Variability of the Upper Ocean at the Equator, 156°E, Observed by R/V Hakuho-Maru during TOGA-COARE IOP

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Abstract

Variations of temperature and salinity in the upper ocean are observed by the R/V Hakuho-Maru, when she stayed at the fixed station at the equator, 156°E, for 15 days in November 1992. The weather was calm for most of the period, and the temperature of the surface mixed layer increased slightly. Analyses suggest that heat fluxes through the sea surface and meridional advection explain most of the change of the heat storage in the mixed layer. EOF and isopycnal analyses suggest wave motion and intrusion of off-equatorial water are the main processes for the variation of temperature and salinity in the upper ocean, along with fluxes through the sea surface and mixing process in the mixed layer.

1. Introduction

The main objective of the oceanic observation in the TOGA-COARE is to monitor responses of the upper ocean to variations in the atmosphere. In the framework of the international operation plan of the TOGA-COARE, the station assigned to the Japanese scientific group was located at the equator, 156°E.

As the equator is the place where the horizontal component of Coriolis force vanishes, many phenomena, such as Yoshida jets, occur in the narrow zone around it (Yoshida, 1959). The geographic center of main observations in the intensive observation period of the TOGA-COARE is set away from the equator (2°S, 156°E) so that the locations represent the general tropical ocean. Yet the behavior of the air-sea coupled system right at the equator is, also crucial for understanding the onset of ENSO events. For this reason, two Japanese research vessels, Hakuho-Maru and Natsushima stationed at the equator in November 1992 and February 1993, respectively.

The phenomenon we are especially interested in is a “westerly burst”, in which a westerly wind of

about 10 m/s continues for about 10 days. It has been discussed that the “westerly burst” may trigger unstable air-sea interactions which lead to an El Niño event (McPhaden *et al.*, 1992; Philander *et al.*, 1984). Unfortunately, throughout the period no such event occurred and the weather stayed calm. Nonetheless observations of an air-sea coupled system under a calm condition is worthwhile for a good understanding of the air-sea interactions.

The R/V Hakuho-Maru stayed at the equator, 156°E, for 15 days from Nov. 12 to 26. During the period, the upper 1000 meters of the ocean was observed by the CTD (Sea-Bird 9) eight times a day in two enhanced operation phases (Nov. 15 to 19 and 23 to 26) and 4 times a day in the rest of the period. We also made an Omega-sonde launching, air turbulent flux measurement, and an ocean microstructure measurement. Once a day (around 1:00 am UTC), sea water was sampled using rosette samplers at 24 levels in the upper 2000 meters.

Routine surface meteorological data are obtained by a Hakuho-Maru Marine Meteorological Observation System and recorded digitally at one minute intervals, during the whole cruise, including the period the Hakuho-Maru stayed at the Equator. Using the data, we calculate the heat fluxes through the

(a)

Fig. 1. Temperature (a) and Salinity (b) distribution in the upper 500 m of the ocean measured by the CTD at the equator, 156°E.

sea surface with a bulk formula (Otohe, 1993).

2. General features

Temperature and salinity in the upper 500 meters are shown in Fig. 1. In this period, sea surface temperature is slightly higher and the depth of 20°C isotherm is about 20 m shallower than in the normal condition. Both temperature and salinity show complicated vertical structure of scale of a few ten's of meters, with multi-steps for temperature and multi-peaks for salinity. These structures changed slowly during the period. Judging from these, the lifetimes of these structures are compatible with or longer than the observation period.

The temperature in the surface mixed layer increased by about 0.5 degree during the period, while the mixed layer thickness decreased by about 10 m.

These changes are consistent with a sea surface weather condition where both convective activities in the atmosphere and sea surface wind are weak most of the time (Fig. 2). On the other hand, the decrease in salinity of the surface mixed layer contradicts to a salinity change that was expected from little precipitation. It suggests that advection can not be ignored. The budgets of heat and fresh water are examined in the next section.

3. Heat and Freshwater budgets in the mixed layer

From sea surface meteorological parameters and short- and long-wave radiation fluxes continuously observed by the Hakuho-Marui Marine Meteorological Observation System, we calculated the heat fluxes through the sea surface, using Payne's ta-

(b)

Fig. 1. (Continued)

ble (Payne, 1972) and an aerodynamic bulk method (Kondo, 1975). Figure 3 shows the variations of the total heat flux and its components during the period. Downward short-wave radiation and latent heat from the ocean are dominant among the components of the total heat flux. Both components roughly compensate each other in a daily average, leaving an average of 44 W/m^2 going into the ocean during the period. In the first 2 days and the last 4 days, when the station experienced a weak atmospheric disturbance, the daily average of the total heat flux dropped to nearly zero. In these periods, both an increase of outgoing latent heat and a reduction of incoming short radiation contributed to decrease the total heat flux.

We defined integrated temperature (IT) using the following equation,

$$IT = \int_{-h}^0 \rho C T dz, \quad (1)$$

where T is sea water temperature, ρ and C are sea water density and the specific heat of the sea water ($\rho C = 4.2E6 \text{ J/m}^3$). h is the depth of integration, which is roughly the depth of the upper mixed layer (75 m). Figure 4 shows the variation of IT in the upper 75 m, which roughly represent the upper mixed layer. Figure 4 also shows the change of IT calculated from the sea surface heat flux, on the supposition that all of the sea surface heat flux is used to increase the temperature in the upper 75 m. Although the magnitude of the variation is only about a half of that of the real IT and the detail of the daily variations does not agree, general features are well reproduced. The difference can be attributed either to errors in the bulk calculation, or to some

Fig. 2. Wind speed (dashed line) and precipitation (solid line) observed on the R/V Hakuho Maru during her stay at the fixed station. Atmospheric convective activities stayed weak, except for the beginning and ending portion of the period.

Fig. 3. Total heat flux through sea surface and its components during the observation.

other components such as horizontal heat transport or entrainment from the deeper ocean. To examine the order of magnitude of IT variation due to horizontal advection, it is estimated from the meridional component of the current at 2°N and 2°S along the same longitude measured by ADCP moorings (Kutsuwada and Inaba, 1994) and temperature measured by ATLAS moorings (Hayes *et al.*, 1991) at the same locations, as follows.

Fig. 4. Anomaly of integrated temperature (IT) in the upper 75 m of the ocean (solid line), accumulation of surface heat flux calculated using a bulk formula (dashed line), and change of IT expected from meridional advection estimated from ADCP mooring and TAO data at 2°N and 2°S , 156°E (dash-dot line).

Fig. 5. Anomaly of integrated salinity (IS) in the upper 75 m of the ocean (solid line), change of averaged salinity expected from fresh water flux through the sea surface (dashed line), and that expected by meridional advection (dash-dot line).

$$\frac{\partial IT}{\partial t} = \int_{-h}^0 \rho C \frac{(T_n - T_s)(V_n - V_s)}{2L} dz, \quad (2)$$

where L is the distance between 2°N and 2°S . T_s , T_n , V_s and V_n are the temperature and meridional current at 2°S and 2°N , respectively. The change of IT due to the meridional advection is plotted in Fig. 4, showing the same tendency to the difference between the IT variation and that estimated from the surface heat flux. Although it is not large enough to fill the gap completely, agreement is reasonable considering possible errors in those calculations. The

Fig. 6. (a) The first two EOF's of the temperature in the upper 500 m of the ocean, and variations in time of their score. (b) Same as (a), except for salinity.

effect of zonal advection is not considered here, but this result suggests that most of the variation of IT in the surface mixed layer can be explained by the heat flux through the sea surface and meridional advection.

Similar budgets are examined for the integrated salinity (IS) in the surface mixed layer (Fig. 5), which is defined by

$$IS = \int_{-h}^0 S dz, \tag{3}$$

where S is salinity. In this case, the mixed-layer depth h is also assumed to be 75 m. The change of IS due to a sea surface fresh water flux is calculated on the assumption that the flux is only used for the variation of the upper 75 m. In this case, fresh water fluxes through the sea surface are calculated from precipitation measured by an optical rain gauge on the Hakuho-maru (Suzuki *et al.*, 1994) and evaporation based on the bulk formula. As we do not have salinity data for sites to the north and

SPECTRUM (temperature)

EOF1(solid line), EOF2(dash line)

Fig. 7. Power spectrum of the scores of the first two EOF's of the temperature. The error bar indicates 95 % confidence interval.

south of this location, we assumed the difference of salinity between 2°S and 2°N to be constant (at 2°S 0.1 psu higher than at 2°N), based on the climatological salinity distribution. Calculations do not agree with the observed change of IS . Especially, after Nov. 18, the integrated salinity began decreasing, while both the surface flux and the meridional advection indicate an increase for the next two days.

There are too many possible sources of errors causing this difference. The estimate of meridional advection is one thing. Zonal advection may not be ignored. The precipitation measured at the ship did not necessarily represent the fresh water flux in the area, as the spatial scale for rainfall is only of the order of kilometers in the tropics. The order of magnitude of those components, however, is the same as the variation of the integrated salinity in the surface mixed layer. This suggests that both the flux through the sea surface and the advection are playing some rôles in the fresh water budget.

4. EOF analysis of the density, temperature and salinity distribution

We calculate EOFs of the density, temperature and salinity distribution in the upper 500 m. (These EOFs are calculated as eigen vectors of the correlation matrix.) Figure 6 shows the first two EOFs for the temperature and salinity. The first EOF of temperature accounts for 39.5 % of the variance (compared to 16.2 % for the second EOF) and the first EOF of salinity accounts for 25.8 % of the variance (compared to 14.8 % for the second EOF). The first two EOFs for the temperature are nearly identical

Fig. 8. T-S diagram of sea water measured by all the casts of the CTD during the period. Crosses indicate sea water observed at 2°N, 156°E and circles indicate sea water observed at 2°S, 156°E. The Hakuho Maru observed at these stations early in Nov. 1992.

to those for the density (not shown), as is expected because density is mostly determined by temperature in the upper ocean in this area. It is not for the case for the EOFs for salinity. The variations in time series of those scores, however, are similar to each other. This suggests that a common mechanism is behind the temperature and salinity variations associated with each of the first two EOFs.

Variations on two time scales stand out in the score of the first EOF, namely a trend-like increase throughout the period, and a high frequency variation. The spectral analysis shows a peak at 2 days (Fig. 7). Kaneko (personal communication) found a peak in the spectrum of the current measured by ADCP moorings at 2°N and 2°S, 156°E. Takayabu and Nitta (1993) found that time scales of cloud clusters in the western tropical Pacific are around 3 days. This high-frequency variation found in the upper ocean may have a relationship to the cloud cluster variation. It appears that there is an oscillation with a period of around a half day. Unfortunately, the time resolution of the observation is not enough to resolve the time scale adequately.

There is a peak and a dip at around the depths

Fig. 9. Variation of temperature anomaly plotted in time vs. the potential density coordinate. The anomaly is the deviation from the average at the same density. The same figure for salinity (not shown) is nearly identical to this figure, as potential density is determined by temperature and salinity. Dashed line indicates a negative contour. (hatched area $< -0.2^{\circ}\text{C}$, dotted area $> 0.2^{\circ}\text{C}$).

of 100 m and 140 m, respectively, in the first EOF. They correspond to the slow change of the complicated structure in the thermocline, and do not correspond to the high frequency variation. This suggests a possibility that the first EOF is a combination of two rather independent motions. One is associated with wave motions with a time scale of 0.5–3 days and longer time scales. The other is a variation due to advection on longer time scales. The period of observation is not long, and they might not be separated in the EOF analysis.

5. Variation due to mixing and advection

Figure 8 is a T-S diagram of all the CTD observations in the period, and Fig. 9 shows an anomaly in temperature plotted in a potential density against time. As the potential density of sea water is determined by temperature and salinity, an anomaly in salinity is almost the same as the temperature anomaly shown in Fig. 9. As the vertical motion associated with waves does not change either the T-S relation or temperature and salinity at the same density surface, variations shown in these figures should be attributed to mixing or horizontal advection.

As is discussed in an earlier section, temperature and salinity changes in the surface mixed layer are likely due to fluxes through the sea surface and horizontal advection. For the lower layers, however, they

should be attributed mostly to the horizontal advection. In the area around the location, the meridional gradient of salinity is strong, so the possibility exists that they are intrusions of water from the north or south along the isopycnal surface.

6. Summary and remaining questions

The Hakuho-Maru observed the variation of the upper ocean at the equator in the western tropical Pacific, under calm atmospheric conditions, for about 15 days. The analysis suggests the variations caused by two factors.

The first is heat and fresh water fluxes through the sea surface and mixing in the surface mixed layer. In the period of observation, incoming solar radiation slightly exceeded outgoing latent heat and the temperature of the mixed layer increased slightly. Heat flux accounted for most of the change in integrated temperature in the mixed layer. On the other hand, the variations of salinity, derived from the fresh water flux through the sea surface and the advection, did not agree well with those of the integrated salinity.

The second is the horizontal advection. It is especially noticeable in the thermocline layer. Intrusions of water from the north and the south most likely cause the variations. Finally, there is vertical motion likely due to wave motion. The vertical motion

is energetic in two frequency bands, namely, 0.5–3 days and longer than 10 days. However, what kind of waves they are, Kelvin waves coming from the west or more local gravity waves, remains to be determined.

Fortunately, there were many other observations around the area at that time. If we can combine those data, it should be possible to answer many of the remaining questions.

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References

- Kondo, J. (1975): Air-Sea bulk transfer coefficients in diabatic condition. *Bound.-Layer Meteor.*, **9**, 91–112.
- Hayes, S.P., L.J. Mangum, J. Picaut, A. Sumi and K. Takeuchi (1991): TOGA-TAO: a moored array for real-time measurements in the tropical Pacific ocean. *Bull. Amer. Meteor. Soc.*, **72**, 339–347.
- Kutsuwada, K. and H. Inaba (1994): Long-Range Measurement of surface Oceanic Current in the Western Equatorial Pacific by Acoustic Doppler Current Profiler. *submitted to J. Meteor. Soc. Japan*.
- McPhaden, M.J., F. Bahr, Y. du Penhoat, E. Firing, S.P. Hayes, P.P. Niiler, P.I. Richardson, and J.M. Toole (1992): The response of the western equatorial Pacific ocean to westerly wind bursts during November 1989 to January 1990. *J. Geophys. Res.*, **97**, 14289–14303.
- Otobe, H. (1993): Sea surface heat budget at the fixed station 156°E on equator, in Preliminary report of the Hakuho Maru cruise KH-92-5
- Payne, R.E. (1972): Albedo of the sea surface. *J. Atmos. Sci.*, **29**, 959–970.
- Philander, S.G.H., T. Yamagata and R.C. Pacanowski. (1984): Unstable air-sea interactions in the tropics. *J. Atmos. Sci.*, **41**, 604–613.
- Suzuki, T., D. Abe, K. Takeuchi (1994): The validity of optical precipitation sensor on the tropical ocean. *submitted to J. Meteor. Soc. Japan*.
- Takayabu, Y.N. and T. Nitta (1993): 3–5 day Day-Period disturbances Coupled with Convection over the Tropical Pacific Ocean. *J. Meteor. Soc. Japan*, **71**, 220–246.
- Yoshida, K. (1959): A theory of the Cromwell Current and of the equatorial upwelling. *J. oceanogr. Soc. Japan*, **15**, 154–170.

TOGA-COARE 期間中に白鳳丸で観測された赤道、東経 156 度における 海洋上層の変動

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1993 年 11 月、白鳳丸により、赤道、東経 156 度の定点において海洋上層の連続観測が行われた。この期間、ほとんど天候は静かで、海洋混合層の水温はわずかに上昇した。混合層における貯熱量の増加の大部分は海面を通じての熱流量との南北の移流によって説明されることが示された。また、EOF 解析や等密度解析により、海洋上層 500 m までの温度、塩分の変化に関しては、海面でのフラックスと混合過程の他、内部波と等密度面に沿っての南北からの海水の貫入が主な課程であることが示唆された。