Short Contribution

Japan-Equator XBT Sections in Late November 1989 and in Early December 1991

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A comparison between Japan-equator XBT sections along 150°E in late November 1989 and along 140°E in early December 1991 is made. The warmest surface water above 29°C diminished to the south of 2–4°N and the surface mixed layer noticeably decreased in thickness in the equatorial region in December 1991; besides, the North Equatorial Countercurrent was intensified. This is considered to be a manifestation of changes in the surface layer of the western equatorial Pacific in the mature phase of El Niño.

1. Introduction

The upper layer (0–100 m) stratification of the western equatorial Pacific was frequently characterized by a thick isothermal layer and warming of sea surface may result in a negative feedback mechanism that is an essential part of the ENSO (El Niño-Southern Oscillation) cycle (Lukas and Lindstrom, 1991; Delcroix et al., 1992). Such decreases in the mixed-layer temperature and thickness in the western equatorial Pacific are known to be a signature of El Niño (Masuzawa and Nagasaka, 1975; Kawabe, 1985). Equatorial current system varies seasonally according to variation in trade winds; when the trades are weaker and in a more northerly position, both the North Equatorial Current (NEC) and the North Equatorial Countercurrent (NECC) are strong (Wyrtki, 1974). During the El Niño of 1982–83, a drastic change in equatorial currents was produced. In the central Pacific, an increased transport in the NECC reached a peak of 60–70 Sv in November 1982 and fell to less than 2 Sv by July 1983 (Kessler and Taft, 1987). The Equatorial Undercurrent (EUC) at 159°W decayed during August 1982, partially reversed during September and rapidly reappeared in January 1983 (Firing et al., 1983). These variations in NECC and EUC were deduced from XBT study in the western Pacific as well (Picaut and Tournier, 1991).

Conditions in the western tropical Pacific Ocean during the 1986–87 El Niño and the ensuing 1988 La Niña were observed more thoroughly than during any previous ENSO cycle (e.g., McPhaden et al., 1990; Delcroix et al., 1992). Zonal currents in the upper 100 m surface layer responded to zonal wind variations typically within a week; in December 1986, strong westerly winds at and to the west of 165°E increased the net eastward transport of warm water to an extreme of 88 × 10⁶ m³s⁻¹. During the mature phase of January to October 1987, anomalous
eastward flows were again observed about the equator on cruises in July and September; this was the result both of local forcing by westerlies and of a first meridional mode Rossby wave propagating westward (Delcroix et al., 1992). In contrast to surface currents including the NECC, zonal currents in the thermocline below 100 m were less variable, but the EUC disappeared for 3–4 weeks in October to November 1987 at a time when the normal eastward directed zonal pressure gradient force reversed along the equator (McPhaden et al., 1990). Monthly variations of the 0/400 decibar dynamic height relative to the 1984–86 mean value computed from XBT profiles in the region 2°S to 2°N, 145–160°E showed a minimum during August–September 1987 and a maximum in March 1989 and returned to near zero by the end of 1989. In late 1987 through early 1989, the thermocline deepened and sharpened; the 20°C isotherm reached a maximum depth of 200 m in March 1989, when the warm pool (the surface layer $T > 28°C$) was 120 m thick. The trend during the remainder of 1989 was roughly toward the “normal” pre-1987 conditions, although the thermocline remained sharper and the warm pool thicker than during most of 1984–86 (Delcroix et al., 1992).

The above comprehensive analyses are centered on the equatorial region south of 20°N or 10°N. However, we are deeply concerned in variations of currents or thermal structures of the western tropical Pacific south of Japan as well. A long XBT section we made in early December 1991 clearly reveals El Niño signals. A previous section was taken in late November 1989. These sections occupied by Research and Training Vessel Umitaka-maru, Tokyo University of Fisheries began at 34°30’S, 140°E immediately south of Japan and extended to 1°S, 154°E in 1989 and to the equator along 140°E in 1991 (Fig. 1). Stations were occupied at intervals of 30’ in latitude with use of T-7 probes (manufactured by Tsurumi Seiki, Japan) to obtain temperature data down

Fig. 1. Cruise tracks of RT/V Umitaka-maru along 140–154°E from 23 November to 1 December 1989, along 140°E from 3 to 10 December 1991 and along 150°E from 12 to 15 December 1991.
to 800 m. In 1991, additional T-6 probe casts were made along 150°E from 7°30’ N to 2°30’ S. For depth determination of XBT records, we followed the maker’s instruction. Emery and Dewar’s (1982) analysis of the mean T-Z relation west of 165°E in the western equatorial Pacific indicates that longitudinal difference as much as 14° between 1989 and 1991 is not important.

As mentioned above, the thermal structure in the western equatorial Pacific in late November 1989 was not completely restored to the normal condition (Delcroix et al., 1992, Fig. 11); however, signals of neither El Niño nor La Niña appeared at that time. In 1991, Climatic Analysis Center (1991) reported a positive sea-surface temperature (SST) anomaly in the equatorial Pacific in April. This anomaly continued to develop and, in September 1991, oceanic conditions in the tropical Pacific indicated an occurrence of El Niño. In December 1991, the time of our observation, El Niño was intensified and the large SST anomaly exceeding 2°C was observed along the equator near 160°W.

The purpose of the present report is to reveal thermal structure in the western tropical Pacific in the ENSO event by comparison with the condition without an event. In the following analysis, the section is divided into three zones, south of 10°N, 10°N to 25°N, and north of 25°N, according to major current system, NECC, NEC and Kuroshio, respectively.

2. Equator to 10°N Region

In the western equatorial Pacific, the surface mixed-layer depth is not always identical to the isothermal layer depth because salinity stratification governs the surface mixed-layer thickness (e.g., Lukas and Lindstrom, 1991; Delcroix et al., 1992). We use a temperature decrease of 1°C from the surface to define the mixed-layer depth for practical convenience.

In 1989 (Fig. 2a), the surface mixed-layer temperature in this region is well above 29°C. The mixed-layer thickness is about 60–70 m from 10°N to 4°N and then gradually increases toward the south to reach a maximum value of 140 m at 0°30’ S (the thickest on the entire section). As mentioned in the introduction, this is a little warmer and thicker than 1984–86 means (e.g., compare with McPhaden et al., 1990, Fig. 1 and Delcroix et al., 1992, Figs. 6 and 11). In 1991, however, the mixed-layer temperature in this region decreased to less than 29°C; the water warmer than 29°C is limited to the south of 2°N on the 140°E section (Fig. 2b) and to the south of 4°N on the 150°E section (Fig. 2c). The mixed-layer thickness is about 30–50 m from 10°N to 2°30’ N at 140°E and about 30–60 m from 7°30’ N to 2°30’ N at 150°E; the thickest mixed-layer is found immediately south of 20°N.

A southward down slope of isotherms in the thermocline is observed near 5°N in both years. This slope reflects the eastward North Equatorial Countercurrent. In 1989, the NECC extends from 5°30’ N to 3°30’ N and isotherms of 11° to 28°C show a southward deepening. In 1991, the NECC on the 140°E section extends over almost the same latitudes (6°N to 3°30’ N) as in 1989 and it stretches north to 7°N along 150°E; isotherms with a southward slope are of 26°C to 8–9°C, a little colder than in 1989 (Table 1). The most noticeable differences are the bottom of isotherms with a southward down slope fell by about 50–200 m and the top of the thermocline was remarkably cooled in 1991. In addition, the thermocline was sharpened along 150°E and greatly increased in slope along 140°E in 1991. The downward stretching of the isotherm slope and the sharpening or the slope increasing of the thermocline clearly indicate intensification of the NECC. The temperature profile relating to the NECC in November 1989 does not differ essentially from the 1984–86 mean at 165°E (Delcroix et al., 1992, Fig. 6).

A vertical spreading of the upper isotherms is found in the NECC region and south. In 1989, the 29°C isotherm shows a slight ridge between 5°N and 2°30’ N and lower isotherms of 27°C
Fig. 2. Vertical temperature sections (a) at 140°-154°E from 23 November to 1 December 1989, (b) at 140°E from 3 to 10 December 1991 and (c) at 150°E from 12 to 15 December 1991.
and $28^\circ$C makes a trough. As a result, nearly homogeneous water, centered at $28^\circ$C, accumulates just above the sharp thermocline. In 1991, the $28^\circ$C isotherm shows a similar ridge, but the $24$–$27^\circ$C isotherms are almost horizontal forming a secondary thermocline at about 100 m. Between this secondary thermocline and the deeper primary thermocline is formed a thermostat centered at $21^\circ$C. This feature is also seen on the 150$^\circ$E section in 1991.

In 1989, deepening of isotherms for 12–15$^\circ$C is easily found at 200–300 m between 1$^\circ$N and 1$^\circ$S. This trough of isotherm is evidently associated with the eastward-flowing Equatorial Undercurrent. Just below the trough is a thermostat with a temperature of 11–12$^\circ$C and at depths of 300–350 m. This thermostat is analogous to that of the Equatorial 13$^\circ$C Water, which exists just below the thermocline within about 5$^\circ$ of the equator in the eastern Pacific (Montgomery and Stroup, 1962). The connection between the 11$^\circ$C thermostat noted here in the western Pacific and the Equatorial 13$^\circ$C Water is not immediately obvious; it is worth further investigation.

Unfortunately, the observation along 140$^\circ$E terminated at the equator in 1991. The equatorward deepening of the 12–15$^\circ$C isotherms is not found near the equator, suggesting that the EUC is weak or missing. On the 150$^\circ$E section, a weakened EUC is formed at almost the same latitudes and depths as in 1989; the thickness of the 11$^\circ$C thermostat is almost the same as in 1989.

A southward down slope of the 7–11$^\circ$C isotherms is clearly depicted immediately north of the EUC in 1989. This slope is associated with the North Subsurface (Equatorial) Countercurrent (NSCC) described by Tsuchiya (1975). The NSCC seems to be formed also in 1991 (for isotherms of 6–10$^\circ$C at 140$^\circ$E and below 12$^\circ$C at 150$^\circ$E). Direct current measurements with ADCP during WEPOCS II (the Western Equatorial Pacific Ocean Circulation Study) confirm the presence of NSCC at 143$^\circ$E in February 1986 and at 155$^\circ$E in January 1986 (Tsuchiya et al., 1989).
Table 1. Isotherms with a downward slope from north to south indicating the North Equatorial Countercurrent.

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<td>165°E</td>
<td>152–154°E</td>
<td>150°E</td>
<td>140°E</td>
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<td>Northern boundary</td>
<td>7°N</td>
<td>5°30'N</td>
<td>7°00’N</td>
<td>6°00’N</td>
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<tr>
<td>Southern boundary</td>
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<td>3°30’N</td>
<td>3°30’N</td>
<td>3°30’N</td>
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<td>Temperature (°C)</td>
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<td>28</td>
<td>26</td>
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<tr>
<td></td>
<td>Depth at northern boundary (m)</td>
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<td>77</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>Depth at southern boundary (m)</td>
<td>90</td>
<td>112</td>
<td>86</td>
</tr>
<tr>
<td>Bottom isotherm</td>
<td>Temperature (°C)</td>
<td>10</td>
<td>11</td>
<td>9</td>
</tr>
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<td></td>
<td>Depth at northern boundary (m)</td>
<td>250</td>
<td>224</td>
<td>311</td>
</tr>
<tr>
<td></td>
<td>Depth at southern boundary (m)</td>
<td>300</td>
<td>251</td>
<td>347</td>
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Main part of the thermocline

| Top isotherm (°C) | 26 | 26 | 22 | 19 |
| Bottom isotherm (°C) | 13 | 14 | 14 | 11 |
| Mean thickness (m) | 90 | 77 | 55 | 81 |
| Core isotherm (°C) | 19 | 20 | 18 | 15 |
| Depth at northern boundary (m) | 140 | 128 | 93 | 110 |
| Depth at southern boundary (m) | 180 | 198 | 195 | 237 |

Slope | 0.09 m/1 km | 0.32 m/1 km | 0.26 m/1 km | 0.46 m/1 km |

*Delcroix et al. (1992, Fig. 6).

### 3. 10°N to 25°N Region

The surface mixed-layer temperature decreases toward the north from 29°C at 10°N to 26°C at 25°N in 1989 and from 28°C to 25°C in 1991. The mixed-layer thickness is almost uniform at about 80 m in both years, except around 20°N in 1991. The general northward down slope of isotherms below about 17°C, clearly shown above 600 m from 10°N to about 28°N in both years, is identified as the westward-flowing North Equatorial Current. The 15°C isotherm level descends from 170 m at 10°N to 330 m at 25°N (0.10 m/1 km) in 1989 and from 150 m to 330 m (0.11 m/1 km) in 1991. Therefore, the NEC seems to be slightly intensified in 1991.

Superimposed on this broad current, a smaller-scale southward down slope of isotherms is found at all depths near 20°N. This slope is a permanent feature and is stronger in the shallower levels (say from 100 m to 300 m) as pointed out by Uda and Hasunuma (1969). The eastward flow associated with this slope is considered to be the Subtropical Countercurrent (SCC) (Yoshida and Kidokoro, 1967). The appearance of the current is quite different in two years. In 1989, SCC extends from 19°N to 20°N and its horizontal temperature gradient is about 2°C/(1° of latitude), while, in 1991, it extends from 19°N to 20°30’N and its horizontal temperature gradient is about 3–4°C/(1° of latitude). That is, SCC is apparently stronger in 1991 than in 1989. In accordance
with this phenomenon, the mixed layer increases in thickness to 140 m at the southern edge of SCC in 1991.

It is clearly shown that a northward spreading of isotherms of 15–20°C occurs just north of SCC. Thus, a nearly homogeneous water is formed between the upper seasonal and the lower permanent thermoclines. This water is called Subtropical Mode Water (STMW) by Masuzawa (1967). Uda and Hasunuma (1969) noted that SCC marks the southern boundary of STMW.

4. 25°CN to 34°30’ N Region

The mixed layer also decreases in temperature toward the north and is nearly uniform in thickness at about 80 m as far north as 30°CN in both years. Farther north, it gradually increases in thickness and reaches a maximum at 32°CN (120 m in 1991) to 33°CN (110 m in 1989).

The Kuroshio is well presented by a sharp southward deepening of isotherms near the northern end of the section in both years. In 1991, the steep slope can be traced to 800 m and extends possibly deeper. It is accompanied by a reversal of isotherm slope above 400 m at 33°–33°30’ N, indicating the existence of a strong countercurrent just north of the Kuroshio. To the north of this countercurrent, there appears to be a weak eastward current. This countercurrent north of the Kuroshio is probably related to a meander of the Kuroshio. In addition, a difference in thermal structure between 1989 and 1991 is found below 300 m north of 27°CN. Deepening of isotherms forms a sharp trough below 300 m at 28°CN in 1989, while isotherms are flattened below 250 m between 27°CN and 28°CN and southward deepening of them north of 28°CN is weakened in 1991.

One feature to be noted is the slight decrease in spreading of isotherms between 15°C and 20°C in 1991; the thickness between 15°C and 20°C isotherms is about 300 m or less. This thickness can be considered as an index of the STMW content. In 1989, the thickness is the largest at 28°CN (nearly 350 m) and mostly about 300 m except south of 27°CN.

5. Concluding Remarks

A comparison between long XBT sections in the western Pacific along about 150°E in late November 1989 and along 140°E with a short equatorial section along 150°E in early December 1991 was made in this brief report. One of the most noticeable differences is that in 1991 the surface mixed layer was cooled (between 4°C and 10°C 29–30°C in 1989 and 28–29°C in 1991) and diminished in thickness (between 2°C and 10°C 60–100 m in 1989 and 30–60 m in 1991) in the equatorial region. A decrease in the mixed-layer temperature was also observed in the 10–25°C region.

Dynamic calculation from XBT data and mean T-S curves cannot be readily applied in the western equatorial Pacific because large salinity variability from the surface down to the salinity minimum of the Antarctic Intermediate Water (Emery and Dewar, 1982, TS-7, Fig. 12g). Nevertheless, we can point out a considerable change in the current system on the basis of horizontal gradient change of isotherms. A marked increase in thermocline sharpness or slope south of 6°C in 1991 indicates intensification of the NECC. A concave downward bending of isotherms about the equator indicating the EUC was not definite along 140°E in 1991, but it was discernible along 150°E. The NSCC flowing eastward in the subsurface layer north of the EUC or under the NECC was readily distinguished by isotherm slopes, but there was a slight difference in temperature range between in 1989 and in 1991. In the tropical or subtropical region north of 10°CN, the detected thermal structure difference suggests development of the SCC and a slight intensification of the NEC and shows a slight decrease of the STMW in early December 1991.
Our result of observations made in early December 1991 is no more than showing one of the features in thermal structure in the northwestern tropical Pacific during the mature phase of El Niño. Mixed layer cooling and diminishing in thickness could be a direct manifestation of El Niño in the western Pacific. Intensifications of the NECC and the SCC suggest an increase of the heat transport toward the eastern Pacific. The intensification of the NECC is due largely to the shoaling of the thermocline ridge at its northern boundary as was pointed out by Wyrtki (1974). Recently, Qiu and Joyce (1992), using the hydrographic data along 137°E collected by the Japan Meteorological Agency since 1967, pointed out a decrease in dynamic height at the northern boundary of the NECC and an intensification of the NECC in El Niño years. They pointed out that the NEC have larger transports in El Niño years as well. Mizuno and White (1992) also showed that the NECC is intensified and that northward heat transport along 130°E at 10°N to 20°N is weakened in El Niño years. In contrast, White and Hasunuma (1980) concluded that the NEC becomes weak in El Niño years and that the NEC and the NECC fluctuate out of phase.

However, neither rise of the NECC nor fall of the EUC in transport did not continue throughout the mature phase of El Niño and they did not always happen at the same time. So far, as observed during the two events of El Niño in the 1980s, growing of the NECC seemed to be followed by a decay of the EUC in the western Pacific (e.g., Picaut and Tournier, 1991; Delcroix et al., 1992). Unlike equatorial currents such as NECC, SEC (South Equatorial Current), and EUC, the NEC may not directly respond to variations in wind stress, sea level, pressure gradient, or thermal structure near the equator. Therefore, we cannot straightforwardly account for the rise and fall of the NEC transport during the El Niño. There was no increase of the transport of 0–400 m deduced from XBT south of 20°N in the western Pacific during the 1982–83 El Niño (Picaut and Tournier, 1991). Besides, the decrease in thickness of the STMW observed in 1991 is not easily explained. Suga et al. (1989) showed that the STMW can be advected to the 137°E section as far as 23°N within one year after formation and less STMW was observed during the period of the typical large meander of the Kuroshio in the late 1970s.

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