Interannual ENSO variability forced through coupled atmosphere-ocean feedback loops

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El Niño/Southern Oscillation (ENSO) events are known to force atmospheric teleconnections that impact extratropical sea surface temperatures and surface winds. In this paper we use focused model experiments to investigate whether this extratropical variability can feedback to, and significantly impact, the Tropics through ocean Rossby waves. We use an atmospheric general circulation model coupled to a reduced gravity Pacific Ocean model to isolate these potential feedback loops and quantify their impact on ENSO variability. We find that anomalous winds and heat fluxes located in regions of maximum mean subduction in the subtropical North Pacific trigger ocean Rossby waves that take approximately four years to reach the equator. Most notably, we demonstrate that this feedback loop causes a primarily 2-year ENSO, when only the Tropics is coupled, to shift to a more realistic broad 2-5 year range by damping ~2 year variability and amplifying ~4 year variability.

1 Introduction

The extent to which North Pacific atmospheric variability can impact the Tropics through ocean pathways is still an open question. The tropical forcing of the North Pacific Ocean on interannual timescales through atmospheric teleconnections has been clearly established [e.g., *Alexander* 1992; *Lau* 1996], partly due to the wealth of atmospheric data and the relatively short time lags involved. There is also observational evidence to suggest that ENSO variability can be triggered by extratropical atmospheric variability [e.g., *Barnett et al.,* 1999; *Vimont et al.* 2001]. ENSO variability may also be forced through ocean pathways from the North Pacific by the subduction of temperature or salinity anomalies, which are advected to the Tropics along mean pathways (e.g., *Gu and Philander* [1997]) or travel as higher-order baroclinic Rossby waves (e.g., *Galanti and Tziperman* [2003]), and impact the structure of the equatorial thermocline or by the wind forcing of first-order baroclinic Rossby waves that impact the depth of the equatorial thermocline (e.g., *Solomon et al.* [2008]). However, due to the sparsity of data in the ocean and the long time lags involved (interannual-to-decadal) the role of teleconnections through ocean pathways in forcing tropical variability remains unclear [*Deser et al.,* 1996; *Schneider et al.,* 1999; *Nonaka and Xie*, 2000; *Power and Colman*, 2006].

In this paper, we explore the extent to which baroclinic ocean Rossby waves that were found to impact ENSO on interannual timescales in a previous study [*Solomon et al.*, 2008, hereafter referred to as SSAM08] are due to coupled ocean-atmosphere feedback loops in the North Pacific. The SSAM08 study found that tropical variability forced through ocean pathways is dependent on the seasonal cycle--allowing for seasonal variations in pycnocline outcropping produced ocean pathways from the western subtropical North Pacific to the equatorial undercurrent, thereby allowing atmospheric variability in the subtropics to impact the Tropics through the ocean. This is consistent with the modeling study of *Goodman et al.* [2005] who showed that annual mean forcing resulted in ocean pathways to the equatorial undercurrent from the North Pacific that subducted east of the dateline while seasonal mean forcing resulted in trajectories that subducted in a broad region across the basin and from the edge of the Tropics to midlatitudes.

2 Experiment design

This study uses the Coupled Pacific Ocean Global Atmosphere (CPOGA) climate model, which consists of a 4.5-layer reduced gravity Pacific Ocean model anomaly-coupled to the NCAR Community Atmospheric Model Version 3 (CAM3) [*Collins et al.,* 2005). The ocean model extends from 50ºS to 60ºN and is run at 1º x 0.5º resolution in the longitudinal and latitudinal directions. The ocean model is coupled to the atmospheric model by updating sea surface temperatures (SSTs) daily in the Pacific basin with output from the ocean model while monthly mean climatological SSTs are prescribed outside the Pacific basin. The atmospheric model forces the ocean model with “anomaly-corrected” wind stresses and heat fluxes calculated using bulk formulae. Anomaly-corrected means that, for the atmosphere, monthly climate mean SSTs from the ocean model’s spin-up run are subtracted and observed monthly climate mean SSTs are added to the ocean model’s SSTs before they are used to force the atmospheric model. Fields that drive the ocean model are similarly anomaly-corrected. Further details about the model set-up, climatology, and variability of the CPOGA model is provided in SSAM08.

The model experiments used in this study employ a modeling strategy that allows us to determine whether subtropical variability forced by atmospheric teleconnections from the tropical Pacific returns to the Tropics through ocean pathways, thereby impacting ENSO variability. This modeling strategy is illustrated in Figure 1. The model experiments were carried out in two stages and are described in Table 1.

First, two simulations with and without coupling in the tropical Pacific (18°S-18°N) were completed (PAC and NP, respectively). NP was run to isolate intrinsic (i.e. independent of the Tropics) extratropical variability. PAC is the control run and includes all processes that can force tropical variability; intrinsic tropical variability, and extratropical variability through both ocean and atmospheric pathways.

In order to isolate the forcing of the Tropics through ocean pathways in NP and PAC we ran two additional simulations. These simulations used 49-years of monthly-mean wind stresses and heat fluxes output from PAC and NP to force the ocean model in the North Pacific (poleward of 18°N) while the tropical Pacific remained coupled and the South Pacific was forced by climatology (referred to hereafter as FPAC and FNP, respectively). In these two simulations, the tropical Pacific was run continuously for 294 years while the anomalous forcing in the North Pacific was repeated to complete a 6-member ensemble with identical 49-year ocean forcing. The ensemble mean of the 6 49-year ensemble members isolates the impact of extratropical variability (with and without atmospheric teleconnections from the Tropics, FPAC and FNP, respectively) on the Tropics through ocean pathways.

3 ENSO variability with and without forcing through ocean pathways

To determine if atmospheric teleconnections from the tropical Pacific are returning to the Tropics by way of ocean pathways and impacting coupled variability there; we first compare the global wavelet spectrum of NINO3.4 SSTs (5°S-5°N, 170°W-120°W) output from the two forced simulations (Figure 2). The FPAC spectrum (black line) has more power at 4 years and less power at 2 years than the FNP spectrum (red line). The differences in power at 2- and 4-year periods are significant at the 99.9% level using an f-test and degrees of freedom calculated following *Torrence and Compo* [1998] for a Morlet wavelet (ω_0=6). The impact of the atmospheric teleconnections on the tropical variability through ocean pathways is therefore seen to damp the 2-year variability and amplify the 4-year variability.

Also included in Figure 2 is the global wavelet spectrum of NINO3.4 SSTs from the 49-year period of the PAC simulation used to force the FPAC simulation (blue dashed line). Even though the PAC and FPAC simulations have unrelated intrinsic tropical variability, the FPAC simulation reproduces the PAC power at 2-years and increased power at 4 years. However, the FPAC simulation has significantly less power for periods greater than 6 years, which may indicate that this variability is forced from the extratropics through the atmosphere, intrinsic tropical variability, or through ocean pathways from the South Pacific. Interestingly, the FNP spectrum is similar to the spectrum of NINO3.4 SSTs that was found for a run that allowed coupling only in the tropical Pacific [SSAM08], indicating that intrinsic North Pacific variability (independent of atmospheric teleconnections from the Tropics) is having little impact on tropical variability on interannual time scales through ocean pathways.

4 Coupled ocean-atmosphere feedback loops

ENSO-related SST anomalies outside the tropical Pacific peak 1-2 seasons after the peak of an ENSO event, due to the 1-2 week lag in the response and the integrated effect of this forcing by the oceans over the next few months [see *Alexander et al., 2002*]. During the March-April period after an ENSO event, wind stress anomalies in the North Pacific exhibit a broad cyclonic circulation centered near 170°E-170°W, 40°N that creates negative anomalous wind stress curl extending from 135°E-160°W, 22-34°N and positive anomalous wind stress curl to the north of this region (March anomalies are shown in Figure 3a). This pattern persists through March and April causing sustained negative wind stress curl anomalies, and therefore downwelling due to Ekman pumping, in the region of maximum mean subduction where isopycnals that intersect the equatorial undercurrent outcrop in the subtropics (the location where the 24.5σ isopycnal outcrops in March is indicated by the red dashed line in Figure 3a). Also coincident with the negative wind stress curl anomalies are positive heat fluxes in the region of positive SST anomalies (results not shown, see SSAM08).

The Ekman pumping and heat flux anomalies in the subtropical North Pacific force thermocline anomalies that propagate westward as baroclinic ocean Rossby waves (Figure 4). SSAM08 found that tropical variability forced from the extratropics through ocean pathways is largest when the North Pacific variability leads the tropical Pacific variability by 4-5 years, indicating that the ocean Rossby wave is a higher-order mode baroclinic Rossby wave, following the estimates of baroclinic phase speeds from observations [e.g. *Chelton and Schlax, 1996*] and models [e.g., *Thompson and Ladd, 2004*]. This higher-order baroclinic Rossby wave essentially follows the advective pathway to the equator (Figure 4, also see discussion in SSAM08). Figure 3b shows the regression of FPAC wind stress anomalies in March with NINO3.4 SST anomalies in October 4 years later. This regression isolates the forcing of the Tropics through ocean pathways, since intrinsic tropical and extratropical variability are filtered out in the ensemble mean. The wind stress anomalies associated with this North Pacific forcing of the Tropics (Figure 3b) bears a striking similarity to the pattern associated with the atmospheric bridge (Figure 3a). The regions of largest subtropical wind stress curl anomalies in the central and western Pacific (where March and April mean subduction is a maximum) are greater than 95% significant in both March and April. These results clearly demonstrate that the wind stress response to the atmospheric bridge can force the tropical Pacific through ocean pathways. Together, Figures 3a and 3b illustrate a coupled ocean-atmosphere feedback loop that shift ENSO variability from a primarily 2-year period to a broader range of 2-5 year periods (Figure 2).

As further evidence of this coupled ocean-atmosphere feedback loop we plot in Figure 3c the regression of March wind stress anomalies in the North Pacific with tropical Pacific SSTs in October 4 years later from the simulation that excludes atmospheric teleconnections from the Tropics (FNP). Figure 3c clearly shows that, without atmospheric teleconnections from the Tropics, extratropical variability west of 170°W does not impact the Tropics through ocean pathways after 4 years. One reason why the FNP anomalies are not as efficient as FPAC anomalies in forcing tropical variability is that in FNP, March wind stress anomalies averaged in the 150°E-170°W,25-40°N region (where wind stress in Figures 3a and 3b reach maximum amplitude) have one month lag autocorrelations less than 0.1. This is an indication that the North Pacific → Tropics leg of the coupled feedback loop requires the sustained forcing of the extratropics by atmospheric teleconnections during an ENSO event to exist.

5 Discussion

In this study, we have shown that a 4-year coupled ocean-atmosphere feedback loop can significantly impact the frequency of ENSO variability on *interannual* time scales in an atmospheric general circulation model coupled to a reduced gravity Pacific Ocean model. We have isolated a distinct wind stress pattern in the North Pacific that is forced from the Tropics and impacts the tropical Pacific through ocean pathways 4 years later. Intrinsic North Pacific variability was found to be less efficient at forcing tropical variability through ocean pathways because wind stress variability in the central and west subtropics decorrelates too rapidly without the sustained forcing of extratropical atmospheric variability that occurs during ENSO events. This sustained forcing causes anomalous subduction of mixed layer water into the permanent thermocline, which travels to the equator along advective pathways. The forcing of the Tropics through ocean pathways on interannual timescales was found to impact the frequency of ENSO events rather than by modulating ENSO variability on decadal timescales, as was found by studies such as *Kleeman et al.* [1999], *Solomon et al.* [2003], and *Wu et al.* [2007].

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References

Alexander M. A, (1992), Midlatitude atmosphere–ocean interaction during El Niño. Part I: The North Pacific Ocean, *J. Climate, 5,* 944–958.

Alexander, M. A., I. Blade, M. Newman, J. R. Lanzante, N.-C. Lau, and J. D. Scott (2002), The Atmospheric Bridge: the influence of ENSO teleconnections on air-sea interaction over the global oceans, *J. Climate, 15*, 2205-2231.

Barnett, T. P., D. P. Pierce, M. Latif, D. Dommenget, and R. Saravanan (1999), Interdecadal interactions between the tropics and midlatitudes in the Pacific, *Geophys. Res. Lett., 26*, 615-618.

Chelton, D. B., and M. G. Schlax (1996), Global Observations of Oceanic Rossby Waves, *Science,* 272, 234-238.

Collins W. D., P. J. Rasch, B. A. Boville, J. J. Hack, J. R. McCaa, D. L. Williamson, B. Briegleb, C. Bitz, S.-J. Lin, and M. Zhang (2005), The Formulation and Atmospheric Simulation of the Community Atmosphere Model: CAM3, *J. Climate, 19*, 2144-2161.

Deser C., M. A. Alexander, and M. S. Timlin (1996), Upper-ocean thermal variations in the North Pacific during 1970–1991, *J. Climate, 9,* 1840–1855.

Galanti, E., and E. Tziperman (2003), A Mid-latitude ENSO teleconnection mechanism via baroclinically unstable long Rossby waves, *J. Phys. Oceanog., 33*, 1877-1888.

Goodman, P. J., W. Hazeleger, P. de Vries, and M. Cane (2005), Pathways into the Pacific Equatorial Undercurrent: A Trajectory Analysis, *J. Phys. Oceanogr., 35*, 2134–2151.

Gu, D., and S. G. H. Philander (1997), Interdecadal climate fluctuations that depend on exchanges between the Tropics and Extratropics, *Science*, *275*, 805-807.

Kleeman R., J. P. McCreary, and B. A. Klinger (1999), A mechanism for the decadal variation of ENSO, *Geophys. Res. Lett., 26*, 743-747.

Lau N.-C, (1996), The role of the “atmospheric bridge” in linking tropical Pacific ENSO events to extratropical SST anomalies, *J. Climate, 9,* 2036–2057.

Livezey, R. E., and W. Chen (1983), Statistical Field Significance and its Determination by Monte Carlo Techniques. *Mon. Wea. Rev., 111,* 46–59.

Nonaka, M., and S.-P. Xie (2000), Propagation of North Pacific interdecadal subsurface temperature anomalies in an ocean GCM, *Geophys. Res. Lett., 27*, 3747-3750.

Power, S. B., and R. Colman (2006), Multi-year predictability in a coupled general circulation model, *Clim. Dyn., 26*, 247-272.

Schneider, N., A. J. Miller, M. A. Alexander, and C. Deser (1999), Subduction of decadal north Pacific temperature anomalies: Observations and dynamics, *J. Phys. Oceanogr., 29*, 1056–1070.

Solomon A., J. P. McCreary, R. Kleeman, and B. A. Klinger (2003), Interannual and decadal variability in an intermediate coupled model of the Pacific region, *J. Climate, 16*, 383-405.

Solomon, A., S.-I. Shin, M. A. Alexander, and J. P. McCreary (2008), The relative importance of tropical variability forced from the North Pacific through ocean pathways, *Clim. Dyn., 31*, 315-331.

Thompson, L., and C. A. Ladd (2004), The Response of the North Pacific Ocean to Decadal Variability in Atmospheric Forcing: Wind versus Buoyancy Forcing. *J. Phys. Oceanogr.*, 34, 1373–1386.

Torrence, C., and G. P. Compo (1998), A Practical Guide to Wavelet Analysis, *Bull. Amer. Meteor. Soc., 79*, 61–78.

Vimont D. J., D. S. Battisti, and A. C. Hirst (2001), Footprinting: A seasonal connection between the tropics and mid-latitudes, *Geophys Res Lett, 28*, 3923-3926.

Wu, L., Z. Liu, and C. Li (2007), Extratropical control of recent tropical Pacific decadal climate variability: a relay teleconnection, *Clim. Dyn., 31*, 315-331.

Model Experiment	**Description**
PAC – Includes both atmospheric teleconnections Tropics → North Pacific and the ocean teleconnections from the North Pacific → Tropics	Ocean-atmosphere anomaly-coupled 50°S-60°N
NP – All tropical variability is suppressed to isolate intrinsic North Pacific variability	Ocean-atmosphere anomaly-coupled 18°-60°N. Ocean and atmosphere forced by climatology 50°S-18°N.
FPAC – The North Pacific → Tropics leg of the coupled feedback loop in PAC is isolated by forcing the North Pacific Ocean with wind stresses and heat fluxes output from PAC	Ocean forced 18°-60°N by 50-years of monthly mean output from PAC. Atmosphere forced poleward of 18° by climatological SSTs. Tropical Pacific coupled. NP Forcing repeated 6 times while the tropical Pacific is run continuously for 294 years.
FNP – The forcing of the Tropics though ocean pathways by intrinsic North Pacific variability is isolated by forcing the North Pacific Ocean with wind stresses and heat fluxes output from NP	Ocean forced 18°-60°N by 50-years of monthly mean output from NP. Atmosphere forced poleward of 18° by climatological SSTs. Tropical Pacific coupled. NP Forcing repeated 6 times while the tropical Pacific is run continuously for 294 years.

Table 1: Description of CPOGA experiments completed for this study.

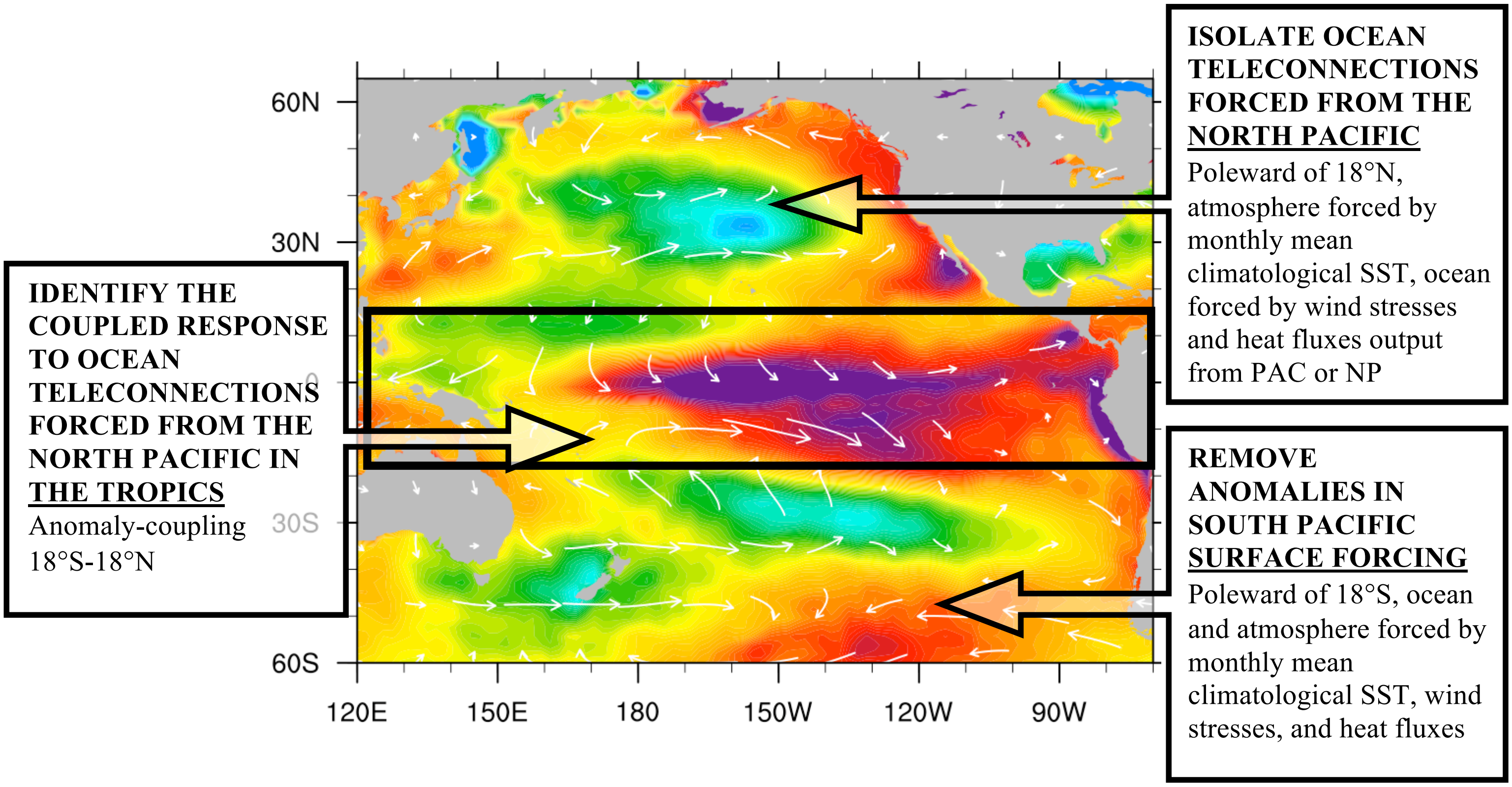

Figure 1: Model configuration designed to limit forcing to the North Pacific Ocean while the tropical Pacific is coupled. Contours and vectors show observed SSTs and surface winds 3 months after the peak of an El Niño event (regressions between 1948-2008 Dec-Jan Southern Oscillation Index with Mar-Apr SSTs and 1000hPa winds from the NCEP/NCAR Reanalysis).

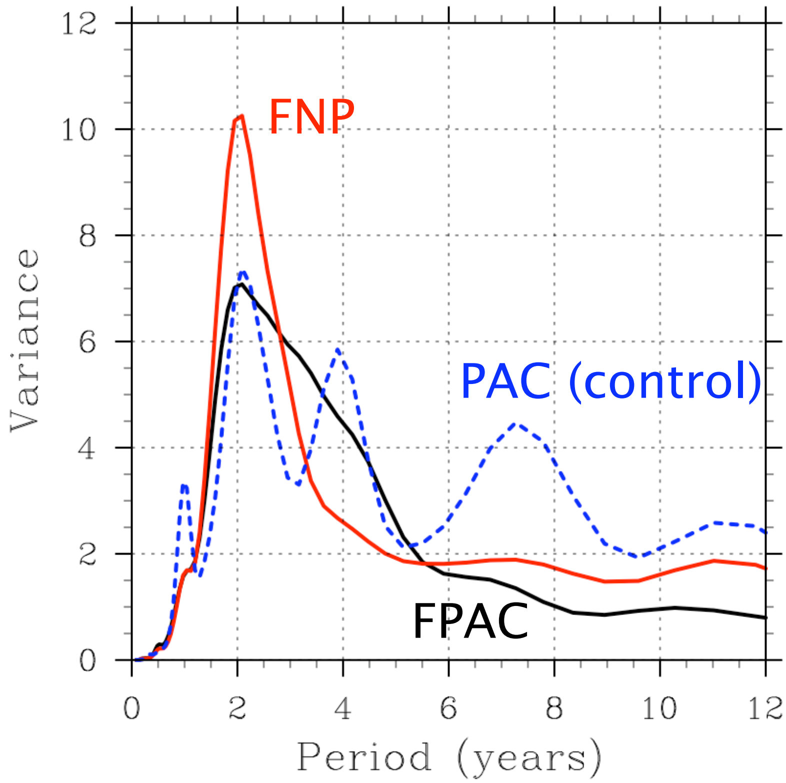

Figure 2: Global wavelet spectrum of NINO3.4 (5°S-5°N, 170°W-120°W) time series calculated from 294 years of monthly mean SSTs output from FPAC (black line), FNP (red line) and the 49-year period from PAC used to force FPAC (blue dashed line). Variance is in units of °C^2.

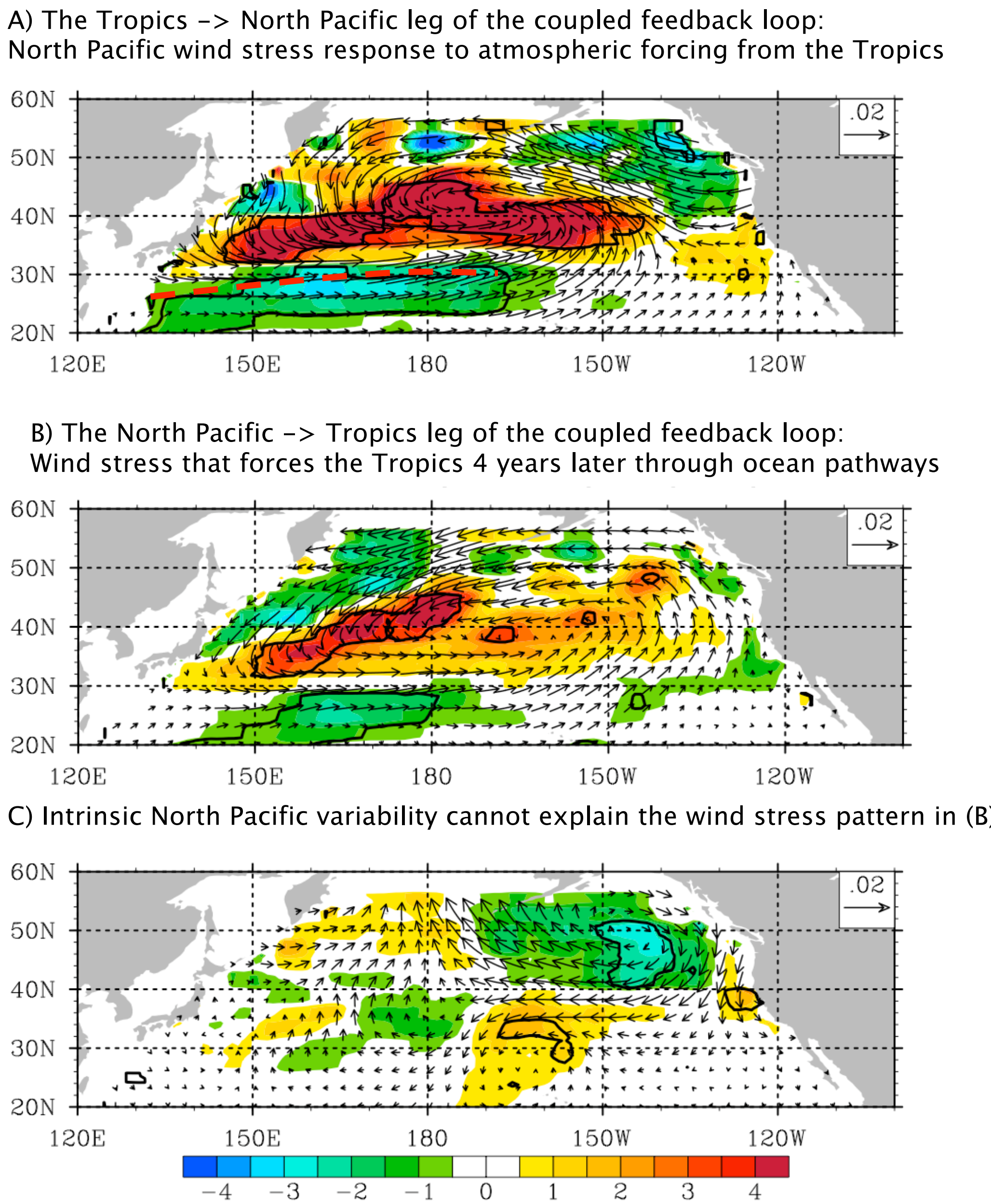

Figure 3: Regression of wind stress (vectors) and wind stress curl anomalies (shading) to NINO3.4 SST anomalies, in units of N m^{-2} $°C^{-1}$ and 10^{-8} N m^{-3} $°C^{-1}$, respectively. Correlations greater than 95% significant indicated with black contours, using a t-statistic with effective degrees of freedom following *Livezey and Chen* [1983]. (A) North Pacific wind stress pattern associated with atmospheric teleconnections from the Tropics. Found by

regressing PAC October NINO3.4 SSTs (when ENSO peaks in the model) with wind stress and wind stress curl anomalies in March of the following year. March mean 24.5σ isopycnal outcropping is indicated by a dashed red line. (B) Impact of baroclinic ocean Rossby waves forced from the North Pacific on tropical variability 4 years later. Found by regressing FPAC ensemble mean wind stress and wind stress curl anomalies in March with NINO3.4 SST anomalies in October 4 years later. (C) Intrinsic North Pacific variability alone cannot explain the wind stress pattern found to force the Tropics through ocean pathways in (B). Found by regressing FNP March wind stress (vectors) and wind stress curl anomalies (shading) with October NINO3.4 SST anomalies 4 years later.

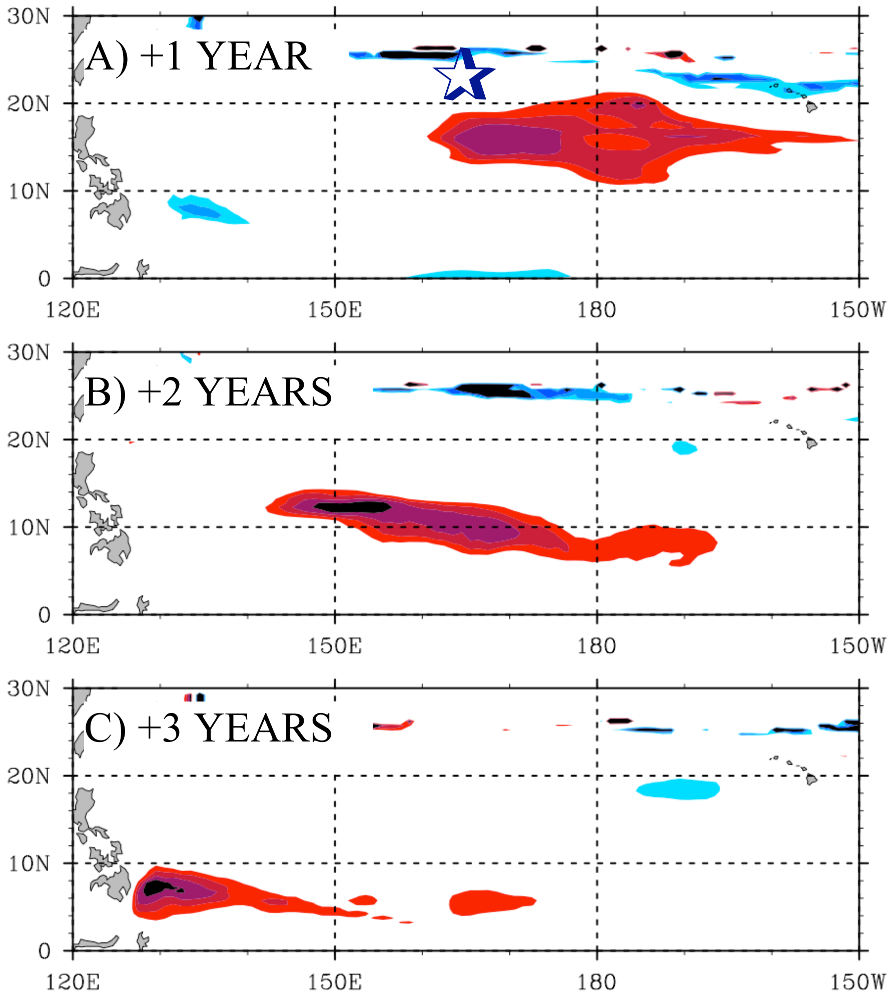

Figure 4: The ocean pathway from the region of subtropical North Pacific forcing to the equator. The signal starts in the region of maximum Ekman pumping and SST anomalies that occur during an El Niño event in late winter-early spring (marked by the blue star, see Figure 3. Correlations between Feb-Mar H(24.5σ) anomalies averaged (19-28N,160-170E) and basinwide H(24.5-25.1σ) anomalies at lags of A) 1 year, B) 2 years, and C) 3 years. Only correlations greater than 95% are plotted. Black contours indicate greater than 99.8% significance (cr=0.45). The first four years are not included in the correlations in order to eliminate any potential problem due to the cycling of the extratropical forcing.