Low-frequency spiciness variations in the tropical Pacific Ocean observed during 2003–2012

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[1] Large-scale spiciness variations in the Pacific Ocean during 2003–2012 are well recorded in the Argo-based Grid Point Value of the Monthly Objective Analysis (MOAA GPV) dataset. Pronounced interannual spiciness anomalies between 25.0–25.5 $\sigma_\theta$ are detected near the outcropping areas in the eastern subtropics of both hemispheres. Differing from previous model results, the observed subtropical variations are more powerful in the North Pacific. While these subtropical signals diffuse quickly as propagating equatorward, large-magnitude anomalies are generated in the off-equatorial tropics (10°–14°N and 3°–7°S) under intensive current perturbation and further communicated to the central equatorial Pacific via interior-ocean meridional flow. Although equator-signal propagation to the eastern Pacific upwelling zones is not discernable, appearance of spiciness anomalies leads to low-frequency thermal variations in the central equatorial Pacific, which may play a role in the increasingly frequent occurrences of ENSO-MoMi events. Citation: Li, Y., F. Wang, and Y. Sun (2012), Low-frequency spiciness variations in the tropical Pacific Ocean observed during 2003–2012, Geophys. Res. Lett., 39, L23601, doi:10.1029/2012GL053971.

1. Introduction

[2] Density-compensated potential temperature $\theta$ and salinity $S$ variations of sea water along isopycnal surfaces are addressed as spiciness variations. Propagation of spiciness anomalies from subtropics to the tropics along the subsurface passage of the subtropical cells (STCs) [McCreary and Lu, 1994] is believed to be an important process affecting low-frequency tropical climate changes [Gu and Philander, 1997]. In the Pacific Ocean, such equatorward propagation in the thermocline has been detected in historical datasets [e.g., Zhang et al., 1998; Schneider et al., 1999] and further confirmed by numerical model simulations [e.g., Giese et al., 2002; Yeager and Large, 2004; Luo et al., 2005]. However, both observations and models results also indicated that anomalies from the North Pacific have been obscure when reaching the tropics, and thus not likely to significantly impact sea surface temperature (SST) at the equator [Schneider et al., 1999; Nonaka and Xie, 2000]. On the other hand, models results showed that spiciness anomalies from the subtropical South Pacific are of larger power and more important in the transitions of tropical Pacific climate [Giese et al., 2002; Yeager and Large, 2004; Luo et al., 2005]. Due to the sparsity of subsurface conductivity measurements, it is difficult to separate spiciness anomalies from planetary wave signals in historical datasets. In this regard, a better description of spiciness variations in the tropical Pacific with recently available observations is urgently demanded to validate the intriguing phenomena in model results.

[3] Accumulation of high-quality data profiles from Argo floats in the past decade has provided us an invaluable tool to monitor subsurface spiciness variations [Johnson, 2006; Sasaki et al., 2010; Li et al., 2012]. Among others, Sasaki et al. (2010) reported the propagation of spiciness anomalies from the northeastern subtropics across the North Pacific basin between 25.0–25.5 $\sigma_\theta$ during 2003–2008. These anomalies are of remarkable magnitude (0.15 psu for salinity) at the origin but greatly diminished along the path. However, whether these anomalies could penetrate to the equator and to what extent they can affect the equatorial SST is unknown. Moreover, the modeled powerful spiciness variations in the South Pacific and their impact on the equatorial Pacific should also be examined with Argo data.

2. Observed Spiciness Variations

[4] In this study, we investigate the low-frequency spiciness variations over the entire tropical Pacific Ocean (120°E–80°W, 25°S–30°N) using a gridded dataset based mainly on Argo data, i.e., the Grid Point Value of the Monthly Objective Analysis (MOAA GPV) [Hosoda et al., 2008]. The MOAA GPV is a global gridded monthly dataset constructed with data records from Argo floats, buoy measurements, and casts of research cruises. For each month, data from various sources are interpolated onto standard pressure levels between 10 and 2000 dbar and then gridded into $1^\circ \times 1^\circ$ fields using the two-dimensional optimal interpolation method (see Hosoda et al. [2008] for details). The final dataset provides monthly temperature and salinity fields from January 2001 to the present. To obtain low-frequency (interannual to decadal) signals, we filtered the data with a 13-month running mean and used the low-passed data between January 2003 and January 2012 for analysis. Thermocline spiciness signals are represented by $\theta$ anomalies between 25.0–25.5 $\sigma_\theta$, where isopycnal surfaces in 0.1 kg m$^{-3}$ bins are decided for each month, and then $\theta$ anomalies are estimated in isopycnal coordinates. During the analysis, we also used the Extended Reconstruction SST (ERSST) version 3b [Smith et al., 2008] from the National Oceanic and Atmospheric Administration (NOAA) and the monthly wind stress data of the ERA-interim [Dee et al., 2011] by the European Centre for Medium-Range Weather Forecasts (ECMWF).
Low-frequency spiciness variability can be quantified by the root-mean-squared (rms) variability of the low-passed \( q \) data (Figure 1a). High spiciness variability can be seen immediately near the outcropping areas in the eastern subtropics of both hemispheres where unstable vertical salinity gradient [Yeager and Large, 2004] and highly variable subduction [Johnson, 2006] and advection [Schneider, 2000] are in favor of spiciness anomaly generation. Signals appear evidently stronger in the North Pacific: the rms variance exceeds 0.3 \( ^\circ\)C between 20\(^\circ\)–30\(^\circ\)N, whereas it reaches only half that value between 10\(^\circ\)–20\(^\circ\)S. While the pronounced spiciness changes in the northeastern subtropics are in consonant with earlier observations [e.g., Zhang et al., 1998; Sasaki et al., 2010], those in the southeastern subtropics appear much weaker than in previous model outputs. Except the biases in numerical simulations, such discrepancy may be also attributed to other reasons. First, in the modeled South Pacific, most large anomalies occur in 1970s and 1980s, whereas those generated in 1990s and early 2000s are visibly weaker [e.g., Yeager and Large, 2004; Nonaka and Sasaki, 2007]. Second, modeled large anomalies are generated mainly between 20\(^\circ\)–30\(^\circ\)S where denser isopycnals, e.g., \( \sigma_\theta = 25.3–25.5 \text{ kg m}^{-3} \), outcrops. Johnson [2006] showed that active diapycnal mixing in this region are sufficiently vigorous to reduce them quickly after generation. Then, those observed between 10\(^\circ\)–20\(^\circ\)S are much weaker. In our results, these subtropical signals diffuse quickly as the propagating equatorward along mean geostrophic streamlines which are represented by the mean acceleration potential (AP; a vertical integral of specific volume deviation from the reference level of 2000 dbar) contours. Signals have been reduced to 0.1\(^\circ\)–0.15\(^\circ\)C magnitudes at 15\(^\circ\)N and 10\(^\circ\)S in the northern and southern hemispheres, respectively.

Spiciness variations in the tropical Pacific are generally disconnected from subtropical signals. It is noticeable that enhanced variability reappears in the off-equatorial tropics, reaching 0.2\(^\circ\)–0.25\(^\circ\)C at 10\(^\circ\)N and 1\(^\circ\)S (regions A and B in Figure 1). Subsequently, these signals can penetrate to the equatorial Pacific through the interior pathways of the STCs [Johnson and McPhaden, 1999], although a large portion are advected to the western Pacific by the North and South Equatorial Currents (NEC and SEC). The elevated variability in the off-equatorial tropics which are distant from outcropping regions indicate anomaly generation involving no effects of air-sea fluxes or subduction. A possible mechanism is through current perturbation. It seems the case in the AP variability and \( q \) field (Figure 1b). The elevated spiciness variances are accompanied by high AP variability and large

Figure 1. (a) Root-mean-squared (rms) \( \theta \) variability (color shading; in \( ^\circ\)C) superimposed by mean AP (black contours; in \( \text{m}^2 \text{s}^{-2} \)) and (b) rms AP variability (color shading) superimposed by mean \( \theta \) (black contours) averaged between 25.0–25.5 \( \sigma_\theta \) based on the low-passed MOAA GVP dataset during 2003–2012. Mean AP contours of 20.4- and 21.0-\( \text{m}^2 \text{s}^{-2} \) are highlighted as black thick curves. The pink rectangles denote the regions A (170\(^\circ\)–156\(^\circ\)W, 10\(^\circ\)–14\(^\circ\)N) and B (147\(^\circ\)–130\(^\circ\)W, 3\(^\circ\)–7\(^\circ\)S).
lateral $\theta$ gradients in their upstream areas. At these latitudes low-frequency current variations are primarily wind-forced 1st-mode baroclinic Rossby waves [Kessler, 1990], and $\theta$ gradients are formed by the distribution of different water masses.

[7] In the yearly maps of spiciness anomaly (Figure 2), equatorward signal propagation along the passage between the mean 20.4- and 21.0-m$^2$ s$^{-2}$ AP contours can be seen in both hemispheres. However, vigorous along-path diffusion and anomaly generation in the off-equatorial tropics make it difficult to identify the origin of signals reaching the central equatorial Pacific. Also varying from year to year are the flow pathways. For example, in the South Pacific, yearly AP contours of 20.4- and 21.0-m$^2$ s$^{-2}$ locate northeast (southwest) of the mean contours during 2003–2005 (2007–2009) in the upstream area of region B, which indicates anomalous advection of warm (cold) water from subtropics and thus produces positive (negative) $\theta$ anomalies in region B.

[8] The situation in region A is more complicated. It has been indicated by the signal discontinuity in Figure 1a that anomalies here are also not simply brought by the mean flow from upstream subtropics. To examine the impact of the hypothesized current perturbation, we conducted a reversed Lagrangian tracing using the reversed monthly isopycnal geostrophic velocity fields. Particles were released in every grid points within region A in January 2007 and January 2010 when local $\theta$ anomaly approximately reaching negative and positive peaks, respectively. Particles were relocated and reassigned with velocities in each day for 2 years. The trajectories of these particles are shown in Figures 3a and 3b. For those released in January 2007, a large number of particles c a nb et r a c dt o1 3 5 –125 W, 14°–19°N, an area greatly influenced by southward intrusion of the cold/fresh California Current water. In contrast, more particles released in January 2010 are traced back to areas less influenced by California Current water and thus with higher climatological potential temperature $\langle \theta \rangle$. A quantitative comparison of $\langle \theta \rangle$ of the ending locations of particles is given in Figure 3c. Additional high $\langle \theta \rangle$ values (>16.5°C) can be seen at 2008 locations (released in January 2010). The ensemble mean value is 0.18°C higher in 2008 than in 2005, which is not qualitatively sensitive to different tracing periods ranging from 1.5–2.5 years. It means that, even without upstream $\theta$ variations, due to current perturbation, positive (negative) spiciness anomalies can be produced in region A through the changes of flow path and water source. We should also note that the 0.18°C difference is smaller than the peak-to-peak $\theta$ difference of 0.4°–0.5°C in region A. This discrepancy may be partly associated with the nonlinear combination of current and spiciness variability, i.e., $U \cdot \nabla \theta$ effect. Hence

Figure 2. Yearly maps of $\theta$ (black thin contours; in °C) and $\theta$ anomaly (color shading; in °C) between 25.0–25.5 $\sigma_\theta$. The green (black) thick curves denote the yearly mean (2003–2012 mean) AP contours of 20.4- and 21.0-m$^2$ s$^{-2}$.
tropical current perturbation is an important contributor for the spiciness anomaly generation in the off-equatorial tropics.

Equatorward signal transmission can be identified in a time-latitude plot (Figure 3d) along the interior pathway which is constructed by averaging low-passed $q$ anomalies between mean AP contours of 20.4- and 21.0-$m^3/s^2$ east of 160$^\circ$E. Negative (positive) anomalies generated north of 30$^\circ$N in 2003–2004 (2006–2007), have been reported by Sasaki et al. [2010]. They are nearly diminished when reaching the tropics due to along-path diffusion. It is anomalies generated in the off-equatorial tropics that could approach the equatorial Pacific Ocean. Similar pattern can be seen in the South Pacific, albeit with smaller amplitudes. Although these anomalies are further diffused, their arrival makes considerable contribution to the low-frequency spiciness variations in the central equatorial Pacific. This process is consistent with Schneider’s [2000] modeled decadal spiciness mode and Kessler’s [1999] observed fact that interannual salinity variations at the equator can not be explained by surface fluxes in its subtropical water source.

### 3. Impact on Equatorial Thermal Variability

A more interesting issue of spiciness variability is their impact on equatorial thermal variability. Arrivals of spiciness anomalies through the interior passage mainly occur between 180$^\circ$ and 130$^\circ$W (recall Figure 1), resulting in $\theta$ changes with amplitudes of 0.2°C in the central equatorial Pacific thermocline (100–180 m; Figure 4a). Note that these variances are clearly independent from signals in the western and eastern basins. The anomalies in the far western Pacific are of the same sign and considerable magnitudes compared to those in the central Pacific, but their impact is confined west of 140$^\circ$E. Eastward signal advection via the equatorial undercurrent (EUC) is not discernable. In the eastern Pacific, on the other hand, $\theta$ variations in this layer are controlled by Ekman pumping by equatorial trade winds, which are clearly indicated by the consistent changes of isopycnal depth (Figure 4a), SST, and zonal wind stress (Figure 4b). Arrivals of spiciness anomalies seem to impact the equatorial Pacific thermal variability in a way distinct from the traditional view. Instead of a further transmitting to the eastern Pacific upwelling zones, they lead to a subsurface warming during 2003–2005 and a subsurface cooling during 2008–2010 in the central Pacific. These fluctuations alter the vertical temperature gradient and thus warm/cool the surface layer by vertical advection, i.e., through $\langle w \rangle \nabla \theta$ effect. Such effect may contribute to the occurrences of the recent 2004–2005 warming and 2010–2011 cooling in the central equatorial Pacific Ocean (Figure 4b), which are also

![Figure 3. Trajectories of the reverse Lagrangian tracing (a) from January 2007 to January 2005 and (b) from January 2010 to January 2008. Green (pink) dots indicate the starting (ending) locations, and color shading denotes 2003–2012 mean $\theta$ (°C) between 25.0–25.5 $\sigma_0$. (c) Histogram of 2003–2012 mean potential temperature $\langle \theta \rangle$ (°C) at the ending locations of the traced particles in January 2005 and January 2008. The ensemble mean values are indicated by thin lines ($\langle \theta \rangle = 15.42^\circ$C in 2005; $\langle \theta \rangle = 15.60^\circ$C in 2008). (d) Latitude-time plot of $\theta$ anomaly (°C) between 25.0–25.5 $\sigma_0$ along the interior pathway. The 14°N, 10°N, 3°S, and 7°S latitudes are marked with black lines. Contour interval is 0.05°C, and contours in every 0.2°C are marked black.](image-url)
Figure 4. Time-longitude plots of (a) \( \theta \) anomaly (color shading; in °C) superimposed by depth (black contours; in m) between 25.0–25.5 \( \sigma_T \) in MOAA GPV and (b) ERSST anomaly (color shading; in °C) superimposed by zonal sea surface wind stress \( \tau_x \) (N m\(^{-2}\)) from ERA-Interim reanalysis. All variables are averaged between 3°S and 3°N and low-passed with a 13-month running-mean before plotting. Contour interval is 0.05°C and 0.25°C for \( \theta \) and ERSST anomalies, respectively.

addressed as ENSO-Modoki events [Ashok and Yamagata, 2009].

4. Summary and Discussion

[11] In this study we investigated low-frequency spiciness variations in the tropical Pacific during 2003–2012 using the MOAA GPV dataset, underscoring the subtropical-to-tropical spiciness signal propagation. Differing from previous model results, the observed subtropical spiciness variations are visi-

[12] bly more powerful in the North Pacific during this period. These anomalies diffuse quickly as propagating equatorward and get nearly diminished before reaching the equator. Instead, under intensive current perturbation, anomalies generated in the off-equatorial tropics (10°–14°N and 3°–7°N) with an rms \( \theta \) magnitude > 0.2°C can finally penetrate to the central equatorial Pacific via the interior ocean pathways. Their arrival at the equator lead to low-frequency subsurface thermal variances in the central Pacific but can not be further transmitted to the eastern Pacific upwelling zones.

[13] Previous studies showed that thermal anomalies, especially those from the North Pacific, prefer western boundary pathways rather than the interior routes to the equator [e.g., Giese et al., 2002; Yeager and Large, 2004], whereas our results reveal clear meridional signal conveying in the central Pacific. Such discrepancy may be associated with the slow changes of the basin-scale circulation gyres in the Pacific Ocean. Spinning up since 1990s [McPhaden and Zhang, 2004; Zhang and McPhaden, 2006], the expansion of the wind-driven subtropical gyres allows more extra-tropical water spreading to the equatorial Pacific in the interior ocean. More arrivals of spiciness anomalies amplify the subsurface thermal variances in the central equatorial Pacific and contribute to the recent increased occurrences of ENSO-Modoki events [Ashok and Yamagata, 2009; Yeh et al., 2009].

References


