Variability of spice injection in the upper ocean of the southeastern Pacific

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ABSTRACT

Seasonal-to-decadal variability of spice injection in the upper ocean of the subtropical southeastern Pacific (SEP) is investigated using 3-day and 0.25-degree simulations spanning from 1982 to 2016 in the Consortium for Estimating the Circulation and Climate of the Ocean (ECO). The spice injection reflects convective mixing through which saline water in the mixed layer is injected into the interior to generate positive temperature and salinity anomalies or spiciness anomalies (SPA). Results show that the spice injection in the SEP occurs during austral winter when the mixed layer is deep, and it leads to a positive SPA in the interior. The interior SPA is found to experience significant interannual variability, which is well correlated with winter mixed layer depth (MLD), with more interior SPA corresponding to deeper MLD. During a strong winter of injection, the interior spiciness change rate can reach up to \(-0.005\) kg/m$^3$/day$^{-1}$ and the gain of spiciness in the interior \(-0.2\) kg/m$^3$ over the SEP region. The interannual-decadal variability of interior SPA in the SEP has a significantly negative correlation to the low-frequency El Niño-Southern Oscillation (ENSO) index, with larger (smaller) SPA during La Niña (El Niño) conditions.

INTRODUCTION

The subtropical southeastern Pacific Ocean (SEP) has long been recognized as an important region for climate studies because subsurface temperature/salinity anomalies there propagate towards the tropics along the geostrophic streamlines and can modify the quasihorizontal thermocline structure. The injection of temperature and salinity anomaly from the mixed layer into the thermocline is often called spice injection since salinity anomaly is density compensated by temperature anomaly, which is referred to as spiciness anomaly.

Southeastern Pacific

In the SEP box, it is the region with deep MLD and large unstable vertical salinity gradients. This SPA injection has interannual-decadal variability, with being weaker from 2008-2015 and stronger from 2011-2013 in both ECOO and observations.

Fig. 1: (a) Schematic of potential density (kg m$^{-3}$) and spiciness (kg m$^{-3}$) in temperature-salinity space. The blue dot lines denote changes of spiciness, temperature and salinity on 25.6 bar water parcel 5 from one month (c) to another (b). Interannual standard deviation (STD) of salinity (color in kg m$^{-3}$) and spiciness (color in kg m$^{-3}$) is superimposed in the climatological Montgomery geostrophic streamlines (black lines), where z$^{*}$ refers to 300 dbar. Montagola’s diagram of anomalies of salinity and spiciness on 25.6 bar along the 28.5 Montgomery geostrophic streamlines.

Fig. 2: (a) SST and heat flux and (b) SSS and freshwater flux, (c) mixed layer depth and surface potential density (black) and surface spiciness (cyan). The black box in (c) marks the key region of anomalies, where the winter mixed layer is deep.

Fig. 3: Depth-time plots of spiciness anomaly over the SEP box from (a) ECOO during 1992-2016 and (b) AVISO during 2002-2015.

ANNUAL CYCLE

MLT and MLD budget

Together with the MLD change, the MLD budget also appears to have significant seasonal variations. During the winter when the mixed layer is shallower, more injection occurs over the entire mixed layer but a negative SPA below the mixed layer; during the winter when the mixed layer is deep, there is a negative SPA on the upper portion of the mixed layer but a positive SPA around the bottom of the mixed layer and below the mixed layer.

Fig. 4: Climatological annual cycle of (a) MLD, (b) temperature flux (black) and its two components of heat flux (red) and entrainment flux (blue), (c) salinity and (d) Ekman pumping.

Fig. 5: (a) The heat and salinity fluxes and entrainment heat and salinity fluxes (red). (b) Interannual variability of MLT (red) and MLD (blue) in the southeastern Pacific Ocean during 1992-2016.

Fig. 6: The MLD is clearly dominated by the surface heat flux (covariance: 93%) (Fig. 6b). For the MLS, its interannual variability is dominated by the vertical entrainment with a mean of their covariance during 1992-2016 reaching 86%.

Fig. 7: (a) Interannual changes of MLD and MLS, (b) the anomaly of spiciness and heat flux and (c) the normalised covariance between MLD and MLS, and the spiciness and the five contributing processes.

Fig. 8: Annual STD of salinity between 25.6 kg/m$^3$ and 26.0 kg/m$^3$ (black and gray lines) as well as STD of MLS (red lines) during 1992-2016. The correlation coefficient between 25.6 kg/m$^3$ black line and red line is 0.72 at 95% significant level.

INTERANNUAL-DECADAL VARIABILITY

Year-to-year difference

The interannual STD of SPA is well correlated with the MLD, suggesting more significant the MLD changes, the larger the SPA is produced in the interior.

Fig. 9: Annual STD of spice injection over 25.6 kg/m$^3$ and 26.0 kg/m$^3$ (black and gray lines) as well as STD of MLS (red lines) during 1992-2016. The correlation coefficient between 25.6 kg/m$^3$ black line and red line is 0.72 at 95% significant level.

During strong injection years, the interior spiciness change rate occurred during the winter with the maximum rate reaching to \(-0.005\) kg/m$^3$/day$^{-1}$. There are a series of the winter injection events contributing to the SPA in the interior, with each of them lasting for a few days. These high-frequency injection events were smoothed out while using the monthly mean data, and the maximum change rate of spiciness in the interior is significantly reduced. The spatial patterns of spiciness generation shows that the winter injection is not uniform, with its value being over 1 kg/m$^3$ in hot spots in 1998.

Interannual-decadal variability

The SST anomaly changes the mixed layer density/stratification and thus modifies the MLD. Further, a deepening (shoaling) of the MLD generates stronger (weaker) spice injection and thus more (less) SPA in the interior. There is larger (smaller) SPA during La Niña (El Niño) conditions.

Fig. 10: Spiciness generation (kg/m$^3$), MLS anomalies (contour from 0 to 9 kg/m$^3$ in 3 kg/m$^3$ intervals), and the ENSO index (red) over the SEP box during 1992-2016. The correlation between between SST and MLD anomalies is 0.08 of 90% confidence level and that between SST and MLS, and ENSO index is 0.14 at 95% confidence level. (d) September MLS anomalies regressed onto the normalized ENSO index.

CONCLUSIONS

The interior SPA is well correlated with winter MLD, with more interior SPA corresponding to deeper MLD.

During a strong winter of injection, the interior spiciness change rate can reach up to \(-0.005\) kg m$^{-3}$/day$^{-1}$ and the gain of spiciness in the interior \(-0.2\) kg/m$^3$ over the SEP region.

The interannual-decadal variability of interior SPA in the SEP has a significantly negative correlation to the low-frequency ENSO index, with larger (smaller) SPA during La Niña (El Niño) conditions.