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## RESEARCH LETTER

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### Key Points:

- Interannual variations of winter submesoscale circulations in the subtropical northeastern Pacific are examined using a hindcast simulation
- The winter submesoscale kinetic energy in the eastern subtropics was high in the years when El Niño events occurred
- The similarities and differences of their variations between the eastern and western subtropics are highlighted

### Supporting Information:

Supporting Information may be found in the online version of this article.

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## Interannual Variations of Submesoscale Circulations in the Subtropical Northeastern Pacific

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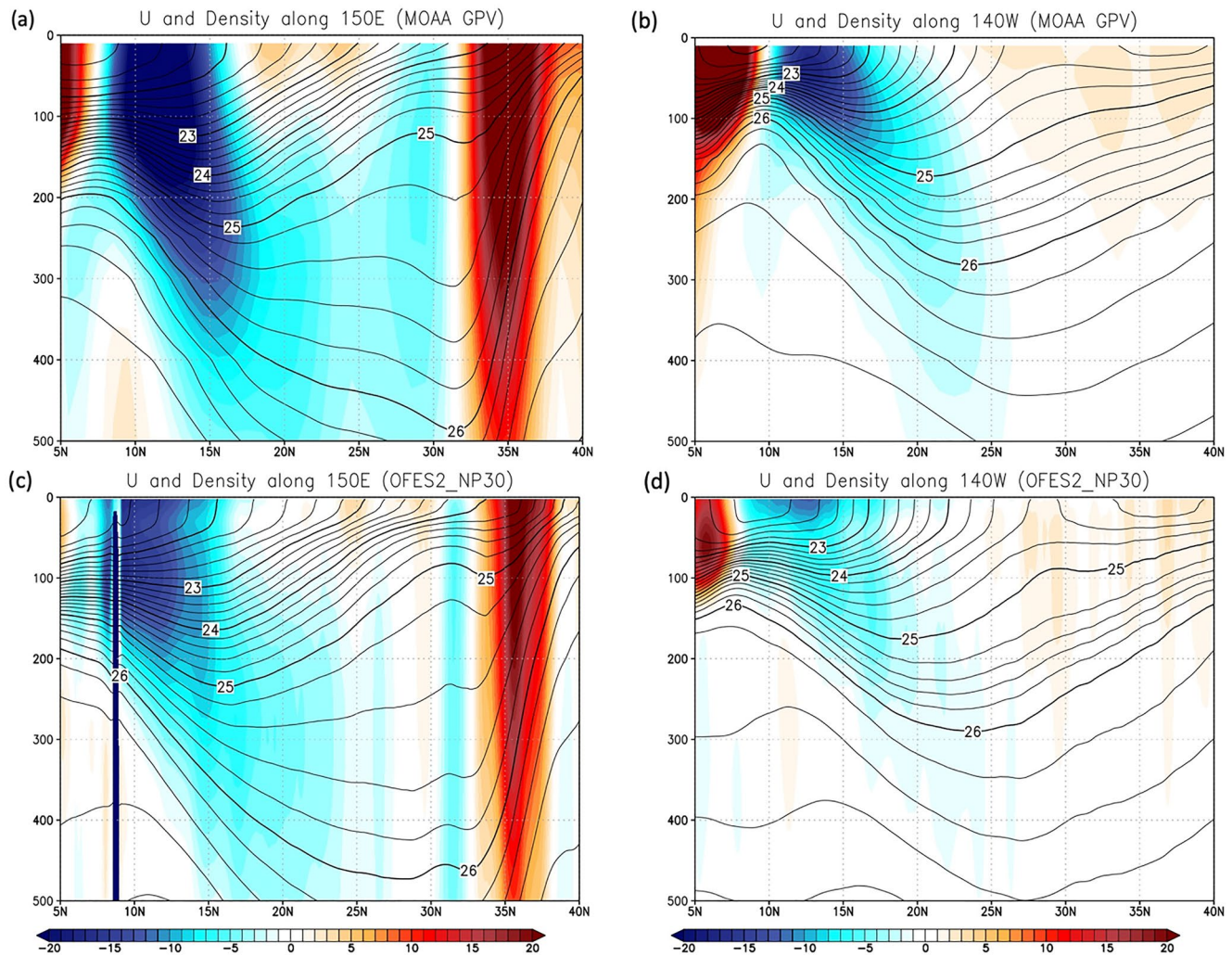
**Abstract** Impacts of oceanic submesoscale circulations on oceanic circulation as well as marine ecosystem and air–sea heat flux have been reported by recent studies. Therefore, their regionality and variations on various timescales are important to understand their impacts. The submesoscale circulations are active in winter, which is mostly enhanced by mixed layer instability (MLI). However, their variations on timescales longer than interannual are not well understood. This study shows the interannual variations of active submesoscale circulations in winter and their mechanism in the subtropical northeastern Pacific using the output of a submesoscale permitting simulation. The submesoscale kinetic energy varies synchronously with the available potential energy release in a process of MLI. El Niño events appear to modulate the interannual variations. In addition, the similarities and differences between the variations in the eastern and western subtropics are highlighted.

**Plain Language Summary** Oceanic submesoscale circulations at scales from one to several tens of kilometers are ubiquitous in the world ocean. Recent studies have reported their significant roles in not only ocean circulation but also marine ecosystem and air–sea coupling via enhanced vertical motions. Therefore, revealing their variations and regionality are crucial to further understanding their roles. Previous studies reported that submesoscale circulations are enhanced within the surface mixed layer in winter by baroclinic instability that extracts energy from sloping isopycnals. However, submesoscale variations on timescales longer than interannual have not been well understood. This study explores the interannual variations in the subtropical northeastern Pacific based on a submesoscale permitting hindcast simulation. The winter submesoscale circulations are more active in the El Niño years than other years. The enhanced submesoscale circulations, as well as their seasonal enhancement in winter, are caused by strengthened baroclinic instability.

## 1. Introduction

Submesoscale circulations on scales from one to several tens kilometers are ubiquitous in the world ocean (e.g., McWilliams, 2016). They play a significant role in not only ocean circulation (e.g., Sasaki et al., 2014) but also marine ecosystem (e.g., Lévy et al., 2012; Uchida et al., 2019), and global heat budget (e.g., Su et al., 2018) via the enhanced vertical motions. Therefore, their regionality and variations on various timescales are key factors in better understanding their roles. The submesoscale circulations are enhanced in winter (Callies et al., 2015; Dong et al., 2020; Mensa et al., 2013; Qiu et al., 2014; Sasaki et al., 2014) mostly by baroclinic instabilities in the mixed layer named mixed layer instability (MLI; Boccaletti et al., 2007; Khatri et al., 2021). However, previous studies focusing on their variations on timescales longer than interannual are limited. Richards et al. (2021) suggested a significant damping of submesoscale circulations in the North Atlantic in the future using simulations under present and future climate conditions. Our previous study (Sasaki, Qiu, et al., 2020) showed their interannual to decadal variations in the subtropical northwestern Pacific in a submesoscale permitting simulation, and suggested the relationship between the variations and the Pacific Decadal Oscillations (PDO; Mantua & Hare, 2002).

In our submesoscale permitting simulation of the North Pacific, the submesoscale circulations are active in the northwestern Pacific, including the subtropics, and in the subtropical northeastern Pacific (Figure S1 in Supporting Information S1). This motivated us to focus on their variations in the subtropical northeastern Pacific, following our previous study focusing on the northwestern Pacific (Sasaki, Qiu, et al., 2020). We also examined meridional vertical sections of mean geostrophic current and potential density in the Argo float observations (Figure 1).



**Figure 1.** Meridional vertical sections of zonal velocity ( $\text{cm s}^{-1}$ , color) and potential density ( $\sigma_\theta$ , contour) along (a, c) 150°E and (b, d) 140°W. (a, b) Argo float observations based on Grid Point Value of the Monthly Objective Analysis using the Argo data (Hosoda et al., 2008) averaged from 2005 to 2016 and (c, d) the ocean general circulation model OFES2 averaged from 1991 to 2018.

The vertically sheared system between the upper and subsurface currents and large meridional density gradients in the upper layer (Figure 1b), similar to those in the subtropical northwestern Pacific (Figure 1a), suggests the existences of active mesoscale and submesoscale circulations (Qiu et al., 2014). This study focuses on interannual variations of submesoscale circulations in the subtropical northeastern Pacific based on our simulation, and highlights their similarities and differences compared with those in the western subtropics (Sasaki, Qiu, et al., 2020). In addition, we attempt to find the climate variability responsible for modulating the variations. This paper is organized as follows. Section 2 describes the data from our submesoscale permitting simulation and the methods used in this study. Section 3 shows the results: the interannual variations of submesoscale kinetic energy (KE) and the climate variability related to their variations. Conclusions and discussions are provided in Section 4.

## 2. Data and Methods

We used the daily mean output from a submesoscale permitting hindcast simulation of the North Pacific from 1991 to 2018. The ocean general circulation model called OFES2 (Sasaki, Kida, et al., 2020) based on MOM3 (Pacanowski & Griffies, 1999) is used to conduct the simulation. The horizontal resolution is  $1/30^\circ$  with the model domain of  $100^\circ\text{E}$ – $70^\circ\text{W}$  and  $20^\circ\text{S}$ – $68^\circ\text{N}$ . The number of vertical levels is 105, and the maximum depth is 7,500 m. The surface fluxes are estimated by the bulk formula (Large & Yeager, 2004) using the atmospheric

data set JRA55-do version 1.1 (Tsujino et al., 2018). A more detailed description is shown by Sasaki, Qiu, et al. (2020). Note that the daily mean output does not mostly include near-inertial flows. OFES2 simulates the eddy kinetic energy (EKE) distribution well, although its magnitude is slightly smaller than that of the satellite observations (Figure 1 in Sasaki, Qiu, et al., 2020). The eddy killing effect in the estimation of surface momentum flux using relative wind considering surface velocity (e.g., Renault et al., 2019) suppresses slightly too much the EKE in OFES2.

The observational data are used to compare with the simulation output. The EKE is estimated from geostrophic velocity of the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) sea surface height data (<https://www.aviso.altimetry.fr>). Now, Copernicus Climate Change Service is in charge of the data (<https://climate.copernicus.eu/>). The potential density and geostrophic velocity based on the reference depth of 2,000 m of Grid Point Value of the Monthly Objective Analysis using the Argo data (MOAA GPV; Hosoda et al., 2008) are also used.

We estimated the available potential energy (APE) release in a process of the MLI parameterized by Fox-Kemper et al. (2008) as in Sasaki, Qiu, et al. (2020). The eddy buoyancy flux along a slope shallower than the mean isopycnal slope slumps the front and reduces the mean APE. The APE release is proportional to a product of mixed layer depth (MLD,  $H$ ) squared and horizontal buoyancy gradient ( $M^2$ ) squared as follows:

$$-\Delta\text{APE}/\Delta t \propto (C - 1)M^4 H^2 / C |f|, \quad (1)$$

where  $C$  is a ratio of the eddy flux slope to isopycnal slope and  $f$  is the Coriolis parameter. We consider only the meridional buoyancy gradient because of its dominance in the subtropical Pacific. We also estimated the surface spectral KE flux to diagnose the scale interaction (Scott & Wang, 2005). The flux is estimated by

$$\Pi(k) = \int_k^{k_s} \text{Re} \left( \widehat{u}^* \cdot \left( u \cdot \widehat{\nabla_H u} \right) \right) (k) dk, \quad (2)$$

where  $u$  is a velocity vector at the surface, caret is the discrete Fourier transform,  $\nabla_H$  is the horizontal gradient operator, and asterisks are complex conjugates.  $k$  is a wavenumber, and  $k_s$  is the largest wavenumber corresponding to the horizontal resolution of the simulation.

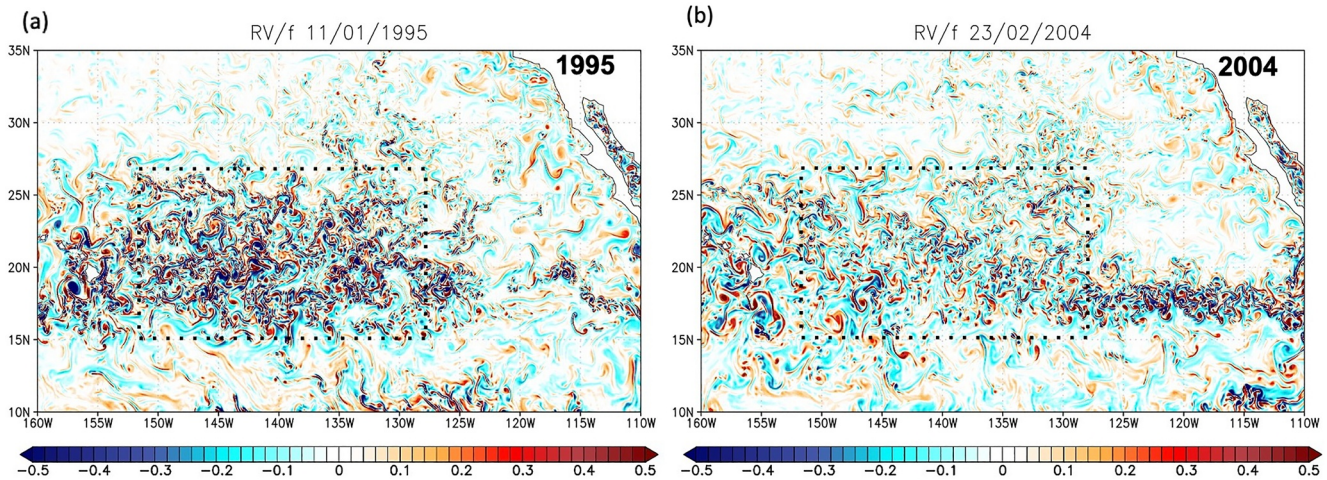
### 3. Results

We examined the mean meridional vertical sections of geostrophic velocity and potential density in the subtropical North Pacific using MOAA GPV averaged in 2005–2018. In the western subtropics along 150°E (Figure 1a) studied by our previous study (Sasaki, Qiu, et al., 2020), the subtropical countercurrent (STCC; Hasunuma & Yoshida, 1978) flows eastward in the upper layer between 18° and 25°N, which splits into two branches of the northern STCC at 24°N and the southern STCC at 18°N (Kobashi & Kawamura, 2002). The North Equatorial Current (NEC) exhibits a strong westward velocity in the upper layer shallower than 200 m between 8° and 15°N, and spreads north and downward below 100 m in the subsurface. This vertically sheared flow structure of the subsurface westward current underneath the upper eastward current generates interior baroclinic instability to induce mesoscale eddies, as shown by Qiu and Chen (2013). The meridional density gradients in the upper layer are strong at the latitudes with the STCC compared with the surroundings (Figure 1a). In winter, MLIs occur within the deep mixed layer and then the submesoscale circulations become active (Qiu et al., 2014; Sasaki, Qiu, et al., 2020).

In the eastern subtropics that is the region of this study, a similar shared structure with the north and downward extent of the maximum westward current of the NEC and its weakening in the upward direction is observed between 15° and 25°N at 140°W (Figure 1b). The eastward current appears at the surface to the north of 23°N. At the latitudes, the meridional density gradients in the upper layer are large compared with the surroundings. These features suggest that both the interior baroclinic instability and MLI possibly occur in the eastern subtropics, as in the western subtropics.

OFES2 (Figures 1c and 1d) well simulates the meridional vertical distributions of zonal velocity, reproducing the vertically sheared currents and the strong meridional density gradient in the subtropics, as in the MOAA GPV (Figures 1a and 1b). Accordingly, it is expected that OFES2 can capture oceanic circulations with mesoscale





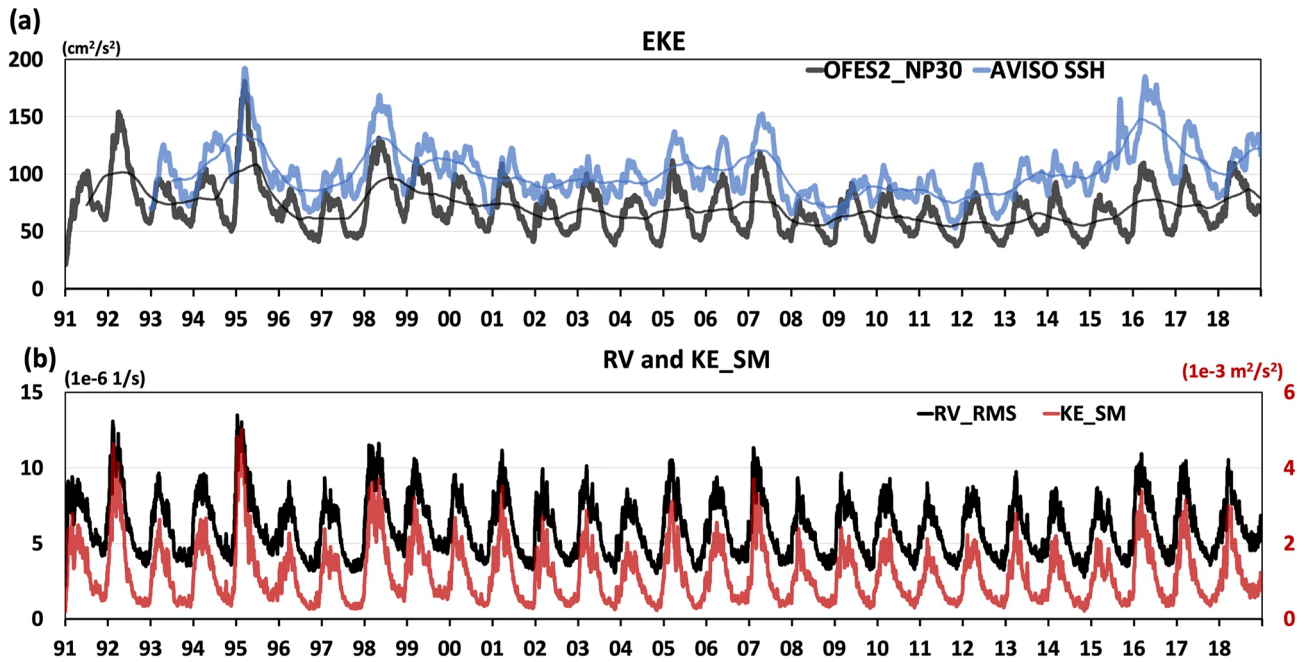
**Figure 2.** Daily mean surface Rossby number (relative vorticity/Coriolis parameter) in the subtropical northeastern Pacific on (a) 11 January 1995 and (b) 23 February 2004. The distribution on the day with maximum root-mean-square of relative vorticity in each year in the box region ( $128^{\circ}$ – $152^{\circ}$ W and  $15^{\circ}$ – $27^{\circ}$ N) of the eastern subtropics is plotted.

eddies and permit submesoscale circulations such as small eddies and filamentary structures in the eastern subtropics as well as the western subtropics (Sasaki, Qiu, et al., 2020). Note that the sheared velocities in OFES2 are slightly weak compared with those estimated in the MOAA GPV based on the geostrophic balance.

The horizontal distribution of daily mean Rossby number in winter exhibits ubiquitous submesoscale eddies and filamentary structures in the subtropical north Pacific (Figure S1 in Supporting Information S1). In the eastern subtropics, the submesoscale circulations are more active in the winter of 1995 than 2004 (Figure 2). The difference is significant, although the submesoscale circulations vary on a weekly timescale (not shown), which may be modulated by atmospheric disturbance. This result suggests interannual variations of the submesoscale circulations in this region, as in the western region. This study examines the box region ( $128^{\circ}$ – $152^{\circ}$ W and  $15^{\circ}$ – $27^{\circ}$ N) in the eastern subtropics with the existence of active submesoscale circulations.

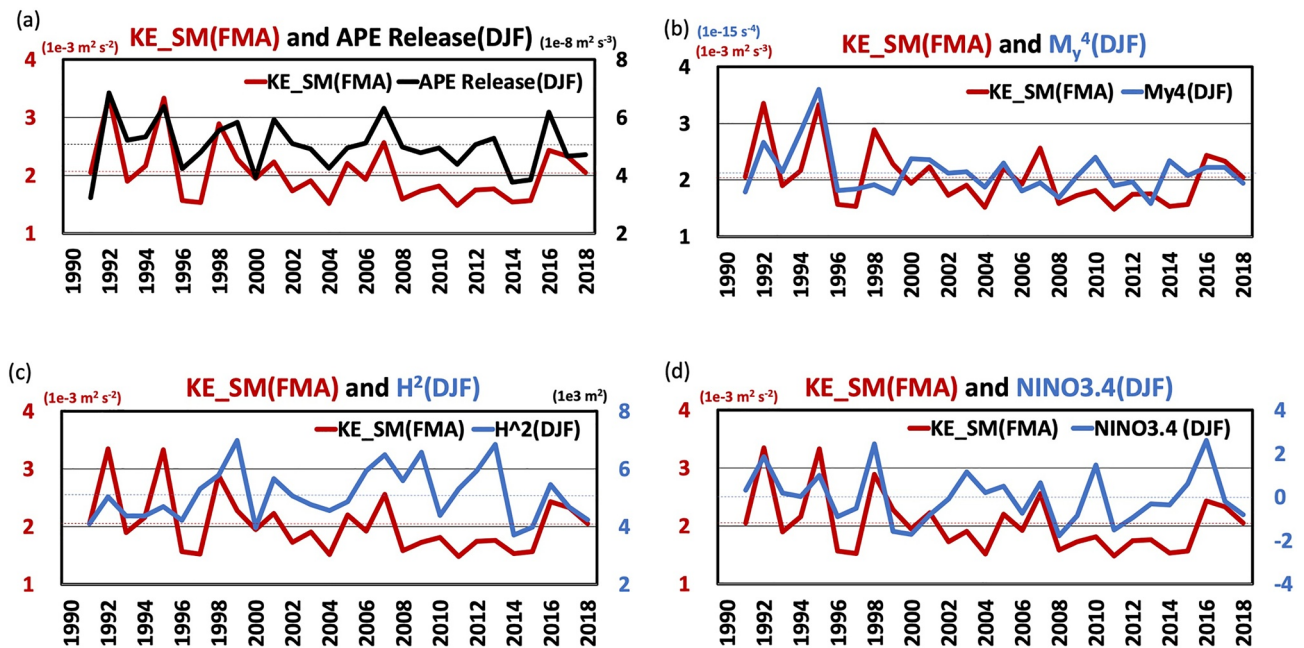
We compared the EKE time series in the box region in OFES2 with that in AVISO observations. The EKE variations in OFES2 are mostly synchronous with those of the observations, although its magnitude is slightly smaller than that of the observations (Figure 3a). The reduction in the EKE magnitude in OFES2 is due to an eddy killing effect in the estimation of surface momentum flux using relative wind considering surface velocity (e.g., Renault et al., 2019). In addition to seasonal variations of the high EKE from winter to spring and the low EKE from summer to autumn, the EKE varies on interannual to decadal timescales. Each EKE peak in OFES2 is slightly earlier than that in the observations. This time lag is due to the difference between the horizontal resolutions of OFES2 and AVISO observations, as explained by Qiu et al. (2014). OFES2 can resolve mesoscale circulations and permit submesoscale circulations, but AVISO can only represent mesoscale circulations. The active submesoscale circulations in winter resolved in OFES2 possibly make the EKE peak earlier than that in the observations (see discussion in Section 4). To examine the variations of submesoscale circulations in OFES2, the time series of KE at scales smaller than 100 km (submesoscale KE) and root-mean-square of relative vorticities are examined (Figure 3b). The submesoscale KE is estimated by using two-dimensional discrete Fourier transformation of the surface velocity field. Both the metrics clearly exhibit seasonal variations of the submesoscale circulations: active in winter and calm in summer. In addition, the winter peaks of both the metrics vary interannually: high in 1992, 1995, 1998, 2007, 2016, and 2017 and low in 1996, 1997, 2004, 2008, 2011, 2014, and 2015.

The yearly time series of winter submesoscale KE in OFES2 (Figure 4a) exhibits interannual variations of the submesoscale circulations. We found that the KE varies synchronously with the APE release estimated from a product of MLD squared and meridional buoyancy gradient squared. It is worth mentioning that the KE variations correlate better with the parameterized APE release variations ( $r = 0.73$ , Figure 4a) than each



**Figure 3.** (a) Time series of daily mean (thick curves) and annual running mean (thin curves) eddy kinetic energy ( $\text{cm}^2 \text{s}^{-2}$ ) in the box region in OFES2 (black curve) and the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) satellite observations (blue curve). (b) Time series of daily mean relative vorticity root-mean-square (RMS; black curve) and submesoscale kinetic energy at scales smaller than 100 km in OFES2 (red curve).

variations of the buoyancy gradient squared ( $r = 0.59$ , Figure 4b) and MLD squared (correlation coefficient  $r = 0.14$ , Figure 4c). The KE synchronously varies with the buoyancy gradient squared between 1991 and 1997 but not after 1998. The correlation between the KE and MLD squared variations is relatively low. These results suggest that the winter submesoscale circulations vary interannually more synchronously with the parameterized



**Figure 4.** (a) Yearly time series of the submesoscale kinetic energy averaged from February to April (red curve) and the parameterized available potential energy release averaged from December to February (black curve) in the box region in OFES2. Blue curves indicate (b) the meridional buoyancy gradient squared ( $M_y^4$ ), (c) mixed layer depth squared ( $H^2$ ), and (d) NINO3.4 index based on OISSTv2 (<https://www.cpc.ncep.noaa.gov/data/indices/>) averaged from December to February. Broken lines indicate the mean values.

APE release in a process of MLI than either of the MLD or the buoyancy gradient alone. In other words, the submesoscale circulations in the eastern subtropics are highly enhanced in the winters when the intensity of the regional MLI is strong.

What climate variability can induce the interannual variations of submesoscale circulations in the eastern subtropics? The composite SST anomaly (SSTA) maps (Figures S2a and S2b in Supporting Information S1) suggest that the submesoscale circulations in winter are active (calm) when El Niño (La Niña) event occurs. The yearly time series of the winter submesoscale KE is mostly synchronous with that of winter NINO 3.4 index (Figure 4d). Although the correlation coefficient ( $r = 0.56$ ) between two time series is not high enough to indicate a robust relationship, the  $t$ -value in  $t$ -test is 3.48, suggesting a significant relationship. Taking a closer look at the time series, the submesoscale KE is not large in the moderate El Niño winters of 2003 and 2010 and not large enough in 2016, which suggests that the relationship in the 2000s is relatively weak compared with that in the 1990s. The El Niño event in 2015–2016 was a mixture of eastern Pacific El Niño and central Pacific El Niño (El Niño Modoki; Paek et al., 2017), which is one possible reason why the large submesoscale KE is moderate in 2016. Further analysis to resolve this issue remains as our future study.

In the El Niño winters, the meridional SST gradient in the eastern subtropics is enhanced by positive and negative SSTAs in the equatorial and subtropical regions, respectively (see Figure S2a in Supporting Information S1). In addition, the composite MLD anomaly maps (Figures S2c and S2d in Supporting Information S1) suggest that the submesoscale circulations are active (calm) when the MLD is deep (shallow), although the MLD difference is small ( $= 4$  m). The MLI in this case is enhanced by the relatively strong meridional density gradient and deep MLD, leading to active submesoscale circulations. Note that there is no relationship between the variations of submesoscale circulations in this region and the PDO (not shown).

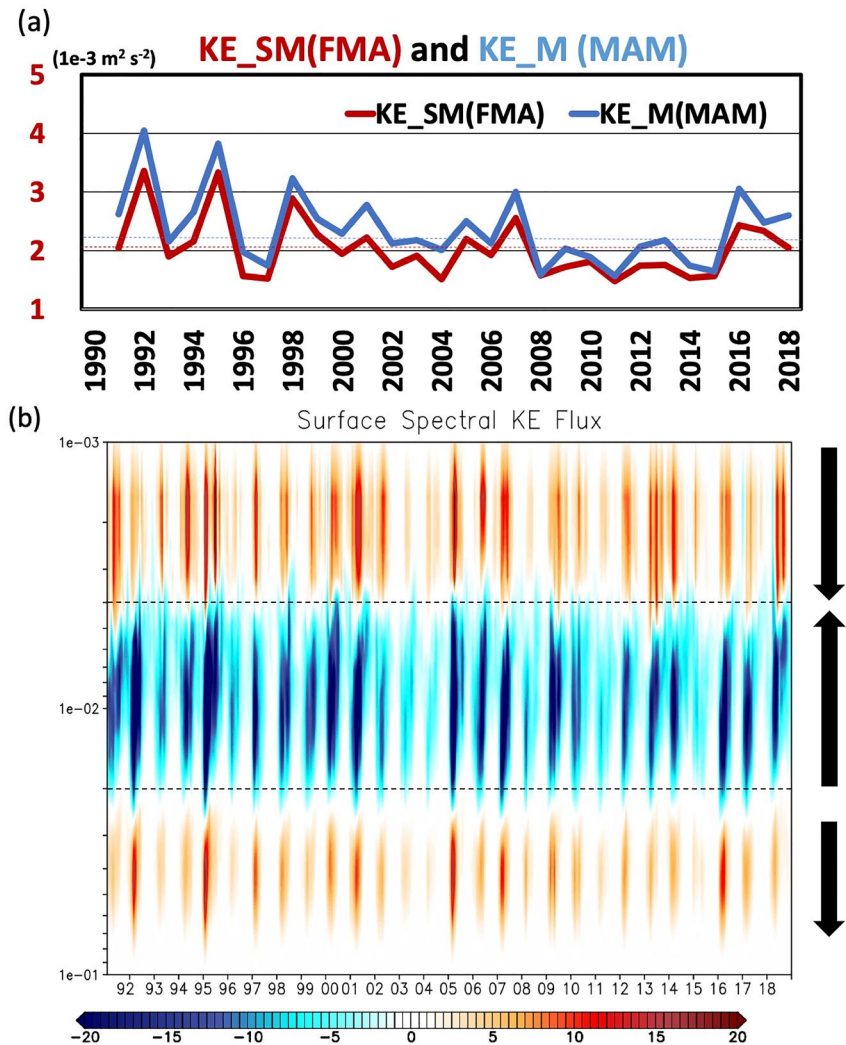
#### 4. Conclusions and Discussions

We examined interannual variations of submesoscale circulations in the subtropical northeastern Pacific in a submesoscale permitting hindcast simulation. As in the western subtropics (Sasaki, Qiu, et al., 2020), the submesoscale circulations are active in winter, and their KE varies interannually. The submesoscale KE is anomalously high in the winters when the parameterized APE release in a process of MLI is large. These results suggest that the activities of winter submesoscale circulations in the eastern subtropics depend on the intensity of MLI in the region as in the western subtropics. On the other hand, the climate variability that modulates the variations of winter submesoscale circulations in the eastern region is different from that in the western region. In the eastern subtropics, the winter submesoscale circulations appear to be more active in El Niño winters, while the variations in the western subtropics appear to be related to the PDO (Sasaki, Qiu, et al., 2020). The different types of climate variability seem to modulate the SST and MLD in the eastern and western regions, respectively, which possibly influence the MLI intensity and then lead to the variations of the submesoscale circulations.

We focused on submesoscale circulations in the subtropical northeastern Pacific, which interact with circulations at various other scales. The yearly time series of the spring peaks of mesoscale KE at scales between 100 and 200 km varies synchronously with that of the winter submesoscale KE with a high correlation value ( $r = 0.90$ ; Figure 5a). The mesoscale eddies possibly become active in spring due to the interior sheared instability, as in the western subtropics (Qiu & Chen, 2013). In addition, KE seems to be transferred from the submesoscale to mesoscale (Figure 5b). The negative KE flux at scales between 50 and 250 km is large in winter. This inverse energy cascade is relatively large mostly in the years when the submesoscale KE is large. Therefore, the interannual variations of submesoscale circulations in winter may partially modulate those of the mesoscale circulations, as in the western subtropics (Sasaki, Qiu, et al., 2020). In addition, the positive KE flux at scales smaller than 50 km and larger than 250 km is also relatively large in the years when the submesoscale KE is large. This suggests the relatively large forward KE transfers from submesoscale to smaller scales and from large-scale circulations to mesoscale in the years.

We diagnosed the parameterized APE release estimated from MLD and buoyancy gradient in a process of MLI to examine submesoscale circulations based on Fox-Kemper et al. (2008). One of the reasons for using the parameterization is that observational data are potentially available for its estimation (Johnson et al., 2016). To





**Figure 5.** (a) Yearly time series of the submesoscale (<100 km) kinetic energy (KE) averaged from February to April (red curve) and mesoscale (from 100 to 200 km) KE averaged from March to May (blue curve) in the box region. (b) Time series of daily surface spectral KE flux ( $1 \times 10^{-10} \text{ m}^2 \text{ s}^{-3}$ ) in the box region. The vertical axis indicates the wavenumber (cycle  $\text{km}^{-1}$ ).  $10^{-1}$ ,  $10^{-2}$ , and  $10^{-3}$  cycle  $\text{km}^{-1}$  correspond to scales of 10, 100, and 1,000 km, respectively. The upward (downward) black arrow indicates the inverse (forward) KE transfer at scales between 50 and 250 km (larger than 250 km and smaller than 50 km).

verify the parameterization, we examined the direct estimation of APE release ( $w'b'$ ,  $w$  is a vertical motion,  $b$  is buoyancy, and prim is a deviation from the local area mean) compared with the parameterized value. The yearly time series of  $w'b'$  in winter in the eastern region is mostly synchronous with that of the parameterized values ( $r = 0.70$ , Figure S3a in Supporting Information S1). This result suggests that the parameterized APE release is generally appropriate for a metric of MLI's intensity. However, the relationship between the submesoscale KE and  $w'b'$  ( $r = 0.53$ , Figure S3b in Supporting Information S1) is relatively obscure compared with that using the parameterized value ( $r = 0.79$ , see Figure 4a). One of the possible reasons is that activity of the winter submesoscale circulations and its interannual variations are relatively weak in this region compared with those in the western region (Sasaki, Qiu, et al., 2020). The other reason is that several dynamic processes not considered in this study, such as frontogenesis and symmetric instability (e.g., McWilliams, 2016), may play a role in activating submesoscale circulations in this region. This study considers neither these processes nor the impacts of tidal and unbalanced inertial-gravity wave motions on submesoscale circulations (Qiu et al., 2018; Rocha et al., 2016). Revealing how these modulate the variations of submesoscale circulations on interannual to decadal timescales remains as our future study.



## Data Availability Statement

The data set for the results in this study is available at Sasaki (2021).

## Acknowledgments

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