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Observation of Temperature and Velocity from a Surface Buoy Moored in the Shikoku Basin (OMLET-88) —An Oceanic Response to a Typhoon—

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A surface buoy was moored from 20 April to 2 November 1988 at 28°48′ N and 135°01′ E where the water depth was 4900 m to measure temperature and velocity in the upper 150 m. The Typhoon 8824 passed at 0300 (JST) on 8 October about 50 km north to the mooring station with a maximum wind speed of 43.5 m s^{-1}. The buoy was shifted about 30 km to southwest and the instruments were damaged. The records of temperature at 0.5 m and velocity at 50 m were obtained. The inertial oscillation caused by the typhoon is described using the current record. The oscillation endured for about 20 days. Deep mixing and vertical heat transport by the typhoon are discussed based on the data from the Ocean Data Buoy of the Japan Meteorological Agency moored at 29°N and 135°E.

1. Introduction

The upper layer of the ocean plays a role of heat reservoir for an annual cycle of insolation. The water is heated in summer and temperature gradients are large in the upper layer. In winter, the water at the surface is cooled by the heat release to the air. The cooled water has higher density and sinks to a depth where water density is equalized. As a result of convection, a mixed layer of uniform temperature is formed in the upper ocean. Thickness of the winter mixed layer exceeds more than hundreds of meters at mid-latitudes.

Heat balance of the upper ocean is not always governed by the local processes of air-sea interactions. Otobe (1989) shows from direct measurements of heat fluxes at the sea surface in the Kuroshio region that a mean of the net heat flux is 132 W m^{-2} in May, 164 W m^{-2} in June, and –473 W m^{-2} from November to February. This clearly indicates that in the Kuroshio region, the heat loss in winter is much greater than the heat gain in summer. The heat must be transported from the surrounding sea areas.

A field program to study heat balance in the open ocean was planned (Toba *et al.*, 1991). The former Ocean Weather Station-T (29°N and 135°E) was selected as the experimental sea area, and a program "Ocean Mixed Layer Experiment at Station-T" (OMLET) was carried out from 1987 to 1991 as an oceanographic component of the Japanese World Climate Research Program (WCRP).

At the OWS-T, ship observations were made from 1948 to 1971 by the Japan Meteorological Agency (JMA). Since 1972, an Ocean Data Buoy has been kept by JMA and meteorological elements at 7.5 m height, water temperature at 1 m, 50 m and 100 m are collected. The long time series is most useful to analyze heat balance in the ocean (cf. Kurasawa *et al.*, 1983).

Time series of temperature and velocity in the upper ocean is important for the OMLET. A small surface buoy was moored about 22 km south to the OWS-T from 20 April to 2 November

1988 (Otobe *et al.*, 1989). Although eight thermometers were set in the upper 100 m and two current meters were set at 50 m and 150 m, records were obtained from the thermometer at 0.5 m depth and the current meter at 50 m due to the damage by the Typhoon 8824 on 8 October. In Section 2, the surface buoy system and the operation are described. In Section 3, daily mean velocity and temperature are described. The current record at 50 m revealed that the inertial oscillation was excited by the typhoon and that it endured for about 20 days. Deep mixing and vertical heat transport by the typhoon is described in Section 4. A summary of the present study is given in Section 5.

2. The Surface Buoy and the Mooring Operation

Figure 1 shows the mooring system for the surface buoy deployed from 20 April to 2 November 1988 at 28°48′ N and 135°01′ E in Shikoku Basin. The buoy (ZWB-110 Modified, Zeni-Light Co.) is designed for use as a marker buoy in a deep sea. The buoy is 440 cm in height and 110 cm in diameter and the buoyancy is 1190 kg. A signal light and a radar reflector are used for warning to ships. A satellite terminal is installed to monitor the buoy position by the Argos System.

The water depth at the mooring site was 4900 m. Tethered line was nylon rope 12 mm in diameter and 4550 m of total length. Steel rope of 6 mm in diameter and 400 m long was used in the upper portion. The total length of the mooring line was 4950 m. Eight self-recording thermometers (RMT, Rigosha) were set at depths of 0.5 m, 10 m, 20 m, 30 m, 40 m, 60 m, 80 m and 100 m. Accuracy of the thermometer was ±0.05°C and sampling time interval was set to be 20 minutes. The uppermost thermometer was attached directly to the buoy, and the remaining were tied to the mooring rope. A thermistor chain was also set in the upper 100 m, and the signal was telemetered by the Argos System. Pressure gauges (RMD, Rigosha) were set at 50 m and 150 m. Electro-magnetic current meters (ACM-5000, Alec Electronic Co.) were set at 50 m and 150 m. Horizontal two-components of velocity are detected by a spherical sensing element of 9 cm in diameter with a resolution of 0.1 cm s^{-1} and an accuracy of 0.5 cm s^{-1}. Azimuth angle of the sensor is detected by a magnetic compass with a resolution of 0.2 degrees. A burst measurement, eight samples at 1 second interval, was made every 60 minutes. An acoustic release (Type L, Nichiyu-Giken Co.) was used for recovery of the mooring.

Total weight of the instruments, the mooring gears and the rope was 255 kg in water. The mooring anchor was 675 kg. Five glass balls of 125 kg buoyancy were used for recovery of the acoustic release. The total weight of the underwater units was 805 kg. Since the buoyancy of the surface buoy was 1190 kg, the buoy system was designed to shift for a force exceeding the anchor drag. A maximum hydro-resistance drag on the mooring line was estimated to be about 300 kg. The nylon rope with a breaking strength of 2500 kg was used.

Deployment of the buoy was made on 20 April 1988 from the R/V Hakuho Maru, Ocean Research Institute, University of Tokyo (Asai, 1988). Signals of thermistor chain stopped just after the deployment. The buoy position was reported by the Argos System until 7 October 1988. On the day, Typhoon 8824 (Nelson) passed near the mooring site. The Ocean Data Buoy at 29°N and 135°E recorded the maximum wind speed of 84.5 knot (about 43.5 m s^{-1}) at 1800Z (GMT) on 7 October. The Argos data became erroneous and stopped in mid-October.

Recovery of the buoy system was made on 2 November 1988 from the T/S Keiten Maru, Faculty of Fisheries, Kagoshima University. The recovered position was about 30 km southwest from the deployed position. The water depth was 4300 m at the recovered site. The instrument

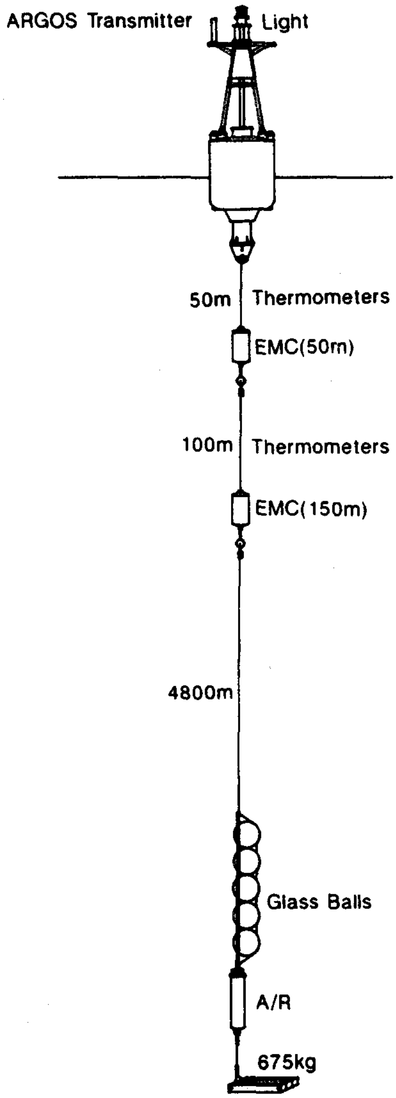

Fig. 1. Surface buoy mooring for the Ocean Mixed Layer Experiment from 20 April to 2 November 1988.

housing was filled with sea water through a cable hole for the thermistor chain. The battery of the Argos terminal was damaged by the sea water. The current meters and one thermometer attached to the buoy were recovered. Remaining thermometers and the pressure gauges were lost due to breaking of tying rope.

3. Observational Results

The temperature record at 0.5 m depth and the velocity record at 50 m depth were obtained from the mooring observation. The current record at the 150 m depth was not obtained due to malfunction of the current meter.

3.1 Daily temperature and current velocity

Daily temperature at 0.5 m depth is shown in the upper panel of Fig. 2. Temperature was 19.4°C on 21 April, and it increased to a maximum value of 29.3°C on 21 July. The high temperature was kept until 7 October, and decreased abruptly by about 3°C with the passage of Typhoon 8824. The low temperature was kept to the end of the record.

Daily averaged current velocities at 50 m depth are shown in the middle panel (the east component) and in the bottom panel (the north component). The mean velocity at 50 m depth was -15.3 cm s^{-1} for the east component, and -0.3 cm s^{-1} for the north component. The mean flow is greater than those of about 5 cm s^{-1} at 1500 m depth obtained from the SOFAR float tracking (Taira *et al.*, 1990). In mid-May the current variation was remarkable with a current speed exceeding 50 cm s^{-1}, and it accompanied with temperature increase by about 2°C. An outbreak of the Kuroshio is suggested for the variation (Toba *et al.*, 1991).

3.2 The inertial oscillation excited by the typhoon

Figure 3 shows the weather map at 1200Z (GMT), or at 2100 (JST), on 7 October 1988. The center of Typhoon 8824 was located at 30°N and 136°E. Points A and B in Fig. 3 show positions of the typhoon center after and before 12 hours. The center of the typhoon passed at around 1800Z about 50 km north to the mooring site.

Figure 4 shows hourly data of temperature at 0.5 m depth and current velocities at 50 m depth on 1–28 October. Temperature decreased abruptly on 7 October when the typhoon approached. Semidiurnal tides were dominant in the currents before the temperature decrease, and the velocity fluctuation with a period of about 24 hour became dominant after it.

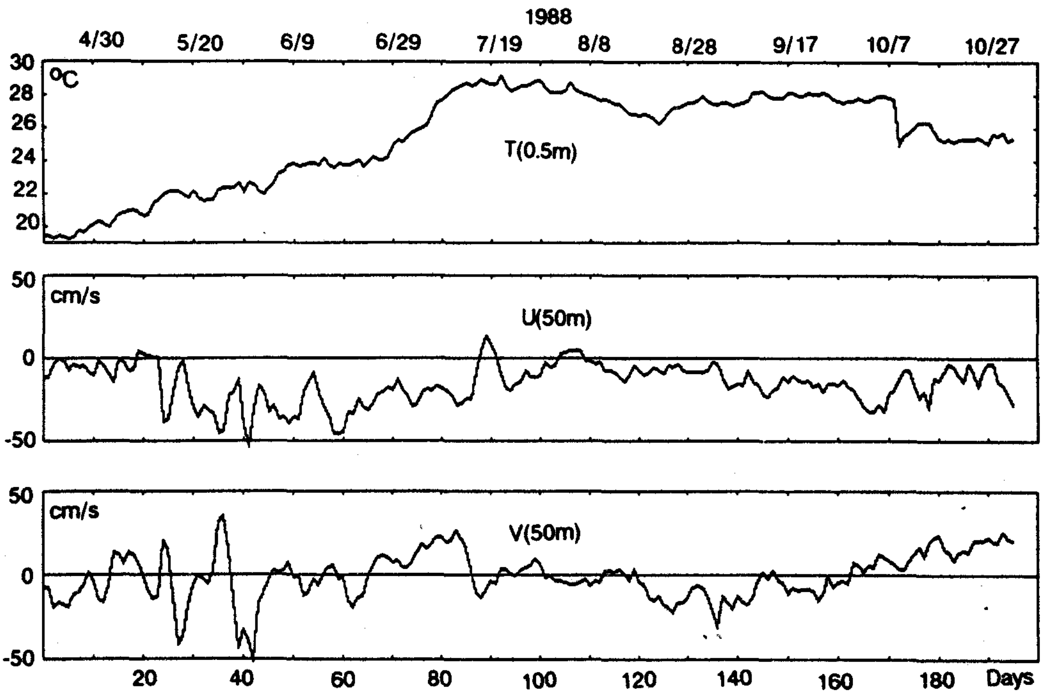

Fig. 2. Daily mean temperature (T) at 0.5 m depth and velocities (U the east component, and V the north component) at 50 m.

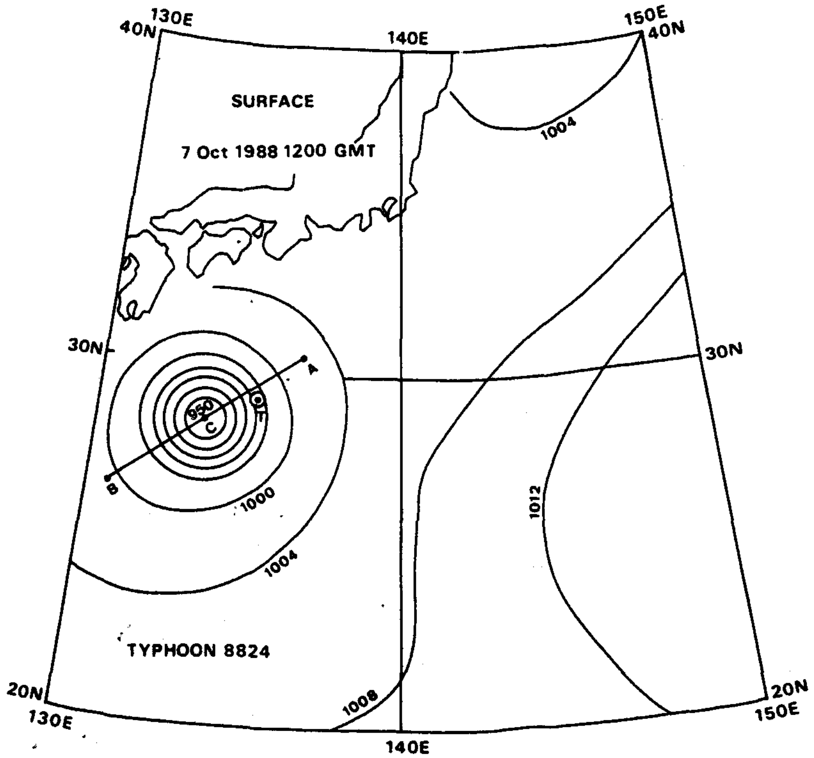

Fig. 3. Weather map at 1200Z on 7 October 1988 (Japan Meteorological Agency, 1988). The mooring station is shown by an open circle with "T". Center of the typhoon 8824 was located at the position marked by a dot "A" at 0000Z on 7 October, a dot with "C" at 1200Z on 7 October, and a dot with "B" at 0000Z on 6 October 1988.

The progressive vector diagram of the current record from 0500 (JST) on 5 October to 0500 on 15 October is shown at the center of Fig. 5. The diagram indicates a northwest flow with a mean speed of about 20 cm s^{-1}, and the clockwise loop on each day. The progressive vector diagram for each day was prepared from the hourly velocities after subtracting the mean flow on the day as shown in the upper and right portion of Fig. 5. The diagram from 0500 on 7 October to 0500 on 8 October does not show any clockwise loop. Onset of the clockwise loop occurred on 8 October with a diameter of 20 km and velocity amplitude of about 80 cm s^{-1} (see Fig. 4).

The latitude of the observational site is 28°48′ N and the inertial period is 24.9 hour. The clockwise loops were considered to be the inertial oscillation excited by the typhoon. The inertial oscillation attenuated gradually, and a clear loop disappeared on 27 October. Duration of the inertial oscillation is about 20 days, and it is much longer than those reported previously (Pollard and Millard, 1973; Price, 1981).

The clockwise rotation of wind direction, the large wind speed, and the course of the typhoon to the left from the observational site, are considered to excite the most energetic inertial oscillation (cf. Greatbatch, 1983).

Figure 6 shows the wind observed every three hour at the JMA Buoy and the current measured every hour at 50 m depth on 6–8 October. The wind rotated clockwise by 170° in 12 hours from 140° and 28.0 knot at 0900Z to 310° and 46.9 knot at 2100Z on 7 October. The

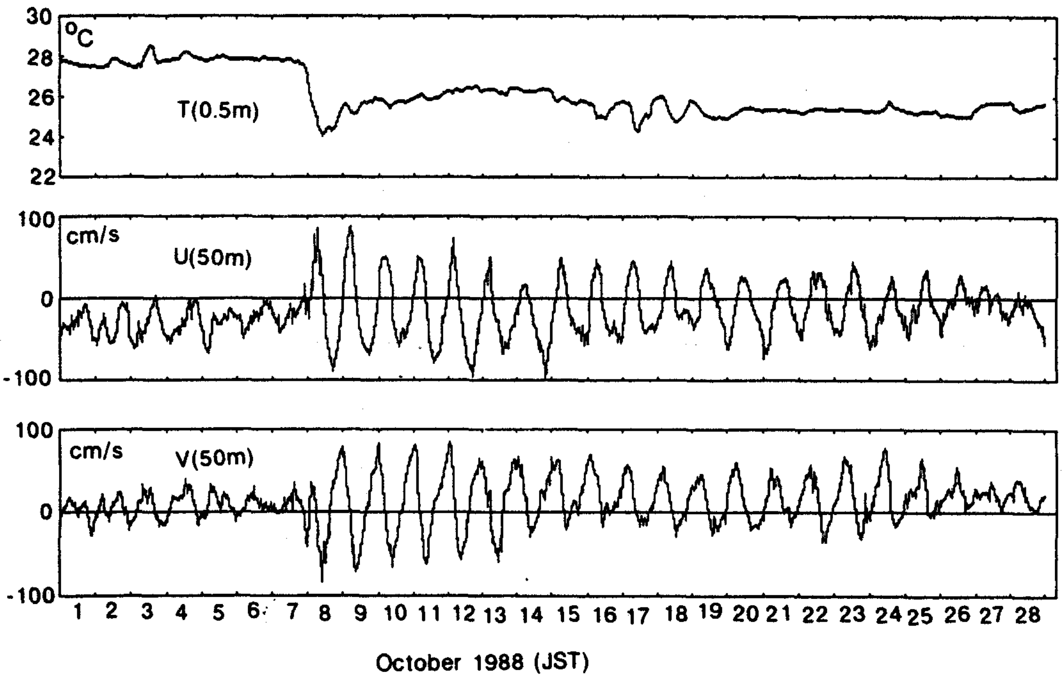

Fig. 4. Hourly values of temperature (T) at 0.5 m and velocities (U the east component, and V the north component) at 50 m depth on 1–28 October 1988.

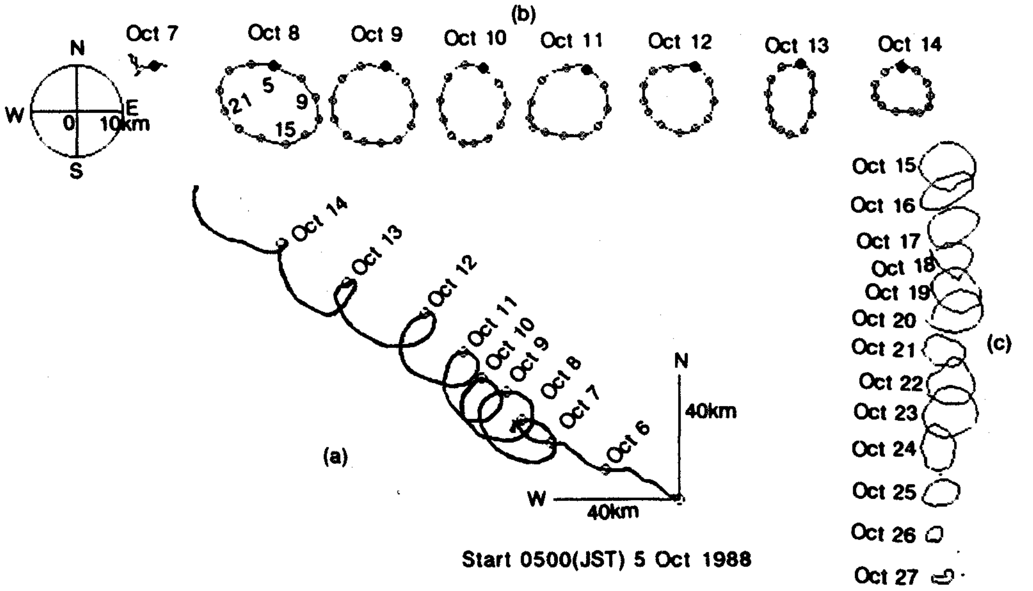

Fig. 5. Progressive vector diagram (a) from current records at 50 m depth (center), and that on each day (b) and (c) after subtracting the daily mean velocity on 7–27 October 1988 (from the upper left to the lower right).

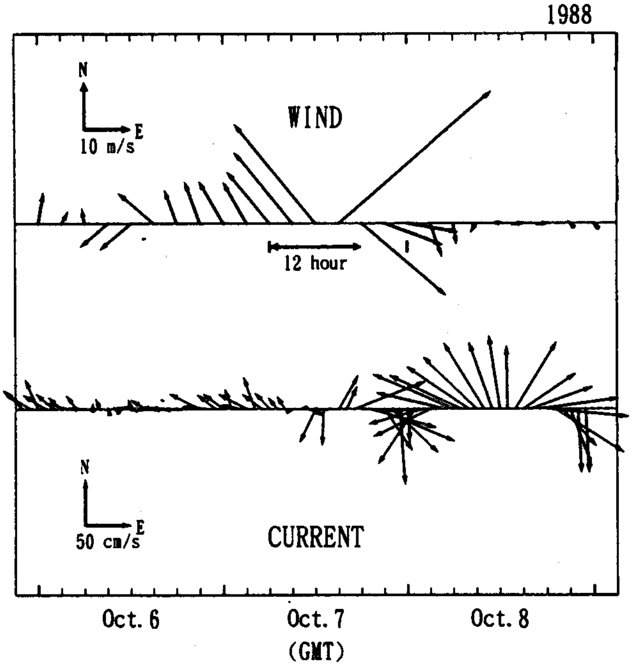

Fig. 6. The wind from the JMA Buoy at 29°N and 135°E and the hourly current velocities at 50 m depth on 6–8 October.

maximum wind was 84.5 knot from 230° at 1800Z. The current began to rotate clockwise from 1800Z. The clockwise turn of the wind in three hours from 1800Z to 2100Z is considered to be the most effective for the excitation of the inertial oscillation.

4. Deep Mixing by the Typhoon

Figure 7 shows temperature at 1 m, 50 m, and 100 m, wind speed, and atmospheric pressure measured at 3 hour interval from the Ocean Data Buoy moored at 29°N and 135°E in the Shikoku Basin (Japan Meteorological Agency, 1990). The temperature at 1 m decreased from 27.5°C at 1500Z on 7 October to 24.4°C at 1800Z when the Typhoon 8824 approached. On the other hand, temperature at 50 m increased from 22.1°C at 1500Z to 25.5°C at 1800Z on the day. A mixed layer was formed by the wind stirring. Temperature at 100 m also increased from 19.8°C at 1500Z to 22.6°C at 2100Z on the day, and it decreased rapidly to 19.3°C at 0000Z on 8 October. The wind speed of 84.5 knot (about 43.5 m s^{-1}) was the maximum at 1800Z on 7 October. The air pressure of 956 hPa was the minimum at 1800Z on 7 October.

Figure 7 shows that vertical heat transfer is a dominant process for the temperature change in the upper ocean during the typhoon. An estimation of the vertical heat transfer was attempted by assuming the temperature of the water column to be represented by the observed temperature at three discrete depths. Figure 8 shows the temperature change in three hours during the typhoon. We assume that the value at 1 m represents temperature from 0 to 25 m depth, the value at 50 m does from 25 m to 75 m, and the value at 100 m does from 75 m to 125 m. Figure 8 clearly shows that the temperature change is different before and after the maximum wind. Before the maximum wind, temperature in the upper 25 m decreased, and it increased in the lower layer.

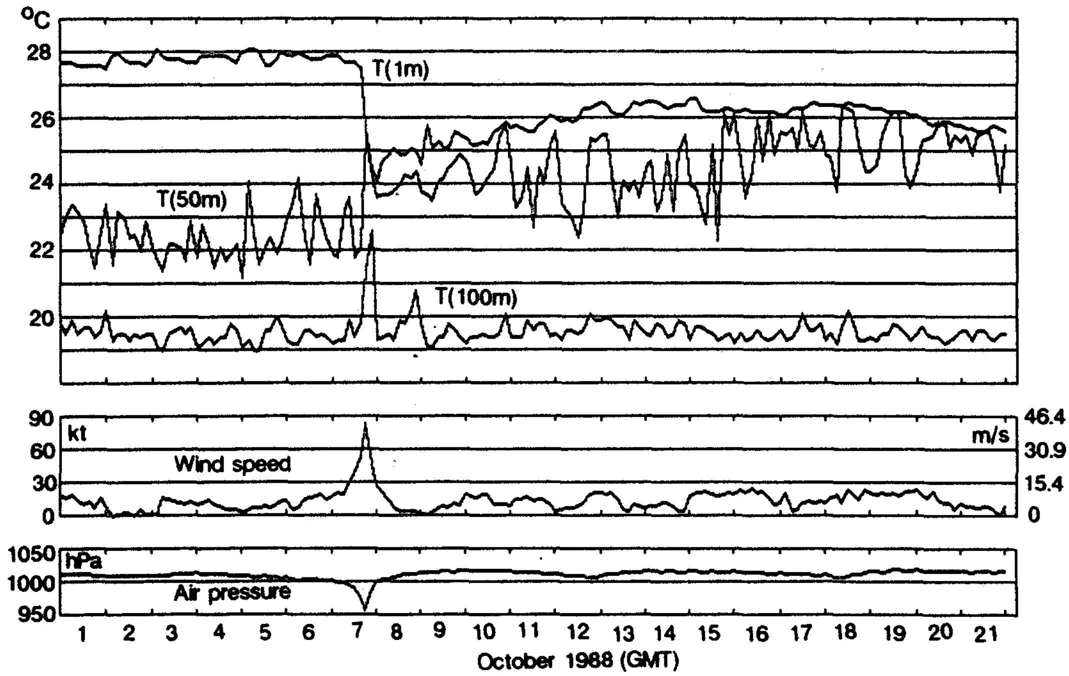

Fig. 7. Temperature at depths of 1 m, 50 m, and 100 m, wind speed and air pressure observed every three hours from the Ocean Data Buoy moored at 29°N and 135°E.

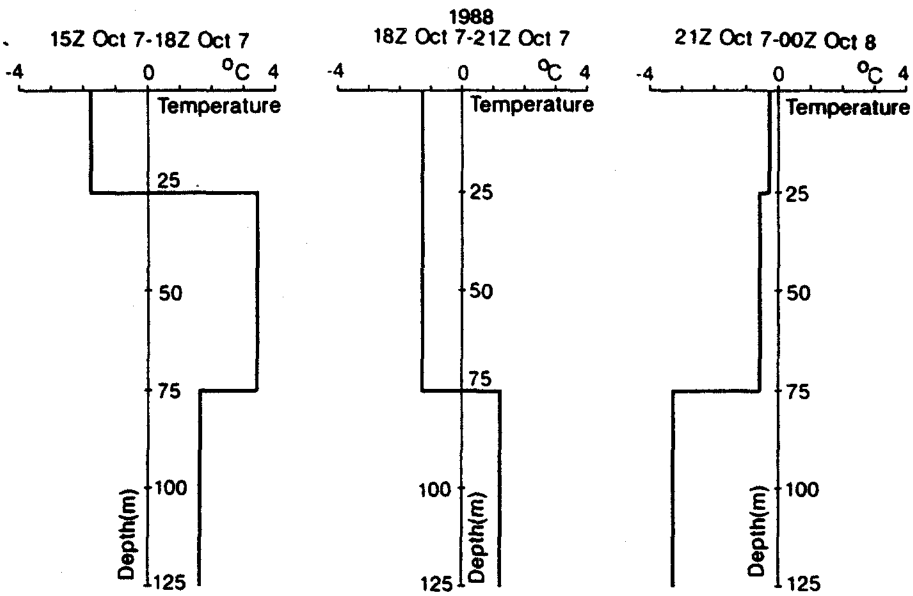

Fig. 8. Vertical profiles of temperature changes in three hours estimated from temperature records at 1 m, 50 m and 100 m depths from the Ocean Data Buoy moored at 29°N and 135°E.

During the maximum wind, temperature decreased in the upper 75 m and it increased in the lower layer. After the maximum wind, heat loss is occurred at the whole layer. Temperature at 100 m was nearly the same before and after the typhoon. On the other hand, the temperature at 1 m decreased and the temperature at 50 m increased after the typhoon.

A vertical heat transfer dominated before and during the maximum wind. The temperature changes of 2°C in the layer 25 m thick and 1.3°C in the layer 75 m thick correspond to (2–4) × 10^8 J, and the heat transfer averaged over 3 hours is 19–37 kW m^{-2}. The vertical heat transfer is 40–78 times as large as that of the winter cooling of 473 W m^{-2} in the Kuroshio region (Otobe, 1989).

5. Summary

A surface buoy was moored in the Shikoku Basin from 20 April to 2 November 1988 at 28°48′ N and 135°01′ E where the water depth was 4900 m to measure temperature and velocity in the upper 150 m. The buoy shifted about 30 km to southwest on 8 October 1988, and the instruments were damaged by the typhoon 8824 with a maximum wind speed of 43.5 m s^{-1}. An analysis of the records of temperature at 0.5 m and velocity at 50 m obtained by the buoy, and the data from Ocean Data Buoy of Japan Meteorological Agency at 29°N and 135°E was made. Main results of this study may be summarized as follows:

(1) A small buoy of 1.1 m diameter is operated safely under the strong wind of a typhoon. The loss of thermometers was caused by breaking of tying thread. An attachment device is requisite for a long term mooring observation.

(2) The surface temperature was a maximum in mid-July. It was decreased by 2°C when the typhoon approached, and the low temperature was kept after the typhoon. The mean current at 50 m depth was 15.3 cm s^{-1} to the west. A large velocity fluctuation was dominant in May 1988.

(3) The inertial oscillation with the maximum speed of 80 cm s^{-1} at 50 m depth was excited by the clockwise rotation of the typhoon wind and it endured for about 20 days.

(4) The typhoon mixed the upper ocean down to 100 m, and vertical heat transport was estimated from temperature records at Ocean Data Buoy of JMA to be 19–37 kW m^{-2}.

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