

内部波に及ぼす流れの効果について (Ⅱ) 短周期内部波の起因

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成層した水域に外力が働くと、水の一部が初めの平衡の位置から動いて振動を始める。その振動は水の成層の安定度により制御される。しかしながら、その安定度の基準であるバイサラ周期よりも短い内部波が、特に秋、冬期にしばしば得られた。

本紙の趣旨は、これらの周期の短い内部波の発生起因について考案することにある。この内部安定性波は流域の密度躍層に発生し、ドップラー効果により見かけの周期が短くなったものとの結果を得た。

ある種の短周期内部波が実際に沿岸の流れの中で発生した事実の例を示し、それを証明することができた。

キーワード：内部波，内部安定性波，安定度，安定層，成層，バイサラ振動

Effects of Tidal Current on Internal waves (Ⅱ) Origin of short-period internal waves

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When external force act on a stable stratified water column, a portion of water moves away from the initial equilibrium position and starts to oscillate under the control of water stability. It has been generally understood that the periods of internal waves in a stable stratum should be within the range between the inertial and Väisälä periods.

However, temperature oscillation with periods shorter than the Väisälä period, particularly during autumn and winter has been observed. The origin of internal wave and periods the same or less than the Väisälä period were examined in this study.

Internal stability waves were concluded to be produced along a pycnocline in a current field, and apparent period of internal stability waves to become shorter than Väisälä periods of pycnocline due to the Doppler effect. The origins of internal waves was observationally determined in one case.

Key Words : internal waves, internal stability waves, stability, stable stratum, stratification, Väisälä oscillation

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1 Introduction

Internal waves occur at surfaces between different density layers within the sea, since the difference gives rise to gravitational pressure, with consequent force restoration, assuming vertical fluid displacement. In a two-layer density area, amplitude of internal waves is maximum at the boundary of the two layers, and decreases linearly with distance above and below.

In shallow water, horizontal velocity of flow generated by internal wave motions was estimated theoretically and confirmed to some extent visually. (Midorikawa (1975¹⁾, 1977a²⁾, 1996³⁾,)). Internal waves were observed previously at the innermost part of Suruga Bay (Midorikawa (1973a⁴⁾, 1973b⁵⁾, 1976⁶⁾)). Based on water temperature, spectral density of temperature oscillation was computed from inertial period to Väisälä period (Midorikawa (1977b⁷⁾, 1977c⁸⁾)).

Krauss (1961⁹⁾) calculated the spectra of current and temperature fluctuation at five stations and concluded peaks in the spectra at the periods 1.5 to 30 minutes to possibly be due to oscillation of stable strata, this time being longer than the Väisälä period.

The author, however, occasionally observed temperature fluctuation has sometimes been observed for periods shorter than the Väisälä period, particularly during autumn and winter. Including simultaneously temperature fluctuation for periods 2 minutes less than the Väisälä period, with free internal stability waves and corresponding to spectral peaks of about 6 minutes and less than the minimal Väisälä period during autumn and winter (Midorikawa (1977c⁸⁾, 1977b⁷⁾)). Internal waves, with periods essentially the same and less than the Väisälä period were examined in the present study.

2 Internal waves in a stratified ocean area

Internal boundary surfaces are present in thermocline in oceanic water, where density differences are due mainly to those in temperature, or at the holocline in coastal water, where density

differences arise mainly from those in salinity.

The vertical movement of water due to internal waves in stratified fluid is maximum at the boundary of two different fluids thus (Defant (1961¹⁰⁾)). The amplitude of an internal wave is maximum at the depth of maximum vertical density gradient, where Väisälä period is minimum.

A water column of stable stratification may be considered a complex oscillatory system during the Väisälä periods, of which energy is absorbed continually by resonance from an external force. The water column acts as a flywheel in this period range, and some of the energy is stored transiently in the "flywheel" and then transferred to a shorter-period. The peak of spectral energy density thus corresponds to characteristic internal oscillation, whose period depends on the stability of the water column. We called these internal stability waves occurred in the stable stratified ocean area NAIBU ANTEISEI-HA in Japanese (Midorikawa 1977c⁸⁾)).

Short-period oscillations occur with free stability internal waves in association with vertical velocity shear of current field. Vertical shear at the pycnocline creates internal stability waves. When tidal waves approach the coast, tidal current becomes stronger in shallow areas and the upper layer portion advances ahead due to the friction at the bottom. Thus, in a wide area near the coast, strong vertical velocity shear appears at the boundary of upper and lower current layers and internally stable waves are consequently generated (Midorikawa (1977b⁷⁾, 1995a¹¹⁾, 1995b¹²⁾, 1995c¹³⁾)).

3 Stability of water stratification and short period internal waves

When the external force acts on a stably stratified water column, a portion of water moves from the initial equilibrium position and starts to oscillate under the control of stratification.

When the water is displaced from the equilibrium position and moves freely, oscillation at the Väisälä frequency occurs as response to the balance between buoyant and inertial force.

The frequency of internal waves is thus limited to

approximately maximum Väisälä frequency.

The lower limit of free internal wave frequency is a function of the latitude, and the upper limit, the Väisälä frequency N , is a function of depth (z). Vertical stability may thus be expressed as,

$$N^2 = -\frac{g}{\rho} \frac{d\rho}{dz} - \frac{g^2}{c^2} \quad (1)$$

as established by Väisälä and Brunt, since N has a dimension of frequency, and is called Väisälä frequency. Component ρ is, density of the medium, c wave speed in the medium, and g , gravitational acceleration.

Brunt-Väisälä frequency N is a measure of the stability of oceanic stratification and given by,

$$N^2 = g \left[-\frac{1}{\rho} \frac{d\rho}{dz} - \frac{g}{c^2} \right] = gE \quad (2)$$

Vertical stability can be expressed by E and is the ratio of the restored acceleration of displaced water to acceleration due to gravity. Frequency in cycles per second is $N/2\pi$, and is the maximum frequency of internal waves in water with stability E .

If $E > 0$, i.e. positive, water is stable and when displaced a short distance vertically, return to its original site, which may be overshoot owing to inertia and oscillate about it. The stability of water may be related to the occurrence of internal waves.

4 Effects of tidal current on internal waves

In the preceding section, the periods of internal stability waves generally exceed minimum Väisälä periods, but in some cases, may be less.

Figure 1, shows temperature oscillations at 20 meters below the surface of coastal water, recorded on December 8. In Figure 1-(a), can be seen regular wave-like shapes possibly due to free internal waves on the left, and the amplitude of the waves decreasing.

About 4 hour after the free waves appeared, remarkably short-period oscillations with periods of 2 minutes occurred as shown in Figure 2 -(b). Spectral density showed peaks for 6 minute periods

and significant peaks for periods shorter than 2 minutes. These spectral peaks were compared with the vertically distributed Väisälä periods.

These peaks the minimum Väisälä period appeared at corresponded to the 6-minute period authors meaning value 6 minutes. The peaks for spectral density may have been due to internal stability waves with periods determined by the stability of stratification.

The spectral peaks with 6 minute periods be due to the free stability waves shown in Figure 1-(a), but no minimum Väisälä period corresponding to the spectral peaks of 2 minutes could be detected.

Spectral peaks with 2 minute periods due to were short-period oscillations as shown in Figure 1-(b). : Even for costal areas, there can be Väisälä periods of 2 minutes in the winter.

How were the oscillations caused ?

What did them generate ?

5 Origin of short-period oscillations

1) Short-period oscillations occur when current velocity increases with considerable vertical shear and small Richardson number.

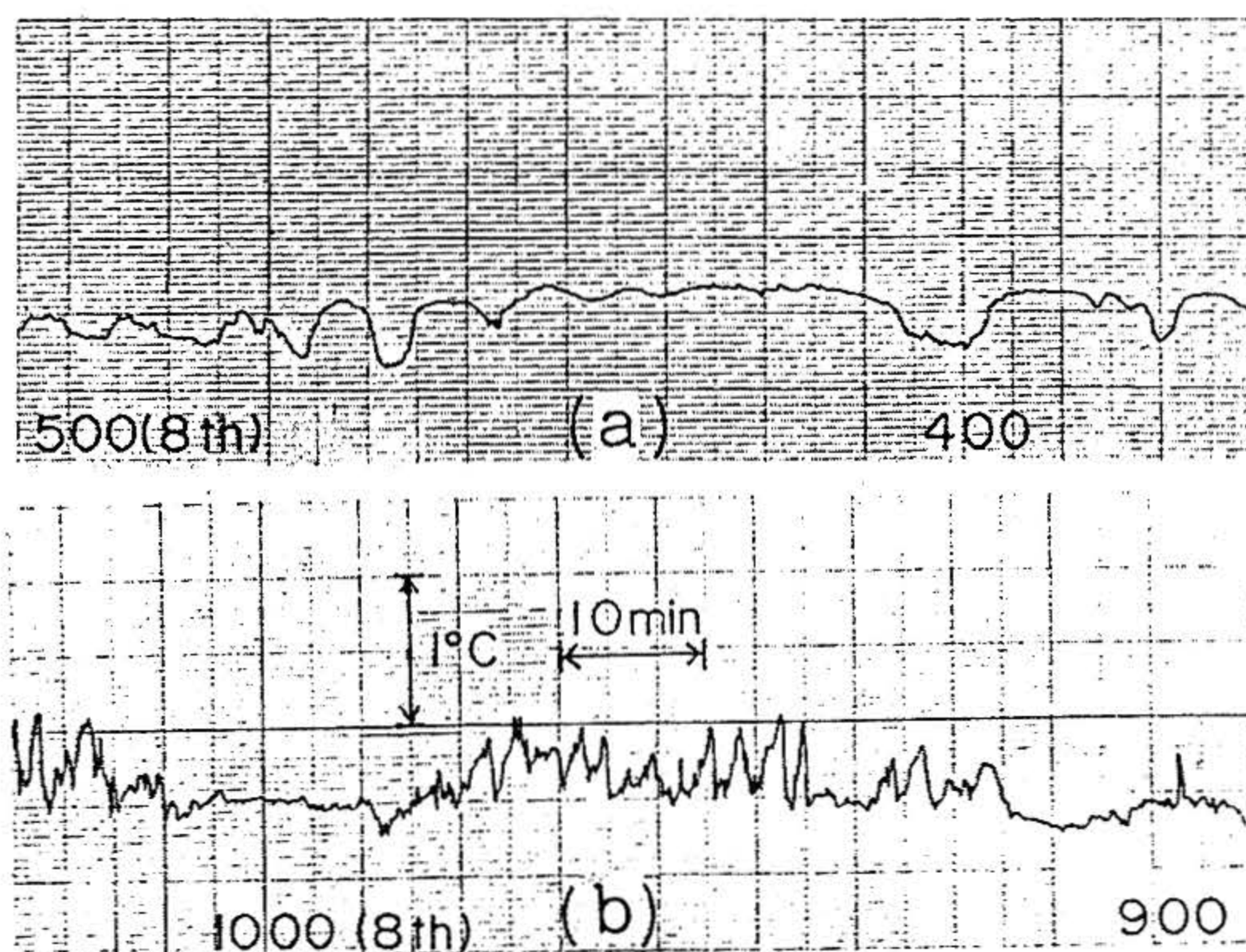
2) Sinusoidal curves of free stability internal waves shown in Figure 1-(a) appear in shallow water when tidal current velocity is virtually almost cease in stratified coastal areas.

3) Spectral density curves have six-minute or less than 2-minute peaks, these periods being. The periods almost the same or longer and shorter than the minimum Väisälä period, respectively.

4) In the spectrum of energy density, high-frequency oscillations and stable internal waves appear at the same time.

The remarkably short-period oscillations may have been produced in a flowing medium. Strong tidal current is restricted to the vicinity of the shore because the observation station were situated near small headland in Suruga Bay.

Internal waves were generated in the offing and propagated towards the coast in a direction perpendicular to that of the current. There is thus no Doppler effect on the waves and frequency is



Figures 1-(a) and (b) show temperature oscillation at 20 meters below the surface on December 8, in slack water (a), and at the site of the flood current (b) respectively. (a): Instead of short-period oscillation, regular wave-like shapes possibly due to free internal waves on the left side of the figure, with decreasing amplitude, were seen. (b): Saw-teeth in shape, not sinusoidal as in the case of free waves.

maintained. Wave periods observed at the stations are thus the same as those of the original waves.

Figure 1-(a), shows no short-period oscillations but regular wave-like shapes possibly indicative of free internal waves in shallow water. Minimum Väisälä period is only 6 minutes. Two and 6 minute period waves are present in the medium.

The frequency of internal stability waves near the coast, which propagated along the depth contour, was affected by current velocity, since the waves move with tidal current.

Internal waves are generated in a flowing medium, and thus apparent period, 'T', was determined based on vertical density and current distributions as

$$T' = 105 \sim 110 \text{ seconds}^{7)}. \quad (3)$$

The values obtained were fairly consistent with temperature data as shown in Figure 1-(b), and with spectral peaks corresponding to 1.5 to 2 minute periods.

Causes of short-period oscillation ?

Internal stability waves may thus be concluded to be generated along a pycnocline in a current field, and apparent periods of internal stability waves to become shorter than the Väisälä period of

the pycnocline owing to the Doppler effect.

What did the internal waves generate ?

For internal waves near the coast, oscillation with period shorter than the minimum of Väisälä period may be observed at the site where is measured. This oscillation is due to the apparent period of internal stability waves generated by vertical velocity shear upstream the tidal current.

6 Discussion

Measurement of tidal current in surface and lower layers, indicated short-period oscillation to be associated with increase in current velocity and vertical shear of current along the pycnocline.

Periods shorter than the minimum Väisälä period may not be actual but only apparent periods due to the Doppler effect, since wave generation depends on velocity shear of tidal current. Short-period oscillation are saw-teeth in shape as apparent from Figure 1-(b) in contrast to free waves which are sinusoidal in shape.

Short-period internal waves may derive from strong tidal current restricted to the shore, that is, internal stability waves may be generated along the pycnocline in a current field.

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(原稿受理 : 1996年 7 月24日)