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Short Contribution

Heat Content Change in the Surface Isothermal Layer of a Warm Core Ring in the Sea East of Japan

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Heat content change in the surface isothermal layer of a typical warm core ring in the sea east of Japan is described based on approximately 90 CTD profiles obtained by one profiling float. Erosion of the seasonal thermocline and development of a surface isothermal layer from the mid-summer to the early winter of 1999 are clearly seen. While heat content change between two consecutive profiles with a 35-hour time interval is much noisier, its 10-day running mean is consistent with net surface heat flux, indicating that surface heat flux dominates the temporal heat content change in the surface isothermal layer in the warm core ring.

Keywords:
· Mixed layer,
· isothermal layer,
· heat flux,
· warm core ring,
· the sea east of Japan,
· profiling float.

1. Introduction

The upper ocean affects atmospheric phenomena by storing heat and later releasing it to the atmosphere through the surface. A better understanding of the upper ocean thermal structure and its variation is therefore a key to improving numerical weather prediction. Despite this, only a few studies have described the temporal variations of the upper ocean thermal structure based on observations in the seas adjacent to Japan, where the rough state of the sea in winter, in particular, makes continuous oceanographic observations difficult. One such result is an intensive marine meteorological and oceanographic study conducted by the Japan Meteorological Agency (JMA) from 1950 to 1953 at the Ocean Weather Station "Tango" in the south of Japan (29°N, 135°E). Kurasawa *et al.* (1983) described the variation of ocean heat content and surface heat flux at station Tango at various time scales, based on the JMA's observational data, and evaluated the contribution of surface heat flux and oceanic heat convergence to the variation of heat content in the surface layer. Another study comprises the surface mooring observations located in the vicinity of station Tango during the Ocean Mixed Layer Experiment (OMLET) in 1988–1991. Otobe *et al.* (2003) presented the result of the temperature observations and examined the heat balance based on the OMLET mooring data, describing variation of ocean heat convergence in relation to the fluctuation of the Kuroshio axis.

A new ocean observing technology, the profiling float, has enabled continuous oceanographic observations to be done, even in a rough sea. One of the greatest benefits of the profiling float is an enhanced ocean CTD profile acquisition capability at regular intervals over several years in a cost-effective way in support of a better description of the variation of the upper ocean thermal structure. The profiling float data are increasingly widely used for studies of upper ocean phenomenon (e.g. Oka and Suga, 2003; Ohno *et al.*, 2004; Sato *et al.*, 2004).

A profiling float was launched in the sea east of Japan in July 1999. The float stayed in a warm core ring for about four months and acquired about 90 CTD profiles in the ring. Here we describe variations of the upper ocean thermal structure in the warm core ring based on the profile data, resulting in a comparison between temporal heat content change in the surface isothermal layer and net surface heat flux.

2. Data and Method

An APEX profiling float 29014 (a unique identifier for a profiling float assigned by the World Meteorological Organization) was launched in the sea east of Japan on July 29, 1999 during a Japanese project named "Studies on Optimum Design for ARGO (SODA)". The float was equipped with a FSI CTD sensor and measured more than 200 profiles in the upper 400 db layer at intervals of 35 hours until it ceased transmitting data on August 26, 2000. The observation interval was set to acquire the maximum number of profiles during the project duration, and no oceanographic interest was taken into considera-

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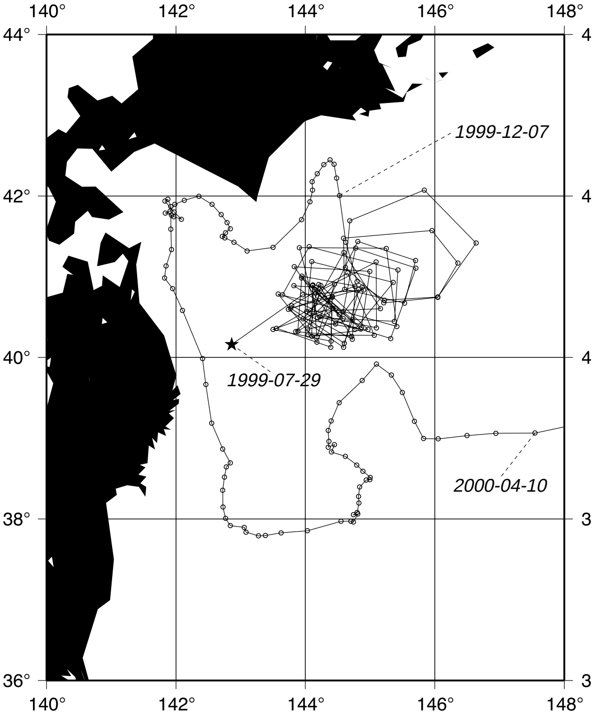

Fig. 1. Trajectory of profiling float 29014. Launch position is denoted by a star.

tion. The vertical resolution of each profile was 5 db in the upper 25 db layer and 10 db below 25 db depth. The profile data of float 29014 used in this study were downloaded from the US Argo Global Data Assembly Center (GDAC) server. Each temperature profile was linearly interpolated with 1 db interval.

The bottom of the isothermal layer is defined as the deepest depth at which the temperature difference from the surface (5 db) does not exceed 0.05°C. The criterion of 0.05°C is stricter than that of 0.5°C used in recent studies, such as those of Oka and Suga (2003) and Sato *et al.* (2004). This is because our intention is to make a precise evaluation of temporal heat content change. A temporal heat content change estimated from the averaged temperature difference of 0.1°C in the 50 m layer in 35 hours is about 170 W/m^2. This is comparable to 50% of the climatological surface heat flux in the area in summer and autumn and is not negligible in terms of this study. We therefore employ the criterion of 0.05°C to exclude possible contamination of heat content change caused by small temperature variation in the surface layer. The accuracy of the sensor (0.002°C) and the use of data measured with a single sensor allow such precise comparison. Salinity profiles obtained with the float are not used because the float did not provide good salinity profiles (Japan Marine Science Foundation, 1999).

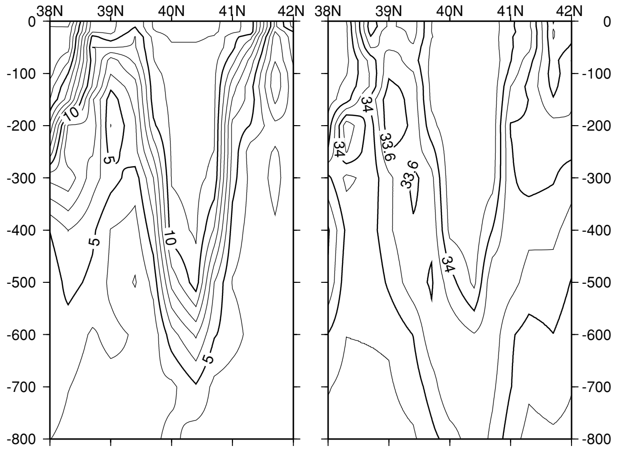

Fig. 2. Temperature (left) and salinity (right) vertical sections along 144°E in May 1999 observed by R/V *Kofu Maru*. Data from Hakodate Marine Observatory (1999).

Temporal heat content change in the surface isothermal layer H is given by

$$H = C_p(T_2 - T_1)P/(t_2 - t_1)\ g, \tag{1}$$

where C_p is specific heat at constant pressure, P the pressure at the deeper bottom of the isothermal layer of the consecutive two temperature profiles, T_1 and T_2 average temperature from the surface to the depth P at time t_1 and t_2 respectively, and g the acceleration due to gravity.

Net surface heat flux (Q) is the sum of short-wave radiation flux (Q_s), sensible heat flux (Q_h), latent heat flux (Q_e) and long-wave radiation flux (Q_b). Here a positive Q value corresponds to heat gain of the ocean. In order to compare the temporal change of the isothermal layer heat content between two consecutive profiles with a profiling interval of 35 hours, hourly components of Q are estimated first in the following manner. An estimation of the daily amount of global solar radiation based on the Japanese Geostationary Meteorological Satellite (GMS5) observation is used to infer hourly Q_s at the float position, by assuming that the diurnal cycle of Q_s is at a maximum at local noon and that sunrise and sunset are at 06:00 and 18:00 local time, respectively. Hourly Q_h and Q_e are calculated from the surface meteorological parameters and the water temperature at the surface (5 db) of the float profile by applying Kondo's aerodynamic bulk formulas (Kondo, 1975). The surface meteorological parameters are derived from an operational numerical atmospheric analysis of the JMA (GANAL). Hourly Q_b is calculated from the meteorological parameters from GANAL, the 5 db water temperature, and the interpolated total cloudiness measured by GMS5, applying the formulas of Clark *et al.* (1974). Average Q during the profil-

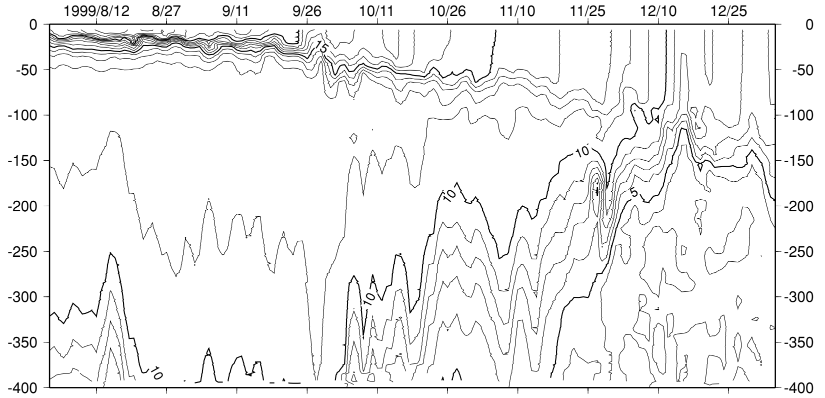

Fig. 3. Temperature profile time series acquired by profiling float 29014 from the start of its mission (July 29, 1999) to the end of December 1999.

ing interval is calculated as the sum of the average of the hourly Q_s, Q_h, Q_e and Q_b during each 35-hour interval.

3. Results

3.1 Movements of the profiling float 29014

Soon after launch, the float was captured in a warm core ring located around 41°N, 144°E with a diameter about 150 km, which was detached from the Kuroshio Extension at around 37°N, 144°E in the summer of 1998 and moved to the north. The float drifted clockwise inside the ring for about four months until it was released from the ring southeast of Hokkaido in early December 1999. After release, the float drifted into the Oyashio water area and moved along the south coast of Hokkaido and the northeast coast of Honshu Island (Fig. 1). In this study, we focus on the period from the launch to early December 1999 during which the float stayed in the ring. In the first two months of the relevant period, the ring was located around 40.5°N, 144°E. In October 1999, it moved northeastward to a location around 41.5°N, 145.5°E in late November, just before it was released from the ring.

3.2 Characteristics of the warm core ring

The warm core ring that captured the float had a layer of homogeneous water developed by vertical mixing due to surface cooling in the winter of 1998/1999. In the hydrographic section along 144°E obtained by R/V *Kofu Maru* in May 1999 (Fig. 2), the water layer is found around 40°N–41°N from the surface to about 400 m depth with temperature and salinity of around 11°C and 34.3, respectively. The water layer was relatively warm and saline in the region, where relatively cold and fresh Oyashio water extends from the northeast, and sharp temperature and salinity fronts were formed at the edge of the ring. These are typical characteristics of warm core rings (or large-scale anti-cyclonic eddies) in the sea east of Japan (e.g. Kawai, 1972), and are similar to the characteristics of the warm core ring 86B in April 1987, after the first winter (Yasuda *et al.*, 1992).

3.3 Variation of temperature in the surface isothermal layer of the warm core ring

The temperature profile time series acquired by the float clearly shows the decay of the seasonal thermocline and the development of a surface isothermal layer from mid-summer to early winter, 1999 (Figs. 3 and 4). In August and September, the thickness of the isothermal layer was 10–15 meters. It gradually deepened in October and November, reaching 70 meters when the float was released from the ring at the beginning of December. The highest temperature in the layer was 24°C, which was observed in the middle of August. It fell gradually from late August to the beginning of December, finally reaching 12°C.

3.4 Comparison between temporal heat content change in the surface isothermal layer and surface heat flux

Because a warm core ring is an isolated water body, it is expected that temperature variation of the surface isothermal layer inside the ring corresponds to heat flux through the ocean surface. It was on this viewpoint that a comparison between temporal heat content changes in the isothermal layer and the surface heat flux was made. The magnitude of the heat content change between two consecutive profiles is several times as large as that of the average surface heat flux during the profiling interval, and the time series of the heat content change is much noisier than that of the heat flux (Fig. 5, upper). On the other hand, running means of 7 profiling cycles (about 10 days) of the heat content change and the heat flux show a similarity from early August to November 26, 1999 (Fig.

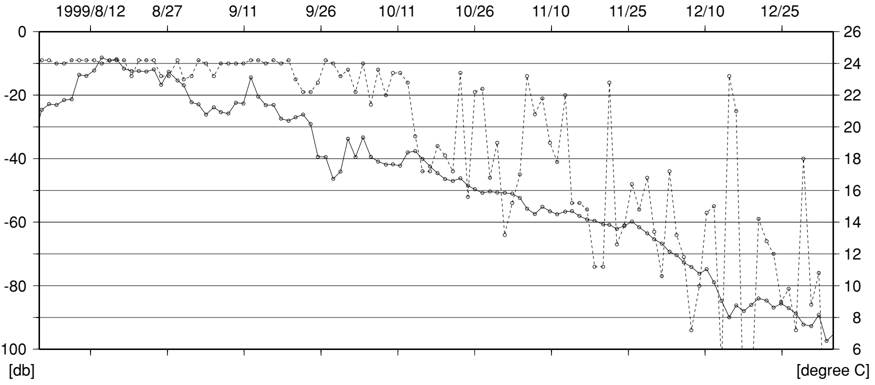

Fig. 4. Time series of isothermal layer depth (dashed line, db) and temperature in the layer (solid line, °C). Isothermal layer depth is defined as the deepest depth at which temperature difference from the surface (5 db) temperature does not exceed 0.05°C.

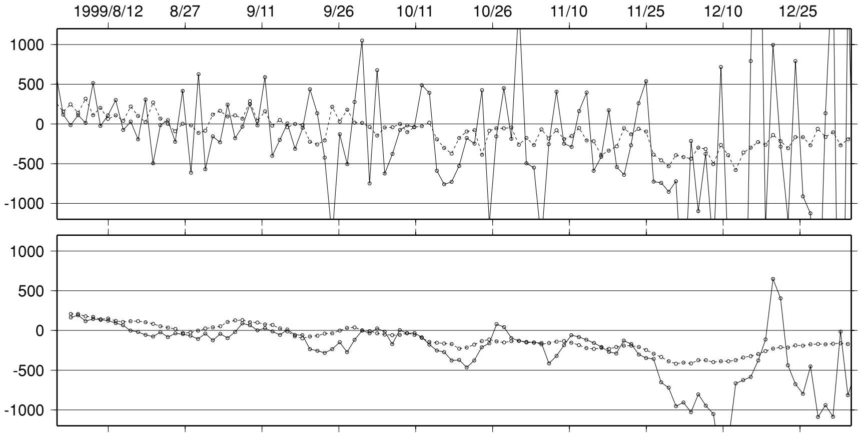

Fig. 5. Time series of heat content change in isothermal layer (solid line) and average heat flux through sea surface (dashed line) between two consecutive profiles (upper), and their seven cycles running means (lower). Positive heat flux corresponds to heat gain of the ocean isothermal layer. A 7-cycle running mean corresponds to about a 10-day running mean. Unit is W/m^2.

5, lower), when the float remained in the ring. After November 26, when the float came closer to the edge of the ring, released from the ring, and drifted into the Oyashio water area, the heat content change is significantly large and is no longer comparable to the heat flux.

4. Summary and Discussion

The variation of upper ocean thermal structure in a typical warm core ring in the sea east of Japan has been described. The erosion of seasonal thermocline and the development of a surface isothermal layer from the midsummer to the early winter of 1999 are clearly seen. While the magnitude of short-term (35-hour) heat content change is much greater than that expected from the surface heat flux, and the time series of heat content change is much noisier, their 10-day running means are similar.

One of the possible causes of the discrepancies between the short-term heat content change and the heat flux is an error in estimating the heat flux. The diurnal cycle of sea surface temperature is not taken into consideration when the net surface heat flux is computed. The 35 hours average heat flux may therefore contain aliasing error from the diurnal cycle. Nor is any consideration given to the motion of the bottom of the isothermal layer associated with the internal tidal wave, which may cause another aliasing error.

Other possible causes of the discrepancies are entrainment and horizontal processes, such as advection and mixing (Hanawa and Toba, 1981). Because entrainment through the bottom of the isothermal layer is taken into account in this study by averaging each profile from the surface to the deeper bottom of the isothermal layers of two consecutive profiles, horizontal processes could be a major cause of the discrepancies. In Fig. 3, changes of the main thermocline depth, which is indicated by the 10°C isotherm, are clearly seen in October and November. Judging from the structure of the warm core ring in Fig. 3, it is considered that the float moved from the central part of the ring to near the edge in the two months. This means that the float did not stay in the same water column all the time and that there is a probability that the float switched from the water column to a neighboring one. Switching to a neighboring water column gives the same result as horizontal advection, and it can cause the inconsistency of the heat content change with the heat flux on a short time scale.

The similarity of 10-day running means indicates that the possible errors and the effects of horizontal processes mentioned above can be reduced by smoothing. The heat content change between neighboring water columns can also be suppressed. This means that the difference of water properties between the neighboring water columns is negligible in a warm core ring, when we discuss the average heat content change in the surface isothermal layer on a time scale longer than 10 days. Thus, it is indicated that the surface heat flux dominates the temporal heat content change in the surface isothermal layer in the warm core ring on a time scale longer that 10 days.

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