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Near Inertial Motion Excited by Wind Change in a Margin of the Typhoon 9019

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An excitation of inertial oscillation in the upper layer east of course of Typhoon 9019 was fortuitously observed at three surface buoys deployed during the Ocean Mixed Layer Experiment (OMLET). The observed inertial oscillation was compared with wind fluctuation measured at Ocean Weather Station T (29°N, 135°E) which was placed at the center of a triangle with three vertexes occupied by the respective surface buoys. Inertial oscillation is effectively excited in the mixed layer at the eastern margin of the typhoon by a rapid decrease of wind rather than by prevailing strong wind. It is shown by means of a least square deviation that the inertial oscillation observed in the mixed layer has a period of 23.9 hours shorter than the local inertial period of 24.7 hours. This shorter period suggests that the inertial oscillation has the finite velocities of phase and group as an inertial internal wave. A theoretically obtained ratio of vertical component of group velocity to that of phase velocity, approximately agrees with observed value. The inertial internal wave is excited by fluctuation of divergence with near inertial period in the mixed layer.

1. Introduction

Near inertial motion was fortuitously observed in the upper layer by current measurements from three surface buoys deployed around St. T (29°N, 135°E) on the schedule of Ocean Mixed Layer Experiment (OMLET). In this paper, it will be shown that the near inertial motion is generated by an abrupt decline in wind velocity accompanied by the passage of Typhoon 9019 and energy of the motion is propagated downwards as an inertial internal gravity wave. The observation method used in this project and the Typhoon 9019 feature which is believed to generate the near inertial motion will be described in Section 2.

Near inertial motions have been observed at all depths in the oceans (e.g., Day and Webster, 1965; Kundu, 1976; Weller, 1982; Lai and Sandford, 1986; Taira *et al.*, 1993). The near inertial motions are generally believed to be generated in the sea surface layer. The generations probably depend on phase of wind change and duration time of strong wind (Veronis, 1956; Pollard, 1980). In Section 3, change of velocity measured in the surface mixed layer at the three stations will be compared with change of wind measured at St. T.

Period of near inertial motion generated in the sea surface layer depends on horizontal scale of the generation, duration of wind and vertical density distribution (Pollard, 1970; Price, 1983). So, the period may differ in every generation. This shows that the necessary period is to be decided in every generation. In Section 3, the maximum likelihood period will be decided using the least square estimation.

Frequency of near inertial motion observed is generally slightly (3% to 20%) above local inertial frequency (Kundu, 1976). In this case, the near inertial motion can be propagated as an inertial internal gravity wave (LeBlond and Mysak, 1978). Vertical components of phase velocity and group velocity of the wave is vice versa. Using this nature of the internal gravity wave, Kundu (1976) and David (1983) estimated the vertical component of group velocity off the coast of Oregon in 100 m of water depth from observed phase velocity. Lai and Sandford (1986) showed that energy of an inertial internal gravity wave generated by a hurricane was propagated downwards on the continental rise south of New England. In Section 4, the vertical components of phase and group velocities will be independently obtained from the current measurement on the deep water. The ratio between the observed phase and group velocities will be compared with an approximated ratio obtained from the dispersion relation of the inertial internal gravity wave.

An inertial internal gravity wave transfers the wave energy by horizontal pressure gradient which periodically changes with time. The pressure gradient is probably made by periodically changing divergence in the surface mixed layer, when the wave is generated by a transient wind. The periodic change of the divergence will be shown by the result from the current measurements in the mixed layer.

2. Descriptions of Observation and the Typhoon 9019

OMLET area was placed on a deeper water region (about 4900 m depth) approximately 480 km southeast of Kyushu (Fig. 1). The three surface buoy systems were set at Sts. KG, TK and KY on 9 September 1990 which were occupied by Faculties of Engineering and of Fisheries (Kagoshima University), Ocean Research Institute (University of Tokyo) and Research Institute for Applied Mechanics (Kyushu University), respectively. Every buoy position was monitored by the Argos System. Each surface buoy system was equipped with a current-meter at the depth of 50 m and thermometers at interval of 10 m to 20 m in the upper layer above 200 m depth. The system at St. KG was equipped with other three current-meters at depths of 150 m, 650 m and 1100 m and that at St. KY other three current-meters at 20 m, 100 m and 150 m. However, the records of current at 650 m and 1100 m were not used in this paper. The current-meters at 50 m depth were located in the seasonal thermocline before a gale, while those were located in the bottom of the mixed layer or at the top of the thermocline after the gale. Time interval of measurements at Sts. KG and TK was hourly, but at St. KY was at every thirty minutes. To measure the meteorological elements and SST, another surface buoy was moored at St. T which was placed at the center of the triangle. The buoy for the meteorological observation has been occupied by the Japan Meteorological Agency.

According to the original schedule of OMLET, the cooperative experiment intended to continue for six months. However, the rope moored at St. KG was cut at the depth of 60 m on 28 September 1990 and therefore, a portion of the buoy system above 60 m depth began to drift. The three buoy systems work together during 19 days from 9 to 28 September 1990.

During the measurement of the three buoy systems, four typhoons came into existence south of St. T and passed around there (Fig. 1). In particular, the Typhoon 9019 took the nearest course to St. T and caused large changes in atmospheric pressure and wind velocity at the station. Atmospheric pressure at the center of the typhoon attained to the minimum of 915 hPa at 9:00 on 18 September of JST at the position (26°36′ N, 129°06′ E) southwest of and 660 km distant

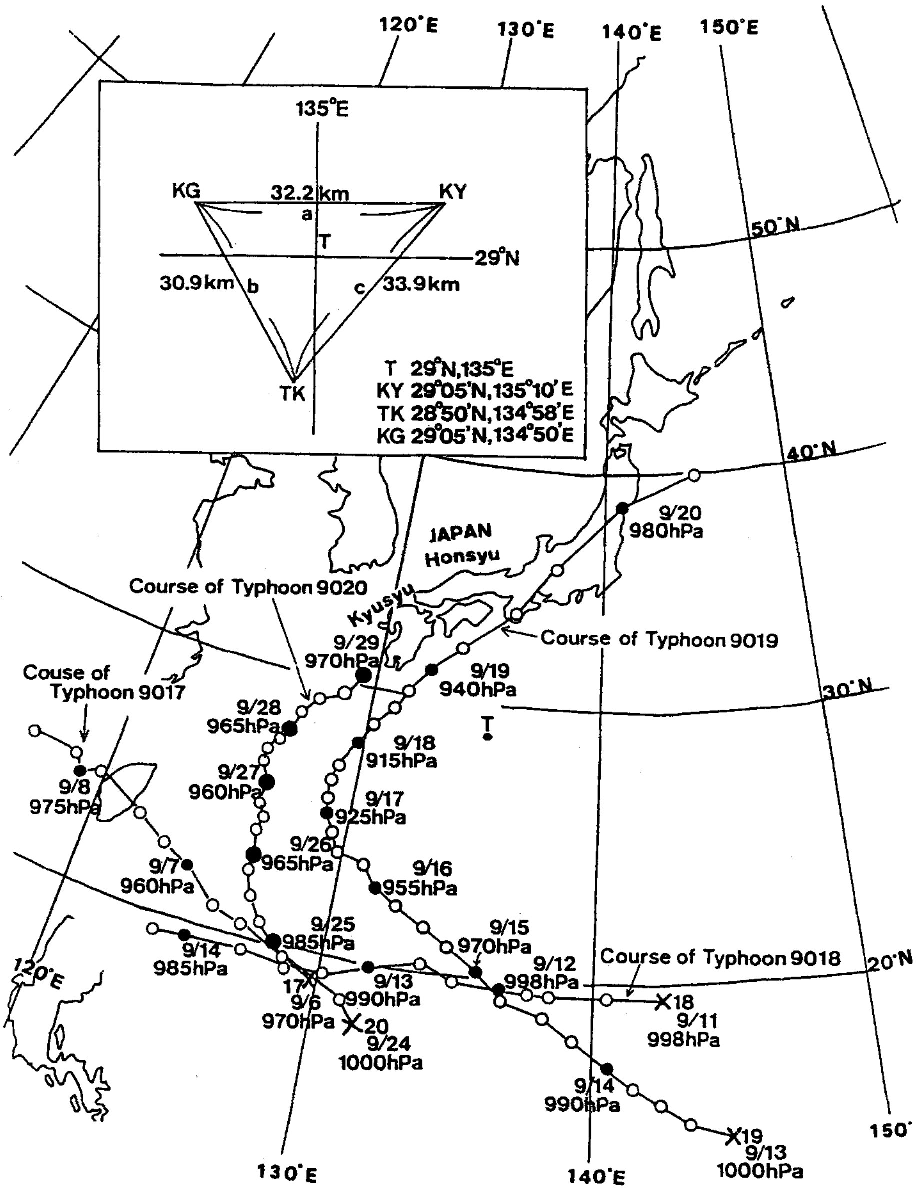

Fig. 1. A map around the deployment of three moorings and course of typhoons. Relative positions of the three moorings are shown at vertexes of a triangle inserted in the upper left of this figure. Positions of the typhoon every 6 hours are indicated by circles. Black circles show the positions at 9:00 on the day shown by numbers.

from St. T. At that time, wind speed within 125 NM (about 230 km) from the center was over 26 m/s and its moving speed was 5.1 m/s.

A duration of a storm on its track, which plays an important role in the excitation of the near inertial motion (Pollard, 1970; Price, 1983), can be estimated from a radius divided by a storm speed. The mean radius of the typhoon was estimated at about 350 km, assuming that the edge

Table 1. Duration of the gale of Typhoon 9019.

Period	Inertia period (hours)	Duration (hours)	Normalized duration
09:00 to 21:00 on 16 Sept.	30.46	32.93	1.08
21:00 on 16 to 09:00 on 17 Sept.	29.16	23.54	0.81
09:00 to 21:00 on 17 Sept.	27.82	24.50	0.88
21:00 on 17 to 09:00 on 18 Sept.	26.48	24.94	0.94
09:00 to 21:00 on 18 Sept.	25.11	16.51	0.66
21:00 on 18 to 09:00 on 19 Sept.	23.69	18.62	0.79
09:00 to 21:00 on 19 Sept.	22.25	10.14	0.46
21:00 on 19 to 09:00 on 20 Sept.	20.30	5.84	0.29

of the typhoon located at 1000 hPa isobar of the atmospheric pressure on the sea surface. Table 1 shows the duration and normalized one by the inertial period at the location of the translating center. A near inertial motion may be effectively excited in the mixed layer under course of a storm if the normalized duration is shorter than 0.5 (Veronis, 1956; Pollard, 1970). The actual and the normalized duration rapidly decrease from 18.62 to 5.84 hours and from 0.79 to 0.29, respectively, during 24 hours from 3:00 on 19 to 3:00 on 20 September. This shows that the near inertial motion under the course of Typhoon 9019 may be more effectively excited after 19 September (Pollard, 1970).

3. Excitation and Period of Near Inertial Oscillation in the Mixed Layer

In this section, we will describe the importance of rapid change of wind in excitation of near inertial oscillation rather than gradual increase of wind speed and determine a period which is peculiar to the observed oscillation. Figure 2 shows variations of ocean currents measured in the upper layer (at 20 m and 50 m depths) and wind. The wind speed gradually increased from 10 m/s on 15 September to the maximum of 20 m/s at noon on 19 September. An inertial oscillation rather decayed during the gale. On the other hand, an inertial oscillation began to excite on 22 September about 1.5 days after an event that the wind speed rapidly decreased from 13 m/s to 4 m/s for only 6 hours in 20 September and the direction rotated clockwise with about twice local inertial period for about one day at first (Fig. 2). If the local wind change excited the near inertial oscillation (see Section 4), the rapid decrease of wind would play an important role in the excitation (Pollard and Millard, 1970; Pollard, 1980). Taira *et al.* (1993) found an energetic excitation of inertial oscillation in the mixed layer of OMLET area after Typhoon 8824 passage. They attribute the excitation to a clockwise rotation of wind and a large wind speed resulted from the typhoon passage. However, inertial oscillation of their case decayed during period of increase of wind speed similar to our case.

A rapid decrease of wind speed can create momentum toward a direction in the mixed layer, and then, current will inertially rotate in the layer. However, if a unidirectional strong wind continues to blow, an inertial motion in the mixed layer is suppressed. The inversely acting wind stress may play an important role in the decay of inertial oscillation in the mixed layer (Pollard and Millard, 1970).

Determination of a period for the excited inertial oscillation is necessary for describing its dispersion process. The most suitable period can be defined as a period when mean squared deviation from a sine curve with the period obtained by the observed current fluctuation takes

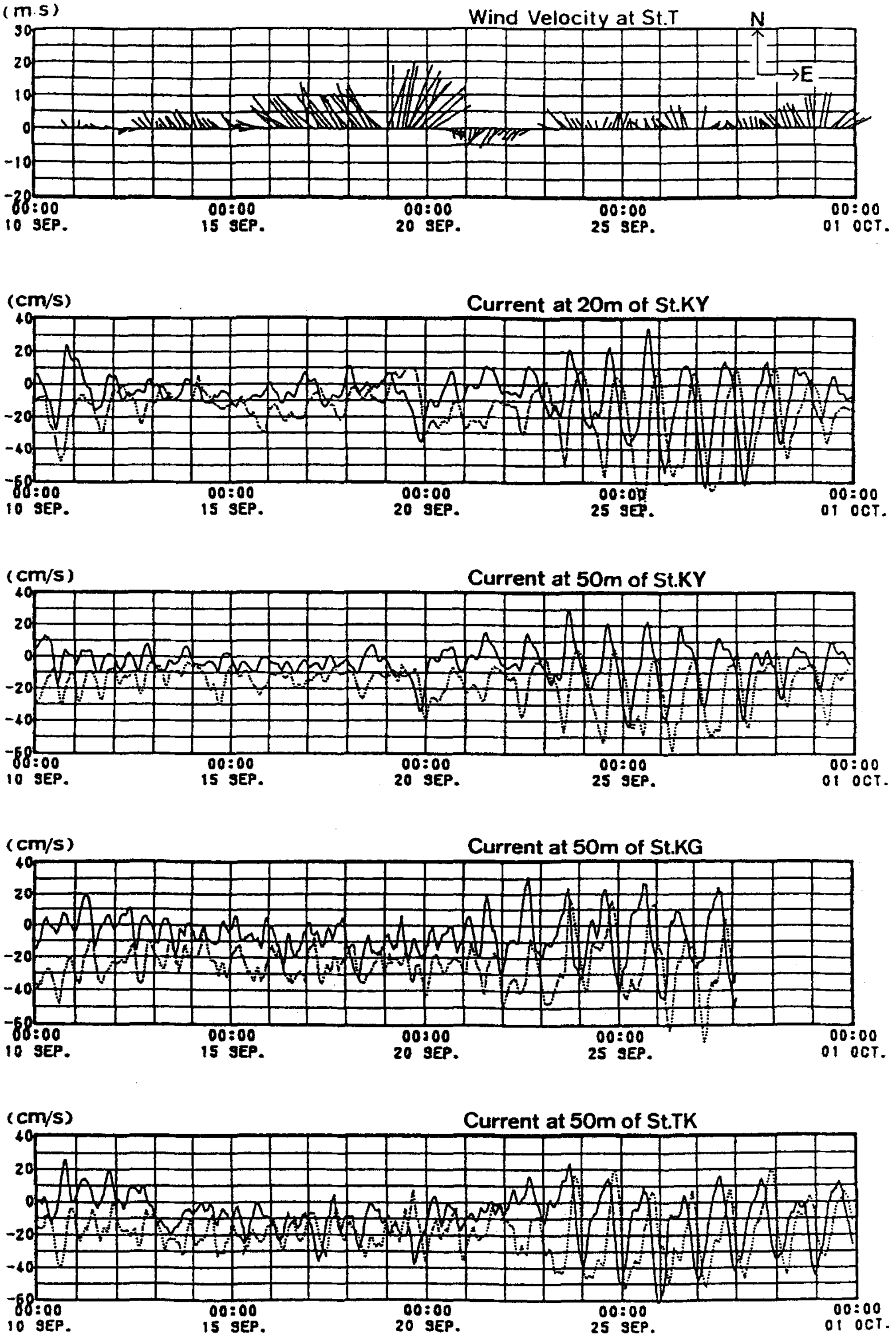

Fig. 2. A comparison between wind velocity at St. T and ocean currents on the upper layer at Sts. KY, KG, and TK. Solid and dotted lines show east and north components of current, respectively.

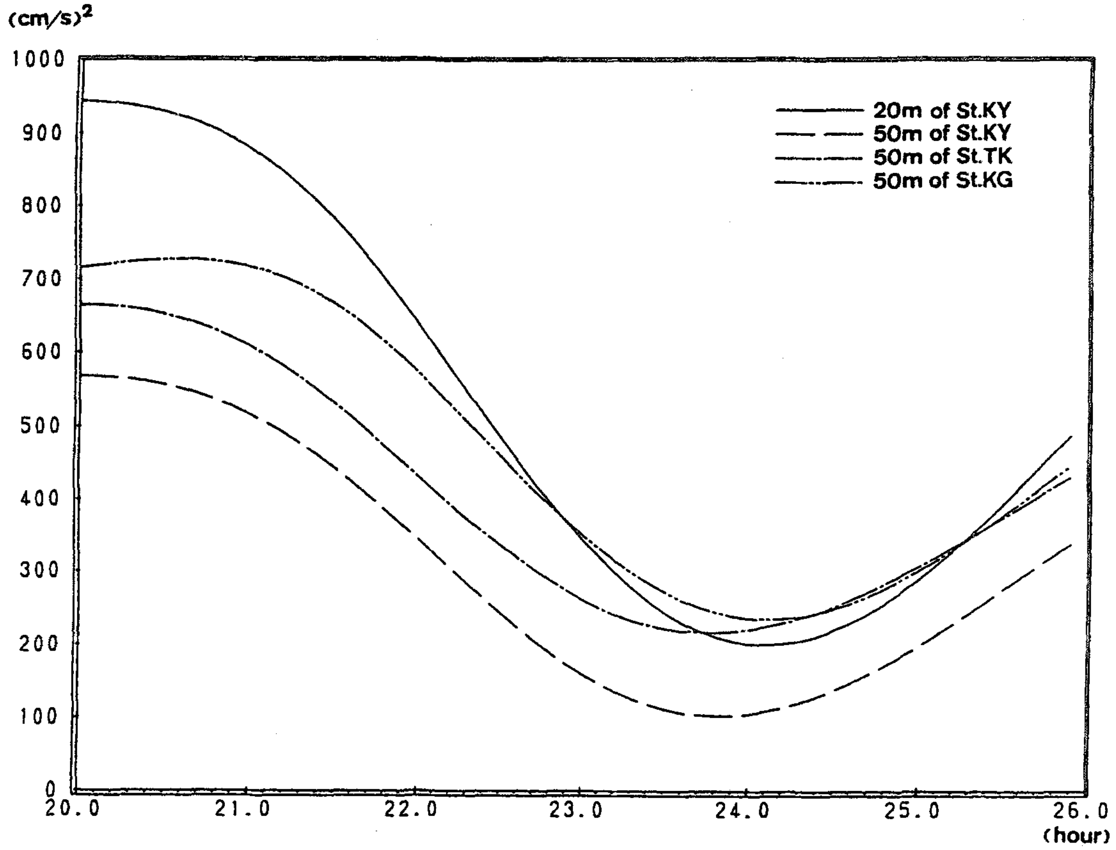

Fig. 3. Distributions of mean squared deviation against assumed period.

the least value. The sine curve can be obtained by changing the period in the method of least square. The most suitable period will be determined for current fluctuations in the mixed layer for 7 days from 22 to 28 September, because the excitation started at 22 September and measurements at all three stations lasted until 28 September (Fig. 2).

The mean squared deviation $\delta(T_i)$ for fitting a period will be defined by the following, although the amplitudes are fluctuating with time:

$$\delta(T_i)=\frac{1}{P}\int_0^P\left[\left\{u(t)-At-u_m-a_i\sin\left(\frac{2\pi}{T_i}t+\alpha_i\right)\right\}^2+\left\{v(t)-Bt-v_m-b_i\sin\left(\frac{2\pi}{T_i}t+\beta_i\right)\right\}^2\right]dt$$

where u and v are the measured east and north components of current, P is the measurement period of 7 days, T_i is a period assumed to be 20 hours through 25.9 hours given at an interval of 0.1 hour, t is a time, A and B are linear increment of u and v with time, u_m and v_m are averages of u and v during P, a_i and b_i are amplitudes, and α_i and β_i are phases for u and v components, respectively. The unknown constants can be obtained by applying the method of least square.

Figure 3 shows distributions of the calculated mean squared deviation against the assumed

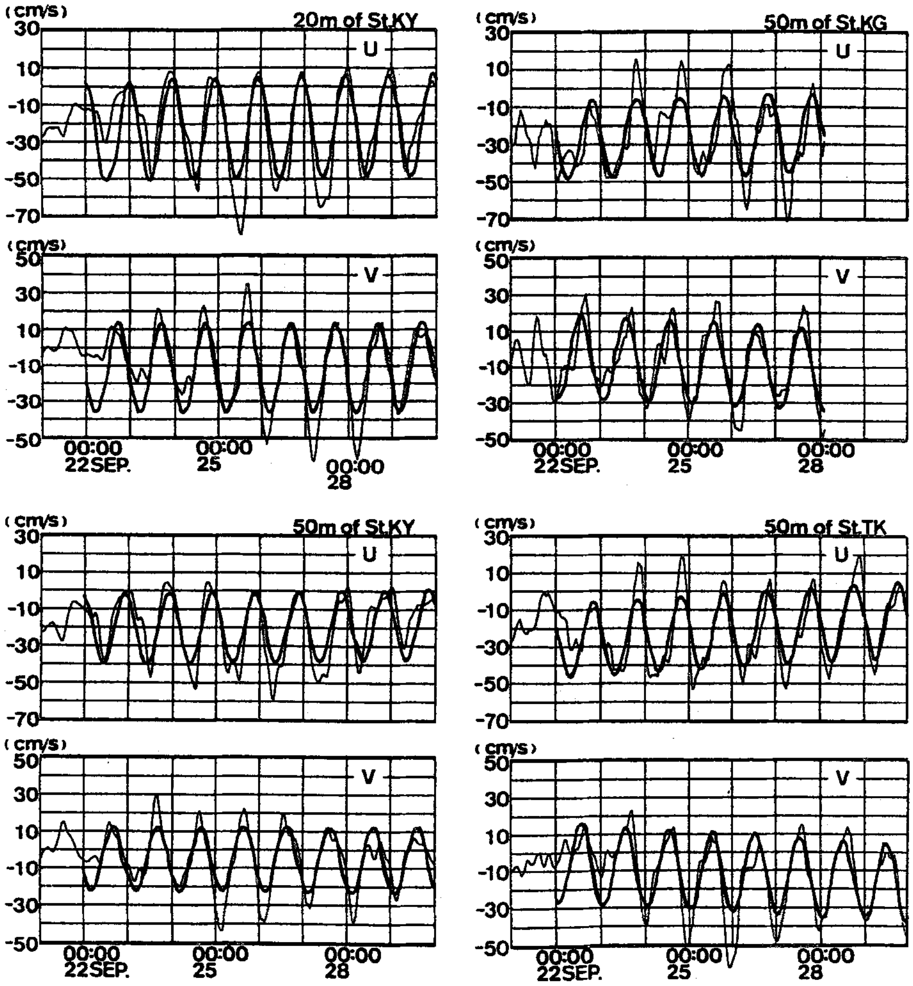

Fig. 4. Fitness of the obtained sine curve with the period of 23.9 hours to the observed current fluctuations in the upper layer.

period T_i. All of the deviations reach a minimum at a period around 23.9 hours. Fitness for the curves obtained by the method of least square by assuming the period of 23.9 hours to the measured currents is shown in Fig. 4. The period of 23.9 hours will be used following analysis to approach the dispersion process. This period is shorter than the local inertial period of 24.69 hours at St. KG, here, it is the shortest among the stations of measurements. So, the excited inertial oscillation can propagate downward as an inertial internal gravity wave.

4. Vertical Radiation of the Excited Oscillation in the Upper Layer

Figure 5 shows fluctuations of ocean current at 100 m depth and 150 m. The excitation of near inertial oscillation begins on 25 or 26 September lagging by 3 or 4 days behind the starting time in the upper layer, 20 m depth and 50 m. The period of oscillation is equal to the period of 23.9 hours as those in the case of the upper layer (see the lagent of Fig. 5). This excitation may be made by the energy of near inertial motion transfered from the upper layer. In this section, we

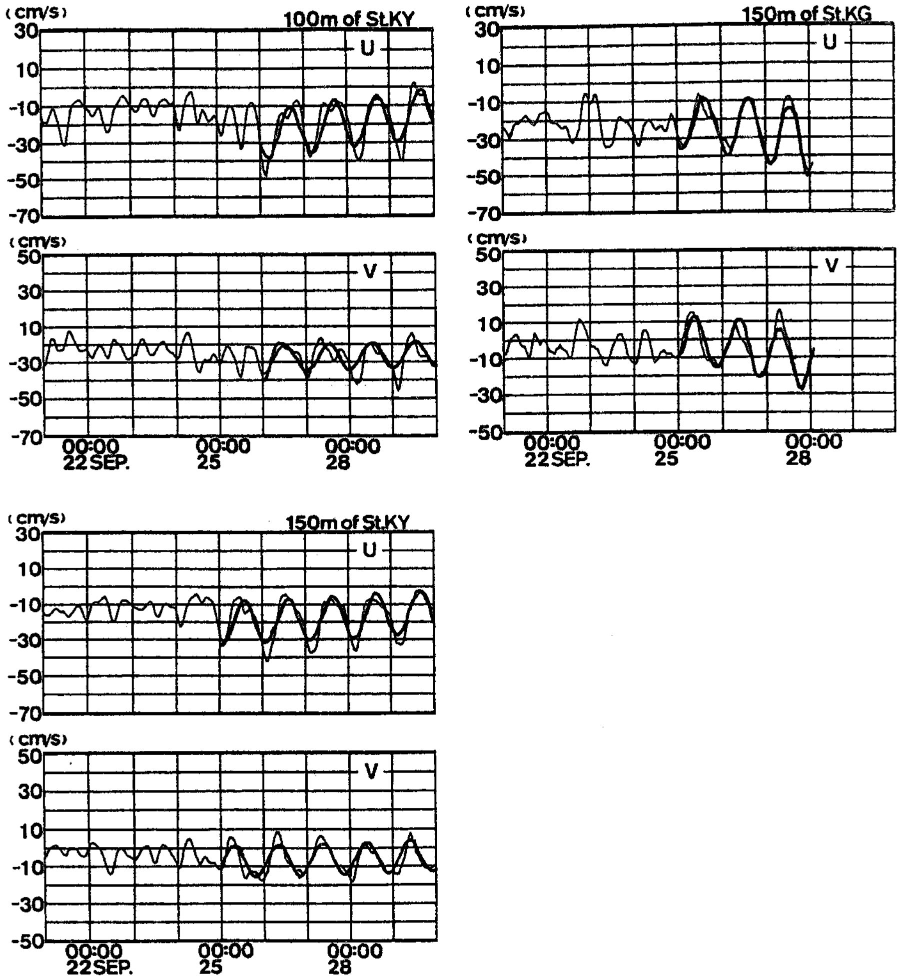

Fig. 5. Observed current fluctuations at 100 m and 150 m depths. The smooth curves are obtained by the method of least square assuming the period of 23.9 hours.

will describe a radiation process of the near inertial motion from the mixed layer to the thermocline. For this purpose, it is necessary to get phase relations of the excited motion among the measurement positions. An important character of inertial or near inertial motion is the rotation of velocity vector. So, a relative phase may be given by an initial angle measured from a reference direction on a hodography.

Figure 6 shows a series of daily hodography with the period of 23.9 hours at 50 m depth of St. KG. Each hodography is obtained by applying the method of least square to the current data of 48 hours period. The 48 hours period starts at noon of the first day till noon of the third day. The mid-point is at noon of the second day. The overlap is taken from noon of the second day to noon of the third day of the period 48 hours. The date shown in the hodography is the second day every frequency. The near inertial motion develops for 5 days from 22 September to 26. The velocity vector is rotating clockwise every day as expected in the northern hemisphere. The direction of vector at 00:00 on each day is approximately steady and heading almost toward

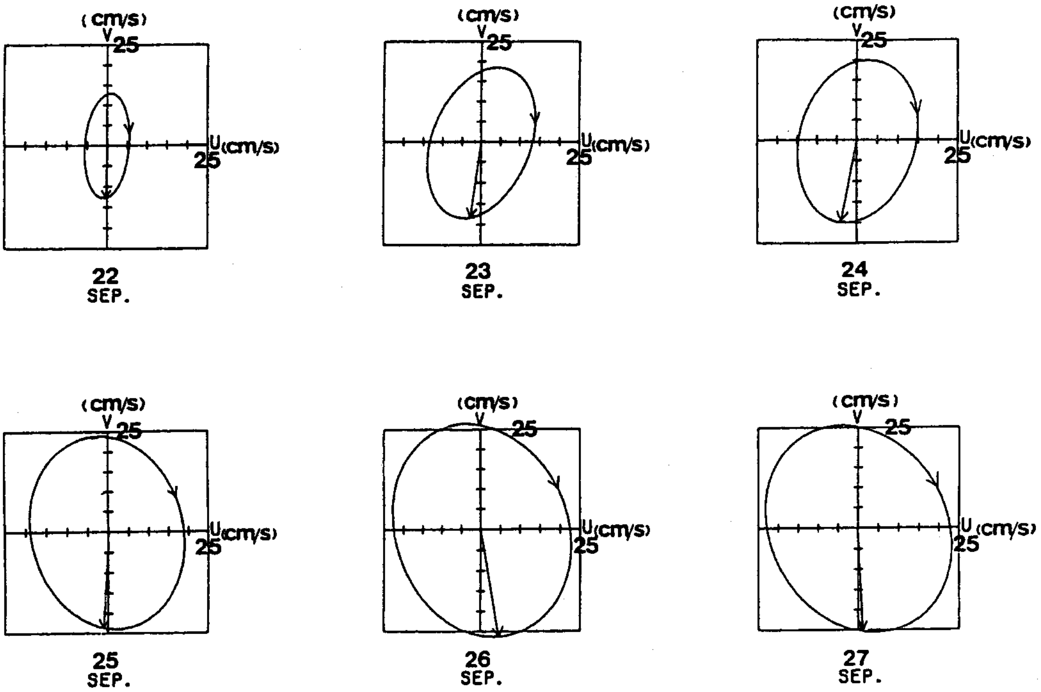

Fig. 6. A series of hodographies with the period of 23.9 hours at 50 m depth of St. KG. A vector drawn from the origin shows the direction of velocity at time $t = 0$ on each day. Every hodography rotates clockwise.

south. This shows that the phase of the near inertial motion is approximately steady for 5 days, although the initial direction of vector at 00:00 on every day should rotate counter clockwise with an angular velocity of 1.5 degrees a day for the steady state because of the determined most suitable period of 23.9 hours, which does not equal to 24 hours. Such characters as the clockwise rotation of hodography and the steadiness of phase during the development are common to the near inertial motion observed at 50 m depth of other two stations and at 20 m of St. KY. The direction of velocity vector counted from the east at 00:00 on every day in the hodographies is assumed as a relative phase among the measurement stations and the days.

Figure 7 shows the time change of the relative phase for all measurement positions. After 22 September when the excitation started, the phases at 20 m depth of St. KY and 50 m of the three stations are almost steady and the phase deviations from the mean for the measurement period are lesser than 20 degrees. After 25 September, when the amplitude of long axis of ellipse in the hodography for the near inertial motion reached to a maximum (Fig. 8), the deviations are smaller than 10 degrees. The order of phase at 50 m depth is Sts. TK, KG and KT, and does not change after 25 September. This phase order and the ordination of the positions of the three stations indicate northeastward propagation of the near inertial motion (Fig. 1).

The relative phases at 150 m depth of Sts. KG and KY are almost steady and the deviations from the means are smaller than 10 degrees, after 25 September when the inertial motion begins to develop at the depth (Figs. 7 and 8). However, the phase at 100 m of St. KY rapidly decreases from 230 degrees on 25 September to 130 degrees on 26 September. Nevertheless, it finally reaches to almost steady state and its deviation is only 5 degrees after 26 September. Thus, the

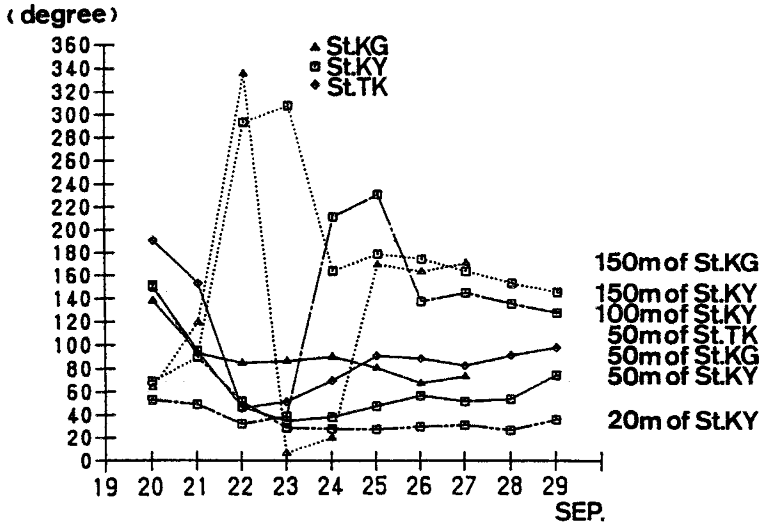

Fig. 7. Time changes of phase of near inertial motion. The phase is defined as the angle counted clockwise from the east (see text).

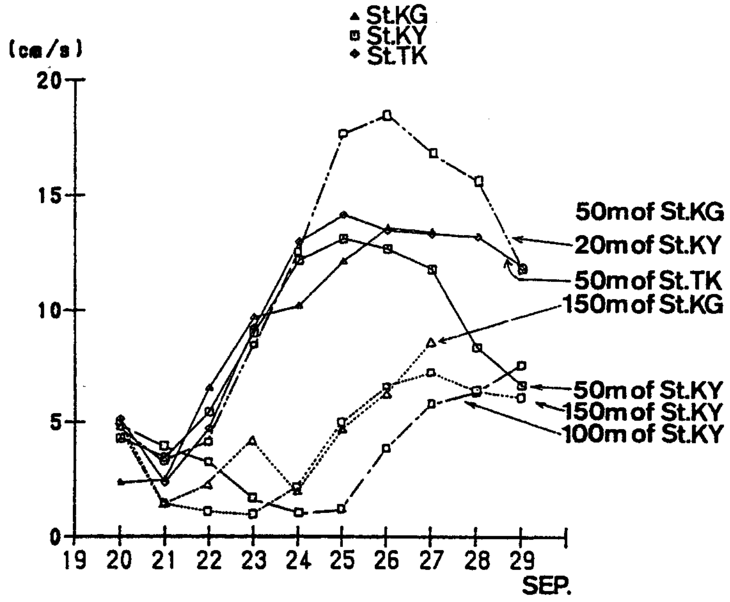

Fig. 8. Time changes of main axis on the hodography for the near inertial motion.

phase at every measurement depth of each station is thought to reach a steady state on 26 September. In this state, the phase increases with increases of depth (Fig. 7). This indicates upward propagation of phase. So, if the near inertial motions in the thermocline is made by an inertial internal wave, its group velocity has a downward component. Here, the observed relation between the vertical components of phase velocity and group will be compared quantitatively with the theoretical one.

The dispersion relation for the inertial internal wave can be described by the following equation, when the Brunt-Väisälä frequency N is independent on position (LeBlond and Mysak, 1973).

$$\left(k_1^2 + k_2^2\right)N^2 = k_3\left(\omega^2 - f^2\right) \tag{1}$$

where $k(k_1,k_2,k_3)$ is a wave number vector, ω a wave frequency and f Coriolis parameter. One can obtain a phase velocity and group one from (1), and then a ratio of vertical component of two velocities. The ratio is represented by

$$-\frac{N^2\left(k_1^2 + k_2^2\right)}{\omega k_3^2} \cdot \frac{k_1^2 + k_2^2 + k_3^2}{\omega k_3^2} = -\frac{|k|^2}{\omega^2} \cdot \frac{k_1^2 + k_2^2}{k_3^2} \cdot \frac{k_1^2 + k_2^2 + k_3^2}{k_3^2}. \tag{2}$$

This relation can be represented by only the frequencies, ω, f and N, by using the dispersion relation (1) and approximated as follows,

$$-\frac{\omega^2 - f^2}{\omega^2} \cdot \left(\frac{\omega^2 - f^2}{N^2} + 1\right) \fallingdotseq -\left(1 - \frac{f^2}{\omega^2}\right) \tag{3}$$

because $\omega^2 = 5.33 \times 10^{-9}$ s^{-1}, $f^2 = 4.99 \times 10^{-9}$ s^{-1} and the order of N^2 is 10^{-4} s^{-1} respectively and then $\omega^2, f^2 \ll N^2$. Actually, N^2 is estimated at 2.00×10^{-4} s^{-1} from temperatures at 50 m and 150 m depth after 25 September and assumed salinity 34.8 psu at both depths. Then the ratio can be calculated from the local inertial frequency and the frequency of the internal wave having near inertial frequency. In the case of the observed period of 23.9 hours and of the local inertial period of 24.75 hours, the ratio becomes –0.0675.

Next, the ratio will be independently obtained by velocities of phase and group which are estimated from the observed character of near inertial motion. In the estimation of group velocity, a front of internal wave is assumed to propagate with its group velocity and the starting time of excitation at each depth is defined as an arrival time of the front. While the starting time cannot be accurately designated, it can be assumed as 22 September for 20 m depth and 50 m, as 25 September or 26 for 100 m depth and 150 m (Figs. 2, 4, 5 and 8). However, the difference of starting time between 100 m depth and 150 m cannot be indicated by the present time resolution. So, the estimation by using differences of the arrival time and of the phase between 100 m depth and 150 m is not made, although the phase at 100 m depth lags behind that at 150 m depth. The vertical component of phase velocity will be calculated from the vertical difference of averaged phase at each station for 3 or 4 days after 26 September when the phase reached the steady state at all measurement positions.

Table 2 shows the vertical component of phase velocity obtained by using the phases at the depths of 50 m, 100 m and 150 m and the ratio of the vertical component of the two velocities. The estimated vertical component of phase velocity is greater than 1.0×10^{-3} m/s estimated by Johnson *et al.* (1976). The values of ratio in the case which the starting time at 150 m depth lags by 4 days behind that of 50 m depth are almost equal to the one theoretically obtained, although the absolute values of those in the case of lagging by 3 days are larger than the theoretical one.

Table 2. Observed vertical component of phase velocity and ratio of vertical component of group velocity to it.

	St. KY 150 m	St. KG 150 m	Mean	St. KY 100 m
Vertical component of phase velocity (m/s)	3.79×10^{-3}	4.28×10^{-3}	4.14×10^{-3}	2.43×10^{-3}
Ratio for lagging by 3 days behind the upper layer	−0.1018	−0.0902	−0.0960	
Ratio for lagging by 4 days behind the upper layer	−0.0762	−0.0675	−0.0712	−0.1189

The middle three columns are cases where the vertical phase difference between 50 m depth and 150 m is used. The far right column is the case where the vertical phase difference between 50 m depth and 100 m of St. KY is used. In this case, the ratio for 3 days lag is not shown, because the relative phase did not reach the steady state on 25 September (Fig. 7).

However,the absolute value of ratio estimated from using the phase at 100 m depth of St. KY is considerably larger, due to the allowing of the vertical component of phase velocity (the right most column of Table 2).

Another important information on the vertical propagation, that is vertical scale of the internal wave, should be estimated. The vertical component of phase velocity may be approximately taken as ω/k_3 under the same order of approximation as (3). If the phase velocity shown in Table 2 will be used, we can obtain the vertical wave length from this approximation. Using the period of 23.9 hours and the phase velocity of 4×10^{-3} m/s (Table 2), the vertical wave length is 340 m. So, the generated internal wave is considerably higher mode, because the Brunt-Väisälä period may be shorter than the period of 23.9 hours through the top of the seasonal thermocline to the near sea bottom.

Gill (1984) shows a possible physical mechanism why the near inertial motion excited in the mixed layer generates the inertial internal wave in the thermocline. A periodic divergence with a near inertial period may be created in the mixed layer by a curl of transient wind stress to act on the sea surface, because an inertial rotation of wind driven current will horizontally vary. He calls such a divergence inertial pumping by analogy with Ekman pumping. The inertial pumping at 50 m depth will be given in the following.

A divergence at a depth can be defined by the amount of out flowing from a region divided by its area. The divergence for the present deployment of three stations shown in Fig. 1 is given as follows:

$$\frac{V_a a + V_b b + V_c c}{S} \tag{4}$$

where V_a, V_b and V_c are velocities at the centers of the sides a, b and c and perpendicular to them, respectively, and direct outward from the inside of triangle and S is its area (see Fig. 1). V_a, V_b and V_c are interpolated from the velocities measured at 50 m depth of Sts. KG, KY and TK, respectively. The fluctuations of divergence calculated by means of (4) is shown in Fig. 9. The

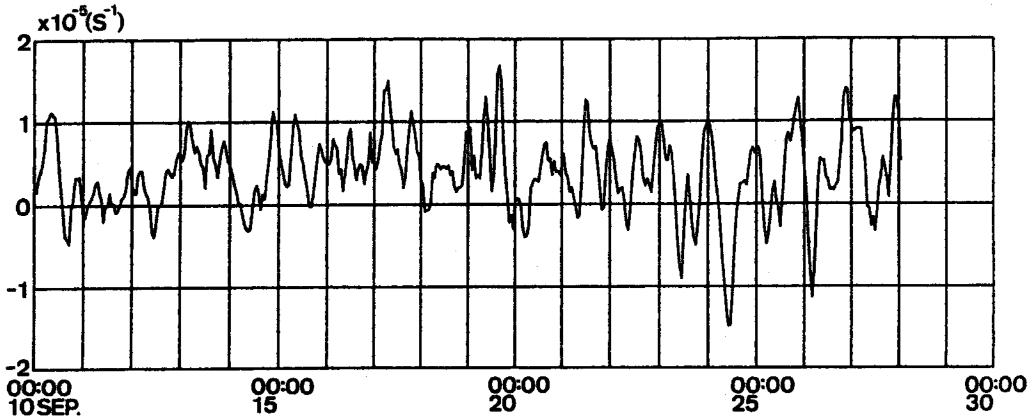

Fig. 9. Time change of horizontal divergence at 50 m depth.

divergence with the period of about 24 hours begins to develop on 23 September and its amplitude reaches to a maximum on 26 September when the near inertial motion at 150 m depth starts. The periodic divergence can create periodic horizontal pressure gradient which is a distinctive characteristic of internal gravity wave.

5. Summary and Discussion

Near inertial oscillations were excited in the mixed layer of OMLET area 450 km distant from and east of the course of Typhoon 9019 which had a radius of 350 km. The excitation is thought to be caused by local wind change on the margin of the typhoon, because of a large difference between the two propagation direction observed from the phase relations among the three stations and assumed from the area where an inertial oscillation might be most effectively generated under the course of the typhoon.

The observed inertial oscillation is thought to be generated by the rapid decrease of wind speed. Rapid decrease of wind speed can more effectively generate an inertial oscillation in mixed layer than prevailing strong wind, because the rapid decrease leaves unidirectional momentum in the mixed layer which appears to us on the earth to rotate but the prevailing strong wind acts against a direction of inertial oscillation on some phases.

The period of generated inertial oscillation is determined by the rather simple way. However, this way is suited to the case of inertial oscillation which has generally a different period for every generation (Pollard, 1970). The determined period is shorter than the local inertial period. So, the generated inertial oscillation can propagate a direction as an internal wave which has a vertical and horizontal components. The observed phase velocity directs upward and group downward. This is a distinctive characteristic of internal wave which is newly generated in the mixed layer. The observed ratio of vertical component of group velocity to phase velocity nearly equals to the theoretically obtained ratio which is approximately derived from the dispersion relation for an inertial internal wave.

The development of divergence fluctuation with the near inertial period at the bottom of mixed layer accompanied the near inertial motion in the thermocline. This phenomenon is thought to reflect energy conversion from an inertial motion in the mixed layer into an inertial internal wave. A vertical vorticity caused by wind action in the mixed layer produces such a divergence fluctuation by Coriolis acceleration.

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References

David, A. B. (1983): The wake of hurricane Allen in the Western Gulf of Mexico. *J. Phys. Oceanogr.*, **13**, 117–129.

Day, C. G. and F. Webster (1965): Some current measurements in the Sargasso Sea. *Deep-Sea Res.*, **12**, 805–814.

Gill, A. E. (1984): On the behavior of internal waves in the wakes of storms. *J. Phys. Oceanogr.*, **14**, 1129–1151.

Johnson, W. R., J. C. Van Leer and C. N. K. Mooers (1976): A cyclesonde view of coastal upwelling. *J. Phys. Oceanogr.*, **6**, 556–574.

Kundu, P. K. (1976): An analysis of inertial oscillations observed near Oregon Coast. *J. Phys. Oceanogr.*, **6**, 879–893.

Lai, D. Y. and T. B. Sanford (1986): Observations of hurricane-generated, near-inertial slope modes. *J. Phys. Oceanogr.*, **16**, 657–666.

LeBlond, P. H. and L. A. Mysak (1978): *Waves in the Ocean*. Elsevier Scientific Publishing Company, New York, 602 pp.

Pollard, R. T. (1970): On the generation by winds of inertial waves in the ocean. *Deep-Sea Res.*, **17**, 795–812.

Pollard, R. T. (1980): Properties of near-surface inertial oscillations. *J. Phys. Oceanogr.*, **10**, 385–398.

Pollard, R. T. and R. C. Millard (1970): Comparison between observed and simulated wind-generated inertial oscillations. *Deep-Sea Res.*, **17**, 813–821.

Price, J. F. (1983): Internal wave wake of a moving storm. Part 1: Scales, energy budget and observations. *J. Phys. Oceanogr.*, **13**, 949–965.

Taira, K., S. Kitagawa, H. Otoba and T. Asai (1993): Observation of temperature and velocity from a surface buoy moored in the Shikoku Basin (OMLET-88)—An oceanic response to a typhoon. *J. Oceanogr.*, **49**, 397–406.

Veronis, G. (1956): Partition of energy between geostrophic and nongeostrophic oceanic motions. *Deep-Sea Res.*, **3**, 157–177.

Weller, R. A. (1982): The relation of near-inertia motions observed in the mixed layer during the JASIN (1978) experiment to the local wind stress and to the quasi-geostrophic flow field. *J. Phys. Oceanogr.*, **12**, 1122–1136.