The Pacific Cold Tongue and ENSO: Sensitivity to the Meridional Wind Stress Climatology

Andrew T. Wittenberg* and S. George H. Philander
Program in Atmospheric & Oceanic Sciences, Princeton University

1. Introduction

The eastern tropical Pacific displays a distinct meridional asymmetry, with cold sea surface temperatures (SSTs) south of the equator, warmer waters to the north, and an Intertropical Convergence Zone that is mostly north of the equator (Philander et al. 1996; Wang and Wang 1999). The asymmetry is linked to southerly surface winds over a broad span of the equatorial eastern Pacific. How do these cross-equatorial southerlies affect the climatological cold tongue and El Niño/Southern Oscillation (ENSO)?

2. Meridional Wind Stresses in Models and Observations

The asymmetry of the east Pacific depends on processes that are notoriously difficult to capture in general circulation models (GCMs). These include stratus clouds south of the equator, atmospheric deep convection north of the equator, and oceanic upwelling & mixing in the equatorial zone. The depth of the equatorial thermocline, which depends on surface forcing throughout the Pacific, also controls the asymmetry. Most atmospheric GCMs produce a tropical tor, and oceanic upwelling & mixing in the equatorial zone. The depth of the equatorial thermocline, which depends on surface forcing throughout the Pacific—but contributes much less to the east Pacific—is sensitive to the meridional wind stress climatology (Wallace et al. 1989; Liu and Xie 2002), generates additional upwelling in a narrow zone just north of the equator.

3. Impact on the Time-Mean Ocean State

Consider an ocean surface mixed layer of depth \( H_m \), embedded in an active layer of depth \( H \) on an equatorial \( y \)-plane. Away from coasts, the Ekman upwelling velocity at the base of the mixed layer is approximately

\[
\text{w} = -\frac{H}{\rho H_m} \beta \frac{\partial}{\partial x} \text{v} - \frac{g}{H_m} \frac{\partial S}{\partial x} = \frac{\rho}{\rho_0} \text{w}_{\text{mix}} \frac{\partial z_{\text{mix}}}{\partial x} = \frac{1}{\rho_0} \frac{\partial z_{\text{mix}}}{\partial x} \text{w}_{\text{mix}} \frac{\partial z_{\text{mix}}}{\partial x}
\]

where \( \beta = \frac{\partial \omega}{\partial y} \) is a nondimensional latitude scale, \( \text{w}_{\text{mix}} \) is the warm layer depth, and \( \tau = (\tau, \tau_y) \) is the vector wind stress. Assuming \( H_m/H = 0.4, \tau_y = (2 \text{ day}^{-1}) \), and \( \beta = 1025 \text{ km} / 2 \), we use the observed mean \( \tau \) from QuikSCAT (Aug 1999–Jul 2003) to compute the upwelling due to each term in (1).

4. Impact on a Stochastically-Driven ENSO

Intensifying the background \( \tau_y \) in a stochastically-driven hybrid coupled intermediate model of ENSO (Wittenberg 2002) increases the SST variability and shifts it eastward. A 40% change in \( \tau_y \) alters the cold extremes enough to be detected in time series as short as 50 years. The results suggest that improving \( \tau_y \) in coupled GCMs could also improve their ENSOs, which typically are too weak and exhibit SST anomalies too far west.

5. Impact on Linear Stability

With the stochastic forcing turned off, the evolution of a tiny initial perturbation reflects the linear stability of the model ENSO. Variability is strongly damped in the absence of background \( \tau_y \), but as \( \tau_y \) increases the wind stress response to SST anomalies strengthens, ENSO grows more unstable. At the critical coupling for instability (dashed), the ENSO period decreases slightly with increasing \( \tau_y \).

6. Understanding the ENSO Sensitivity

To understand the model’s ENSO sensitivity to background \( \tau_y \), we substitute parts of the control clivarlog model into the \( \tau_y = 0 \) case and vice versa (right). Clearly, it is the meridional overturning that most affects the stability, by determining the air-sea feedback strength in the east Pacific. In the control the ENSO period is sensitive to thermocline depth as well, while for \( \tau_y = 0 \) it is sensitive to SST. The NINO3 heat budget (below) shows why. Terms are scaled by the surface heat flux which acts as a linear damping on SST anomalies. Zero phase corresponds to the SST peak and indicates a destabilizing term, while 90° leads SST and indicates a transitioning term. Advection by mean overturning (wmt, wmt) dominates the growth & transitioning that drive the SST tendency (dot); hence the stability dependence on this overturning. By enhancing SST gradients and reducing the vertical temperature gradient, \( \tau_y \) alters other feedbacks that control the period—like those due to zonal current and upwelling anomalies (upmt, wpmt).

References


*Address for correspondence: Dr. Andrew T. Wittenberg, Atmospheric & Oceanic Sciences Program, Sayre Hall, Forrestal Campus, Princeton University, Princeton, NJ 08544-0710. Email: Andrew.Wittenberg@noaa.gov