Decadal Variability of Upper-Ocean Heat Content Associated with Meridional Shifts of Western Boundary Current Extensions in the North Pacific

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(Manuscript received 28 October 2016, in final form 2 May 2017)

ABSTRACT

Generation and propagation processes of upper-ocean heat content (OHC) in the North Pacific are investigated using oceanic subsurface observations and an eddy-resolving ocean general circulation model hindcast simulation. OHC anomalies are decomposed into physically distinct dynamical components (OHC_r) due to temperature anomalies that are associated with density anomalies and spiciness components (OHC_x) due to temperature anomalies that are density compensating with salinity. Analysis of the observational and model data consistently shows that both dynamical and spiciness components contribute to interannual–decadal OHC variability, with the former (latter) component dominating in the subtropical (subpolar) North Pacific. OHC_r variability represents heaving of thermocline, propagates westward, and intensifies along the Kuroshio Extension, consistent with jet-trapped Rossby waves, while OHC_x variability propagates eastward along the subarctic frontal zone, suggesting advection by mean eastward currents. OHC_x variability tightly corresponds in space to horizontal mean spiciness gradients. Meanwhile, area-averaged OHC_x anomalies in the western subarctic frontal zone closely correspond in time to meridional shifts of the subarctic frontal zone. Regression coefficient of the OHC_x time series on the frontal displacement anomalies quantitatively agree with the area-averaged mean spiciness gradient in the region, and suggest that OHC_x is generated via frontal variability in the subarctic frontal zone.

1. Introduction

Global and regional upper-ocean heat content (OHC) is modulated on a wide range of low-frequency time scales (seasonal to multidecadal and secular) due to atmospheric thermal and dynamical forcings (e.g., Willis et al. 2004; Levitus et al. 2005). The OHC thus acts as climate memory and may provide a source of skills for seasonal to decadal predictions (Mochizuki et al. 2010; Branstator and Teng 2010; Teng and Branstator 2011; Mochizuki et al. 2012) if it affects sea surface temperature (SST) and the overlying atmosphere locally and remotely. Yet, regional expressions of OHC variability remain to be fully understood.

Earlier numerical (Latif and Barnett 1994; Kwon and Deser 2007; d'Orgeville and Peltier 2009; Teng and Branstator 2011; Taguchi and Schneider 2014) and observational studies (Zhang and Levitus 1997) report that OHC anomalies in the North Pacific often propagate eastward along the northern periphery of the subtropical gyre. Taguchi and Schneider (2014, hereinafter TS14) analyzed mechanisms for generation and propagation of decadal-scale OHC anomalies in a long-term...
climate model simulation. In their model, large OHC variability in the North Pacific is confined along the subarctic frontal zone (SAFZ) where mean northward decrease of temperature and salinity density compensates and forms large gradients of mean spiciness (e.g., Veronis 1972; Schneider 2000). The simulated frontal zone exhibits internally generated decadal-scale fluctuations in its latitudinal position, which are highly correlated with the time series of the spiciness component of OHC anomalies averaged over the upstream SAFZ. These features lead the authors to hypothesize that the existence of the spiciness gradients in the background mean fields and anomalous currents associated with the frontal shift that cross the mean spiciness gradients favor the generation of large OHC anomalies through anomalous advection of mean spiciness gradients (schematically shown in Fig. 1). Once generated, the density-neutral spiciness anomalies act as passive tracers and are advected eastward by the background eastward mean currents. This hypothesis, derived from a low-resolution climate model that does not resolve important physics of the ocean mesoscale, remains to be tested with higher-resolution datasets.

The objective of the present study is to characterize the interannual–decadal OHC variability in the extratropical North Pacific using historical observations and a high-resolution ocean general circulation model (GCM) hindcast simulation that well represents the oceanic mesoscale (Masumoto et al. 2004; Sasaki et al. 2008). This allows us to test the coarse-resolution coupled GCM analysis-based hypothesis by TS14 on the generation of OHC anomalies via anomalous advection of spiciness. Questions to be addressed are the following: What are the relative contribution of Rossby waves and spiciness to total OHC variability and what are their regional difference in the North Pacific, particularly in relation to western boundary current variability? What are the spatiotemporal structure, the propagation feature, and the origin of each process contributing to the OHC variability?

The rest of the manuscript is organized as follows. Section 2 describes the data and method used in this study. Section 3 presents spatiotemporal structures of analyzed OHC variability, while section 4 discusses the generation mechanism of the OHC variability. Section 5 provides a summary and discussion.

2. Data and method

a. Data

The main datasets used in this study are monthly mean oceanic temperature and salinity from an objective analysis of historical observation by Ishii and Kimoto (2009) (hereafter referred to as the Ishii analysis) for the period 1945–2012 and an ocean GCM hindcast simulation using the Ocean General Circulation Model for Earth Simulator (OFES; Masumoto et al. 2004; Sasaki et al. 2008, hereafter referred to as the OFES hindcast) for the period 1950–2014. The Ishii analysis is based on the World Ocean Database (WOD05) and World Ocean Atlas (WOA05), the Centennial In Situ Observation Based Estimates (COBE), historical expendable bathythermograph (XBT) and mechanical bathythermograph (MBT) observations, and Argo profiling buoy data. Observational data are gridded on a 1° × 1° grid with 24 vertical levels in the upper 1500 m by an optimal interpolation technique (Ishii et al. 2005). We use a version in which a depth bias correction is applied for XBT and MBT observations (Ishii and Kimoto 2009). This analysis has been used to study ocean heat content variations (Ishii et al. 2005), sea level change (Ishii et al. 2006; Suzuki and Ishii 2011), and sea level variations (Suzuki and Ishii 2015) during the past six decades.

The OFES hindcast simulation is configured for a near-global domain (75°S–75°N) with 0.1° longitude and latitude resolution and forced with the daily mean National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) atmospheric reanalysis data (Kalnay et al. 1996). It reproduces well mesoscale eddies, western boundary
currents, and their interannual–decadal variations in the midlatitude North Pacific (Nonaka et al. 2006; Taguchi et al. 2007; Nonaka et al. 2008; Taguchi et al. 2010; Sasaki and Schneider 2011).

Besides the major oceanic datasets, we use an atmospheric reanalysis and an oceanic index: the Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015) for surface sensible and latent heat fluxes, and the Oyashio Extension index (OEI; Frankignoul et al. 2011). The OEI represents meridional shift of the Oyashio Extension (or SAFZ) and is the first principal component of the Oyashio Extension position in latitude for the zonal sector 145°E–170°E, which is detected as the latitude of maximum meridional gradient of SST based on objectively analyzed air–sea fluxes (OAFlux) dataset compiled for the period 1958–2012 at a 1° × 1° grid (Yu et al. 2008).

b. Analysis method

First, we remove from monthly data of the Ishii analysis and OFES hindcast their linear trends and monthly climatologies to focus on the natural variability of the data. The residual temperature anomalies are then decomposed into 1) temperature anomalies \( T'_\rho \) that are associated with density anomalies (dynamical component) and 2) temperature anomalies \( T'_x \) that are density compensating with salinity (spiciness component). Temperature anomalies are assumed to result from displacements of the mean field with components \( \delta x_\rho \) perpendicular to isopycnals and \( \delta x_x \) parallel to isopycnals:

\[
T' = T - \bar{T} \approx -\nabla T(x) \cdot (\delta x_\rho + \delta x_x) = T'_\rho + T'_x, \quad (1)
\]

where \( T \) is monthly mean temperature, \( \bar{T} \) is the monthly mean climatology of \( T \), and \( T' \) is the monthly temperature anomaly. Applying the same approach to density anomalies, and noting that \( T'_x \) does not impact the density field, \( T'_\rho \) can be further written as

\[
T'_\rho = \frac{dT'}{dp} \rho', \quad \text{with} \quad \frac{dT}{dp} = \frac{\nabla T \cdot \nabla p}{|\nabla p|^2}. \quad (2)
\]

Note that \( T'_x \) is computed as the residual and thus includes dynamical temperature anomalies arising from nonlinear processes that are not represented in Eq. (2). Readers are referred to TS14 for the detailed derivation of Eqs. (1) and (2) and to Furue et al. (2015) for an alternative derivation for a specific case considering only vertical density gradients. The decomposition Eq. (1) is useful in characterizing the OHC variability, as dynamical and spiciness components follow distinct underlying mechanisms. Specifically, the former follows Rossby wave dynamics (e.g., westward-propagating, satellite-observed sea surface height anomalies; Qiu and Chen 2005, 2010) while the latter behaves as a passive tracer subject to advection by background flows (e.g., southwestward propagating of spiciness anomalies in the North Pacific subtropical gyre detected in Argo observations; Sasaki et al. 2010).

Finally, \( T'_\rho \) and \( T'_x \) are vertically averaged over the upper 400-m depth to define dynamical and spiciness component of OHC anomalies, \( \text{OHC}'_\rho \) and \( \text{OHC}'_x \), respectively. We choose the depth range of 0–400 m in our definition of OHC to focus on the upper ocean where the thermal variability may affect sea surface temperature and the overlying atmosphere.

3. Spatiotemporal structures of decomposed OHC variability

This section describes the interannual–decadal variability of dynamical and spiciness components of OHC, \( \text{OHC}'_\rho \) and \( \text{OHC}'_x \), respectively, in the extratropical North Pacific Ocean represented in the Ishii analysis and OFES hindcast.

a. Horizontal structure

Figures 2a and 2b show the interannual–decadal variability of \( \text{OHC}'_\rho \) and \( \text{OHC}'_x \), respectively, based on the Ishii analysis. Contrary to TS14’s coupled GCM in which the spiciness component dominates in the OHC variability, both components contribute to the total OHC variability in the Ishii analysis. The \( \text{OHC}'_\rho \) variability is large in the subtropics, particularly along the Kuroshio Extension (KE), around 35°N, and the Subtropical Countercurrent and Hawaiian Lee Countercurrent, west and northeast of Hawaii, respectively, indicating that the \( \text{OHC}'_\rho \) variability reflects the variability in the thermocline associated with these ocean currents. On the other hand, the \( \text{OHC}'_x \) is large in the subpolar region, particularly around the Kuroshio–Oyashio confluence region and along the subarctic frontal zone. The North Pacific subarctic frontal zone is characterized by sharp gradients in latitude of density-compensating temperature and salinity (e.g., Kida et al. 2015; contours in Fig. 2c). This hydrographical feature is quantified by the upper 400-m mean spiciness gradient \( \nabla T'_x \), \( \int_0^{400m} (\nabla T'_x) \, dz \), where \( H = 400 \text{ m} \) and \( \nabla T'_x \) is computed by Eq. (8) in TS14 (shading in Fig. 2c). The mean spiciness gradient is large in the region where meridional gradients of density-compensating temperature and salinity are large. It is clear that the region of large mean spiciness gradient (contours in Fig. 2b) corresponds well to that of the large variability of \( \text{OHC}'_x \) (shading in Fig. 2b), consistent with TS14.
Although the Ishii analysis indicates large OHC variability occurs along oceanic frontal zones, particularly in the North Pacific western boundary currents, the historical data sampling that constitutes the dataset may be insufficient to represent the oceanic frontal variability. Therefore, we turn to the OFES hindcast that has sufficient horizontal resolution to represent North Pacific western boundary current variability (Nonaka et al. 2006; Taguchi et al. 2007; Nonaka et al. 2008; Taguchi et al. 2010; Sasaki and Schneider 2011). Overall features of the OHC variability in the OFES hindcast, shown in Figs. 2d–f, are consistent with those based on the Ishii analysis. Specifically, the variability of OHC_\rho and OHC_x is large along the KE and SAFZ, respectively, and the latter corresponds well in space to the mean spiciness gradient. Meanwhile, differences exist. First, the amplitude of the variability is generally more than 2 times larger in the OFES hindcast than in the Ishii analysis for both the components of OHC (notice the color scale difference in Fig. 2). Second, the large variability of OHC_x along the SAFZ corresponds more tightly to the mean spiciness gradient with smaller meridional scale in the OFES hindcast than in the Ishii analysis. Third, the Ishii analysis puts the largest variance of OHC_\rho off the coast of Japan (Fig. 2b) while the OFES hindcast does not (Fig. 2e). This could be related to the mean circulation simulated in the OFES hindcast, which shows in this area a northward extension of the Kuroshio.

Fig. 2. (a) Standard deviation of nonseasonal, detrended OHC_\rho (dynamical component of the upper-ocean heat content anomalies as measured with temperature anomalies averaged over the depth range of 0–400 m; shading; K) for the period of 1950–2012 based on the subsurface ocean analysis data of Ishii and Kimoto (2009) (Ishii analysis). Superimposed with black contours is dynamic height relative to 2000 m (contoured every 0.2 m s^{-2}). (b) As in (a), but for OHC_x (spiciness component of OHC). Superimposed with black contours are mean spiciness gradients averaged over the depth range of 0–400 m (c) As in (a), but for mean spiciness gradients averaged over the depth range of 0–400 m (shading; K m^{-1}) and climatological mean temperature (yellow contours) and salinity (cyan contours) averaged over the depth range of 0–400 m (d)–(f) As in (a)–(c), but based on the OFES hindcast simulation.
(Nonaka et al. 2008), while the Oyashio in reality bifurcates southward at 40°N from the subpolar front (e.g., Kida et al. 2015) and feeds the coastal flow that may yield properties in the mixed water region. The large variations of OHC off the coast of Japan thus may be a function of a modulation of this bifurcation, which OFES simulates incorrectly, pointing to the difficulties of simulating the separation of western boundary currents (WBCs). Nevertheless, these features suggest that the KE and the SAFZ both play an important role in generating interannual–decadal OHC variability but emphasize different component of OHC anomalies.

b. Vertical structure

To further examine the distinct features of OHC and OHC variability, we examine in Fig. 3 latitude–depth sections of interannual–decadal standard deviation for each component of the temperature anomalies, \( T'_\rho \) and \( T'_\chi \) averaged over the longitudinal sector of 150°–170°E. In the Ishii analysis, the standard deviation of \( T'_\rho \) (the dynamical component associated with density anomalies) is large along the main pycnocline associated with the KE around 35°N, indicating that the \( T'_\rho \) variability is generated by heaving of the pycnocline (Fig. 3a).

On the other hand, \( T'_\chi \) variability (the spiciness component) is large along the SAFZ, located around 40°–42°N in this zonal sector, and has a shallower vertical structure than along the KE (Fig. 3b). In the SAFZ, background temperature contours (cyan in Fig. 3b) tilt more steeply than potential density contours (black) because temperature and salinity compensate each other for density in SAFZ, yielding meridional gradients of potential density smaller than implied by temperature alone. Therefore, temperature contours cross the density contours in SAFZ, which results in large temperature gradients along the isopycnals and hence large mean spiciness gradients (Figs. 2c and 3c). The maximum loading of \( T'_\chi \) variability corresponds to the maximum northward (negative) gradients (\(-6 \times 10^{-6} \text{K m}^{-1}\)) of mean spiciness that appear in the 0–200-m depth range in SAFZ (Fig. 3b). The close correspondence between mean spiciness gradients and \( T'_\chi \) variability indicates

Fig. 3. (a) Latitude–depth section of standard deviation of detrended annual mean \( T'_\rho \) (dynamical component of temperature anomalies) averaged over the zonal sector of 150°–170°E based on the Ishii analysis (shading; K). Superimposed with black contours is potential density \( \sigma_T \) (contour interval 0.5). (b) As in (a), but for \( T'_\chi \) (spiciness component). Superimposed with cyan contours is temperature (contoured every 2.0 K). (c) As in (a), but for the meridional gradient of mean spiciness (shading; K m \(^{-1}\)). (d)–(f) As in (a)–(c), but based on the OFES hindcast.
that any anomalous currents crossing the mean spiciness gradient give rise to large spiciness anomalies due to anomalous advection (see section 4 for further discussion).

Vertical structures of $T_p^x$ and $T_x^x$ variability in the OFES hindcast are very similar to those found in the Ishii analysis as shown in Figs. 3d–f, with $T_p^x$ variability tightly associated with the mean spiciness gradient. In addition, the separation of the two components’ variability in the two oceanic frontal zones associated with the deeper KE and the shallower SAFZ is even clearer with narrower meridional scales in each front in the OFES hindcast than in the Ishii analysis, suggesting that the two WBCs affect different component of upper-ocean temperature and thus OHC anomalies.

It is worth mentioning that there is a secondary spiciness temperature $T_p^x$ variability north of the SAFZ around 46°–58°N in the 100–200-m (50–140 m) depth range in the Ishii analysis (OFES hindcast). Although the zonal sector shown in Fig. 3 includes both the Okhotsk Sea and the North Pacific Ocean west and east of Kamchatka Peninsula, respectively, a regional analysis shows that the shallow secondary $T_p^x$ variability mainly reflects the variability in the latter (figure not shown). Hence, we examine the depth–season section of $T_p^x$ variability in the upstream Oyashio to the west of Kamchatka Peninsula (52°N, 160°–170°E; Fig. 4a). The shallow $T_p^x$ variability reaches its maximum just beneath the deep wintertime mixed layer in March–April. The variability persists through the warming season at the same depth below seasonal thermocline. The seasonal evolution of the variability suggests that the spiciness anomaly $T_p^x$ is diabatically generated at the base of the winter mixed layer. The depth–time section of the

![Fig. 4. (a) Depth–season diagram of interannual standard deviation of monthly mean spiciness component temperature anomaly $T_p^x$ based on the Ishii analysis averaged over an Oyashio region off Kamchatka Peninsula (52°N, 160°–170°E; color shading; K). Superimposed with contours are climatological monthly mean temperature (contoured every 1°C). (b) Depth–time diagram of monthly mean spiciness temperature anomaly $T_p^x$ based on the Ishii analysis for the period 1950–2012. Superimposed with contours are total temperature in March for every year (contoured every 1 K).](image-url)
monthly mean spiciness anomaly $T^s$ and the total temperature in March corroborates this conjecture (Fig. 4b). Note that $T^s$ tends to be warmer (cooler) than normal at the 100–150-m depth range in years when the wintertime mixed layer depth is shallower (deeper). Interestingly, the sign of the anomaly tends to persist for several years (e.g., positive around 1998–2000, negative around 1988–91) and sometimes for a decade (negative around 1965–76).

c. Time evolution

To examine the temporal evolution of the OHC anomalies, we first define reference time series of $\text{OHC}^r$ and $\text{OHC}^x$ variability based on the Ishii analysis and OFES hindcast, by area-averaging OHC anomalies in the two regions where the variability of each component of OHC is large: one representing the KE region (33°–38°N, 145°–170°E, white box in Figs. 2a,d) for the $\text{OHC}^r$ variability and the other representing SAFZ (slanted box within 38.5°–42.5°N, 148°–160°E shown with white lines in Figs. 2b,e). Superimposed with orange line is standardized 36-month running mean OEI based on OAFlux SST.

![Fig. 5. (a) Time series of area mean $\text{OHC}^r$ averaged over the KE region (33°–38°N, 145°–170°E; white box in Figs. 2a,d). Red-blue bars (black curve) show monthly mean (36-month running mean) time series based on the Ishii analysis, while the green curve shows the 36-month running mean time series based on the OFES hindcast. (b) As in (a), but for $\text{OHC}^x$ averaged over the SAFZ (slanted box within 38.5°–42.5°N, 148°–160°E shown with white lines in Figs. 2b,e). Superimposed with orange line is standardized 36-month running mean OEI based on OAFlux SST.](#)
from a warm/salty phase in 1970s to a cold/fresh phase in 1980s is captured by both the Ishii analysis and OFES hindcast, while the OFES time series deviates from the observed counterpart after 1990. It is worth noting that the aforementioned phase transition can be seen not only in OHC$_x$ time series for SAFZ but also in OHC$_r$ time series in KE region both in the Ishii analysis and OFES hindcast. The correlation between the two variables is particularly high ($r = 0.81$) in the OFES hindcast, indicating that OHC$_r$ in the KE region and OHC$_x$ in SAFZ change synchronously. The high correlation is in contrast with a previous study by Nonaka et al. (2006), who used the same OFES hindcast and argued that the KE and SAFZ evolve differently, unlike a coherent temporal evolution of the Kuroshio–Oyashio front in earlier coarse-resolution studies. The discrepancy may be due to different variables [subsurface temperature and salinity in Nonaka et al. (2006) and the spiciness component of ocean heat content in the present study] or different analysis periods. The correlation in the Ishii data is only 0.44 but still statistically significant at 95% level. A possible underlying mechanism for the covariability is further discussed in section 5.

d. Propagation

The temporal evolution of OHC$_r$ associated with the standardized reference time series in the KE region, based on the Ishii analysis, is examined in Fig. 6a. The evolution of OHC$_r$ is characterized by westward propagation of OHC$_r$ that appears initially in the eastern

Fig. 6. (a) Lagged correlation (color shading) and regression (contours, every 0.1 K) coefficients of annual mean OHC$_r$ based on the Ishii analysis associated with the standardized reference time series of OHC$_r$ averaged over the KE region ($33^\circ$–$38^\circ$N, 145$^\circ$–170$^\circ$E; cyan boxes in the panels for lag 0 yr). Positive (negative) lags indicate that OHC$_r$ lags (leads) the reference time series. OHC$_r$ with (top)–(bottom) lag = −3, −2, −1, and 0 yr are shown. (b) As in (a), but based on the OFES hindcast. Regression coefficients are shown at every 0.2 K.
North Pacific around 170°–150°W. At lag $-3$ yr the initial $OHC_{\rho}$ in the eastern North Pacific have a weak amplitude ($0.1$ K per one standard deviation of the reference time series) and a broad meridional scale between 30° and 40°N. During the westward propagation, the anomalies are concentrated along a narrow meridional band along the KE and are amplified up to 0.3 K along the KE at lag 0. In the OFES hindcast, a similar propagation feature is detected for $OHC_{\rho}$ (Fig. 6b), while the concentration to the KE is clearer than in the Ishii analysis because of the better representation of the meridionally narrow oceanic front associated with the KE in the former than the latter. The westward intensification and concentration of the signals with initially broad meridional scale is consistent with jet-trapped Rossby waves proposed by Sasaki et al. (2013).

A longitude–time section of $OHC_{\rho}$ averaged over the latitudinal range of 34°–40°N captures the westward propagation of the anomalies (Fig. 7). For example, both the Ishii analysis and OFES hindcast represent westward propagating, negative anomalies that arrived at the western boundary in early 1980s. The phase propagation of $OHC_{\rho}$ corresponds well to that of dynamic height anomalies relative to 2000 m (contours in Fig. 7), suggestive of linear first-mode baroclinic Rossby waves. The phase speed is roughly estimated as 3.9 cm s$^{-1}$ (solid black lines), about 50% faster than the westward phase speed of the linear first-mode baroclinic Rossby waves under the longwave approximation ($2.63$ cm s$^{-1}$ for the latitudinal range averaged over 34°–40°N; Qiu 2003). Sasaki et al. (2013) estimated a 5.0 cm s$^{-1}$ westward phase speed of sea level anomalies associated with the meridional shift of the KE jet based on satellite altimeter observation and discussed possible causes of the faster phase speed estimation of the jet-trapped Rossby waves than the linear first-mode baroclinic long Rossby waves. These propagation features of $OHC_{\rho}$, along with its vertical structure confined in the main pycnocline associated with the KE, collectively suggest that the variability of the dynamical component...
OHC represents westward-propagating jet-trapped Rossby waves.

In contrast, OHC signals associated with the standardized reference time series in SAFZ (Fig. 8) propagate along the SAFZ. In both the Ishii analysis and OFES hindcast, the OHC emerges east of Japan around 40°N at lag from −2 to 0 yr and subsequently propagates eastward into the central–eastern subarctic North Pacific. The correlation is rather weak after a lag of +2 yr in the Ishii analysis, while the correlation is higher in the OFES hindcast. The meridional scale of the eastward-propagating OHC is approximately 10° latitude in the Ishii analysis and less than 5° latitude in the OFES hindcast, presumably due to the difference in horizontal resolution to represent oceanic frontal structure along SAFZ in the two datasets, which manifests in the meridional scale of mean spiciness gradients (Figs. 2c,f). The propagation path also exhibits a subtle difference between the two datasets: OHC in the Ishii analysis propagates east-northeastward while the propagation path is more zonal in the OFES hindcast. The paths are consistent with differences in distributions of the mean dynamic height and sea surface height, a proxy of geostrophic surface streamfunction (contours in Figs. 2a and 2d for the Ishii analysis and OFES hindcast, respectively). The correspondence between the eastward propagation of OHC and the eastward mean current inferred from the dynamic height or sea surface height fields in the subarctic North Pacific, including their subtle difference between the two datasets, implies that the

Fig. 8. As in Fig. 6, but for lagged correlation (shading) and regression coefficients (contours) for (a) the Ishii analysis (contours every 0.025 K) and (b) the OFES hindcast (contours every 0.1 K) of OHC associated with the standardized reference time series of OHC averaged over the SAFZ (slanted box within 38.5°–42.5°N, 148°–160°E shown with white lines in the panels for lag 0 yr). Coefficients with (top)–(bottom) lag = −2, 0, +2, and +4 yr are shown. Cyan contours display OHC standard deviations of 0.175 and 0.4 K for the Ishii analysis and OFES hindcast, respectively.
eastward $OHC_x$ propagation is due to the advection of the spiciness by the background mean current (TS14).

Considering the difference in the propagation path and the meridional scale of the anomalies, we quantify in Fig. 9 the eastward propagation of $OHC_x$ by constructing longitude–time transects of the anomalies that exceed typical thresholds of $OHC_x$ standard deviation (cyan contours in Fig. 8). $OHC_x$ propagations agree reasonably well between the Ishii analysis and OFES hindcast after mid-1970s with eastward-propagating warm and cold anomalies alternating about every 10 years.1 Most prominent are negative signals that departed off Japan (145°E) during the mid-1980s (shown with pink solid lines in Fig. 9). The eastward propagation speed is comparable to climatological mean current velocity averaged over the upper 400-m depth and over the region where the $OHC_x$ variability exceeds the threshold (cyan contours in Fig. 8b; 6.74 cm s$^{-1}$). The spiciness component of OHC anomalies by construction behaves as a passive tracer. The quantitative correspondence between the eastward-propagating $OHC_x$ and the background eastward current confirms the eastward advection by background mean current of spiciness anomalies reported previously in coupled GCM studies (d’Orgeville and Peltier 2009; TS14).

Figure 8 also captures signals that are likely unrelated to the aforementioned eastward-propagating $OHC_x$ originating from the northwestern Pacific. At lag -2 and 0yr, negative anomalies appear off the Gulf of Alaska. The anomalies could be generated through upwelling

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1 The OFES hindcast displays westward propagation during 1965–75 as well. Given that the band of high $OHC_x$ signals is more zonally oriented in the OFES hindcast than the Ishii analysis, this analysis band is more subject to the westward-propagating Rossby waves, which may lead to successive generation of spiciness anomalies as current anomalies propagate westward via anomalous advection (see section 4).
forced by concurrent alongshore wind variability (Pozo Buil and Di Lorenzo 2015).

4. Generation of OHC$_x$ anomalies

While it is well known that the westward propagating linear first-mode baroclinic or jet-trapped Rossby waves seen in OHC$_p$ are forced by wind-induced Ekman pumping in the central to eastern North Pacific, the generation mechanism for the spiciness anomalies in the SAFZ off Japan is less clear. Based on the analysis of a CGCM control simulation for 150 years, TS14 hypothesized that the existence of the mean spiciness gradient and axial variability of the oceanic frontal zone favor the generation of large OHC anomalies through the advection of the mean spiciness by the associated anomalous currents. Here we test this hypothesis in the OFES simulation that is forced with observed surface fluxes and resolves oceanic fronts and eddies better than the CGCM used in TS14.

Assume the flow is adiabatic in the thermocline without isopycnal diffusion so that spiciness (temperature anomalies on isopycnal surfaces) is governed by

$$\frac{\partial T'_x}{\partial t} + \mathbf{u}_h \cdot \nabla_h T'_x = -\nabla_h \cdot \mathbf{u}_h T'_x, \quad (3)$$

where $\mathbf{u}_h$ is horizontal currents on isopycnal surfaces, and $\nabla_h$ designates horizontal gradients. The heat budget is linearized around a background current and temperature gradient on isopycnal surface, as indicated by the overbar. The term on the right-hand side represents spiciness generation via anomalous advection across background mean spiciness gradients and the two terms on the left-hand side show local temporal change and advection of spiciness anomalies by background mean currents, respectively. Kilpatrick et al. (2011) applied this equation to subtropical subduction regions, whereas we apply it here to the frontal zone in the North Pacific. Assuming $\mathbf{u}_h$ is constant along the parcel trajectory and integrating Eq. (3) from an upstream coordinate $x = x_0$ at $t = t_0$ (i.e., the western end of the SAFZ) yields

$$T'_x(x, t) - T'_x(x_0, t_0) = -\int_{t_0}^{t} dt' \mathbf{u}_h'[x - \mathbf{u}_h(t - t'), t'] \cdot \nabla_h T'_x, \quad (4)$$

where the term on the left shows the spiciness change over the time period during which a water parcel travels from location $x_0$ to $x$ with the background mean current, whereas the term on the right represents the integral of the anomalous advection along the parcel trajectory.

In the OFES hindcast, qualitative evidences support the process expressed in Eqs. (3) and (4). First, we show composite mean anomalous advection terms for periods with high and low OHC$_p$ in the SAFZ (OHC$_p$–SAFZ; Figs. 10a,b). During the high (low) OHC$_p$–SAFZ phase, positive (negative) signals in the upstream SAFZ around 40°–41.5°N, 147°–152°E, result from anomalous northward (southward) currents (figure not shown) that cross large mean meridional spiciness gradients (purple contour). This indicates that OHC$_p$ variability in the SAFZ is associated with anomalous advection generated by meridional shifts of the SAFZ. We estimated the integrated anomalous advection by constructing a joint probability density function (PDF) of the anomalous advection term and climatological mean sea surface height (SSH; Figs. 10c,d). Here, SSH serves as a proxy for streamlines due to $\mathbf{u}_h$, and the average of the anomalous advection term at a particular SSH bin (shown in black dots) approximately represents advection term integrated along the streamline. The PDF distribution is biased in the positive (negative) quadrant showing more occurrences of positive (negative) anomalous advection for the high (low) OHC$_p$–SAFZ composite. The magnitude of the bias of approximately $0.5 \times 10^{-7}$ K s$^{-1}$ indicates spiciness generation of around 0.57 K of a particle passing through the SAFZ area (~40° in longitude) with a mean current speed of about 0.15 m s$^{-1}$. Both sign and magnitude are consistent with the hypothesis that the variability of OHC$_x$ in SAFZ is generated by the process governed by Eqs. (3) and (4).

Second, the variance of the spiciness anomalies is collocated with the mean meridional spiciness gradient (Figs. 2e,f) and the time series of meridional frontal displacement $\Delta y(t)$ and spiciness anomalies OHC$_x(t)$ averaged over the subarctic transition region (41°–43°N, 154°–158°E) are correlated at 0.68 (0.92) for the monthly mean (36-month running mean) as shown in Fig. 11. The frontal displacement $\Delta y(t)$ is estimated by zonally averaging from 154° to 158°E the latitude of the maximum meridional temperature gradient at 100-m depth, the depth where the meridional temperature gradients are largest in the SAFZ (Fig. 3e). Note that although both OHC$_x$ and $\Delta y(t)$ are derived based on temperature gradients, the correspondence between the two time series is not trivial, because OHC$_x$ is computed as a residual of OHC$_p$ that is based on three-dimensional temperature and density gradients [Eq. (2)] whereas the frontal shift is estimated only based on the meridional temperature gradient. The regression coefficients between OHC$_x(t)$ and $\Delta y(t)$ of $6.13 \times 10^{-6}$ K m$^{-1}$, close to the value of $5.54 \times 10^{-6}$ K m$^{-1}$ of the mean spiciness gradients averaged over the transition region, confirms the meridional displacements of the front dominate over vertical ones.
Third, the low-frequency phase change of OHC\(_x\) anomalies in the SAFZ (Fig. 9b) co-occurs with the arrival of the westward propagating OHC\(_x\) anomalies (Fig. 7b), implying that the density signals induce meridional current anomalies. These three findings suggest that the spiciness anomalies OHC\(_x\) are generated via anomalous advection associated with meridional shifts of the subarctic frontal zone. While we here emphasize the large-scale, wind-driven shifts of the front, recent observations show that decadal modulation of the eddy field paced by the arrival of wind-driven Rossby waves (Qiu and Chen 2005, 2010; Taguchi et al. 2010) are associated with changes of water masses in the mixed water region (Oka and Qiu 2012). The impact of these eddy effects on changes in OHC\(_x\) should be tested in a future study.

Last, anomalous advection may lead to spatial resonance (Saravanan and McWilliams 1998) if mean advection and the anomalous advection due to Rossby waves are as-sociated with changes of water masses in the mixed water region (Oka and Qiu 2012). The impact of these

Fig. 10. (a) Composite mean (shading) of anomalous advection term [right-hand side of Eq. (3)] based on OFES hindcast for the years when annual mean OHC\(_x\) averaged over the SAFZ (slanted box within 38.5°–42.5°N, 148°–160°E shown with white slanted box in Fig. 2b) exceeds its half standard deviation (>0.5\(\sigma\); high OHC–SAFZ). Superimposed with thin (thick) black contours show climatological SSH contoured every 10 cm (at −25 and 15 cm). Purple contours indicate meridional gradient of mean spiciness at \(-1 \times 10^{-7} \text{K m}^{-1}\). (b) As in (a), but for composite mean when OHC\(_x\) are below −0.5\(\sigma\) (low OHC–SAFZ). (c) PDF (shading) of the high OHC–SAFZ composite mean, bin-averaged anomalous advection term (y axis; K s\(^{-1}\)) and climatological mean, bin-averaged SSH (x axis). Black dots show PDF-weighted averages of the anomalous advection term along each value of the bin-averaged SSH. (d) As in (c), but for PDF of the low OHC–SAFZ composite mean. PDFs are estimated for the domain designated by red slanted box in (a),(b).
5. Summary and discussion

We have analyzed oceanic subsurface observations and an eddy-resolving OGCM hindcast simulation to characterize interannual–decadal variability of the upper-ocean heat content (OHC) anomalies in the extratropical North Pacific. Analysis of the observational and the OGCM datasets consistently shows that both the dynamical (associated with density/pressure change) and spiciness (density compensating) components, OHC$_\rho$ and OHC$_\chi$, respectively, contribute to interannual–decadal OHC variability, while the former (latter) dominates in subtropical (subpolar) regions. OHC$_\chi$ variability represents heaving of the thermocline, propagating westward and intensifying along the Kuroshio Extension, a feature consistent with the jet-trapped Rossby waves. OHC$_\chi$ variability propagates eastward along the subarctic frontal zone (SAFZ) with a phase speed comparable to the speed of the background mean current, suggestive of advection of spiciness by the mean current. OHC$_\chi$ variability tightly corresponds to horizontal mean spiciness gradient in space, whereas area-averaged OHC$_\chi$ in SAFZ closely corresponds in time to meridional shifts of the front, consistent with the hypothesis of OHC generation via spiciness generation associated with the frontal variability (TS14).

Upper-ocean heat content variability and steric sea level variability are often linked with changes in water mass properties. For example, Suzuki and Ishii (2011) reported that in the North Pacific subtropics positive sea level trends in recent decades are associated with upper-ocean density change caused by warming and freshening of the subtropical mode water due to surface buoyancy forcing. The variability of OHC, defined here as temperature anomalies averaged over the upper 400-m depth range, may be subject to such diabatic surface forcing. We repeated our analysis for the OHC defined as temperature anomalies averaged over the depth range of 100–400 m excluding the 0–100-m depth range, which contains in most regions the winter mixed layer that is in direct contact with the atmosphere. The result is qualitatively unchanged and suggests that the OHC variability documented in this study is mainly generated adiabatically by ocean circulation change. In particular, our study reveals that interannual–decadal OHC variability is strongly constrained by the oceanic frontal zones such as the KE and SAFZ. While Seager et al. (2001) and Nonaka et al. (2006) have shown the importance of oceanic frontal zones in decadal temperature variability, our study establishes that the different physics is at play for dynamically active and passive tracers, along the KE and SAFZ, respectively.

Relatively coarse-resolution climate models, such as the one used in TS14, tend to represent the separated KE and SAFZ as a single, broad, so-called Kuroshio–Oyashio Extension (KOE) front. Unlike the finding of the present study, OHC variability in TS14’s coupled GCM is dominated by the spiciness component and dynamical component OHC variability is nearly absent, which is possibly due to too strong mean spiciness gradient along the KOE front. The dominance of the eastward-propagating spiciness signals may be one reason for detected bias of the slower than observed westward phase speed of the first baroclinic Rossby wave in CMIP3 models (Sueyoshi and Yasuda 2009). The differences in conclusions between the present study and TS14 highlight the importance of resolving the observed frontal structures in climate models. The fidelity of climate models to represent the two distinct OHC variability detected in this study should be investigated in a future study.

While the upper-ocean heat content variability is primarily induced by atmospheric forcing, it is of great interest in terms of climatic implication whether OHC variability, particularly its eastward-propagating spiciness component, leaves an imprint on SST, heat flux, and the overlying atmosphere. Figure 12 shows lag-regressed SST and surface heat flux anomalies associated with the OHC$_\chi$ variability in SAFZ. Positive OHC$_\chi$ appear in SAFZ (lag = 0 yr in Fig. 8) and subsequently propagate eastward (lag = +2 and 4 yr). They are accompanied by eastward propagating positive SST anomalies (red contours in Fig. 12) that reach 150°W at lag +2 (+4) yr for the Ishii analysis (OFES hindcast). Associated with the SST anomalies, statistically significant heat flux anomalies from the ocean to the atmosphere of 10–30 and 20–60 W m$^{-2}$ in the JRA-55 and OFES hindcast, respectively, suggest that the OHC$_\chi$-rooted SST anomalies are damped by, and hence force, the atmosphere. This is consistent with earlier coupled GCM and
observational studies (Kwon and Deser 2007; Frankignoul and Kestenare 2002; TS14). Moreover, d’Orgeville and Peltier (2009) reported that in their coupled GCM (CCSM3) eastward propagating spiciness anomalies originating from the northwestern Pacific propagate to the Bering Sea and affect SST and sea ice cover via upwelling. Their influence on the atmosphere reverses the polarity of the Pacific decadal variability. From another perspective, the OHC variability is large in the SAFZ, whose frontal and the associated SST variability are known to influence the basin-scale atmospheric circulation (Frankignoul et al. 2011; Taguchi et al. 2012; Okajima et al. 2014; Smirnov et al. 2015). It is interesting to point out that the OEI, an index representing the meridional shifts of the SAFZ (Frankignoul et al. 2011), is highly correlated with the OHC time series averaged over the SAFZ (Fig. 5b; $r = 0.70$ for 36-month running mean). Given that the OHC and the associated SST anomalies propagate eastward and persist for 2–4 years after they are generated by SAFZ shifts, the OHC variability documented in this study may contribute to the eastward expansion of SST anomalies and low-frequency, persistent forcing on the atmosphere associated with meridional shifts of the Oyashio Extension or SAFZ. These climatic implications of the OHC variability require further studies.

FIG. 12. As in Fig. 8, but for lagged correlation (shading) and regression coefficients (black contours) of (a) sensible plus latent heat flux anomalies based on JRA-55 (contours every 10 W m$^{-2}$) and (b) net heat flux anomalies in the OFES hindcast associated with the standardized reference time series of OHC (contours every 20 W m$^{-2}$) averaged over the SAFZ (slanted box within 38.5°–42.5°N, 148°–160°E shown with cyan lines in the panels for lag 0 yr). Positive heat flux indicates upward heat release from the ocean to the atmosphere and negative vice versa. Red and blue contours display regression coefficients of SST for $-1.0$ and 1.0 K, respectively, based on the Ishii data in (a) and OFES hindcast in (b). Coefficients with (top)–(bottom) lag = $-2$, 0, +2, and +4 yr are shown.
Given its climatic influence, it would be of societal benefit if the SAFZ shifts were predictable. While KE variability is predictable 3–4 years in advance in OFES (Taguchi et al. 2007; Nonaka et al. 2012; Qiu et al. 2014), the present study shows that OFES reproduces the observed history of the OHC$_\chi$ variability in SAFZ (black and green curves in Fig. 5b) and SAFZ shifts (orange curve in Fig. 5b and black curve in Fig. 11) with modest skill only. The difficulty in hindcasting the SAFZ variability arises from a number of reasons. First, quasi-stationary (so-called Isoguchi) jets, which are thought to connect the subtropical KE variability with subarctic SAFZ variability (Isoguchi et al. 2006; Kida et al. 2015; Wagawa et al. 2014), are absent in the OFES hindcast. The lack of Isoguchi jets in OFES is hinted at in the meridional gradient of mean spiciness (Figs. 2c,f) with two southwest–northeast-tilted cores around 150°–155°E and 160°–170°E in the Ishii analysis but with a zonal character in the OFES hindcast. Second, recent studies reveal that the western boundary currents such as the KE and subarctic currents exhibit large intrinsic variability on interannual–decadal time scales even under the climatological mean currents (Pierini 2006; Taguchi et al. 2007; Penduff et al. 2011) or among multimember ensemble simulations under interannually varying atmospheric forcing (Nonaka et al. 2016). In a single-member simulation of the OFES hindcast, meridional shifts of the SAFZ or OHC$_\chi$ variability may be affected by both chaotic intrinsic variability and deterministic, wind-forced variability. Obtaining a realistic mean state and variability in the subarctic region remains a modeling challenge.

Despite the difficulty in simulating the observed history of meridional shifts of OHC$_\chi$ in SAFZ, our results may contribute to enhanced predictability of the OHC$_\chi$ variability in SAFZ. As shown in section 3c, the time series of OHC$_\chi$ in SAFZ and OHC$_\rho$ in the KE region are significantly correlated each other, particularly in the OFES hindcast. By comparing the longitude–time section based on the OFES hindcast of OHC$_\rho$ (Fig. 7b) in the KE region and OHC$_\chi$ in SAFZ (Fig. 9b), it is interesting to point out that the eastward-propagating OHC$_\rho$ anomalies emerge upon the arrival of westward-propagating OHC$_\chi$ anomalies, a feature consistent with the covariability in the time series of OHC$_\rho$ in the KE region and OHC$_\chi$ in SAFZ. Quantitatively, lag correlation between the two time series with 3-yr low-pass filter applied exhibits a maximum of 0.83 when OHC$_\rho$ in the KE region leads OHC$_\chi$ in the SAFZ by 10 months (figure not shown). Hence, the variability of KE induced by wind forcing may be linked with the subsequent spiciness variability in SAFZ that is generated by anomalous advection. In reality, physical processes underlying this link could be through the variability in eddy heat transport from the KE (Sugimoto et al. 2014) or advective effect of Isoguchi jets (Wagawa et al. 2014), although the latter is unlikely in the OFES hindcast. The issue requires further studies using datasets that can represent the variability of KE, SAFZ, and Isoguchi jets all together.

While the OHC$_\rho$ variability discussed here has interannual to decadal time, and 100–200-km horizontal scales across the western boundary current, there are shorter time scale spiciness variability from mesoscale to submesoscale near the KE region. For instance, Nagai et al. (2015) observed from subinertial to near-inertial spiciness variability across the KE front at thermohaline filaments with the vertical scales of a few tens of meters, which could enhance double diffusion and diapycnal diffusions of tracers. Investigating multiscale interactions of spiciness variability near the strong frontal regions using submesoscale eddy-resolving OGCMs (e.g., Sasaki and Klein 2012; Sasaki et al. 2014) is another interesting direction for future studies.

Acknowledgments. We thank Dr. Young-Oh Kwon for providing us with Oyashio Extension index and Drs. Claude Frankignoul and Humio Mitsudera for fruitful discussion. Comments from Dr. Yoshinori Sasaki and two anonymous reviewers helped improve the manuscript. JRA-55 data were obtained from http://diss.dtkl.iis.u-tokyo.ac.jp/dl/storages/filelist/dataset:204. The OFES hindcast simulation was carried out on the Earth Simulator under the support of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). We gratefully acknowledge support by JAMSTEC through JAMSTEC-IPRC Joint Investigation (JIJI), by the Japanese Ministry of Education, Culture, Sports, Science and Technology through a Grant-in-Aid for Scientific Research in Innovative Areas 2205 (22106006, 22106009, and 22106010), by the Japan Society for Promotion for Science through KAKENHI (24540476 and 15K05284), by the Japanese Ministry of Environment through the Environment Research and Technology Development Fund 2-1503, by the U.S. Department of Energy, Office of Science, through Grant DE-SC0006766, and by the National Science Foundation through Grant OCE-1357015. B.T. is in part supported by the Arctic Challenge for Sustainability (ArCS) Program and by the Japan Science and Technology Agency through Belmont Forum CRA “InterDec.”

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