The impact of ocean surface currents on Sverdrup transport in the mid-latitude North Pacific via the wind stress formulation

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A more complete wind stress ($\boldsymbol{\tau_n}$) formulation takes into account the ocean surface currents ($\boldsymbol{V_o}$), while the conventional wind stress ($\boldsymbol{\tau_c}$) popularly used in ocean circulation models is only a function of 10-m winds ($\boldsymbol{V_{10}}$). An analytical solution is derived for the difference of Sverdrup transport induced by using $\boldsymbol{\tau_n}$ instead of $\boldsymbol{\tau_c}$. A scaling analysis of the analytical solution indicates a 6% reduction of the Sverdrup transport in the North Pacific (i.e. the Kuroshio transport in the East China Sea) when Ekman velocity dominates the ocean surface currents. Due to the quadratic nature of wind stress, four nonlinear terms contribute equally to this difference: two "vorticity torque" terms and two "speed gradient torque" terms. A pair of 12.5-year (July 2002-2014) HYbrid Coordinate Ocean Model simulations that only differ in the wind stress formulation are used to test the analytical solution. The model results (2004-2014) confirm that using $\boldsymbol{\tau_n}$ instead of $\boldsymbol{\tau_c}$ reduces the Sverdrup transport in the North Pacific by 8% to 17% between 23° N and 32° N. The reduction rate of the simulated 11-year mean Kuroshio transport through the East Taiwan Channel and Tokara Strait is 8.0% (-2.5 Sv) and 12.8% (-4.8 Sv), respectively, in good agreement with the Sverdrup transport reduction rate, which is 7.4% (-2.6 Sv) and 15.4% (-6.3 Sv) at the corresponding latitude.The local effect of changing wind stress/wind work and Ekman transport due to the inclusion of $\boldsymbol{V_0}$ in the wind stress formulation is negligible compared to the Kuroshio volume transport change estimated in this study.

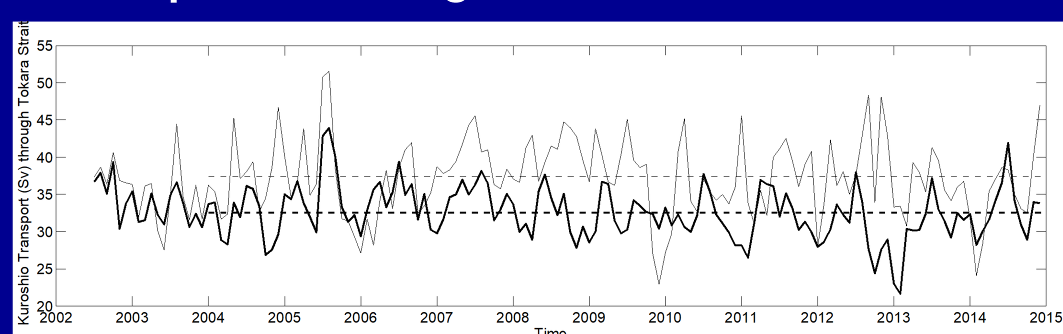

Figure 1. Time series of monthly Kuroshio transport (Sv) through Tokara Strait for both Experiments 1 (thin line, τ_c) and 2 (thick line, τ_n). The corresponding dashed lines show the 11-year (2004-2014) mean transport (37.4 Sv for Experiment 1, 32.6 Sv for Experiment 2). The location of the transect at Tokara Strait is shown in Figure 3.

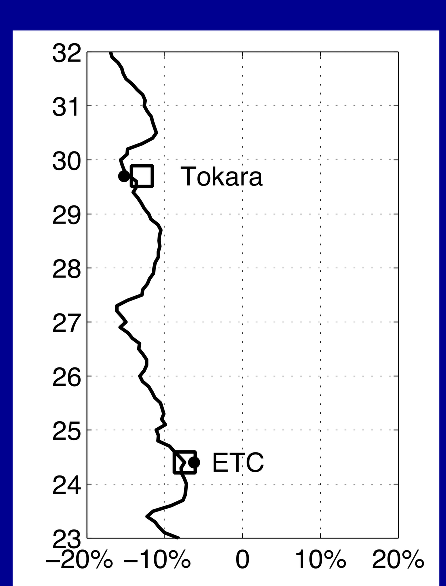

Figure 5. The zonally-integrated Sverdrup transport change (%, as a percentile to M_c) as a function of latitude due to the effect of ocean currents in the wind stress formulation. The corresponding Kuroshio transport difference and $-2\frac{V_{o\_s}}{V_{10\_s}}$ from the HYCOM simulations are shown with squares and solid dots, respectively.

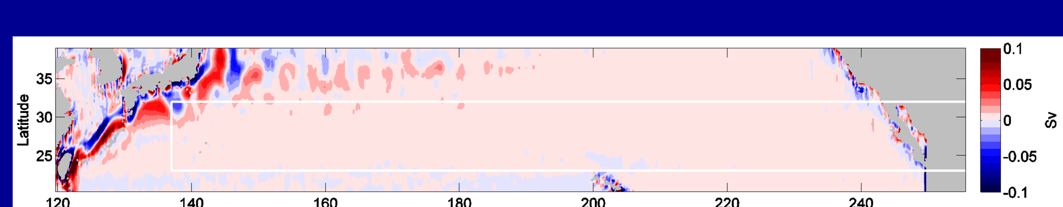

Figure 6. The Sverdrup transport (Sv) difference ($M_n - M_c$) in the north Pacific. The while box highlights our study area.

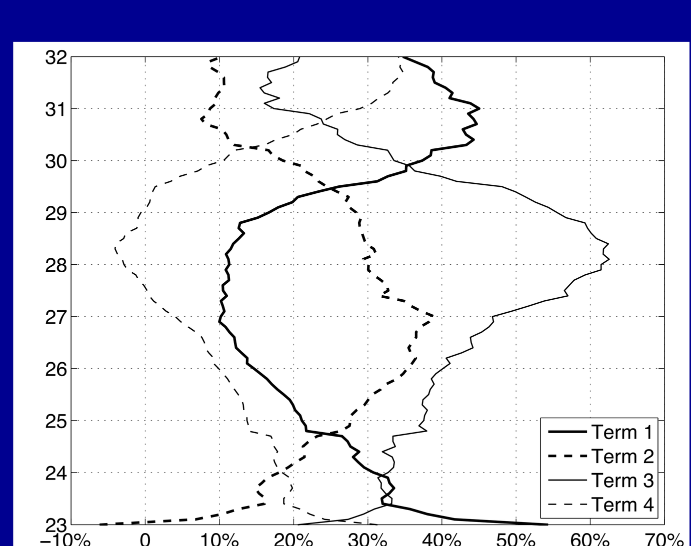

Figure 7. The relative importance of the four nonlinear terms in the right hand side of equation (1) as a function of latitude due to the effect of ocean currents in the wind stress formulation. Terms 1 to 4 are $-\frac{\rho_{air}C_d|\boldsymbol{V_{o\_s}}|\nabla\times\boldsymbol{V_{10\_s}}}{M_n - M_c}$, $-\frac{\rho_{air}C_d\nabla(|\boldsymbol{V_{o\_s}}|)\times\boldsymbol{V_{10\_s}}}{M_n - M_c}$, $-\frac{\rho_{air}C_d|\boldsymbol{V_{10\_s}}|\nabla\times\boldsymbol{V_{o\_s}}}{M_n - M_c}$, $-\frac{\rho_{air}C_d\nabla(|\boldsymbol{V_{10\_s}}|)\times\boldsymbol{V_{o\_s}}}{M_n - M_c}$, respectively.

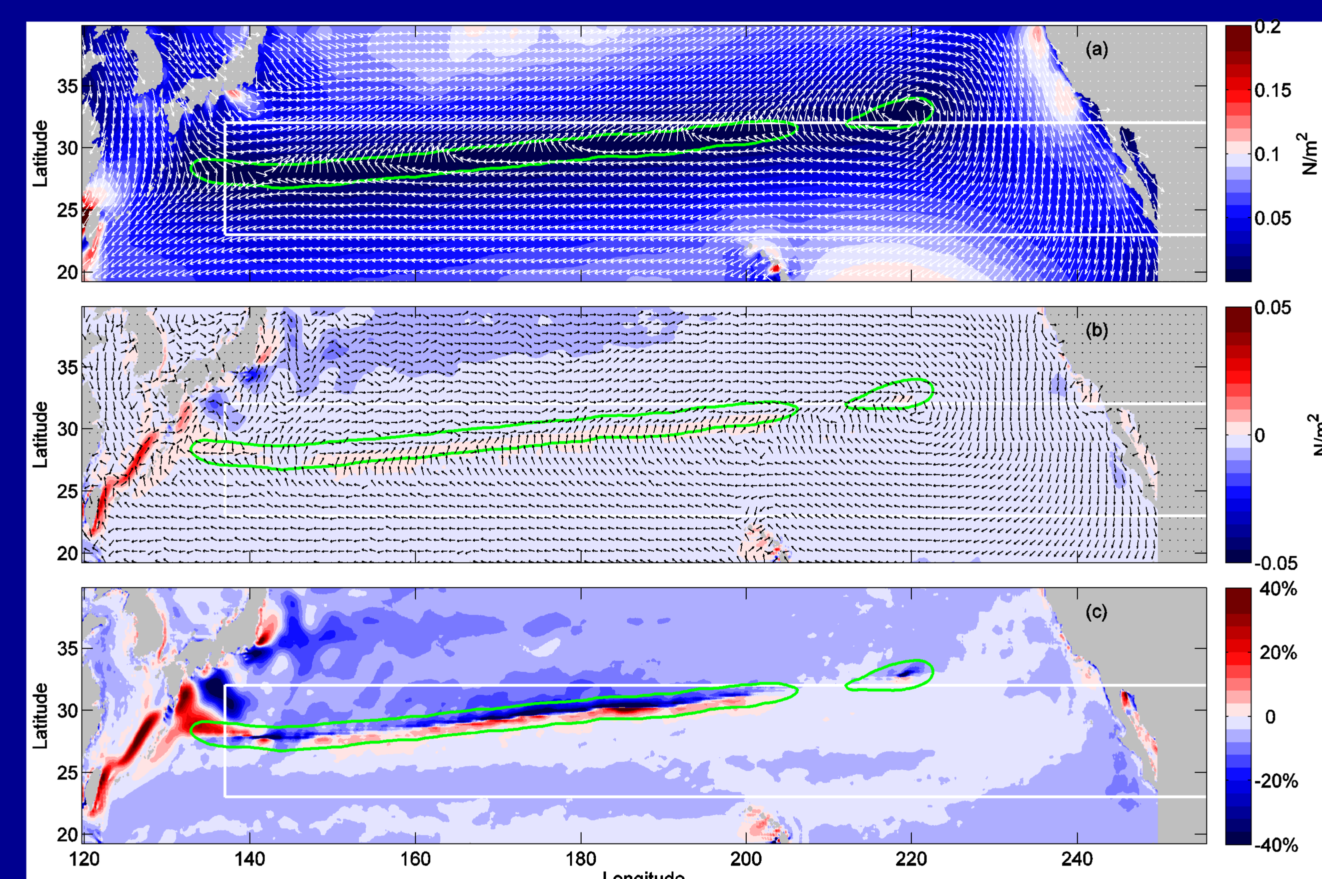

Figure 2. (a) Mean NCEP CFSR wind stress magnitude (N/m²) ($|\boldsymbol{\tau_{c\_s}}|$, without the effect of ocean currents) averaged over 2004 to 2014 in the North Pacific. The wind direction is shown with white arrows. (b) Mean wind stress magnitude difference ($|\boldsymbol{\tau_{n\_s}}| - |\boldsymbol{\tau_{c\_s}}|$) induced by $\boldsymbol{V_{o\_s}}$. The direction of $\boldsymbol{V_{o\_s}}$ is shown with black arrows. (c) The ratio of mean wind stress magnitude difference ($|\boldsymbol{\tau_{n\_s}}| - |\boldsymbol{\tau_{c\_s}}|$) induced by $\boldsymbol{V_{o\_s}}$ to the wind stress magnitude without the effect of ocean currents ($|\boldsymbol{\tau_{c\_s}}|$). The white box defines the region of interest from 23° to 32°N and 137°E to the American coast. The green lines are the 0.01 Pa isoline and represent the weak wind stress zone in the mid-latitude North Pacific.

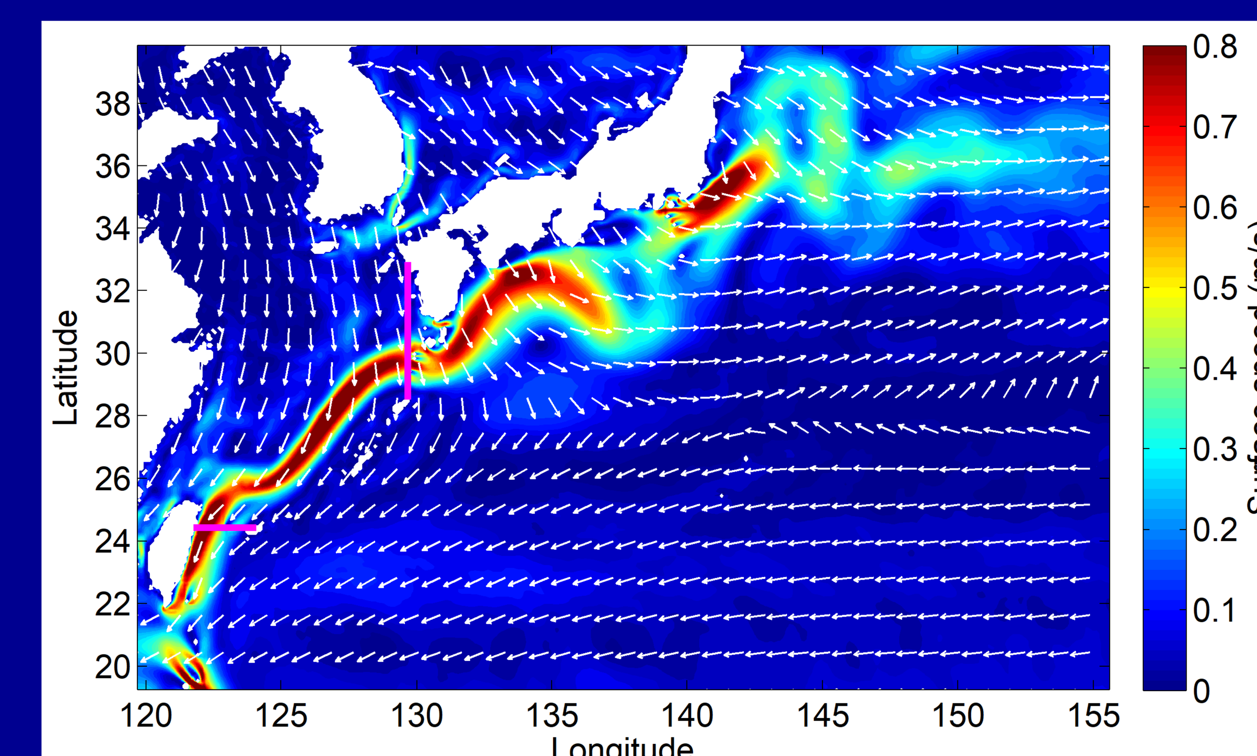

Figure 3. The steady state ocean surface current speed (m/s; $|\boldsymbol{V_{o\_s}}|$) from HYCOM Experiment 2 with the effect of the ocean currents in the wind stress bulk algorithm. The wind direction associated with the steady state wind stress $\boldsymbol{\tau_{c\_s}}$ is shown with white arrows. The magenta lines show transects at the East Taiwan Channel and Tokara Strait where HYCOM transport is computed.

$$M_n - M_c = \frac{\rho_{air}C_d}{\beta}\{-|\boldsymbol{V_{o\_s}}|\nabla\times\boldsymbol{V_{10\_s}} - \nabla(|\boldsymbol{V_{o\_s}}|)\times\boldsymbol{V_{10\_s}} \quad (1)$$

$$\frac{M_n - M_c}{M_c} = -2\frac{\boldsymbol{V_{o\_s}}}{\boldsymbol{V_{10\_s}}} = 6\% \quad (2)$$

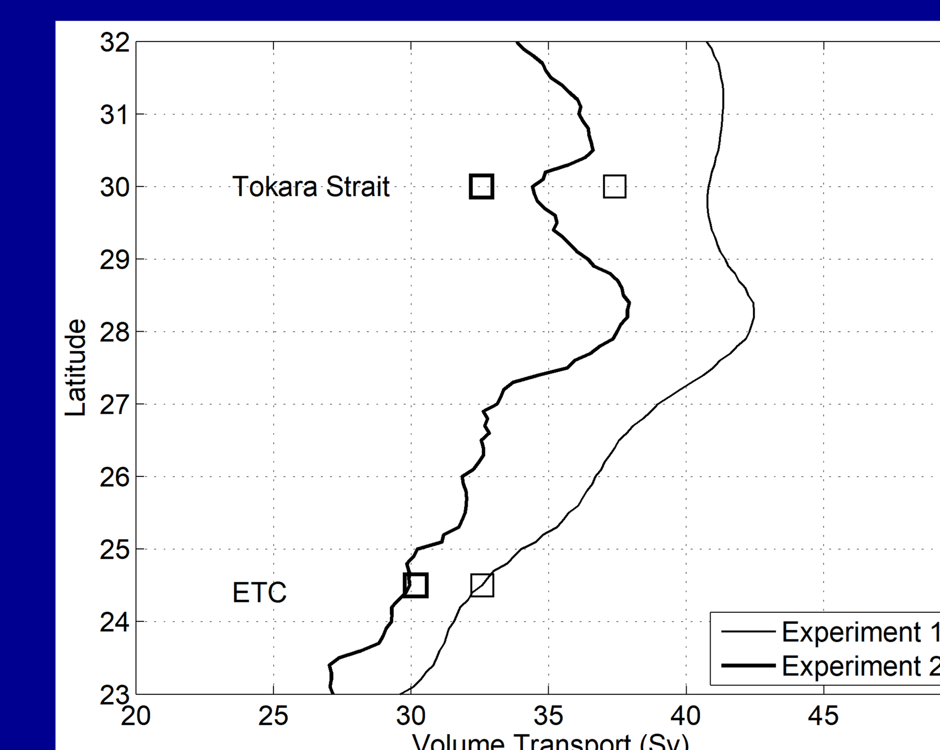

Figure 4. The zonally integrated Sverdrup transport (Sv) as a function of latitude and computed for the white box shown in Figure 2 from the two HYCOM simulations. Thick line shows results from the HYCOM Experiment 2 with ocean currents in the wind stress formulation, while the thin line shows results from the HYCOM Experiment 1, without ocean currents in the wind stress formulation. The corresponding simulated 11-year mean Kuroshio transports (squares) through the magenta transects shown in Figure 3 are also shown.

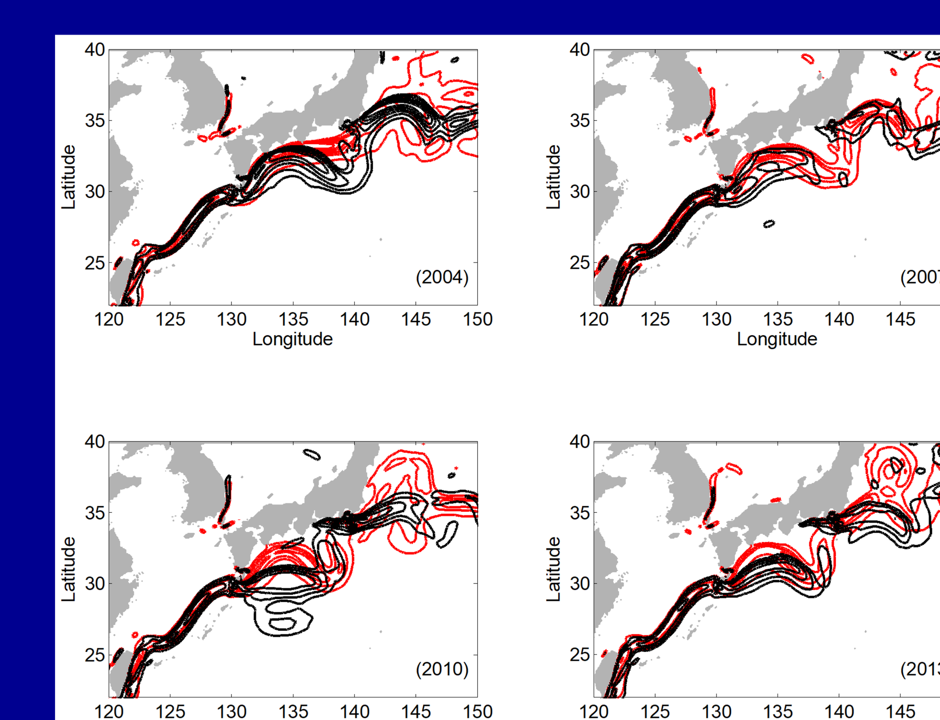

Figure 8. Annual mean Kuroshio pathway defined by the surface speed contours in 2004, 2007, 2010, and 2013. Black (red) isolines of ocean surface speed show the Kuroshio pathway from the HYCOM Experiment 1 (2) without (with) the effect of the ocean currents in the wind stress bulk algorithm.

Table 1. Kuroshio volume transport (Sv) through the East Taiwan Channel and Tokara Strait and the Sverdrup transport at the corresponding latitude from the HYCOM Experiment 2, with ocean currents in the wind stress formulation ($\boldsymbol{\tau_{n\_s}}$) and Experiment 1, without ocean currents in the wind stress formulation ($\boldsymbol{\tau_{c\_s}}$). The difference of Sverdrup transport, Kuroshio transport, and Ekman transport induced by $\boldsymbol{V_{o\_s}}$ are also shown.

Location		τ_{c_s}	τ_{n_s}	$\tau_{n\_s} - \tau_{c\_s}$	Ekman transport ($\tau_{n\_s} - \tau_{c\_s}$)
East Taiwan Channel	Sverdrup	32.6	30.0	-2.6	-0.03
	Kuroshio	32.6	30.2	-2.5	
Tokara Strait	Sverdrup	40.8	34.5	-6.3	-0.01
	Kuroshio	37.4	32.6	-4.8	

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