Mechanism of Interannual Cross-equatorial Overturning Anomalies in the Pacific Ocean

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Overview

- The meridional overturning circulation (MOC) transports heat and mass latitudinally from the tropics to the high latitude and vice versa.
- Recent evidence shows that the variability of MOC in the Indian and Pacific Oceans (PMOC) dominates the variability of the global MOC on interannual timescales. It is known that the interannual variability of PMOC is characterized by a prominent cross-equatorial cell (CEC) spanning the tropics between 18° S and 20°N (Tandon et al., 2020).
- This CEC is potentially an important influence on interannual climate variability, but the mechanism responsible for this CEC is not yet understood. This study seeks to elucidate the mechanism of the CEC in the Pacific Ocean using version 4.2 of the Estimating the Circulation and Climate of the Ocean (ECCO) state estimate (Forget et. al., 2015, 2016).

Interannual PMOC Variability and Cross Equatorial Cell (CEC)

- On interannual timescales, the strongest PMOC variability is concentrated in the tropics (Fig. 1a).
- In contrast with the time mean PMOC, the variability of the PMOC spans the full depth of the ocean.
- Principal component analysis (PCA) revealed that PMOC variability is characterized by a cross-equatorial cell (CEC) over 18°S-20°N (Fig 1.b).
- The first EOF accounts for 51% of the variability. (Fig 1b), and second EOF (not shown) accounts for 27% of the variability.
- In its positive phase, the first EOF dynamically implies a clockwise overturning cell with the upper layer flow moving northward.
- The time-series of principal component (PC1) captures the time variations of the CEC, and used as index to relate the CEC to other variables (Fig. 1c) . Hereafter, we refer to PC1 as the "PMOC Index".

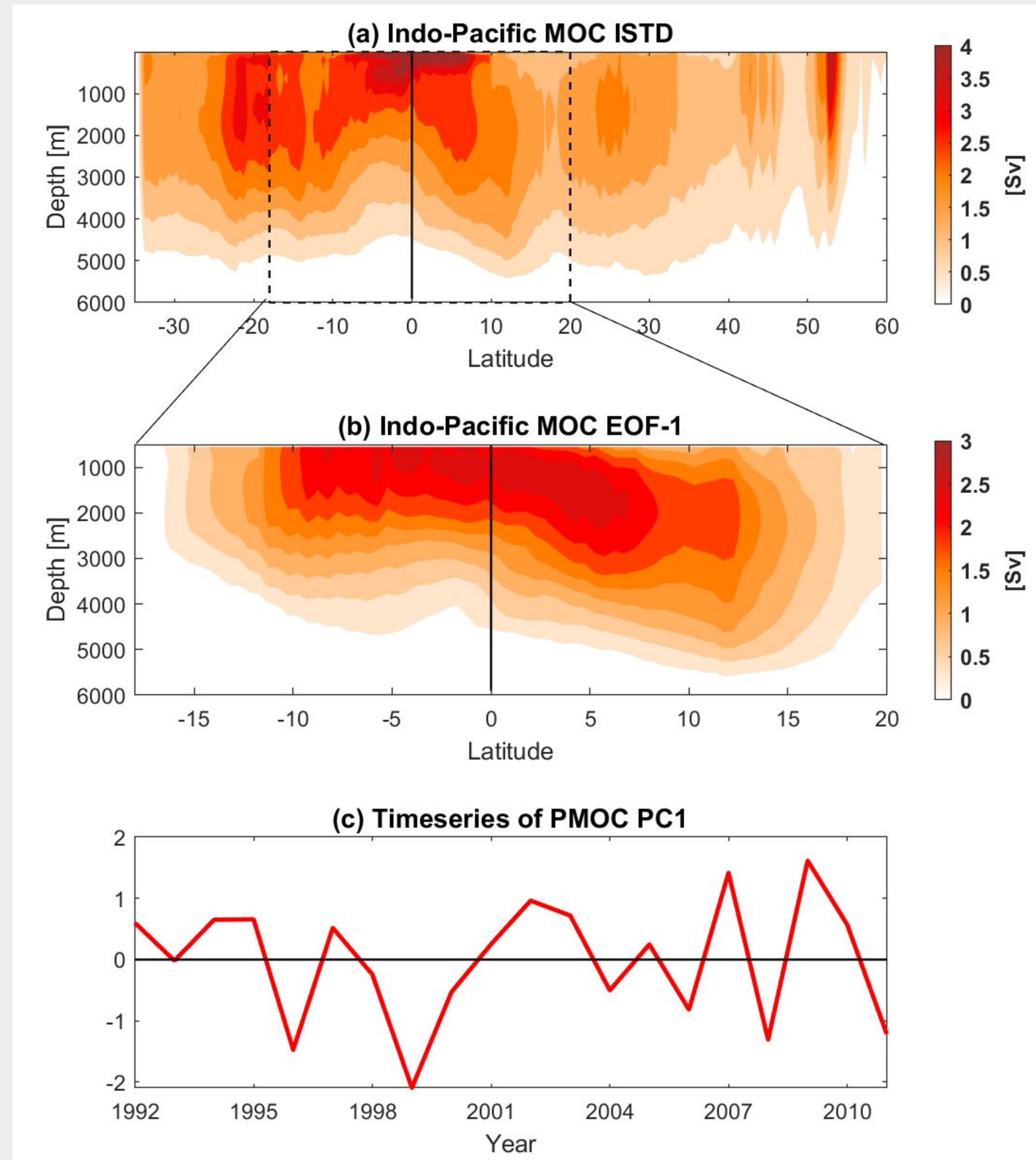

Figure 1: (a) The interannual standard deviation of the MOC streamfunction in the Indian-Pacific Ocean. (b) The first EOF of annual mean MOC streamfunction in the Indian-Pacific Ocean computed over 18° S-20°N below 500 m. (c) The first principal component timeseries corresponding to the first EOF shown in panel (b).

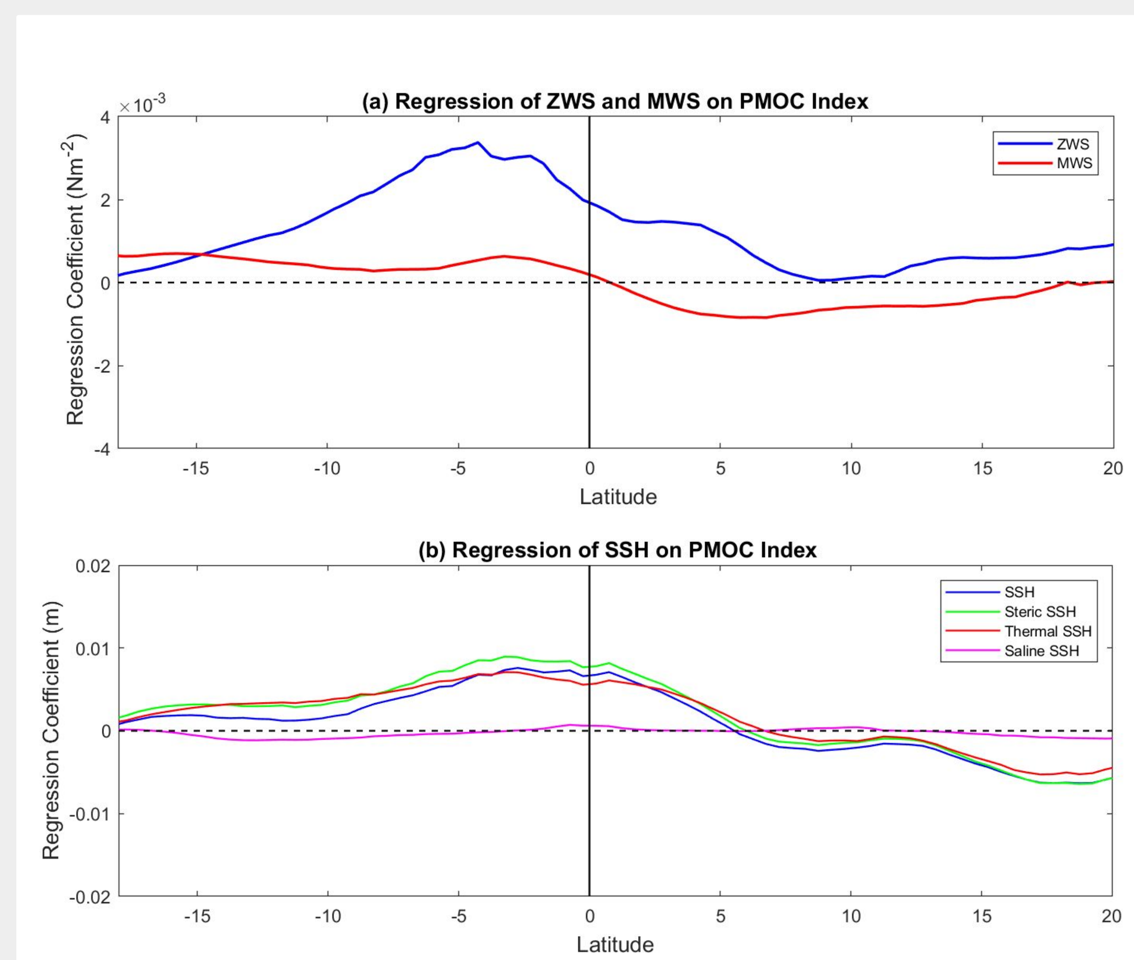

Figure 2: (a) Regressions onto the PMOC index of annual mean zonally averaged wind stress in the Indo-Pacific. Blue and red lines indicate the zonal and meridional wind stresses, respectively. (b) As in (a), but for SSH, (blue), total steric SSH contribution (light green), thermal SSH contribution (red), and saline SSH contribution (magenta).

Role of Wind Stress and Sea Surface Height (SSH)

Do zonal and meridional wind stresses play a role?

- On seasonal timescales, equatorially antisymmetric zonal wind stress (ZWS) anomalies are responsible for the cross-equatorial Ekman transport (Jayne and Marotzke, 2001). One might expect such a mechanism to apply on interannual timescales as well.
- However, the regression analysis (Fig. 2a) reveals that ZWS anomalies associated with the interannual variability of PMOC are symmetric across the equator.
- Positive values of ZWS within the region of the CEC would imply Ekman transport convergence near the equator.
- Interestingly, meridional wind stress (MWS) anomalies are showing similar sign to that of the climatological mean.
- Both ZWS and MWS anomalies cannot directly explain the anomalous northward transport associated with the positive phase of CEC.

If it's not Ekman transport, then what drives the near-surface flow in the CEC?

- Alternatively, the regression of SSH anomalies onto PMOC index (blue line in Fig. 2b) indicates a north-south gradient, where SSH is anomalously high south of the equator and anomalously low north of the equator.
- These SSH anomalies would generate a northward pressure gradient, and would drive northward flow across the equator.
- Also, the hypothesis of SSH driving the CEC is confirmed with the lag correlation of the SSH Seesaw Index(SSI), which is measure of meridional SSH gradient around the equator (not shown).

To what are extent tropical SSH anomalies driven by density anomalies?

- The magnitude and structure of zonal mean steric SSH anomalies closely follow the SSH variations, which suggests that the SSH anomalies are generated by density changes rather than dynamical changes (light green line in Fig. 2b).
- Isolating the thermal and saline contributions to the density anomalies, the thermal regression (red line in Fig 2b) closely resembles steric SSH regression, and saline regression (blue line in Fig. 2b) is relatively flat with respect to latitude.

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Continued from Page 1

To what are extent tropical SSH anomalies driven by density anomalies?

- This role of temperature in driving SSH variations is further confirmed in Fig. 3a, which shows the regression map onto the PMOC index of total SSH (shading) and thermal SSH (contours).
- The spatial structure and magnitude of the total and thermal SSH anomalies are mostly the same (Fig.3a).
- These results suggest that the SSH anomalies driving the near surface branch of the CEC are generated by temperature anomalies in the upper ocean.
- In SODA 3.12.2, the salinity effect appears to amplify rather than cancel the thermally-driven SSH anomalies.

How are these Temperature Anomalies Generated in the Equator?

Role of atmospheric heat transport

To address this question, we have produced regression maps (latitude-longitude plots) of several quantities onto the PMOC Index.

- Figure 3b shows that the anomalies of wind stress are responsible for a strong eastward flow in the equatorial region, which would be expected to drive the warm water from the Western Pacific to the Eastern Pacific.
- The cool anomalies in the western and subtropical Pacific are associated with equatorward windstress.
- The warm anomaly peaks south of the equator in the eastern Pacific, and the cold anomaly peaks north of the equator in the western Pacific, in accordance with the zonal mean structure in Fig. 2b.

Role of oceanic heat transport

- The regression patterns of annual mean surface currents on to the PMOC index (vectors in Fig. 4) show warm anomalies in the Eastern Pacific and eastward transport in the ocean.
- The horizontal advective heating anomalies (shading in Fig.4) indicates that the anomalous eastward flow at the equator would be expected to transport the relatively warm water from the Western Pacific to the Easter Pacific.
- This suggests that wind-driven transport within the ocean may be partly responsible for generating warm anomalies in the eastern equatorial Pacific.
- Away from the equator, the role of ocean currents appears to be small.

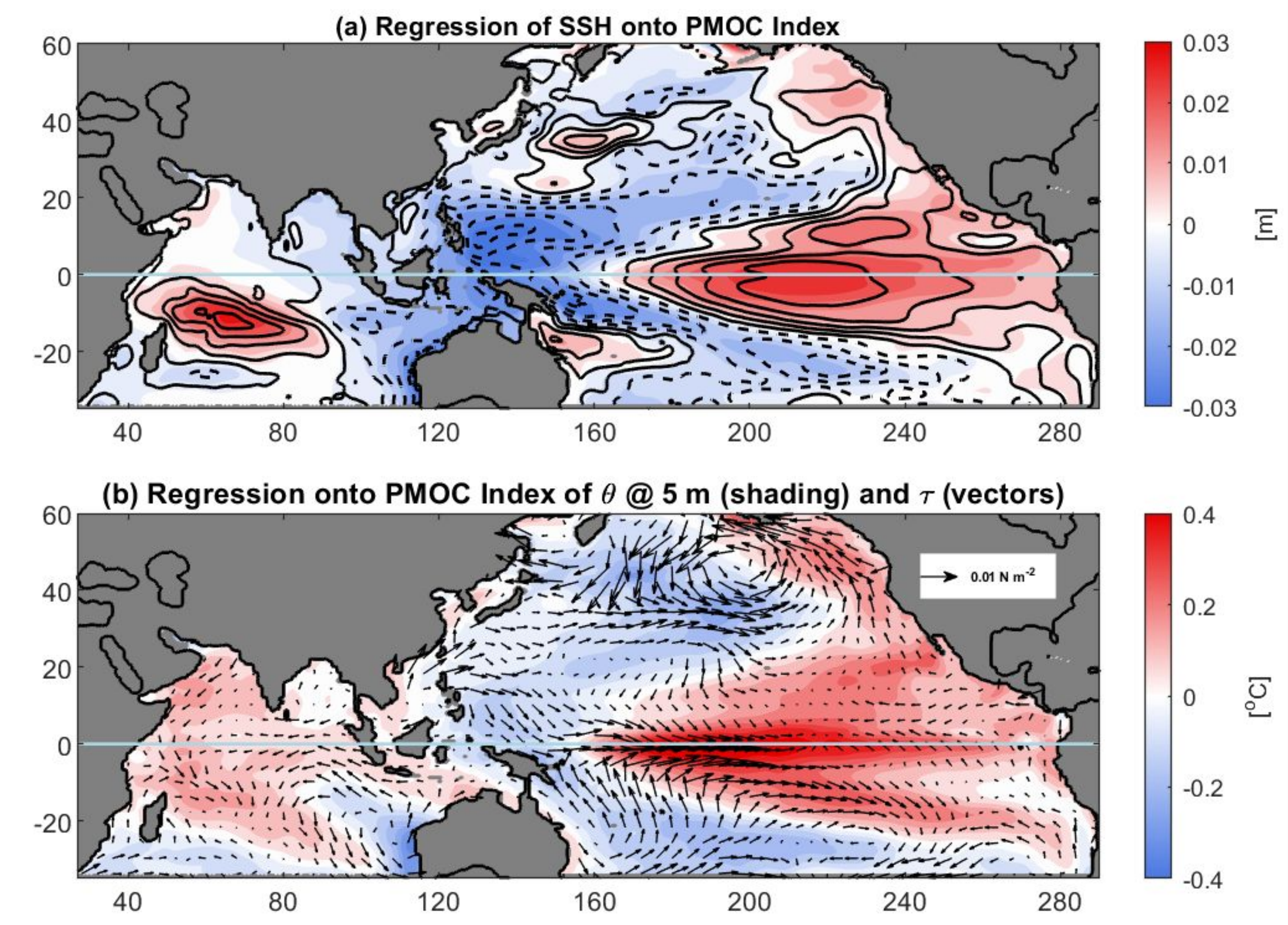

Figure 3. Regressions onto the PMOC index of (a) annual mean SSH (shading), thermal SSH (contours), (b) potential temperature at 5 m (shading) and wind stress (vectors) in the Indo-Pacific. The shading/contour interval in (a) is 4 mm, with negative contours dashed, and the shading interval in (b) is 0.05°C. The unit vector in (b) denotes 0.01 N m^{-2}.

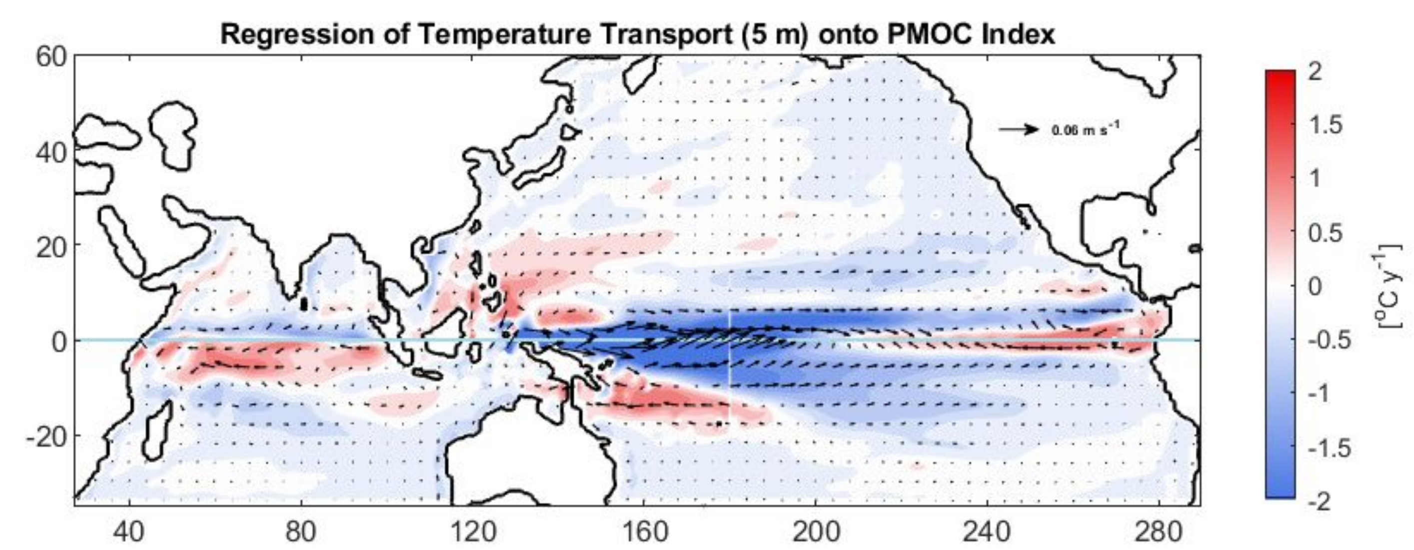

Figure 4. Regression onto the PMOC index of annual mean temperature transport (shading), and ocean velocity at 5 m (vectors) in the Indo-Pacific. The shading interval is 0:25°C y^{-1}

Conclusions

The simplified mechanism for the positive phase of the CEC is outlined as follows:

- On interannual timescales, wind stress anomalies generate anomalies of temperature and salinity in the tropics.
- These temperature and salinity anomalies generate equatorially antisymmetric anomalies of zonal mean SSH, which in turn generate an anomalous north-south pressure across the equator.
- This anomalous pressure gradient drives anomalous northward cross-equatorial flow in the upper Pacific Ocean (above approximately 500 m).
- This anomalous northward flow in the upper Pacific Ocean is compensated by a southward flow in the deep Pacific, thereby forming a clockwise overturning circulation cell.
- The CEC is still ultimately wind-driven (as found by Tandon et al., 2020), but our results show that the influence of wind stress variations is mediated through the generation of density anomalies near the equator.
- Additional observations and improved ocean state estimates and analyses are needed in order to monitor the CEC in the deep tropical Pacific Ocean directly and understand its behaviour.

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