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内部波に及ぼす潮流の効果（Ⅲ）
内部安定性波の起因

緑川　弘毅[*1]

駿河湾の奥部で内部波の観測を行った。1分から1時間程の短周期領域において，スペクトルに現われた周期は，水の鉛直密度分布から計算されたバイサラ振動の周期よりも短かいものがしばしばあった。

流れの中の密度躍層に沿って発生する内部波の成因の一つを実証できた。バイサラ周期よりも短かく，振幅も大きな内部波が11月と12月に現われたが，夏期には顕著でなかった。沿岸域においては，夏期には安定度が強すぎて振幅が大きくなりにくいのだろうか。

これらの内部波の起因となる物理的環境を考察した。潮流が増強しつつあり，リチャードソン数が小さくなるときに大きな振幅を持つ短周期の内部波が，流れの中に出現する。

キーワード：内部波，内部安定性波，安定度，成層，バイサラ振動，潮流，
リチャードソン数

The Effect of Tidal Current on Internal Waves (Ⅲ)
The origin of internal stability waves

Koki MIDORIKAWA[*2]

Internal waves were observed in several subsurface layers at the innermost part of Suruga Bay. In the shorter period range from one minute to one hour, peaks of energy density were found occasionally in the range shorter than the minimum of Väisälä periods computed from the vertical distribution of water density.

One of the origines of internal stabililty waves generating along a pycnocline in a current field has been found and confirmed actually by observation. Short-period oscillations with periods less than the Väisälä period and large amplitudes appeared particularly, in November and December. In summer, the oscillations weren't seen remarkably. It may be too stable to occur noticeable internal stability waves in summer though in a strong current field of the coastal area.

In this paper, the physical surroundings for the cause of them are considered. When the velocity of tidal current is increasing, Richardson's number becomes small and the large amplitude of short-period oscillations appears in a current field.

Key Words: Internal waves, Internal stability waves, Stability, Stratification, Väisälä oscillation, Tidal current, Richardson's number.

＊1　海洋観測研究部

＊2　Ocean Research Department

1 Introduction

Internal waves occur at surfaces between different density layers within the sea, because the density difference leads to a gravitational pressure restoring force if fluid is displaced vertically. In a two-layer density area, maximum amplitude of internal waves exists at the boundary of the two layers, and decreases linearly with distance above and below.

Ekman (1904[1]) explained the phenomena of "dead water" in terms of internal waves generated by a vessel moving slowly in a shallow surface layer of low-density. He applied the wave equation to explain the dead water effect. Keulegan (1953[2]) and Long (1956[3]) gave the equation for the velocity of free internal waves, neglecting the effect of the earth's rotation.

Internal waves owe their existence to the stratified density structure of the two fluids, with a very sharp density change occurring along the interface and with the characteristic that, the smaller the density contrast, the shorter the period, and the slower the propagation speed. In deep water, longer waves travel faster than shorter ones. And the phase speeds of internal waves are much smaller than those of surface gravity waves.

Surface water temperature and salinity gradients are comparatively sharp and any exitation that disturbs the pycnocline will tend to propagate away from the region of generation as internal waves.

The author made observations of internal waves at the innermost part of Suruga Bay by means of measuring temperature fluctuations at several subsurface layers. The methods and instruments have been reported in a previous paper (Midorikawa, K. (1973a[4] and 1973b[5])), Midorikawa, K. and T. Miyazaki (1977a[6]), Midorikawa, K. (1977b[7] and 1977c[8])).

From the records of water temperature, spectral energy densities of temperature oscillation were computed for the range from the inertial period (Midorikawa (1973a[4])). In the range of short-period oscillation there are peaks corresponding to the inertia and tidal periods, while in the range of shorter periods a number of peaks are found.

With regard to the temperature oscillations of shorter periods, Kalle (1942[9]) reported the temperature oscillations of periods from 15 seconds to several minutes at various depths down to 21 meters. He inferred that these were caused by the oscillations of stable strata because of their wave-like features.

Krauss (1961[10]) calculated the spectra of current and temperature flucutuations measured at five stations, and concluded that the peaks in the spectra at the periods of 1.5 to 30 minutes may be due to the oscillations of stable strata, since the frequenies were lower than the Väisälä period.

Eckart (1961[11]) postulated that free internal waves theoretically exist only between the inertia and Väisälä periods, and such gravitational waves are called stability waves. Namely, There should be no waves with periods shorter than the minimum Vaisala period.

The author, however, occasionally observed temperature flucutuations with periods shorter than the Väisälä period, particularly during autumn and winter. The purpose of this paper is to discuss an internal wave, the period of which lies in the range of the Väisälä period and below.

2 Stability of water stratification and short-period internal waves

When an external impulse acts on a stably straitfied water column, a portion of water moves from its initial equilibrium position and starts to oscillate. The oscillation is controlled by the stability of water stratification.

The vertical stability can be expressed by

$$N^2 = -g\Gamma \qquad (1)$$

as introduced by Väisälä and Brunt, since N has a dimension of frequency, where Γ =stability of stratification (Krauss, W. (1966[14]). And N is given by $N = \sqrt{g\Gamma}$, the values associated with ocean thermoclines ranging from 10^{-1} to 10^{-3} radians $\sec^{-1}$. Hence, internal waves-periods ($T = 2\pi / \sqrt{g\Gamma}$) less than several tens of minutes are normally occupied.

The vertical movement of water due to an internal wave in stratified fluid is maximum at the boundary of two different fluids (Lamb, (1932), Defant, (1961[12])), and this theory can be applied to a stratified ocean, introducing the idea of cellular structure of internal waves, which indicates that the amplitude of an internal wave is maximum at the depth of maximum vertical density gradient, where the Väisälä period is minimum.

LaFond (1961[13]) studied horizontal movements of water parcels due to internal waves, and showed that the directions of movement are oppsite in the upper and lower layers of the boundary. Combining these results, it can be concluded that a shear due to horizontal movement of water caused by an internal wave is maximum at the stratum of the minimum Väisälä period.

In Fig. 1 , the periods of internal stability waves corresponding to the peaks of spectral energy density of temperature oscillations are compared with the Väisälä periods estimated from the vertical density distributions.

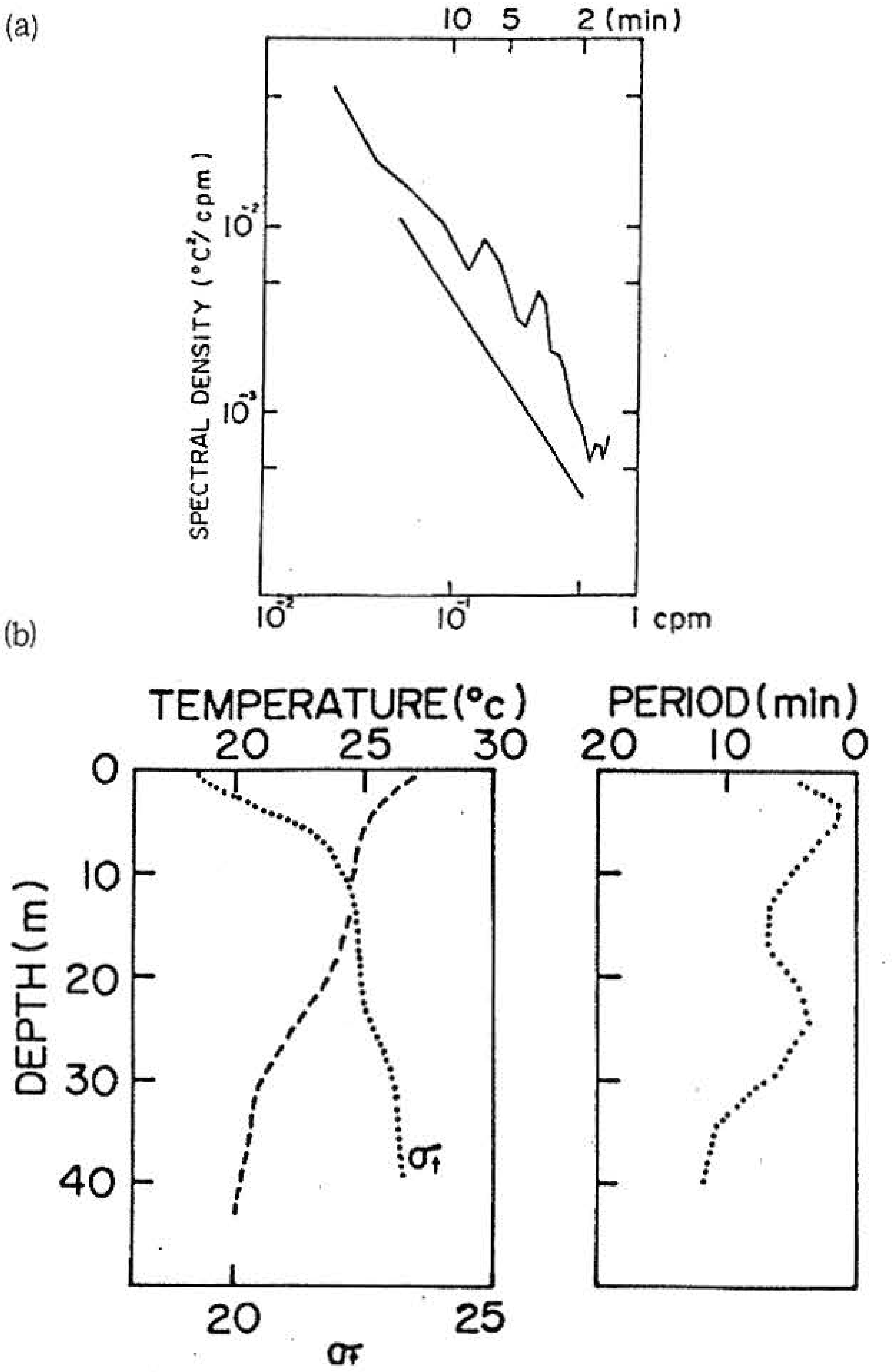

Fig. 1 (a) : Spectral energy density of temperature data measured from September 3 to 4 .
(b) : The vertical distributions of average temperature and Väisälä period.

As an example of spectral density of temperature oscillations of a stable water column, the result of estimation is shown in Fig. 1 (a), together with the vertical distributions of temperature, density, and Väisälä period (Fig. 1 (b)). The vertical distributions in the figure are the average computed from the daily temperature and salinity measurements. The vertical distribution of the Väisälä period is estimated from the average density distribution.

The peaks of the spectrum lie at approximately 4 minutes, while the Väisälä periods have two minima at about 2 and 5 minutes at the depth of approximately 5 and 25 meters, respectively. The peaks of energy density in Fig. 1 (a) are considered to be caused by the internal stability waves, whose periods are defined by the stability of stratification.

It is quite feasible to consider that in a three-layered ocean, internal waves are generated at both boundaries separately, and thus a bimodal temperature oscillation appears. Therefore, the periods at the peaks of energy density, 4 and 7 minutes, correspond to the two minima of Väisälä periods, 2 and 5 minutes respectively, and the former is a little longer than the latter.

Similar relations were usually found in short-period internal waves observed on other occasions during the course of the present studies, and this is in good agreement with the conclusion of Eckart.

3 The effect of tidal current on short-period internal waves

In the preceding section, the periods of internal stablity waves were compared with the Väisälä periods. The periods of internal stablity waves are generally longer than the minimum of the Väisälä periods, but on some occasions, internal waves with a period shorter than the minimum of Väisälä periods were also observed.

Temperature oscillations of short period appeared occasionally in the middle layers or in the lower layers, especially in November and December, and the range of temperature oscillation sometimes reached about 1 ℃.

Fig. 2 illustrates the results of measurements, i. e.

the current velocity at 1.5 meters below the surface (top panel), the vertical temperature distribution (middle) and the amplitude of temperature oscillations of short period (bottom). The amplitude means the range of temperature variations appearing at each layer. The amplitude becomes large when the tidal current changes direction from northward to southward, around 16:00, while the amplitude decreases when the southward current velocity attains the maximum, after 18:00.

Fig. 3 illustrates Richardson's number computed from the mean density distribution and the velocities at depths of 1.5 and 10 meters below the surface, together with the northward components of velocities. Comparing Fig. 2 and 3, it is noticeable that the large amplitude of short-period temperature oscillations appears when the velocity of tidal current is increasing, especially after the current turned (e.g. around 16 o'clock), and the vertical shear of the current is large with small Richardson's number.

It should also be noticed that the phase of the current fluctuation in the upper layer is in advance of that in the lower layer, consequently the vertical shear vanishes shortly after the velocity of the upper layer reaches the maximum, and Richardson's number becomes large.

It is thought that if Richardson's number (Ri) becomes sufficiently large, the stabilizing effect of the density distribution overcomes the potential instability and turbulence is not possible. Miles (1961[15]) showed that a stratified shear flow is stable if Ri>1/4 everywhere in the flow.

The Richardson's number, Ri, is the square of the ratio of Väisälä frequency, N, to the vertical shear. Ri<1/4 is a necessary condition but not a sufficient condition for shear flow instability to occur in the flow. This means that in the ocean, a weakly stratified fluid colum that has a strong baroclinic velocity structure may become unstable and oscillate with increasing amplitude.

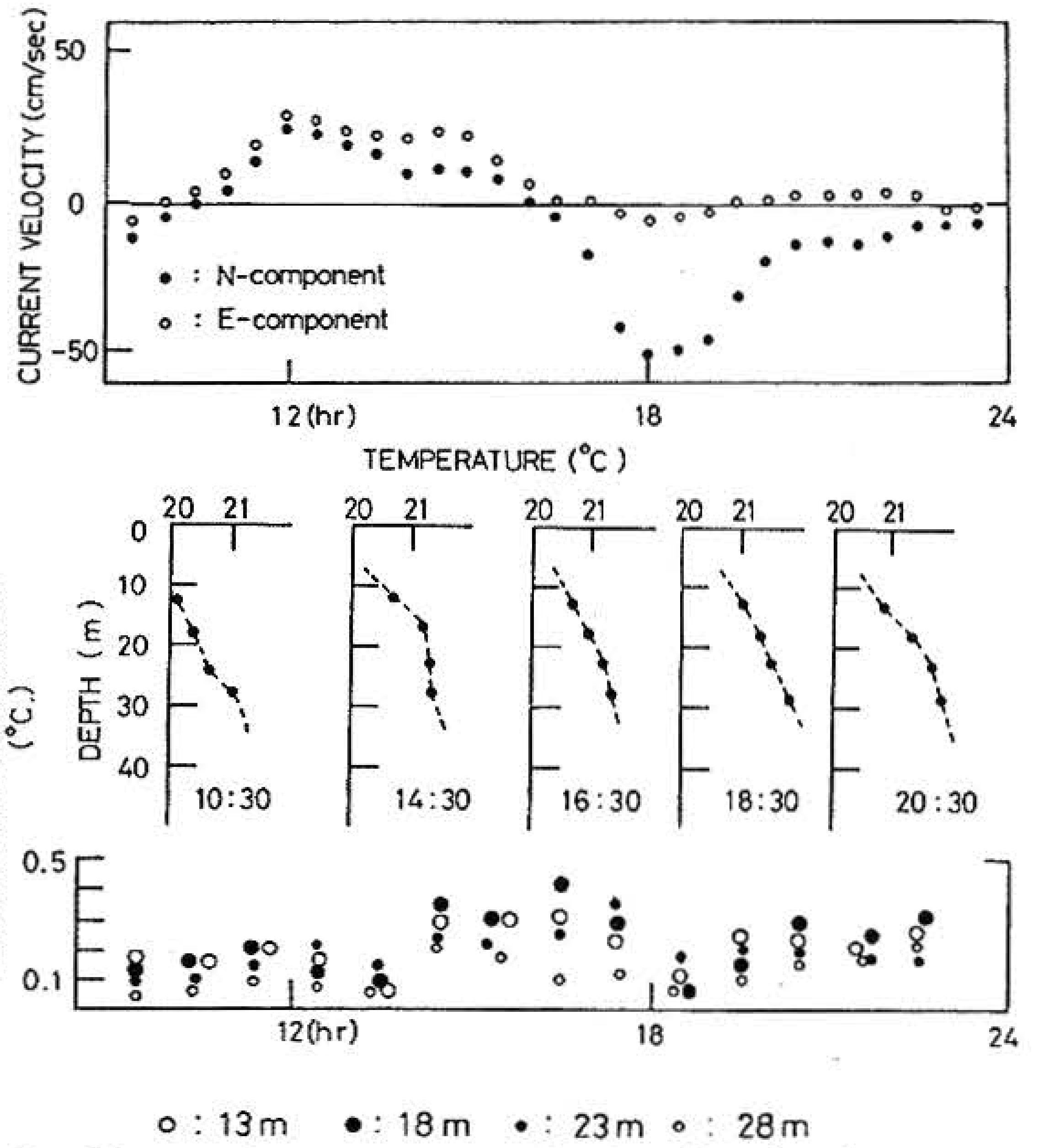

Fig. 2 The surface current velocity (top), the vertical temperature distri-butions(middle) and the amplitude of the temperature fluctuations (bottom) measured on November.

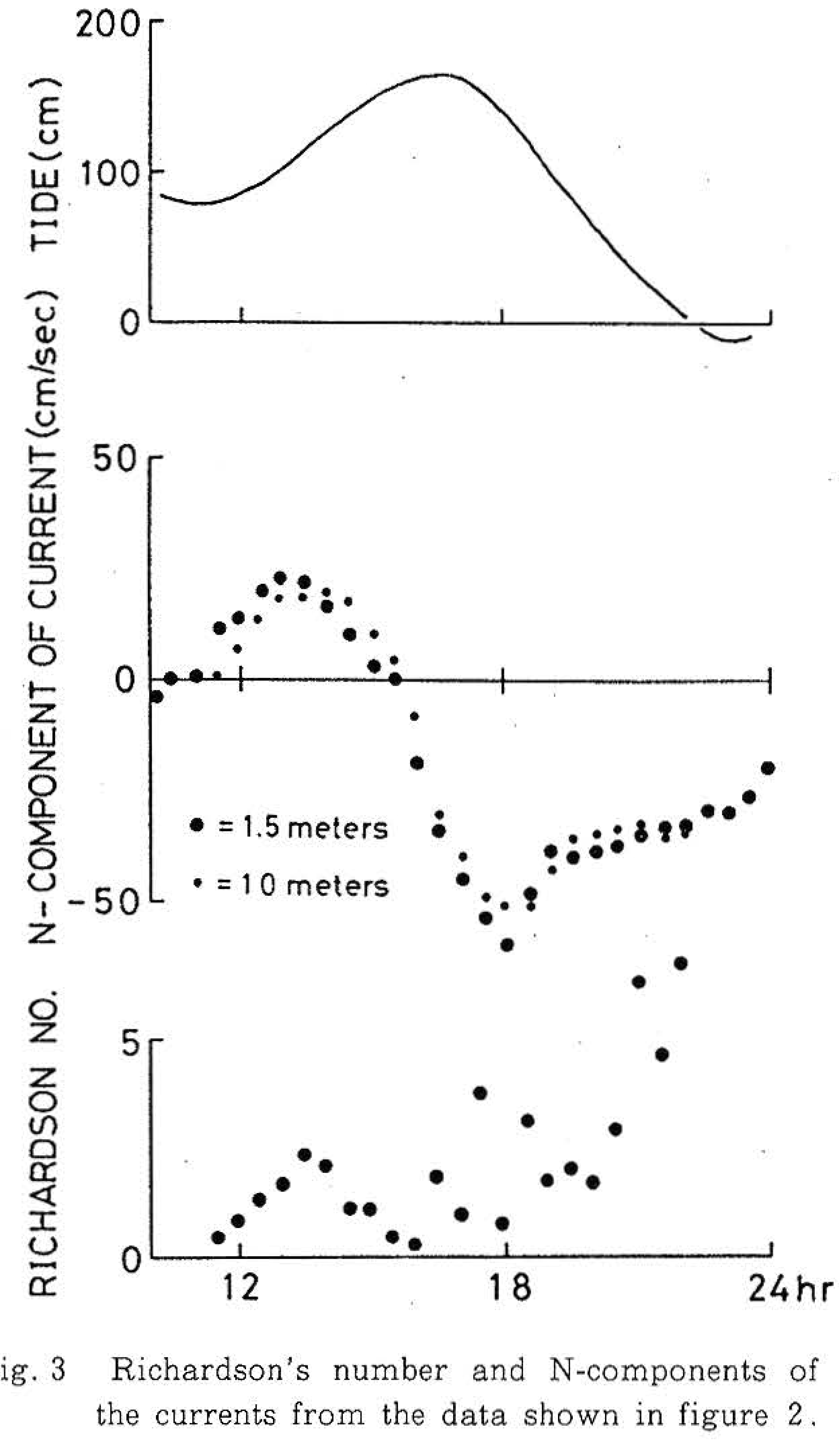

Fig. 3 Richardson's number and N-components of the currents from the data shown in figure 2.

4 Origin of internal stability waves

4.1 Resonant interaction between surface waves and internal waves

Internal waves are gravity waves that propagate beneath the sea surface along pycnoclines or thermoclines. They may be generated in the ocean by any of a variety of mechanisms, i.e., interactions of currents with bottom topography, tidal motions, atomospheric pressure fields, or interactions between surface waves of different frequencies (Wunsh, C. (1975[16])). Namely, the tidal flow of straitified water against bathymetric feature such as undulant shore, or the interactions between the surfs of the coast and internal waves are thought to be a cause of the excitations of internal waves.

When two surface waves with wave-numbers k_1, k_2 and frequencies ν_1, ν_2, interact at the second order, bounded disturbances result from the interaction with the horizontal wave-numbers $k_1 \pm k_2$ and frequencies $\nu_1 \pm \nu_2$. If the wave-numbers are almost equal, the frequency difference $\nu_1 - \nu_2$ can be small while the wave-number difference is comparable in magnitude with k_1 or k_2.

An internal wave with this wave-number, $k_1 - k_2$ has a frequency $n = \nu_1 - \nu_2$. The internal waves thus seem to get energy gradually from the surface waves by means of the resonant interaction among them (Phillips (1969[17])).

A water column of stable stratification can be considerd as a complex oscillatory system and it has eigenvalues, i. e., Väisälä Periods, to which the energy is absorbed continually by a resonance from an external force. In other words, the water column acts like a kind of flywheel in this period range, and a certain part of the energy is stored transiently in the "flywheel" and then transferred to a shorter-period range. Therefore, the peak of spectral energy density corresponds to a characteristic internal oscillation, whose period is determined by the stability of the water column.

4.2 Short-period oscillations near the coast

Coastal observations sometimes recognize oscillations which have a period of a few minutes, and this is considered as surf-beat (Nakano (1941[18]), Munk (1941[19])). One of the possible origins of short-period oscillations is an atmospheric disturbance approaching the station of observation.

During the course of temperature measurements in Suruga Bay, short-period osillations were observed occasionally, but in most cases, because of the general atmospheric and / or oceanographic conditions near the measurement site. Neither a surf-beat nor an atmospheric disturbance was considered to be the cause of these short-period oscillations of water temperature in the intermediate layer (Midorikawa (1977b[7], 1995[20])), (Midorikawa and Sakakida (1996 a[21])) and (Midorikawa (1996b[22])).

As mentioned in the previous section. short-period oscillations occur simultaneously with free stability internal waves associated with the vertical velocity shear of current field. It is generally accepted that a vertical velocity shear at the pycnocline creates internal stability waves.

When the tidal current becomes stronger in shallower areas, the phase of tidal current in the upper layer advances ahead of that in the lower layer due to the friction at the bottom. Consequently, in a wide area near the coast, a strong vertical velocity shear appearing at the boundary of upper and lower layers and undulations of currents by bottom topography, thus generate internal stability waves.

We can see that the tidal current flows parallel to the depth contour or in other words, parallel to the coast by means of the result of harmonic analysis of tidal current in the area. For internal stability waves generated in the offing, and propagated towards the coast, the direction of wave propagation is perpendicular to the current direction, therefore the waves conserve frequency, and the period observed at the station is the same as that of the original waves.

For internal stability waves generated near the coast and propagated along a depth contour, the frequency observed at the fixed station is modified by the current velocity, in the Doppler effect, because the source of the waves moves with the tidal current, while the frequency is measured at a fixed point.

5 Conclusion

Internal stability waves generated along a pycnocline in a current field has been actually confirmd by observations. When a pycnocline exists, the current velocities of the upper and lower layers are generally not the same, and the phase of tidal current in the upper layer advances ahead of that in the lower layer due to the friction at the bottom.

In an area near the coast, a strong vertical velocity shear appearing at the boundary, and undulating currents due to the bottom topogrphy generate internal stability waves.

Short-period oscillations with periods less than the Väisälä period and large amplitudes appeared, particularly, in November and December. In summer, the oscillations weren't seen remarkably. It may be too stable for noticeable internal stabillity waves to occur in summer though in a strong current field.

Weakly stratified water with small Richardson's number that has a strong baroclinic velocity structure may become unstable and oscillate with increasing amplitude. When the velocity of tidal current is increasing, the Richardson's number becomes small and short-period ocillations with large amplitude appears.

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