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Key Points:

- Subduction was weakening in western North Pacific during 2003–2013
- The weakening is influenced by local thermal process
- Change of mixed layer depth in STMW formation region is dominated by horizontal heat advection

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Weakening of subduction in the Subtropical Mode Water formation region observed during 2003–2013

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Abstract Subduction plays an important role in the formation of the Subtropical Mode Water (STMW). Variation of subduction in the western North Pacific was studied using gridded monthly data from Argo float profiles. The results revealed that there exists a weakening trend of subduction in the STMW formation region (28°N–35°N, 142°E–175°W) due to decreasing winter mixed layer depth (MLD) during 2003–2013. In the STMW formation region, the mean subduction rate was about 64 m yr^{-1} and showed a decreasing trend at -3.44 ± 2.47 m yr^{-2} during 2003–2013. Meanwhile, the late winter (March) MLD showed a decreasing trend at -4.02 ± 2.41 m yr^{-1}. Associated with the weakening subduction, the STMW volume had a similar decreasing trend in late winter. Diagnostic calculation indicated that change of the mixed layer temperature (MLT) is the key factor in determining the MLD variations in the STMW formation region. It is demonstrated that the increasing MLT tends to decrease oceanic density and stabilize the upper ocean. This oceanic processes act to weaken the vertical mixing and decrease the MLD, resulting in the weakening of subduction.

1. Introduction

The process of water entering the permanent pycnocline from the base of mixed layer is called subduction [*Qiu and Huang*, 1995]. Subduction rate is defined as the volume of mixed layer water entering the thermocline [*Williams*, 1991], which depends on the background circulation variation and strong seasonal cycle of the mixed layer depth (MLD) at the transition from winter to spring. Subduction plays an important role in the formation of the oceanic mode waters, characterized by a nearly vertically homogeneous layer of low potential vorticity (PV) [*Oka and Qiu*, 2012]. Water mass formed in the northwestern Pacific subtropical gyre near the Kuroshio front through the subduction process is called Subtropical Mode Water (STMW) [*Bingham*, 1992; *Hanawa and Talley*, 2001; *Oka*, 2009], characterized with nearly uniform temperature (16–19°C) and low PV ($<2 \times 10^{-10}$ m^{-1} s^{-1}) located between the isopycnal surfaces of 25.0 σ_θ and 25.6 σ_θ [*Masuzawa*, 1969]. STMW plays an important role in memorizing the air-sea interaction effects, and the subduction rate variability is significant in explaining the climate variability of the western North Pacific (WNP).

Subduction formed through wind-driven vertical pumping and lateral induction induced by the late winter MLD variability is an important branch of subtropical overturning cells (STCs), which links the extratropical and tropical oceans [*Gu and Philander*, 1997; *Liu and Huang*, 1998] . Variation of STCs corresponds well with El Niño-Southern Oscillation (ENSO) [e.g., *Gu and Philander*, 1997; *Zhang et al.*, 1998] and Pacific Decadal Oscillation (PDO) [*Qu and Chen*, 2009]; therefore, the variability of STMW is of major importance for climate changes in North Pacific. Interannual variability of the STMW is closely related to the subduction rate in the STMW formation region [*Suga and Hanawa*, 1995; *Qu and Xie*, 2002]. Based on hydrographic data, *Suga et al.* [2008] indicated that the low PV variation of STMW was primarily owing to the changes of subduction rate in WNP. The STMW is reduced (strengthened) when the Kuroshio Extension path is unstable (stable). Unstable (stable) Kuroshio Extension path leads to a strong (weak) upper ocean stratification, hindering (promoting) the development of the MLD [*Qiu and Chen*, 2006]. *Davis et al.* [2011] demonstrated that there is a no lag relation between SMTW and PDO index based on the Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2), while *Qiu and Chen* [2005] concluded that the decadal variability of STMW presented a lagging response to the wind forcing related to PDO based on satellite altimetry data. Previous studies have put forward that subdution rate shows obvious interannual and decadal variation in the STMW formation region based on model outputs. Using results from the eddy-resolving ocean general circulation model (OGCM), *Qu and Chen* [2009] indicated that the decadal variability of North Pacific subduction rate corresponds well with the Pacific Oscillation (PDO). It is pointed out that there exists an anticorrelation relationship for the subduction rates variabilities in western and eastern North Pacific [*Chen et al*., 2010]. Based on a quasi-global climate system ocean model, *Hu et al*. [2011] found that the interannual and decadal variations of subduction rate in North Pacific are associated with variabilities of Ekman and geostrophic advections and the MLD. *Liu and Huang* [2012] indicated that the subduction rate varies greatly on interannual and decadal scales owing to the variation of MLD in late winter. Most of the existing researches on subduction rate in the North Pacific were completed on the basis of numerical simulation outputs, due to the lack of observational data. However, a monthly global data set of temperature and salinity have been created since 2001, owing to the international Argo project started in 2000 [e.g., *Hosoda et al*., 2008], which provides us a useful tool to investigate subdution variation with observational data. Latest result based on Argo data confirmed that variability of subduction rate in STMW formation region correlated well with PDO [*Toyama et al*., 2015].

Long-term trend of the subduction rate was investigated with observational data in this study. We calculated the subduction rate over the WNP based on Argo data and presented the trend of subduction rate from 2003 to 2013.The rest of the paper is organized as follows. Section 2 introduces the data and methods used in this study. Changes of subduction in the STMW formation region during 2003–2013 and its influences on the STMW are investigated based on observational data in section 3. In section 4, the mechanism of the subduction changes in STMW formation region is discussed. Summary and concluding remarks are provided in section 5.

2. Data and Method

The temperature and salinity from the Grid Point Value of the Monthly Objective Analysis (MOAA GPV) from March 2003 to March 2014 are used in this study. The MOAA GPV is a global $1^\circ \times 1^\circ$ grid data set of monthly temperature and salinity starting from January 2001 to the present [*Hosoda et al*., 2008]. To inspect the coverage of the Argo profiles, yearly sparseness defined as the average distance to the four nearest floats from each $1^\circ \times 1^\circ$ grid point was calculated following *Toyama et al*. [2015]. Figure 1 shows the sparseness at 10 dbar in March from 2001 to 2014, which is similar to the result of *Toyama et al*. [2015]. It can be seen from Figure 1 that the sparseness becomes significantly smaller over the central and the eastern North Pacific since 2003, which means that there are more Argo profiles. The interpolation errors of T and S are provided with the data set of MOAA GPV, the process of error estimation was detailed in *Hosoda et al*. [2008]. In the western North Pacific, the interpolation errors of T and S also decrease significantly since 2003 (figure not shown). Hence the MOAA GPV data are credible in the WNP to investigate the subduction rate after 2003. In this study, we mainly use the data after 2003.

Subduction rate is calculated followed *Qiu and Huang* [1995]:

$$S=-\overline{\left[w_{EK}-\left({}^{\beta}/_{f}\right)\int_{-h_m}^{0} vdz\right]}+\left(h_{m,0}-h_{m,1}\right)/T, \tag{1}$$

where S is the subduction rate, w_{EK} is the Ekman pumping velocity derived from NCEP/NCAR reanalysis wind stress data, and the term with β denotes the vertical velocity reduction due to the meridional geostrophic velocity (v) in the surface layer derived from MOAA GPV data. Because the Ekman layer is much shallower than the winter mixed layer, the vertical pumping velocity at the base of the winter mixed layer is generally smaller than the Ekman pumping velocity in the Pacific subtropical regions [*Qiu and Huang*, 1995]. The geostrophic current (Figure 2a) is calculated in reference to 1500 dbar by MOAA GPV data. Its pattern is similar to the results of *Zhang et al*. [2013] calculated by MOAA GPV data using P-vector method. The overbar in equation (1) indicates an average over a yearly (T) Lagrangian trajectory, and $h_{m,0}$ and $h_{m,1}$ represent the March MLD in the first and second year, respectively. Here the MLD at each grid point is determined as the depth at which potential density σ_θ increases by 0.125 kg m^{-3} from the 10 dbar depth based on MOAA GPV data [*Ren and Rise*, 2010; *Katsura et al*., 2013]. During subduction process, the wind-driven Ekman flow converges at the surface and flows along the base of the mixed layer. Hence subduction process consists of two parts: vertical pumping through the base of the mixed layer and lateral induction