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Properties, formation, and dissipation of the North Pacific Eastern Subtropical Mode Water and its impact on interannual spiciness anomalies

Shota Katsura*

Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa, Japan

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ABSTRACT

The properties, formation, and dissipation of the North Pacific Eastern Subtropical Mode Water (ESTMW), their interannual variability, and impact on spiciness anomalies in the upper permanent pycnocline were investigated using Argo profiling float data in 2005–2015. The core temperature and salinity of ESTMWs were horizontally compensated to a constant density, and core potential density concentrates in a range of 24.5–25.2 kg m^{-3} with two distinct peaks. ESTMWs showed different spatial distribution and persistence for its core potential density. Denser ESTMWs with a potential density of 24.9–25.2 kg m^{-3} were formed in winter mixed layer depth maximum centered at 30°N, 140°W and lighter ESTMWs of 24.5–24.9 kg m^{-3} were formed south and east of it. After formation through shoaling of the winter mixed layer, the former persisted until the following autumn and a small part of it subducted in winter, while the latter dissipated in summer. The formation region of ESTMW corresponded to the summer sea surface density maximum resulting from its poleward sea surface salinity front. Sea surface density maximum maintains weak stratification during summer, preconditioning the deepening of the winter mixed layer and hence the formation of ESTMWs. A relationship between the ESTMW formation region and the summer sea surface density maximum was also found in the North Atlantic and the South Pacific, implying the importance of sea surface salinity fronts and the associated summer sea surface density maximum to ESTMW formation. Interannual variations of ESTMW reflected that of the winter mixed layer in its formation region, and the thickness of ESTMW was related to the Pacific decadal oscillation. ESTMW contributed to the occurrence of spice injection and affected spiciness anomalies in the upper permanent pycnocline through its formation and dissipation.

1. Introduction

Mode water is a water mass characterized by low potential vorticity (PV) and a vertically homogeneous density layer. It forms in association with deep winter mixed layer mainly due to strong convective mixing and obtains a property as a pycnostad being capped by a seasonal pycnocline in early spring. During the following winter, a part of the mode water is entrained into the mixed layer, while the rest subducts into the permanent pycnocline and continues to be advected by gyre circulation. Mode water retains the winter conditions of its formation region due to its large volume and efficiently transports temperature and salinity anomalies, which result mainly from ocean-atmosphere interactions, to the downstream through subduction and advection processes. In fact, winter sea surface temperature (SST) anomalies re-emerge in the following winter in the mode water formation regions of the world's oceans, which is thought to relate to subduction and advection of mode water (Hanawa and Sugimoto, 2004; Sugimoto and Hanawa, 2005a). In addition, mode water behaves as a large reservoir of biogeochemical parameters, such as nutrients (Palter et al., 2005; Krémeur et al., 2009; Sukigara et al., 2011) and CO_2 (Bates et al., 2002), and its subduction and advection affect downstream biological production and ocean acidification (Oka et al., 2015).

The North Pacific Eastern Subtropical Mode Water (ESTMW) is one of mode waters in the North Pacific subtropical gyre along with the North Pacific Subtropical Mode Water (Masuzawa, 1969) and the Central Mode Water (Nakamura, 1996; Suga et al., 1997). ESTMW was first identified as a thermostad with a temperature range of 16–22 °C in the eastern subtropical North Pacific from expendable bathythermograph data (Hautala and Roemmich, 1998). It is formed in the winter mixed layer depth (MLD) maximum centered at 30°N, 140°W (Fig. 1). In this region, winter cooling is not as strong as in the other mode water formation regions and cannot explain the existence of a deep winter mixed layer. Hautala and Roemmich (1998) suggested that weak stratification associated with a horizontal minimum in buoyancy frequency, called a stability gap, in the subarctic–subtropical transition zone (Roden, 1970, 1972; Yuan and Talley, 1996) helps winter vertical

* Address: Atmosphere and Ocean Research Institute, The University of Tokyo, 5-1-5, Kashiwanoha, Kashiwa, Chiba 277-8568, Japan.
E-mail address: katsura@aori.u-tokyo.ac.jp.

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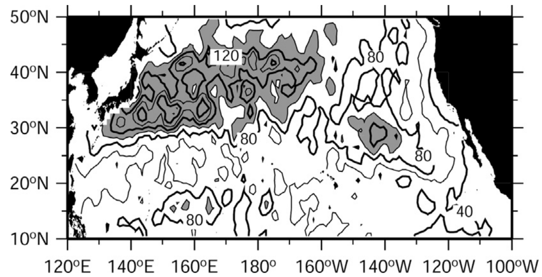

Fig. 1. Distribution of MLD in the North Pacific in February from monthly climatological fields described in Section 2. Gray shading indicates MLD > 100 dbar.

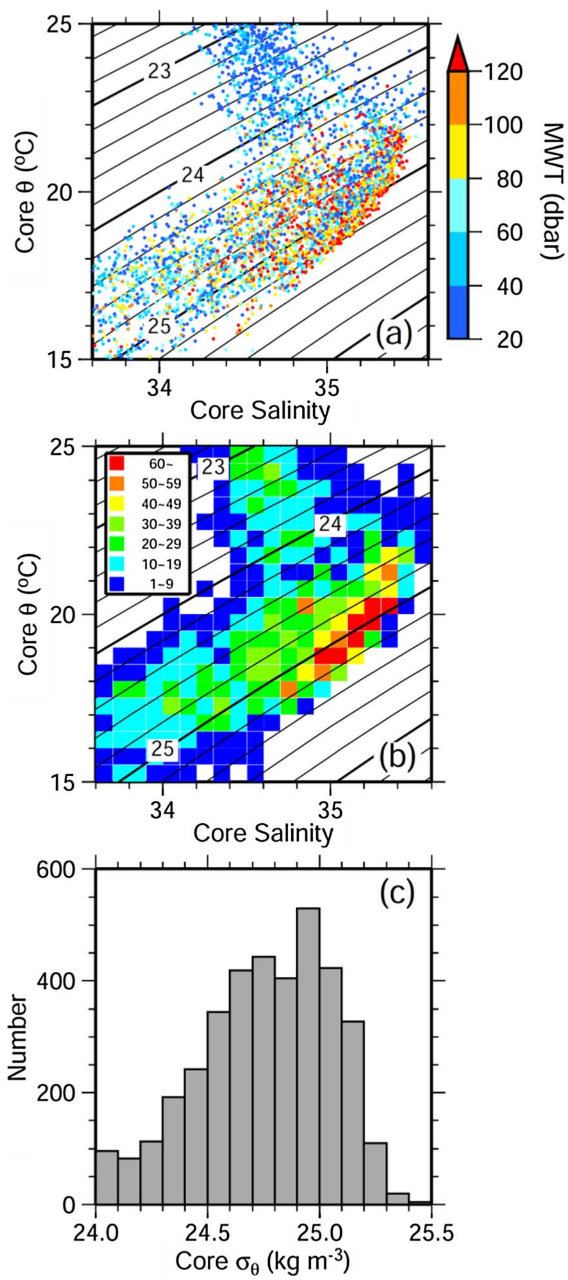

Fig. 2. (a) θ-salinity relationship at the core of mode waters from Argo profiles with MWT > 20 dbar in April–June of 2005–2015 in 15 − 35°N, 155 − 125°W (dots). Color indicates MWT. (b) Number of plots in (a), classified in each 0.1 (salinity) × 0.5 °C (θ) bin. (c) Histogram of number of plots in (a) respect to core σ_θ. Contours in (a) and (b) denote σ_θ. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mixing to form the deep winter mixed layer in this region. Modelling studies also suggested that weak summer heating due to stratus cloud (Ladd and Thompson, 2000) and the poleward Ekman advection of saltier water (Toyoda et al., 2004) play important preconditioning roles in the deepening of the winter mixed layer.

After formation, ESTMW rapidly thins and a large part of it is dissipated while the rest of ESTMW subducts through a small density advection mechanism (e.g., Hosoda et al., 2001). Previous studies showed that the vertical structure between the base of ESTMW and the permanent pycnocline is favorable for mixing due to salt finger convection, the double diffusive convection which occurs when warm/salty water overlies cool/fresh water (Sugimoto and Hanawa, 2007; Toyama and Suga, 2010). Sugimoto and Hanawa (2007) suggested that this is the main factor driving the rapid dissipation of ESTMW, and that its temperature anomalies are also dissipated, leading to the non-reemergence of winter SST anomalies in the ESTMW formation region (Sugimoto and Hanawa, 2005b). After modification through salt finger convection, ESTMW loses its classification as a pycnostad and becomes a constituent of the central water in the eastern part of the subtropical gyre (Toyama and Suga, 2012).

Recent accumulation of salinity data from Argo profiling floats has revealed the subduction and propagation of density-compensating (warm/salty or cool/fresh) temperature/salinity anomalies on the isopycnal surface, called spiciness anomalies, in the North Pacific subtropical gyre (Sasaki et al., 2010; Kolodziejczyk and Gaillard, 2012; Katsura et al., 2013), which have been hypothesized to play an important role in decadal climate variability (Hanawa, 1996; Gu and Philander, 1997). In the eastern subtropical South Pacific, diapycnal mixing of salinity at the base of the winter mixed layer generates spiciness anomalies on denser isopycnal surfaces without outcrop (Kolodziejczyk and Gaillard, 2013), called spice injection (Yeager and Large, 2004, 2007), and this region corresponds to the South Pacific ESTMW formation region (Wong and Johnson, 2003; Sato and Suga, 2009). Considering these facts, the North Pacific ESTMW might contribute to the occurrence of spice injection and affect interannual spiciness anomalies in the permanent pycnocline via salt finger convection despite its rapid dissipation. However, in contrast to the North Pacific Subtropical Mode Water and the Central Mode Water, properties, formation, and dissipation of the North Pacific ESTMW and their interannual variability have not been fully investigated using hydrographic observation.

The purpose of this study is to investigate the properties, formation, and dissipation of the North Pacific ESTMW using Argo profiling float data. The impact of the North Pacific ESTMW on interannual spiciness anomalies in the upper permanent pycnocline is also explored. This paper is structured as follows: the data and methods used are described in Section 2. Properties, formation, and dissipation of ESTMW and its interannual variability as well as their relation to spiciness anomalies are examined in Section 3. Relationship between interannual variation of ESTMW and climate variability, and preconditioning of the ESTMW formation in other ocean basins are further discussed in Section 4. Finally, a summary of the findings is presented in Section 5.

2. Data and method

2.1. Data

Temperature and salinity (S) data from Argo profiling floats in the North Pacific during 2005–2015 were used in this study. The profiles before and after March 2015 were from the Argo Global Data Assembly Center (ftp://usgodae.org/pub/outgoing/argo; ftp://ftp.ifremer.fr/ifremer/argo) and Advanced automatic QC Argo data ver. 1.2. from Japan Agency for Marine-Earth Science and Technology, respectively. They were edited as outlined in Oka et al. (2007). Each profile was interpolated at an interval of 1 dbar using the Akima spline (Akima, 1970), and then potential temperature (θ), potential density (σ_θ),