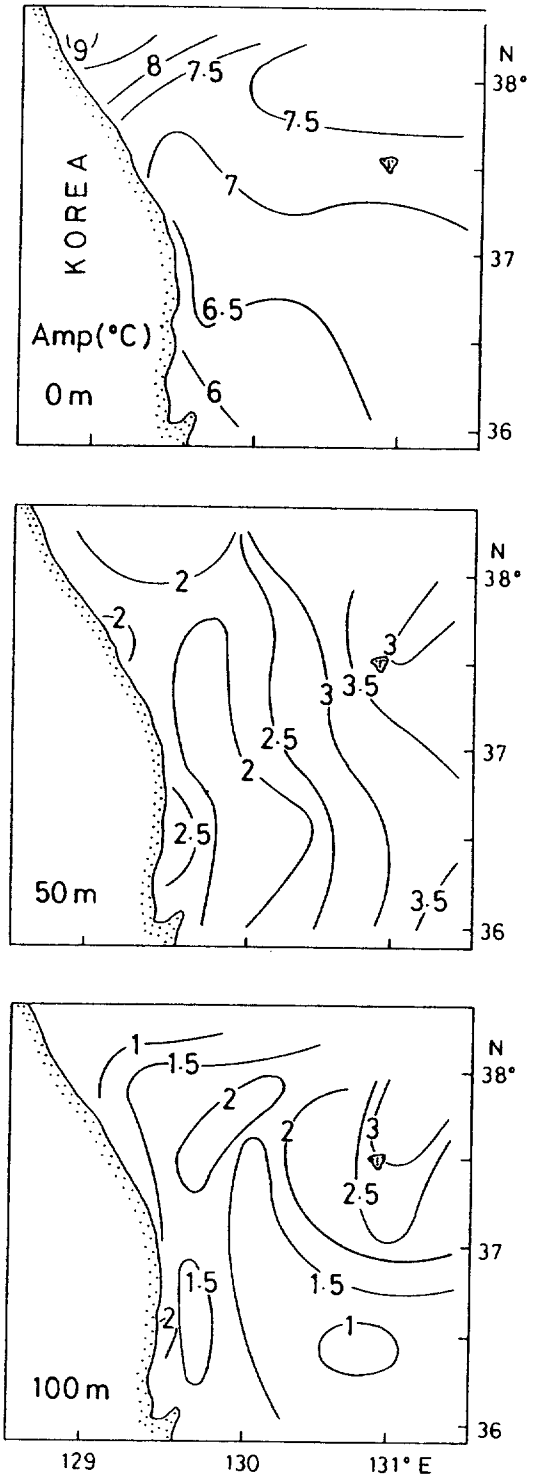

Fig. 3. Horizontal distributions of the annual amplitudes (℃) at 0, 50 and 100 m.

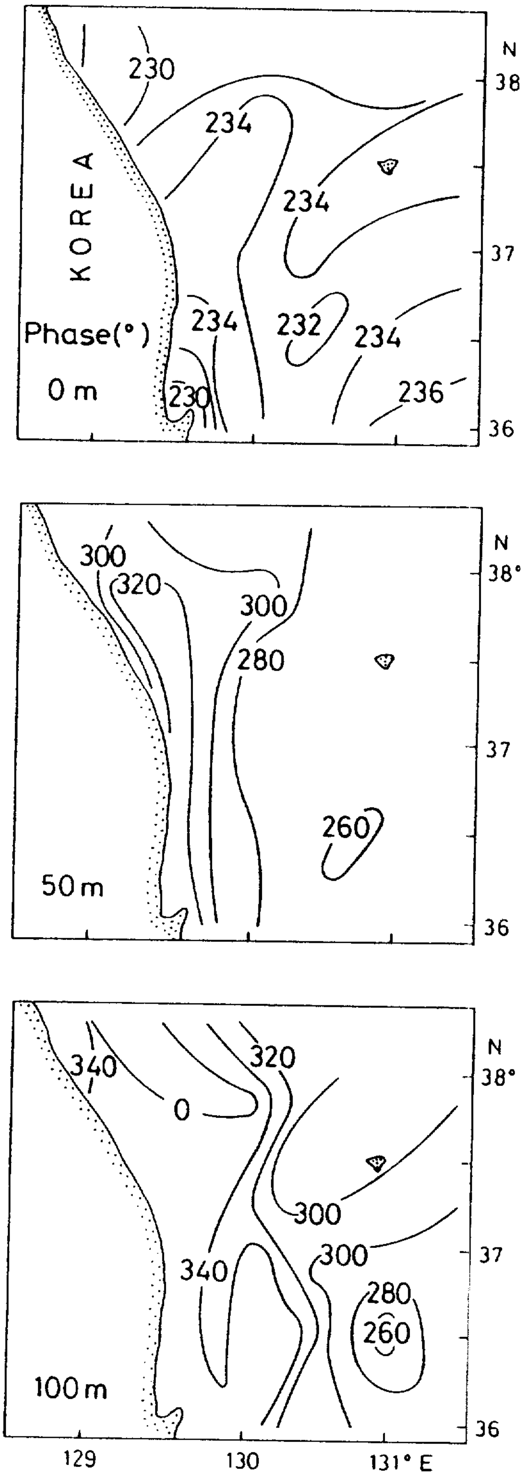

Fig. 4. Horizontal distributions of the annual phases (degrees) at 0, 50 and 100 m.

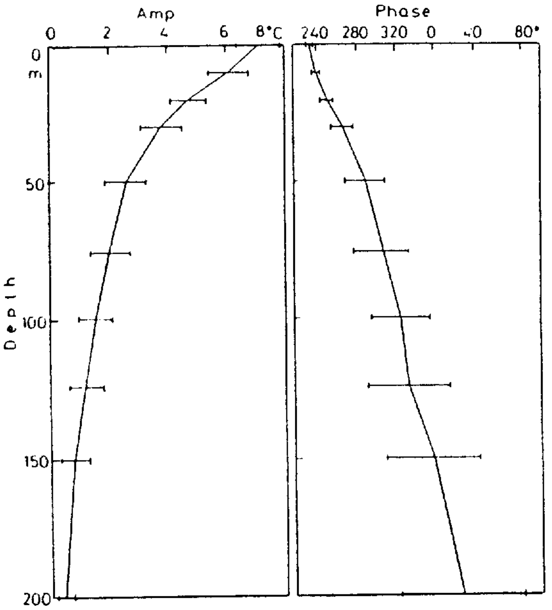

Fig. 5. Vertical distributions of the horizontally averaged annual amplitude and phase. The bars denote standard deviations at each standard depth.

The profiles of mean temperature in vertical planes along the zonal section of the Lines 102, 104 and 106 are shown in Fig. 6. The corresponding profiles of the annual amplitudes and annual phases are shown in Figs. 7 and 8, respectively.

The isotherms of mean temperature have downward slopes with the offshore distances (Fig. 6). The downward slopes are mild in the surface layer and steep in the subsurface layer. The slopes of isotherms are steep near the coast and they become mild in regions far away from the coast. The nearshore region with a steep downward slope is limited to a few tens miles in the southern part (Line 102) and is extended to a wider region in the northern part (Line 106).

The profiles of annual amplitudes (Fig. 7) show that the amplitude decreases rapidly with depths in the upper layer. The amplitudes are larger than 6 °C at the sea surface and only about 2 °C at 100 m. In the top 50 m layer, the depth with a constant amplitude increases with offshore distances. Annual amplitudes greater than 3 °C are limited within 30 m near the coast and they extend deeper than 50 m in offshore region away from the coast. Profiles of the annual phases (Fig. 8) show that the

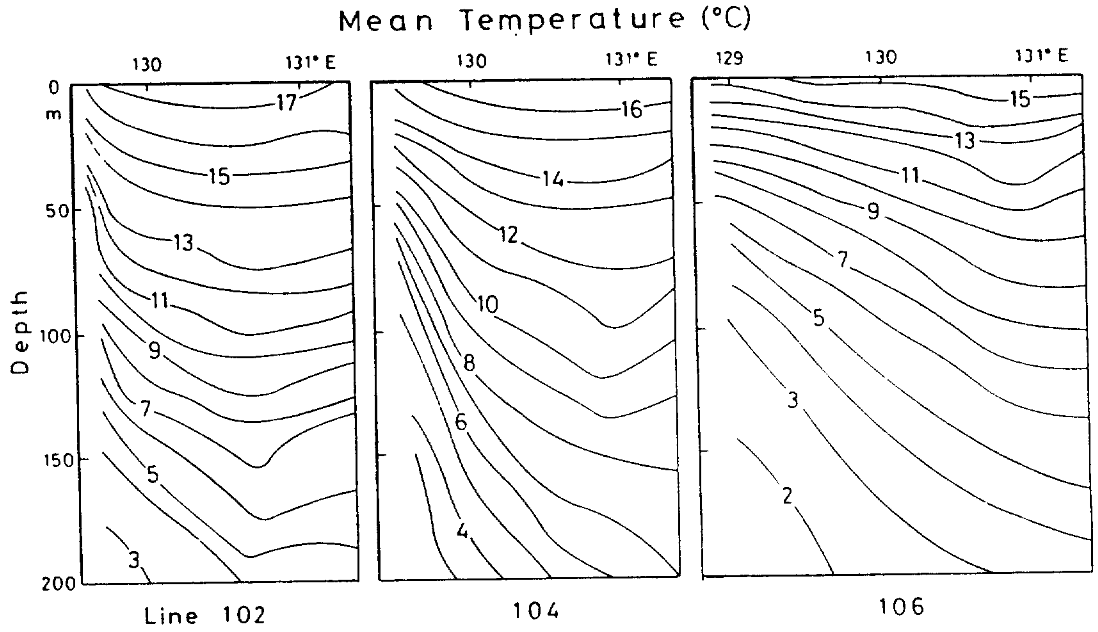

Fig. 6. Vertical distributions of the mean temperatures (°C) along the Lines 102, 104 and 106.

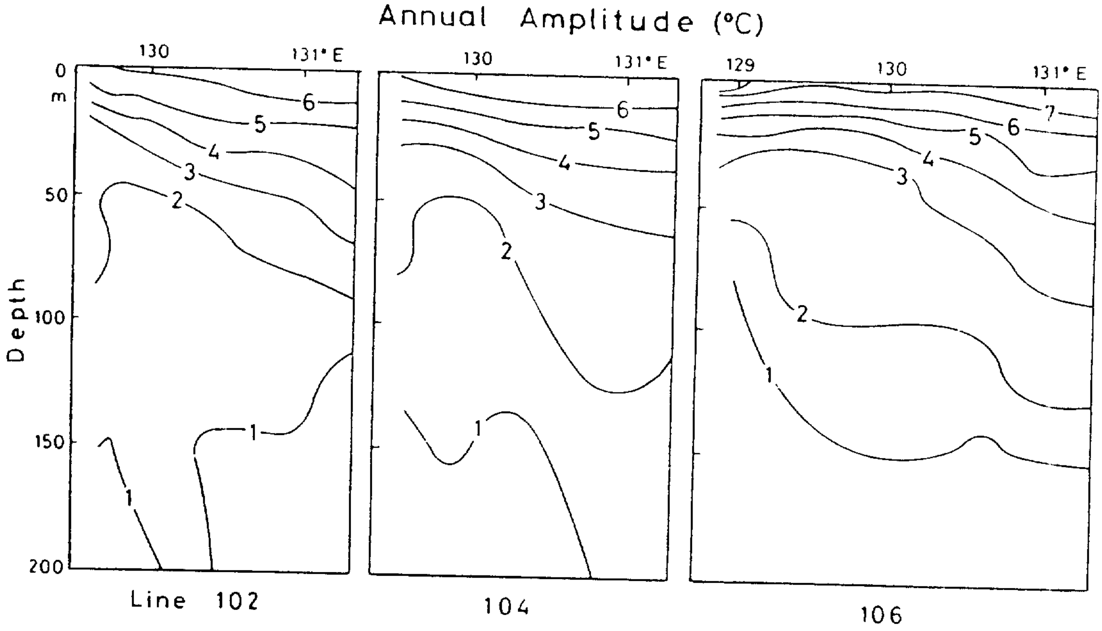

Fig. 7. Vertical distributions of the annual amplitudes (°C) along the Lines 102, 104 and 106.

phases in the upper 50 m are horizontally almost uniform. In the subsurface layer deeper than 50 m, the annual phases vary greatly with offshore distances. In the vertical section along the Line 106, an abrupt change of phase is found at 130°E in the subsurface layer deeper than 50 m.

Fig. 9 shows horizontal distribution of e-folding depths of the annual amplitudes, which are determined by fitting the observed

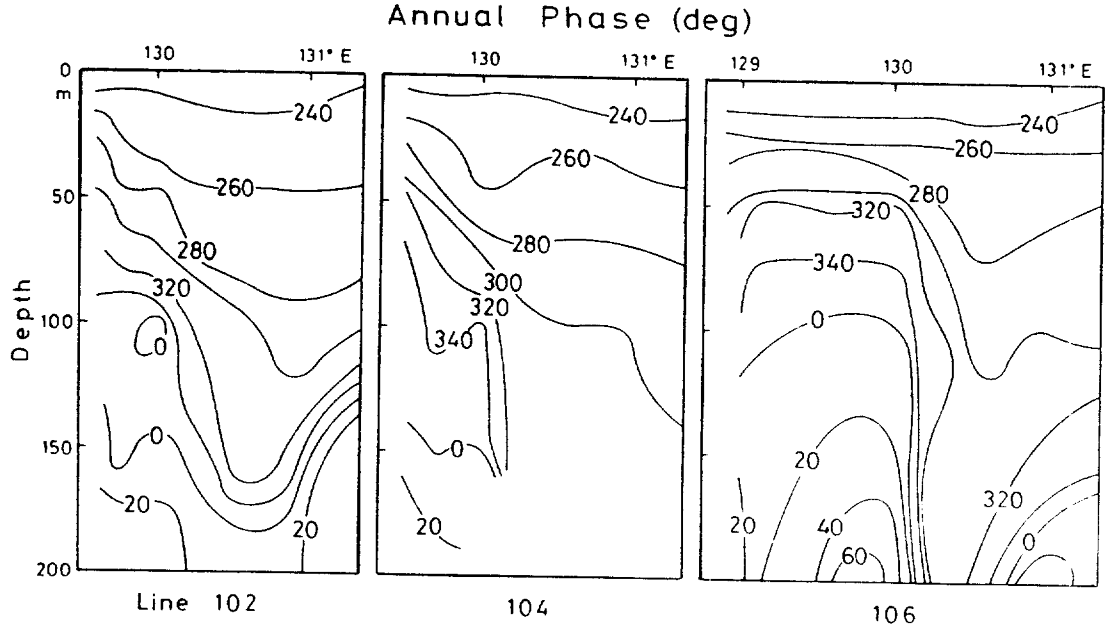

Fig. 8. Vertical distributions of the annual phases (degrees) along the Lines 102, 104 and 106.

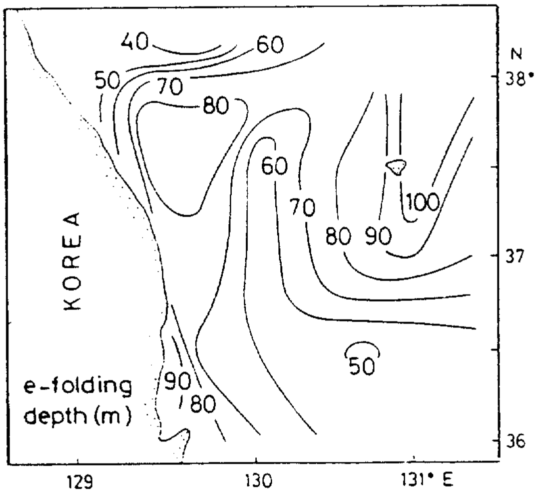

Fig. 9. Distribution of e-folding depths (m) associated with the annual variation of water temperature.

amplitudes in the upper 100 m to an exponential function (2). The e-folding depths are between 40 and 100m. Relatively small e-folding depths of 50-60m are found near 130°E.

Fig. 10 shows horizontal distribution of depths at which the annual phase lags one month from that at the sea surface. The depths with phase difference of one month are 20 to 50 m, and they show regional differences. The depths of one month phase difference is less than 30 m in coastal region (west of 130.4°E) and greater than 30 m in offshore region.

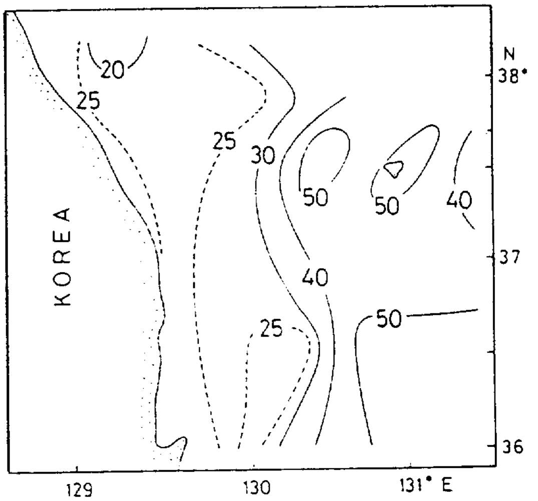

Fig. 10. Distribution of the depths (m) at which the annual phase of water temperature lags one month from that at the sea surface.

VERTICAL EDDY CONDUCTIVITY

From the vertical distributions of the annual amplitude and phase we can determine the vertical eddy conductivity as follows. In an absence of heat advection by ocean current, the vertical diffusion of heat associated with annual variation of SST is described by

$$\partial T/\partial t = K\ \partial^2 T/\partial z^2 \tag{4}$$

with boundary conditions

$$\begin{aligned} T &= A\cos(\omega t) && \text{at } z=0 \\ T &= 0 && \text{at } z=\infty, \end{aligned} \tag{5}$$

where T is the temperature, K is a vertical eddy conductivity which is assumed constant at all depths, A is the amplitude of SST, and ω is annual angular frequency. The solution of (4) and (5) is

$$T(z, t) = A\exp(-\alpha z)\cos(\omega t - \alpha z) \tag{6}$$

where

$$\alpha = (\omega/2K)^{1/2}. \tag{7}$$

Eq. (6) shows that the annual amplitude decreases exponentially with depth, and the annual phase increases linearly with depth. The e-folding depth is $1/\alpha$, and the vertical slope of the phase is α.

Vertical distributions of horizontally averaged annual amplitude and phase (Fig. 5) show that the amplitude decreases nearly exponentially with depth and the phase increases almost linearly with depth. The magnitude of α determined from an e-folding depth of 65 m is 1/65 m^{-1} or 1.53×10^{-4} cm^{-1}. On the other hand, the magnitude of α, determind from an increase of phase by 180° or π radians associated with an increase of depth by 200 m, is $\pi/200$ m^{-1} or 1.57×10^{-4} cm^{-1}. The magnitude of vertical eddy conductivity K, computed by (7) with α of 1.57×10^{-4} cm^{-1}, is 4.0 cm^2/sec. This value lies within a typical range of vertical eddy conductivity between 1 and 100 cm^2/sec determined by the same method in different parts of the ocean (Neumann and Pierson, 1966, p. 439).

Vertical distributions of annual amplitudes and phases differ from place to place (Figs. 9 and 10). If the annual variation of temperatures in the subsurface layer were described precisely by (6), then the horizontal distributions of e-folding depths and the depths with a phase change of one month should be similar, because both of them are inversely proportional to α. A comparison of Figs. 9 and 10 shows that the distribution of e-folding depths is approximately equal to that of depths with a phase change of two months.

DISCUSSION AND CONCLUSIONS

In this paper, we analyzed the annual variation of temperatures in the upper 200 m off southwest coast of Korea by means of harmonic analysis, and represented the horizontal and vertical distributions of the mean, the annual amplitudes and the annual phases.

As one expects, the mean temperatures and the annual amplitudes decrease with depth and the annual phases increase with depth. The vertical eddy conductivity estimated from the vertical distribution of horizontally averaged annual amplitudes and phases is 4 cm^2/sec. The annual variation of water temperature shows not only vertical changes but also horizontal inhomogeneities.

The isotherms of mean temperature in the coastal region are nearly parallel to the coastline, whereas those in offshore are almost zonal (Fig. 2). The distribution of mean temperatures suggests that there should be quite strong coastal jets in the coastal region within a few tens miles from the coast. However, from the distribution of mean temperature alone, we cannot determine whether the coastal currents flow northward or southward.

A clear contrast between coastal and offshore regions is revealed in the distribution of the annual phase (Fig. 4). In a subsurface layer (50 and 100 m), the annual phase in coastal region lags behind that in the offshore region. A similar contrast is also found in the change of annual phase with depth (Fig. 10).

In this paper, we showed that the vertical distributions of the annual variation of water temperature in the subsurface layer of the coastal region is quite different from that in the offshore region.

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