

# Footprinting: A seasonal connection between the tropics and mid-latitudes

Daniel J. Vimont and David S. Battisti

University of Washington - JISAO, Seattle, Washington

Anthony C. Hirst

CSIRO Atmospheric Research, Aspendale, Victoria, Australia

**Abstract.** A connection between the mid-latitude and tropical Pacific is identified in a coupled general circulation model (CGCM). The connection involves a seasonal coupling between winter mid-latitude atmospheric circulation anomalies, and summer equatorial wind stress anomalies. The seasonal coupling results from a “footprinting” mechanism, in which the summer tropical atmosphere responds to subtropical sea surface temperature (SST) anomalies that are generated by the mid-latitude atmospheric variability during the previous winter. Details of the connection, and of the footprinting mechanism are presented. Implications for interannual ENSO and decadal ENSO-like variability are discussed.

## 1. Introduction

The connection between tropical and mid-latitude variability of the ocean-atmosphere system is of considerable importance in understanding the mechanism causing the variability in either region, as well as the potential predictability of its impacts. For interannual time scales, it is known that ENSO contributes to the mid-latitude climate anomalies via teleconnections: the so-called “atmospheric bridge” [Alexander, 1992; Lau and Nath, 1996]. This mechanism may also explain some of the connection on decadal time scales, in particular the mid-latitude anomalies that are associated with decadal ENSO-like variability [Zhang *et al.*, 1997]. Conversely, it has recently been suggested that, for decadal time scales, mid-latitude atmospheric variability may influence tropical variability by producing zonal wind stress anomalies in the tropics [Barnett *et al.*, 1999; Pierce *et al.*, 2000]. This study identifies the latter connection in the CSIRO CGCM, as well as the mechanism by which mid-latitude atmospheric variability produces tropical zonal wind stress anomalies.

## 2. Model description

The connection between the mid-latitudes and tropics is investigated using two configurations of the CSIRO CGCM [Gordon and O’Farrell, 1997]. Each configuration consists of the CSIRO atmosphere, land, and sea-ice models coupled to a different representation of the ocean. In the first simulation (the DYN simulation [Hirst *et al.*, 2000]), the atmo-

sphere, land, and sea-ice models are coupled to a dynamic ocean GCM. The second simulation (the MIX simulation [Watterson *et al.*, 1997]) parameterizes the ocean as a 50-meter mixed layer with no ocean dynamics. In both the DYN and MIX simulations, the coupling is interactive, allowing the atmosphere to respond to any surface heat flux anomalies produced by the ocean. The DYN simulation is integrated for 1000 years, and the MIX simulation for 470 years.

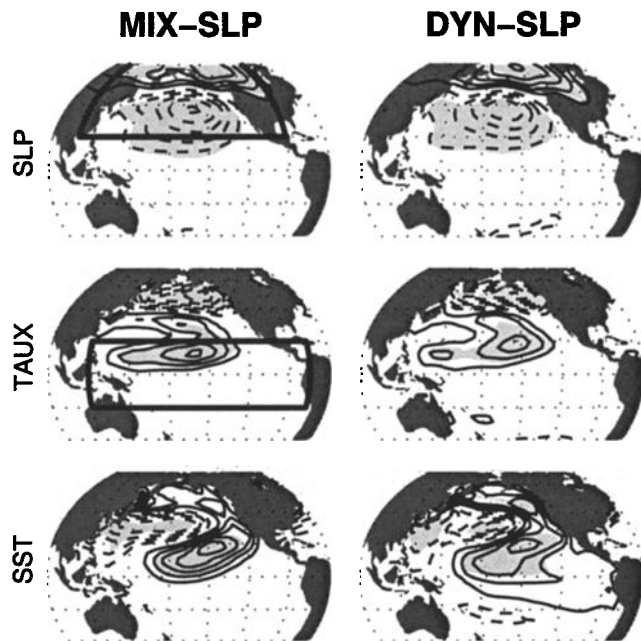
## 3. Structure of the connection

In this section we identify the connection between mid-latitude atmospheric variability and ENSO-like tropical variability hypothesized in Section 1. This hypothesis states that intrinsic mid-latitude atmospheric variability (IMAV), which may be reflected in, for example, North Pacific sea-level pressure (SLP) patterns, produces equatorial zonal wind stress anomalies. The tropics adjust to these zonal wind stress anomalies, through coupled dynamics, producing an equatorially symmetric, ENSO-like pattern of variability.

The connection between IMAV and equatorial zonal wind stress anomalies is identified in the following manner. First, we require that IMAV be independent of tropical forcing associated with the model’s ENSO and decadal ENSO-like variability. This independence ensures that tropical zonal wind stress anomalies are caused by IMAV (the hypothesized forcing), and not by coupled tropical variability (the hypothesized response). Independence is established by defining IMAV in the MIX simulation, in which coupled equatorial dynamics, and hence ENSO and decadal ENSO-like variability, are absent<sup>1</sup>. Note that the use of the MIX simulation does not preclude the possibility that non-ENSO-related tropical variability may be affecting the structure of IMAV, as will be shown in section 4. Next, we seek a structure of the IMAV that covaries with tropical zonal wind stress anomalies. This structure is defined by applying singular value decomposition (SVD) analysis to mid-latitude (20°N–90°N, 110°E–90°W) SLP and tropical (120°E–65°W, 20°S–20°N) zonal wind stress in the MIX simulation (domains shown in Figure 1). Both fields are *annually averaged* (Nov.–Oct.)<sup>2</sup>, detrended, and standardized prior to analysis.

<sup>1</sup> Vimont *et al.* [2001] show that coupled equatorial dynamics dominate the interannual ENSO and decadal ENSO-like variability in the DYN simulation.

<sup>2</sup> The seasonality is essential in producing the connection, and will be discussed in Section 4. First, we must verify that the connection exists.



**Figure 1.** Annually averaged regressions onto standardized time indices of IMAV from the MIX simulation (MIX-SLP, left column) and the DYN simulation (DYN-SLP, right column). From top to bottom: SLP (contour interval 0.25 hPa), zonal wind stress (contour interval 0.025 N m<sup>-2</sup>) SST (contour interval 0.07 K). Solid (dashed) lines denote positive (negative) values, the zero contour is omitted. Regions where the time index explains more than 25% of the local variance are lightly shaded.

The standardized time series associated with the leading SLP pattern resulting from SVD analysis is used to describe IMAV in the MIX simulation, and will be labeled **MIX-SLP**.

Regression maps of annually averaged SLP, zonal wind stress, and SST onto MIX-SLP, are shown in the left column of Figure 1. The SLP map shows the pattern of IMAV in the MIX simulation: a dipole SLP pattern across the Pacific, with anomalous high and low SLP to the north and south of 50°N. To the south of the anomalous low, the model produces anomalous westerly wind stress anomalies that extend to the equator (note that the zero contour is omitted), establishing the connection between IMAV and equatorial zonal wind stress anomalies in the annually averaged data. Tropical SST anomalies associated with MIX-SLP are primarily contained in the northern hemisphere, and bear little resemblance to ENSO-like SST anomalies.<sup>3</sup>

The connection outlined at the beginning of this section states that the tropics adjust to the zonal wind stress anomalies associated with IMAV through coupled dynamics, producing an ENSO-like pattern of variability. We use the DYN simulation to investigate the dynamic response of the tropical coupled ocean-atmosphere system. A time index of IMAV in the DYN simulation is generated by projecting the standardized SLP from the DYN simulation onto the leading spatial pattern of SLP resulting from SVD analysis of the MIX simulation (the exact pattern used to define MIX-SLP). The resulting time series is labeled **DYN-SLP**. This method only ensures that the *structure* of the spatial pattern

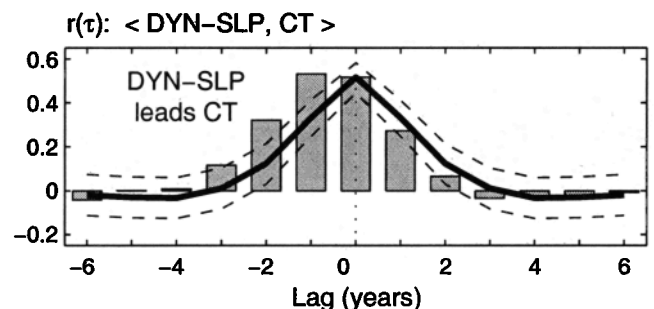
used to define DYN-SLP is independent of tropical forcing associated with ENSO and decadal ENSO-like variability; the temporal relationship between DYN-SLP and tropical variability must still be addressed.

Regression maps of SLP, zonal wind stress, and SST from the DYN simulation onto DYN-SLP are shown in the right column of Figure 1. In the northern hemisphere mid-latitudes, all three regression maps strongly resemble their counterparts in the MIX simulation. In the tropics, though, a striking difference is seen in the SST regression map for the DYN simulation, where an equatorially symmetric, ENSO-like pattern of variability spans the equator.

The regression maps in Figure 1 establish a connection between IMAV and tropical ENSO-like variability, but taken alone, provide insufficient evidence to conclude that IMAV influences tropical ENSO-like variability: ENSO-like tropical variability may force a mid-latitude pattern that projects onto the SLP pattern described by MIX-SLP. Causality is determined by examining the lagged correlation between DYN-SLP and the cold tongue (CT) index. A null hypothesis is defined as the case where tropical variability forces mid-latitude variability, in accord with the “atmospheric bridge” hypothesis [Alexander, 1992; Lau and Nath, 1996], and in contrast to the hypothesis we seek to identify. Because the atmospheric bridge hypothesis is a simultaneous connection, the null hypothesis is the automatic lagged correlation between DYN-SLP and the CT index: given that DYN-SLP is correlated with the CT index at zero lag and that the CT index is autocorrelated with itself at lag  $\tau$ , DYN-SLP should automatically be correlated with the CT index at lag  $\tau$  by:

$$\text{NULL } r_{\text{DYN-SLP, CT}}(\tau) = r_{\text{DYN-SLP, CT}}(0) \cdot r_{\text{CT, CT}}(\tau) \quad (1)$$

The actual lagged correlations between DYN-SLP and the CT index, the automatic lag correlations under the null hypothesis, and the 95% confidence levels on the null hypothesis correlations are plotted in Figure 2. Note that the lagged correlation peaks when DYN-SLP *leads* the CT index by one year ( $r(\tau = -1) = 0.53$ ), and is distinguishable from the null hypothesis at lags of one to three years. The spectrum of DYN-SLP (not shown) is white, while the CT index shows preferred periodicities of 6–9 years [Vimont *et al.*, 2001]. Cross-spectral analysis indicates that DYN-SLP tends to lead the CT index by about 9 months for time scales longer than 4 or 5 years. Thus, we demonstrate the causality hypothesized at the beginning of this section, that atmospheric variability intrinsic to the mid-latitudes (IMAV) influences tropical ENSO-like variability.



**Figure 2.** Lagged correlation between DYN-SLP and the CT index (bars), null hypothesis (solid line), and 95% confidence interval on the null hypothesis (dashed lines).

<sup>3</sup>The CT index is defined as SST averaged from 6°S – 6°N, 180° – 90°W, and is a commonly used index of interannual ENSO and decadal ENSO-like variability [Zhang *et al.*, 1997].

#### 4. Footprinting mechanism: linking IMAV with tropical wind stress anomalies

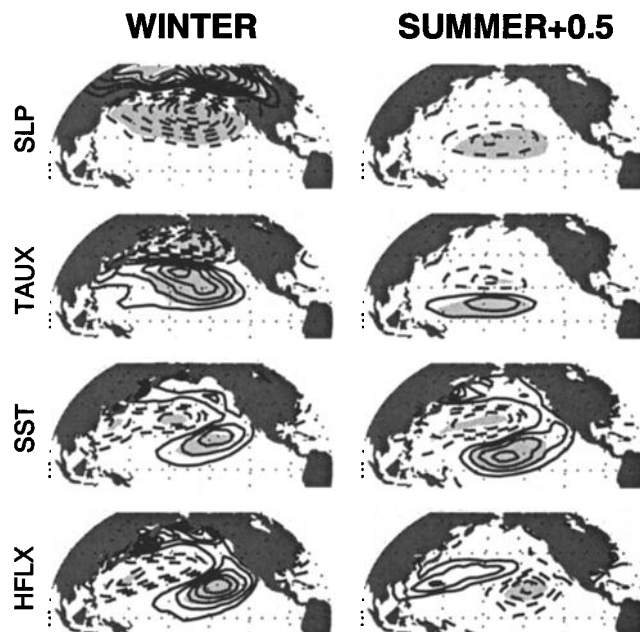
In this section, we investigate the mechanism connecting IMAV with tropical zonal wind stress anomalies. First, the role of the oceanic mixed layer is determined by examining the structure of IMAV in a separate 500 year simulation of the (uncoupled) CSIRO atmosphere model forced by the annually varying SST climatology (see *Watterson [2001]*). The dipole SLP structure of IMAV is present in the uncoupled simulation (without an oceanic mixed layer), but has little signal in tropical zonal wind stress south of about  $10^{\circ}\text{N}$  (results not shown). Thus, tropical zonal wind stress anomalies associated with IMAV do not extend to the equator by atmospheric processes alone, signifying an essential role of the oceanic mixed layer.

To illuminate the role of the oceanic mixed layer, the structure of winter IMAV is examined in the MIX simulation. The mid-latitude atmosphere is most energetic during winter. Thus, the winter anomalies are more likely a better representation of IMAV than the annually averaged anomalies. A time index of winter IMAV is constructed in the same fashion as DYN-SLP: winter (NDJFM) averaged SLP from the MIX simulation is projected onto the now familiar SLP pattern resulting from SVD analysis of the annually averaged MIX data. The resulting time series is labeled WIN-MIX-SLP.

Simultaneous regression maps of winter (NDJFM) averaged SLP, zonal wind stress, SST and net heat flux onto WIN-MIX-SLP are plotted in the left column of Figure 3. In the tropics, there are subtle but important differences between the maps of SLP and wind stress during winter (Figure 3), and those using annually averaged data (Figure 1). During winter, SLP anomalies extend only slightly south of  $20^{\circ}\text{N}$ , and zonal wind stress anomalies vanish at about  $5^{\circ}\text{N}$ . Along the equator, zonal wind stress anomalies are very weak, and easterly. Although these distinctions are subtle, they significantly affect the strength of the equatorial coupled dynamical response.

Differences between the structure of annual and winter tropical SLP and zonal wind stress anomalies (c.f. Figure 1 with Figure 3) must arise from differences in the summer. We shall see that these differences reflect a summer response to conditions persisting from the previous winter. The summer response is investigated by regressing summer (MJJAS) averaged data onto the WIN-MIX-SLP index from the previous winter.

Regression maps of summer averaged SLP, zonal wind stress, SST, and net heat flux onto WIN-MIX-SLP are shown in the right column of Figure 3. Thus, the left column of Figure 3 represents simultaneous winter patterns of variability associated with WIN-MIX-SLP, and the right column of Figure 3 represents conditions that exist during the following summer. The summer SLP regression map consists of a localized anomalous low centered at around  $18^{\circ}\text{N}$  that explains the different structure of tropical SLP anomalies between the annual and winter regression maps (compare Figure 3 with Figure 1). Summer zonal wind stress anomalies include a tongue of westerly equatorial anomalies that complete the connection between IMAV and tropical zonal wind stress anomalies outlined in Section 3. The subtle differences between winter and summer tropical zonal



**Figure 3.** MIX simulation: Regressions of winter season (NDJFM, left column) and the following summer season (MJJAS, right column) data onto the time index of winter IMAV (WIN-MIX-SLP). From top to bottom: SLP (contour interval 0.3 hPa), zonal wind stress (contour interval  $0.04 \text{ N m}^{-2}$ ), SST (contour interval 0.1 K), and net surface heat flux (contour interval  $2 \text{ W m}^{-2}$ , positive down). Plotting convention as in Figure 1.

wind stress anomalies in Figure 3 are important because, unlike the winter wind stress pattern, the summer wind stress pattern yields a large projection on the oceanic equatorial Kelvin wave, and hence is likely to have a more substantial influence on the coupled system in the tropics (i.e., on ENSO and the decadal ENSO-like variability).

The mechanism linking the winter and summer variability is revealed by examining the winter and summer SST and heat flux maps (Figure 3, bottom two rows). During winter, positive tropical SST anomalies are collocated with downward net surface heat flux, indicating that IMAV forces the winter SST anomalies. During summer, the SST pattern is nearly identical to previous winter's SST pattern, indicating that the winter SST anomalies persist into the summer season. However, the relationship between SST and surface heat flux is reversed during summer: positive SST anomalies are collocated with upward net surface heat flux anomalies. This relationship indicates that the ocean is forcing the atmosphere during the summer months. The summer atmosphere responds by producing the monsoon-like circulation anomalies seen in the SLP and zonal wind stress regression maps.

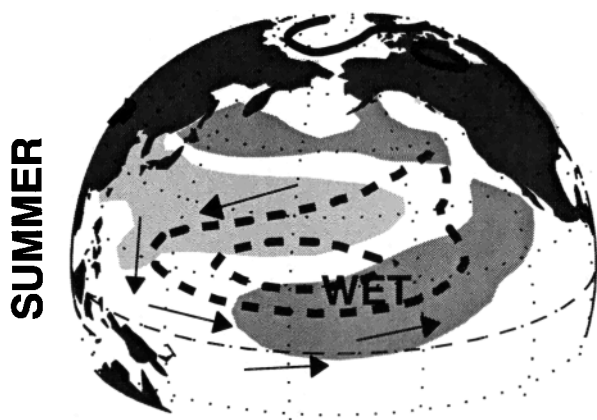
#### 5. Summary and discussion

This study has established a seasonal connection between mid-latitude atmospheric variability, and tropical zonal wind stress anomalies in the CSIRO CGCM. The mechanism producing this connection is summarized in Figure 4. During the winter months, when intrinsic mid-latitude atmospheric variability is most energetic, the atmosphere imparts a SST "footprint" onto the ocean via changes in the surface heat flux. The SST footprint persists into the summer season, when the mid-latitude atmosphere is more

## FOOTPRINTING MECHANISM



A. ATM imparts SST footprint onto the ocean during the winter months



B. SST footprint persists into the following summer, when it forces ATM

**Figure 4.** Schematic illustration of the “Footprinting” mechanism, for winter (top) and summer (bottom). Contours denote SLP anomalies; dark and light shading denote positive and negative SST anomalies, vectors denote wind stress anomalies, and text indicates anomalous precipitation.

quiescent. During summer, the SST footprint damps, and in the subtropics *forces* an atmospheric circulation anomaly that includes zonal wind stress anomalies that extend onto and south of the equator, with a large projection onto the oceanic Kelvin signal. Finally, the adjustment of the tropics by coupled dynamics produces an equatorially symmetric, ENSO-like pattern of variability. Hence, wintertime variability intrinsic to the atmosphere in the North Pacific, through footprinting subtropical SST anomalies that force summertime atmospheric circulation anomalies, is a powerful forcing on the coupled tropical system in the CSIRO model. We emphasize that footprinting is not the *primary* ENSO mechanism, but should be included when considering the contribution to stochastic forcing that affects ENSO.

We note that the surface mixed layer in the DYN simulation cannot effectively be less than 50 m (owing to the coarse resolution). Summer mixed layers in the tropics are often observed to be considerably less than 50 m, which could limit the effect of the previous winter’s mixed layer anomalies on the atmosphere. We encourage examination of solutions from coupled GCMs with higher vertical resolution and high fidelity surface mixing parameterization to validate the proposed mechanism.

The existence of the footprinting mechanism in the CSIRO CGCM raises the question: “does the footprinting mechanism exist in observations?” Preliminary investigation suggests that it does. A more complete investigation of the footprinting mechanism in the CSIRO CGCM, as well as in observations, is currently underway.

**Acknowledgments.** We are grateful to E. S. Sarachik and J. M. Wallace for their guidance. Thanks to A. Miller, I. G. Watterson, reviewers at CSIRO, and one anonymous reviewer for their comments and suggestions. This publication was supported by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement #NA67RJO155, Contribution #831.

## References

- Alexander, M. A., Midlatitude atmosphere-ocean interaction during El Niño. Part II: the Northern Hemisphere atmosphere, *J. Clim.*, *5*, 959-972, 1992.
- Barnett, T. P., D. W. Pierce, M. Latif, D. Dommenges, and R. Saravanan, Interdecadal interactions between the tropics and midlatitudes in the Pacific basin, *Geophys. Res. Lett.*, *26*, 615-618, 1999.
- Gordon, H. B. and S. P. O’Farrell, Transient climate change in the CSIRO coupled model with dynamic sea ice, *Mon. Weather Rev.*, *125*, 875-907, 1997.
- Hirst, A. C., S. P. O’Farrell and H. B. Gordon, Comparison of a coupled ocean-atmosphere model with and without oceanic eddy-induced advection. Part 1: Ocean spin-up and control integrations, *J. Clim.*, *13*, 139-163, 2000.
- Lau, N.-C. and M. J. Nath, The role of the “Atmospheric Bridge” in linking Pacific ENSO events to extratropical SST anomalies, *J. Clim.*, *9*, 2036-2057, 1996.
- Pierce, D. W., T. P. Barnett, and M. Latif, Connections between the Pacific Ocean tropics and midlatitudes on decadal time scales, *J. Clim.*, *13*, 1173-1194, 2000.
- Vimont, D. J., D. S. Battisti, and A. C. Hirst, Pacific interannual and interdecadal equatorial variability in a 1000 year simulation of the CSIRO coupled general circulation model, *J. Clim.*, *Submitted*, 2001.
- Watterson, I. G., S. P. O’Farrell and M. R. Dix, Energy and water transport in climates simulated by a general circulation model that includes dynamic sea ice, *J. Geophys. Res.*, *102*, 11027-11037, 1997.
- Watterson, I. G., Wind-induced rainfall and surface temperature anomalies in the Australian region, *J. Clim.*, *14*, 1901-1922, 2001.
- Zhang, Y., J. M. Wallace, and D. S. Battisti, ENSO-like interdecadal variability: 1900-93, *J. Clim.*, *10*, 1004-1020, 1997.

D. J. Vimont, Dept. of Atmospheric Sciences, University of Washington - JISAO, Box 354235, Seattle, WA 98195-4235. (e-mail: [dvimont@atmos.washington.edu](mailto:dvimont@atmos.washington.edu))

(Received May 8, 2001; revised July 5, 2001; accepted July 14, 2001.)