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Interannual variability of subsurface temperature in summer induced by the Kuroshio over Bungo Channel, Tosa Bay, and Kii Channel, south of Japan

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A B S T R A C T

Using historical *in situ* temperature record, we investigate interannual variability of temperature in summer over Bungo Channel, Tosa Bay, and Kii Channel (hereafter "BTK"), south of Japan. This study aims to reveal the interregional relation of the subsurface temperature variability between the shelf and slope as well as between BTK, and specify the primary cause of the temperature variability in terms of the Kuroshio path. It is shown that 100-m temperature on the slope of BTK is synchronous with each other and highly correlated with coastal sea levels from Kyushu to Kii Peninsula, suggesting that subsurface temperature over the slope varies simultaneously on spatial scales of 400–500 km in the along-slope direction. The 100-m temperature on the slope is also correlated with the near-bottom temperature on the shelf, implying that the near-bottom temperature is determined mainly by the larger-scale variability over the slope. The Kuroshio state in summer of each year is classified into the large meander (LM), non-large meander (NLM), and intermittent larger meander (IM) propagating eastward along the slope. It is found that remarkable temperature increases are accompanied by the IM propagations south of BTK. Temperatures during the IM and LM period are significantly different, the means of which are the highest and lowest, respectively. Temperature during the NLM period with the second highest mean value exhibits the largest variance. Statistical analysis suggests that this variance is related to the Kuroshio axis shift over Izu Ridge between the nearshore and offshore NLM paths.

1. Introduction

Bungo Channel, Tosa Bay, and Kii Channel ("BTK") are the shelf–slope regions around Shikoku, south of Japan (Fig. 1b). In this study, "shelf" and "slope" of BTK are defined as the regions with a water depth of 10–100 m and 100–900 m, respectively (details are explained in Section 2). It is well known that the Kuroshio takes two stable paths, the large meander (LM) and non-large meander (NLM) path (Yoshida, 1964; Taft, 1972). The NLM is further divided into the nearshore and offshore NLM paths (nNLM and oNLM) by the Kuroshio axis position over Izu Ridge, which can be detected by sea levels at Hachijyojima or Miyakejima (Kawabe, 1985, 1986). The Kuroshio axis is also largely displaced offshoreward on an intraannual time scale due to the generation and propagation of an intermittent small meander (Nitani, 1975; Zhu et al., 2001; Ebuchi and Hanawa, 2003). Most of the intermittent meanders occur during the NLM period (Nagano and Kawabe, 2004), and some of them called "trigger meander" develop into the LM (Yoshida, 1964; Solomon, 1978; Kawabe, 1980; Tsujino et al., 2006; Usui et al., 2008).

It has been considered that temperature on the shelf of BTK is seriously affected by the offshore Kuroshio and its frontal variation. Particularly, in summer, two contrasting types of oceanic water intrusion into the shelf dramatically change thermal, chemical and biological structures (Fujiwara et al., 1997; Takeuchi et al., 1997, Takeuchi, 2001; Ozaki et al., 2003; Katano et al., 2005; Hirose et al., 2007; Hayami et al., 2005, 2006; Hirota et al., 2001; Ichikawa and Hirota, 2004). One is the surface intrusion of warm oligotrophic water from the Kuroshio, such as *Kyucho* in Bungo Channel (Takeoka and Yoshimura, 1988; Takeoka et al., 1993) and Surface Slope Water (SSW) intrusion in Kii Channel (Takeuchi et al., 1997). The other is the subsurface intrusion of upwelled cold eutrophic water, such as Bottom Intrusion in Bungo Channel (Kaneda et al., 2002b), cold-dome structure with an anticlockwise circulation in Tosa Bay (Saito, 1994; Kuroda et al., 2008), and Bottom Slope Water (BSW) intrusion in Kii Channel (Takeuchi et al., 1997). These two types of water intrusions are thought to occur on an intra-seasonal time scale and contribute significantly to the interannual variation of mean temperature in summer on the shelf of BTK, in particular, that of the near-bottom temperature on the shelf.

Kaneda et al. (2002a) pointed out that the interannual variation of mean temperature in summer near the bottom (75 m) on the shelf of Bungo Channel can be controlled by the intensity of Bottom Intrusion. The temperature is positively correlated with the Kuroshio

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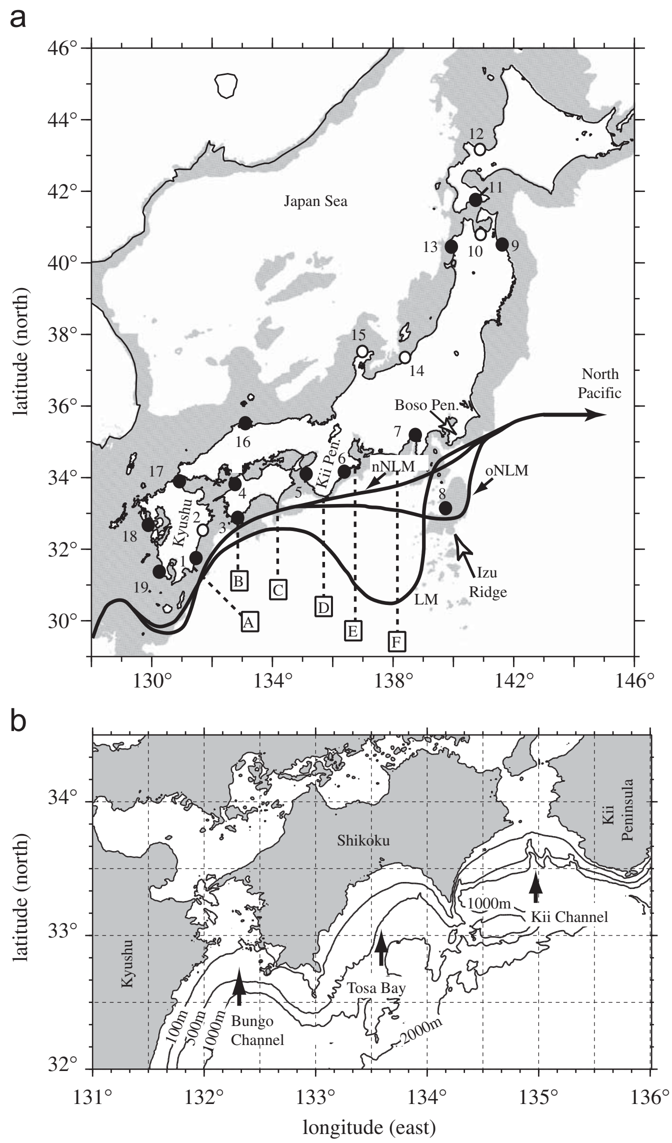

Fig.1. (a) Schematic view of the Kuroshio paths referred to as "LM", "oNLM" and "nNLM". Axis distance from Capes (A) Toi, (B) Ashizuri, (C) Muroto, (D) Shiono, (E) Daio, and (F) Omae is estimated along each dashed line. Hourly and monthly sea levels are collected from tide gauges denoted by closed and open circle, respectively (1: Aburatsu, 2: Hosojima, 3: Tosashimizu, 4: Matsuyama, 5: Wakayama, 6: Owase, 7: Uchiura, 8: Hachijyojima, 9:Hachinohe, 10:Asamushi, 11:Hakodate, 12:Oshoro, 13:Fukaura, 14: Kashiwazaki, 15: Wajima, 16: Sakai, 17: Moji, 18: Nagasaki, 19:Makurazaki). Gray-shaded area indicates water depths less than 1000 m. (b) Bathymetry around BTK.

axis distance from Cape Toi (Fig. 1a). The authors suggested that the Bottom Intrusion can be governed by the bottom Ekman dynamics, as discussed in Ichikawa and Kaneda (2000). Takeuchi et al. (1997) stated that the interannual variation of mean temperature in summer near the bottom (50 m) on the shelf of Kii Channel depends on the appearance of either SSW or BSW intrusion. The temperature is negatively and positively correlated with the Kuroshio axis distance from Cape Shiono (Fig. 1a) for the distance less and greater than 30 miles (∼56 km), respectively. Takeuchi (2001) suggested that the appearance of westward flows at the southeastern mouth of Kii Channel (Takeuchi et al., 1998), can suppress the BSW (enhance the SSW) intrusion and increase the near-bottom temperature in this channel.

To briefly sum up, the near-bottom temperatures on the two shelves of Bungo and Kii Channels seem to be controlled by the different Kuroshio axis condition and physical dynamics, as noted in Takashi et al. (2006). However, this issue has not been verified mainly because there have not been any comparative studies for the near-bottom temperature between BTK under the same data processing and data analysis method.

In order to obtain a better perspective prior to the comparative studies conducted in this study, it is instructive to note a close relation between coastal sea levels and subsurface temperature over the slope, just offshore of the shelf. According to Kawabe (1980), monthly sea-level variation along the Pacific coast from Kyushu to Kii Peninsula, about 400 km apart, is almost synchronous with each other, regardless of either the LM or the NLM period. On the basis of Kuroda et al. (2007), monthly coastal sea-level variation around Tosa Bay is controlled primarily by dynamic height variation on the slope, the most of which depends on subsurface (0–450 m) temperature variation characterized by vertically in-phase displacement of isotherms. This close relation between the sea level and temperature makes us expect that, for time scales longer than a month, subsurface temperature over the slope from Kyushu to Kii Peninsula, including BTK, should be synchronous or highly correlated with each other as well as the coastal sea levels there.

In this study reported here, using historical *in situ* temperature record, interannual variability of temperature in summer is examined for BTK with a particular focus on the subsurface (100 m) temperature on the slope and the near-bottom (50 m) temperature on the shelf. This study aims to reveal the interregional relation of the temperature variability between the shelf and slope as well as between BTK, and to specify the primary cause of the temperature variability in terms of the Kuroshio path variability.

This paper is organized as follows. Data and data processing is described in Section 2, and the interregional relation of interannual temperature variability is investigated together with coastal sea levels (Section 3). A statistical relation, applicable to any of BTK, between the Kuroshio path and subsurface temperature is proposed in Section 4. Several issues are discussed in Section 5, and Section 6 summarizes findings from this study.

2. Data and data processing

2.1. Definition of the shelf and slope

Before describing data and data processing, we explain the details of how to separate "shelf" and "slope". As mentioned above, the shelf and slope are defined as the regions with a water depth of 10–100 m and 100–900 m, respectively. The boundary of 100 m between the shelf and slope is useful in comparing results from this study with previous studies focusing on the near-bottom temperature on the shelves (e.g., Kaneda et al., 2002a; Takeuchi et al., 1997). The lower boundary of the slope (900 m) is based on the result of Kuroda et al. (2007) that sea-level variation except 1-year cycle around Tosa Bay is negatively correlated between an inshore and an offshore area. This result implies that the subsurface temperature at a depth can be out of phase between the inshore and offshore areas, divided by a transition zone with a water depth of 750–900 m. The lower boundary (900 m) of the slope roughly corresponds to this transition zone. Individual shelf and slope of BTK (six regions) are surrounded by thick line in Fig. 2a.

2.2. Preparation of monthly mean time series

Our analysis is based on monthly mean time series of water temperature, the Kuroshio axis position, air temperature, and coastal sea level, processed as follows. Some monthly mean time