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

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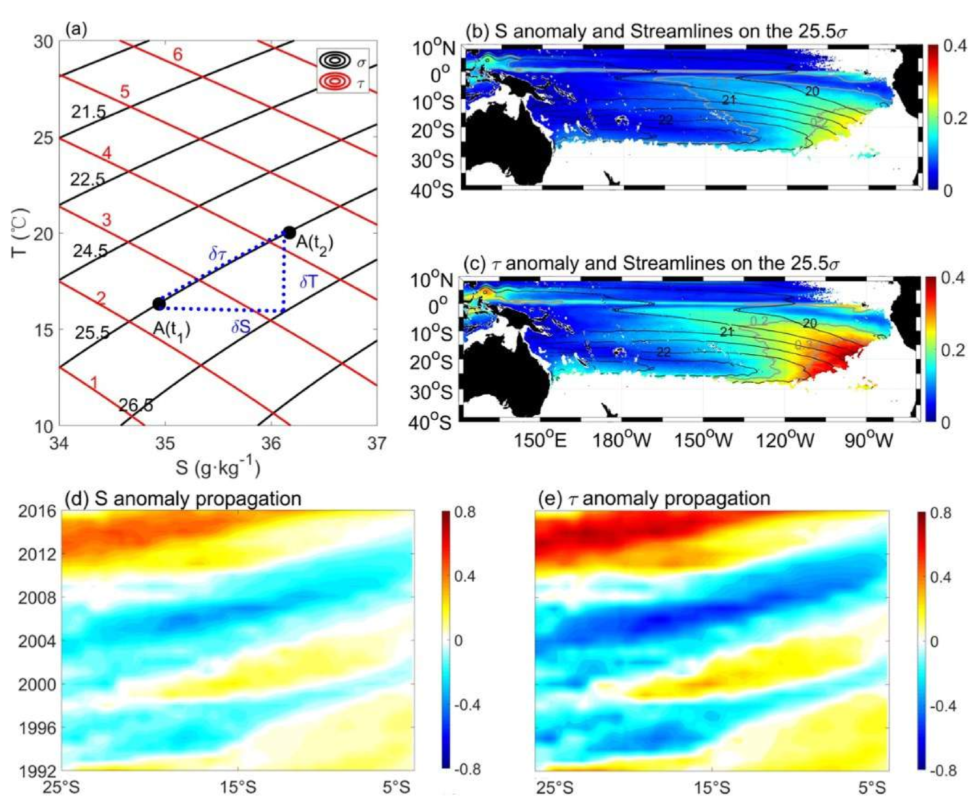
ABSTRACT

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 1992 to 2016 in the Consortium for Estimating the Circulation and Climate of the Ocean (ECCO). The spice injection refers to convective mixing through which saline water in the mixed layer is injected into the interior to generate positive temperature and salinity anomalies or spiciness anomaly (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 $kg{\cdot}m^{-3}{\cdot}day^{-1}$ and the gain of spiciness in the interior ~0.2 $kg{\cdot}m^{-3}$ 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.

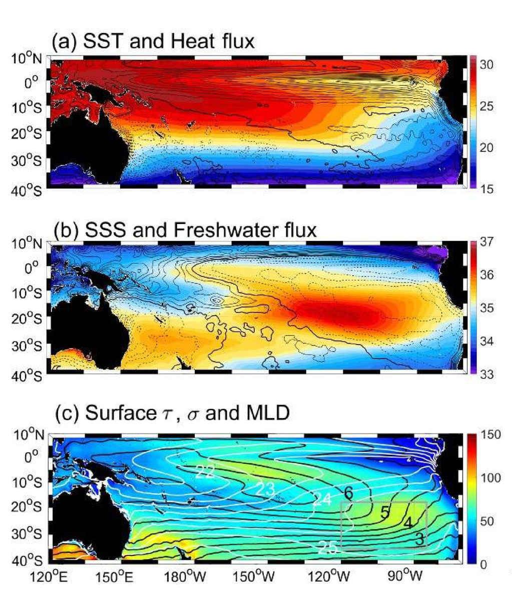
INTRODUCTION



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 equatorial 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

Fig. 1: (a) Schematic of potential density ($kg{\cdot}m^{-3}$) and spiciness ($kg{\cdot}m^{-3}$) in temperature-salinity space. The blue dot lines denote changes of spiciness, temperature and salinity on 25.5σ for a water parcel A from one moment (t_1) to another (t_2). Interannual standard deviation (STD) of (b) salinity (color in $g{\cdot}kg^{-1}$) and (c) spiciness (color in $kg{\cdot}m^{-3}$). Superimposed is the climatological Montgomery geostrophic streamlines (black lines, $m^2{\cdot}s^{-2}$) referred to 2000 dbar. Latitude-time diagram of anomalies of (d) salinity and (e) spiciness on 25.5σ along the 20.5 Montgomery geostrophic streamline.

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 2008-2010 and stronger from 2011-2013 in both ECCO and observations.

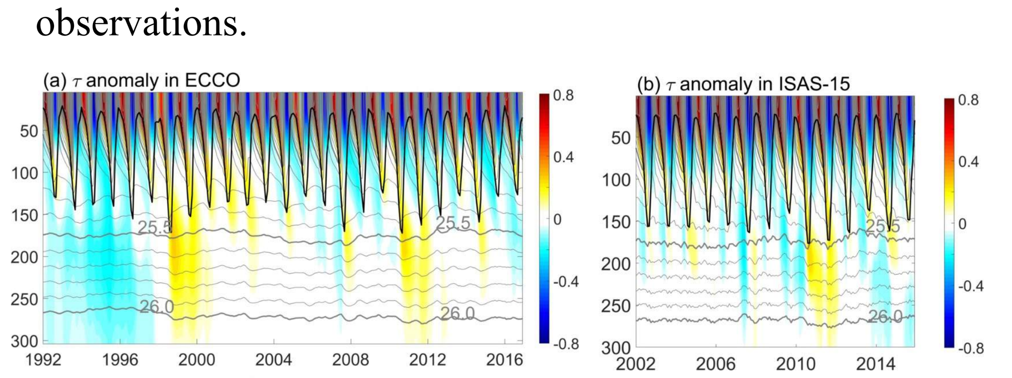
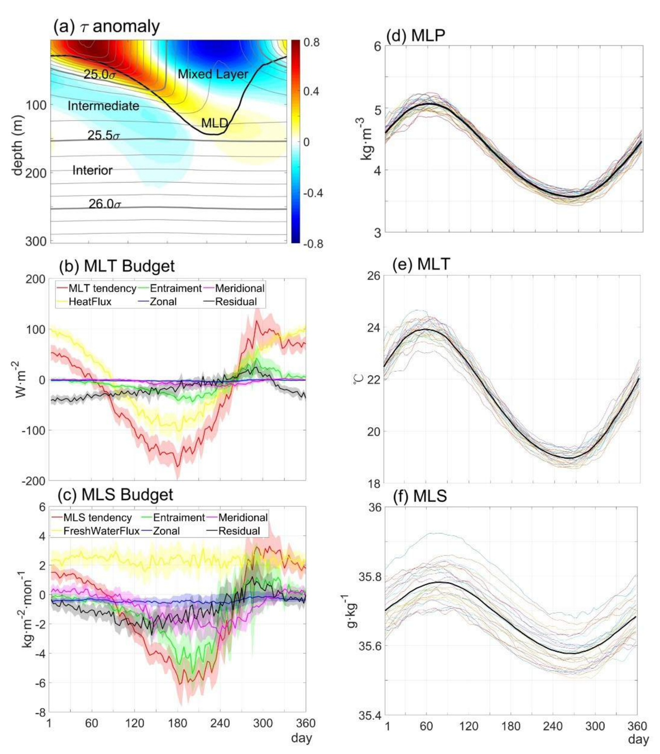


Fig. 2: (a) SST and heat flux and (b) SSS and freshwater flux. (c) mixed layer depth and surface potential density (black) and surface spiciness (white). The black box in (c) marks the key region of anomaly in the southeastern Pacific Ocean (SEP) where the winter mixed layer is deep.

Fig. 3: Depth-time plots of spiciness anomaly over the SEP box from (a) ECCO during 1992-2016 and (b) ISAS-15 during 2002-2015.

ANNUAL CYCLE

➢ MLT and MLS budget



Together with the MLD change, the MLP also appears to have significant seasonal variations. During the summer when the mixed layer is shallow, there is a positive SPA 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:(a) Seasonal evolution of spiciness, MLD and density over the SEP box. Balance terms for (b) mixed layer MLT budget and (c) MLS budget, with associated shadow representing one STD. Annual cycle of (d) mixed layer spiciness (MLP), (e) MLT, and (f) MLS, with thin color lines representing years from 1992-2016 and black thick line being their mean.

➢ Major contributions

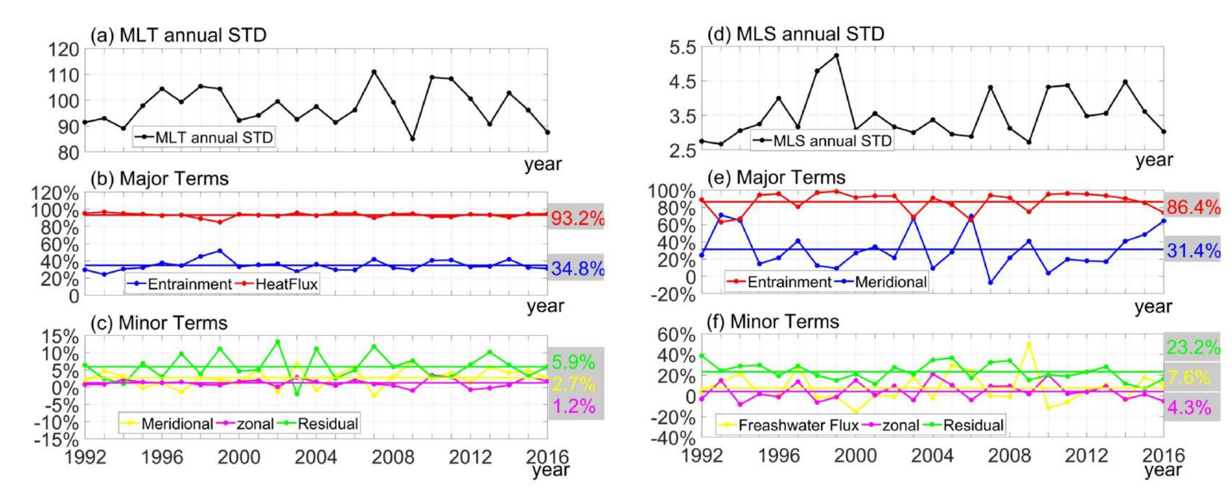


Fig. 5: (a, d) Interannual changes of MLT and MLS. (b, c) Normalized covariance between MLT tendency and the five contributing processes. (e, f) Normalized covariance between MLS tendency and the five contributing processes.

The MLT 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%.

➢ MLD variations

The seasonal buoyancy flux change has a principal effect on the seasonal variation of the MLD in the SEP. For the interannual variability of MLD, all three factors of the buoyancy flux, friction velocity and Ekman velocity play a role.

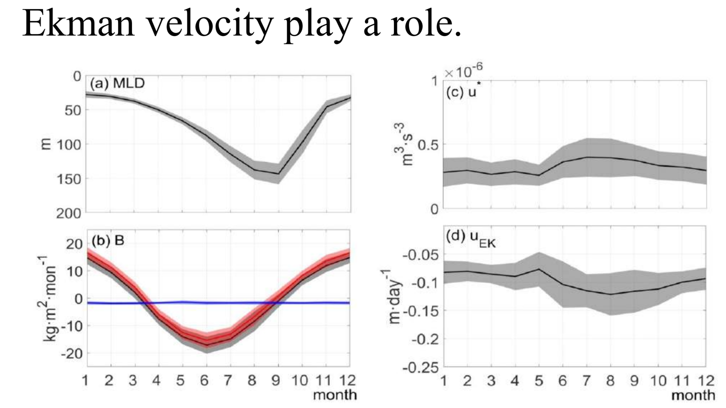


Fig. 6: Climatological annual cycle of (a) MLD, (b) buoyancy flux (black) and its two components of heat flux (red) and freshwater flux (blue), (c) friction velocity and (d) Ekman pumping.

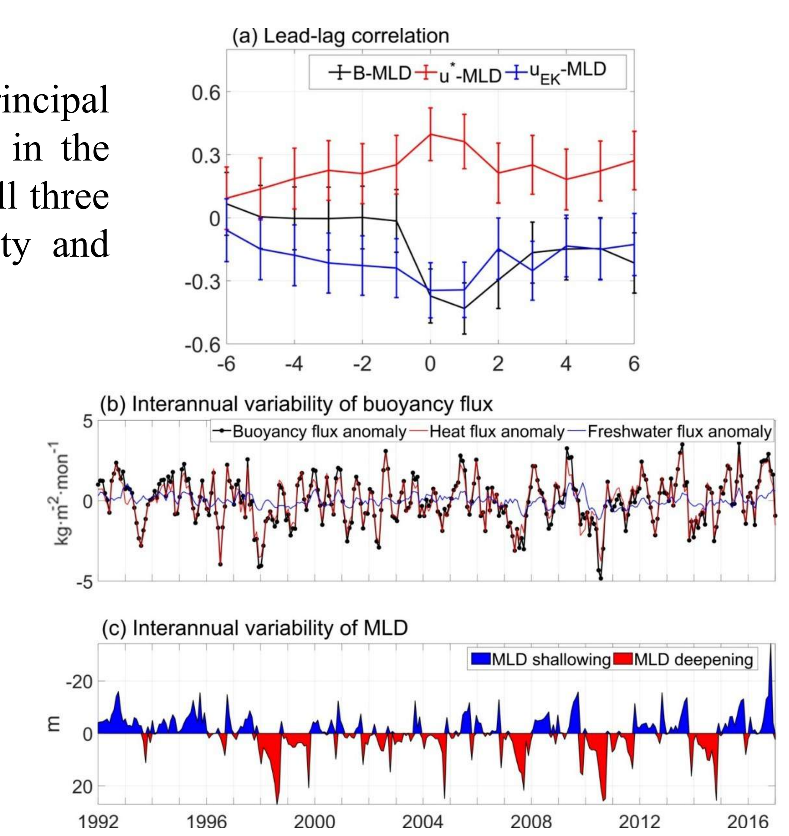
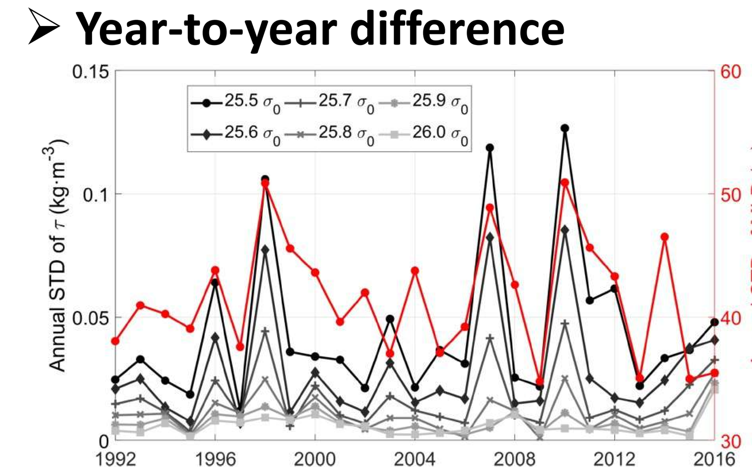


Fig. 7: (a) The lead-lag correlations between interannual MLD and interannual buoyancy flux (black), friction velocity (red), and Ekman velocity (blue). (b) Anomalies of buoyancy flux (black) as well as its two components of heat flux (red) and freshwater flux (blue), with positive (negative) values indicating that ocean gains (losses) buoyancy. (c) Anomalous MLD (m), with positive (negative) values with red (blue) color denoting a deepening (shoaling) of the mixed layer.

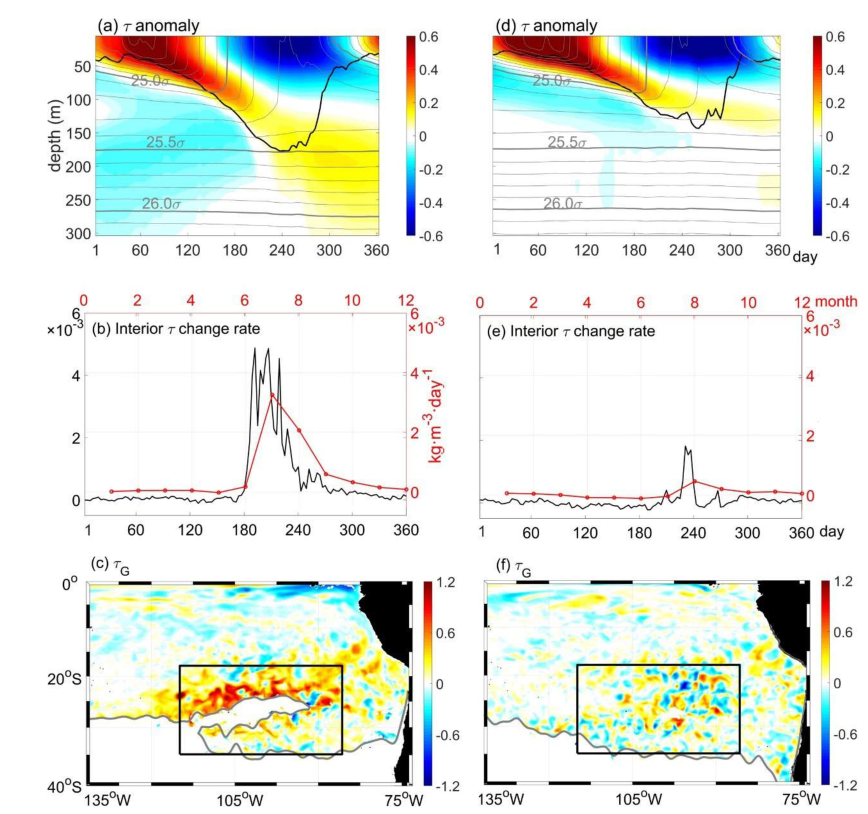
INTERANNUAL-DECADAL VARIABILITY

➢ Year-to-year difference



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

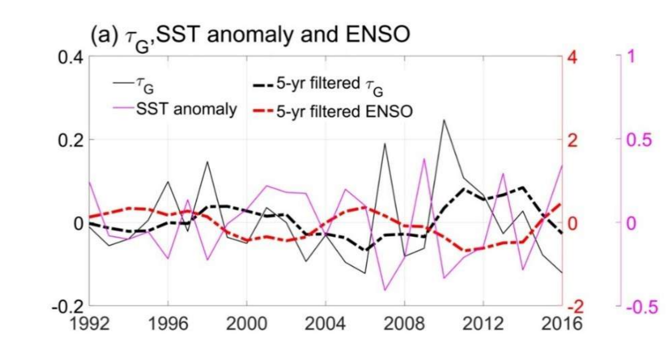
Fig. 8: Annual STD of spiciness between 25.5σ and 26.0σ (black and gray lines) as well as STD of MLD (red line) during 1992-2016. The correlation coefficient between 25.5σ black line and red line is 0.72 at 99% significant test level.



During strong injection years, the positive spiciness change rate occurred during the winter with the maximum rate reaching to ~0.005$kg{\cdot}m^{-3}{\cdot}day^{-1}$. 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 $kg{\cdot}m^{-3}$ in hot spots in 1998.

Fig. 9: (a, d) Evolution of spiciness anomaly, MLD, and potential density over the SEP box. (b, e) Evolution of interior spiciness change rate calculating from 3-day data (black) and monthly-mean data (red). (c, f) Spatial pattern of late winter spiciness generation ($kg{\cdot}m^{-3}$). The panels on the left (right) hand side are for the strong (weak) injection year of 1998 (1997).

➢ 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.

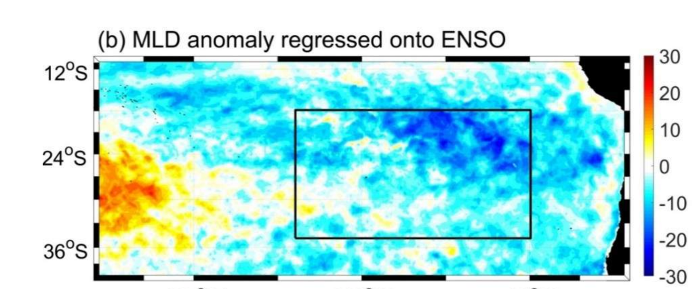


Fig. 10: Spiciness generation τ_G on 25.5σ (black), SST anomaly (magenta), 5-year filtered τ_G (thick black) and the ENSO index (red) over the SEP box during 1992-2016. The correlation between τ_G and SST anomaly is -0.68 at 99% confidence level, and that between 5-yr filtered τ_G and ENSO is -0.74 at 99% confidence level. (b) September MLD anomalies regressed onto the normalized ENSO (color; m).

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 $kg{\cdot}m^{-3}{\cdot}day^{-1}$ and the gain of spiciness in the interior ~0.2 $kg{\cdot}m^{-3}$ 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.

Reference: Wang, Y., & Luo, Y. (2020). Variability of spice injection in the upper ocean of the southeastern Pacific during 1992-2016. Climate Dynamics. DOI: 10.1007/s00382-020-05164-y