

# Decadal Variations in the Pacific Meridional Mode

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## Abstract

This study examines decadal variations in the Pacific Meridional Mode (MM), a phenomenon known to arise from the coupling between surface winds and sea surface temperatures in the subtropical Pacific. The MM coupling strength has increased during the past four decades in a step-wise manner, with the first increase around 1976 and the second around 1993. The 1976-enhancement is accompanied by an intensification of the Aleutian Low and the 1993-enhancement is accompanied by an intensification of the Pacific Subtropical High. Evidence is presented to show that the 1976-enhancement is related to a phase change in the Pacific Decadal Oscillation (PDO), while the 1993-enhancement is related to a phase change in the Atlantic Multi-decadal Oscillation (AMO). The recent emergence of the Central Pacific El Niño, which is often preceded by the MM, is a consequence of the joint influences of the PDO and AMO.

Key word: Pacific Meridional Mode, Pacific Decadal Oscillation, Atlantic Multi-decadal Oscillation

## 1. Introduction

The Pacific Meridional Mode (MM) is a leading mode of the coupled ocean-atmosphere variability in the subtropical Pacific [Chiang and Vimont, 2004] characterized by co-variabilities in sea surface temperature (SST) and surface wind. Wind fluctuations associated with extratropical atmospheric variability, such as the North Pacific Oscillation (NPO), induce SST anomalies in the subtropical Pacific via surface evaporation, which then feedback to modify the atmospheric winds via convection. Through this wind-evaporation-SST feedback mechanism [Xie and Philander, 1994], the two-way interaction is prolonged and extends the atmosphere-induced SST anomalies equatorward from near Baja California toward the tropical central Pacific to form the spatial pattern of the MM. Atmosphere-ocean coupling also sustains the MM from boreal winter, when the extratropical atmospheric variability peaks, to the following seasons. This behavior of the MM is referred to as a seasonal footprinting mechanism [Vimont *et al.*, 2001; 2003] and has been invoked to suggest how extratropical atmospheric variability in boreal winter can influence or excite El Niño events the following spring or summer [e.g., Anderson, 2003; Chiang and Vimont, 2004; Chang *et al.*, 2007; Alexander *et al.*, 2006, 2010].

More recently, the MM and the seasonal footprinting mechanism were used to describe the generation mechanism of a non-conventional type of El Niño that is referred to as the Central-Pacific (CP) El Niño [Yu and Kao, 2007; Kao and Yu, 2009]. In contrast to the conventional Eastern-Pacific (EP) type of El Niño

that has SST anomalies spreading westward from the South American Coast, the CP El Niño has most of its SST anomalies confined around the International Dateline. While the generation of the EP El Niño involves traditional El Niño dynamics centered on thermocline variations along the equatorial Pacific, the generation of the CP El Niño is linked to forcing from the extratropical atmosphere [Yu *et al.*, 2011; Yu and Kim, 2011; Kim *et al.*, 2012; Yu *et al.*, 2012]. The extratropical atmospheric forcing is suggested to penetrate into the tropical central Pacific through the MM via the seasonal footprinting mechanism. Since the CP El Niño has occurred more frequently in recent decades [Ashok *et al.*, 2007; Kao and Yu, 2009; Kug *et al.*, 2009; Lee and McPhaden, 2010], it is natural to wonder whether the MM has also experienced slow variations, and how these slow variations, if any, are related to the leading decadal variability modes in the Pacific or even the Atlantic, such as the Pacific Decadal Oscillation (PDO; Mantua *et al.*, 1997) and Atlantic Multidecadal Oscillation (AMO; Kerr, 2000; Enfield *et al.*, 2001). Statistical analyses are conducted here using over sixty years of observational and re-analysis data to answer these two questions.

## 2. Data and Methodology

Two datasets were used in this study. For the atmosphere, monthly 10m surface winds and sea level pressure (SLP) from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis were used [Kistler *et al.*, 2001]. For the ocean, monthly SSTs from National Oceanic and Atmospheric Administration

(NOAA)'s Extended Reconstructed Sea Surface Temperature (ERSST) V3b dataset [Smith and Reynolds, 2003] were used. The interannual anomalies in these variables were obtained by removing their seasonal cycles and linear trends. Monthly indices for PDO and AMO, which are also used in this study, were downloaded from NOAA (<http://www.esrl.noaa.gov/psd/data/climateindices/list/>). Data from 1948-2010 were analyzed in this study, with a particular focus on the period 1962-2004.

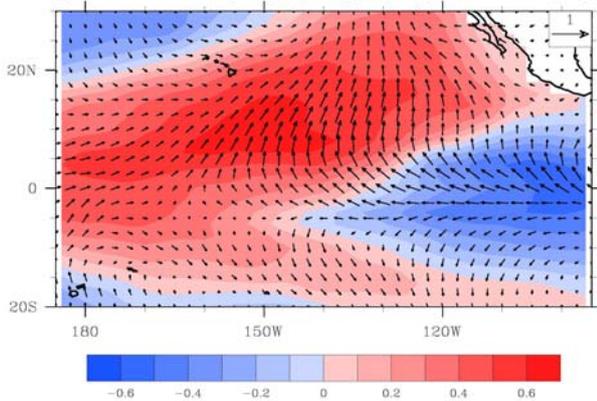


Figure 1: First SVD mode of SST and 10-m wind anomalies for Pacific Meridional Mode.

To identify the MM, a singular value decomposition (SVD; Bretherton *et al.*, 1992) analysis was applied to the cross-covariance matrix between surface wind and SST anomalies in the region 20°S-30°N and 175°E-95°W. Before applying the SVD analysis, we removed the regressions of the 10-m wind and SST anomalies with the cold tongue index (SST anomalies averaged over 6°S-6°N, 180°-90°W) to exclude the El Niño influence. The leading SVD mode shown in Figure 1 depicts the SST and surface wind anomaly patterns of the MM. The pattern is characterized by warm SST and southwesterly wind anomalies extending from the Baja California coast to the tropical central Pacific. The southwesterly wind anomalies represent a weakening of the climatological northeasterly trade winds in the northern subtropics, and are co-located with warm SST anomalies due to the reduced surface evaporation associated with the weaker trade winds. A pair of principal components (PCs) was also produced as part of the SVD analysis. The PCs represent the temporal variations of the MM-associated SST and surface wind anomalies and are referred to, respectively, as the SST and wind indices of the MM.

### 3. Result

Since the MM is a mode of coupled atmosphere-ocean variability, the MM intensity can be measured by the strength of the coupling between SST and surface wind anomalies. Slow variations in the MM coupling can be examined by calculating the correlation coefficients between the SST and wind indices of the MM in a window running from the beginning to the end

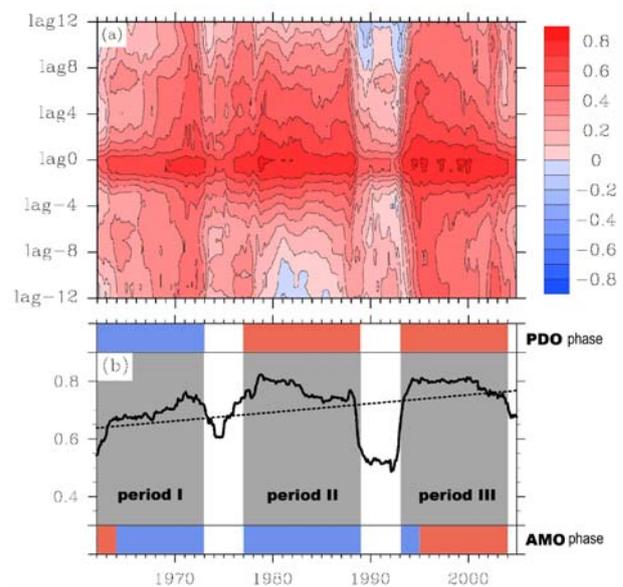


Figure 2: (a) 121 month running lead-lag correlation coefficient between MM SST index and MM wind index. Negative means wind lead SST. (b) The maximum correlation coefficient at any lag of (a) in every time step. The gray shading is used to emphasize the three different periods (1962-1972, 1977-1988 and 1993-2004). The shadings on the top and bottom are the positive/negative (red/blue) phases of the 12-year low pass filtered AMO and PDO, respectively.

of the analysis period. Figure 2a shows the result of such a running lead-lag correlation calculation with a 121-month moving window for the period 1962 to 2004.

This figure shows that the maximum correlation typically occurs when the surface wind index leads the SST index by about one month (i.e., at lag -1), which reflects the wind-induced nature of the SST variability associated with the MM. The maximum correlations decay gradually toward positive lags, which is related to the cross-seasonal nature of the MM coupling associated with the seasonal footprinting mechanism. The maximum correlation coefficients were also used to represent the coupling strength of the MM and display its temporal variations in Figure 2b. There is an increasing trend in the strength of the MM coupling, with the correlation increasing from about 0.64 in the 1960s to about 0.77 in the 2000s (indicated by the dashed line in Figure 2b). This implies that the extratropical influence on the tropical Pacific of the MM via the seasonal footprinting mechanism has increased over the past four decades, which can help explain the increasing occurrence of the CP El Niño. Another noticeable feature in Figure 2b is that the coupling strength dropped around 1976 and 1993 but rose afterward to stronger values. These two weaker “gaps” divide the years 1962-2004 into three periods: 1962-1972 (Period I), 1977-1988 (Period II), and 1993-2004 (Period III). The increasing trend of the MM coupling strength occurred in a step-wise manner, which started with a weak coupling during Period I, was elevated after the 1976 gap to a

stronger coupling during Period II, and was further intensified again after the 1993 gap to the strongest coupling during Period III.

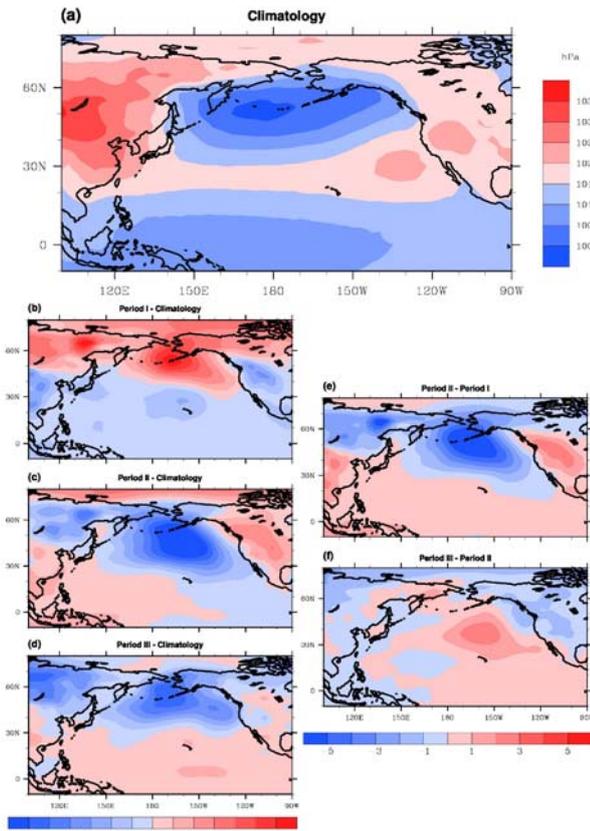


Figure 3: (a) The DJF climatology (1948-2010) of SLP. (b), (c) and (d) are the deviations from climatology for the three different periods (1962-1972, 1977-1988 and 1993-2004). (e) and (f) show the difference between two periods.

To understand the reasons why the MM coupling strength is different during these three periods, we show in Figure 3a the climatological SLP averaged in boreal winter (December-January-February; DJF), which is the season when the MM typically develops. The DJF climatology is dominated by an Aleutian Low over the North Pacific and a Pacific Subtropical High over the eastern subtropical Pacific. The winter mean SLP during each of the three periods was also calculated and their deviations from the climatology are shown in Figures 3b-d. The mean SLP in Period I is most different from the climatology in its weak intensity of the Aleutian Low (Figure 3b). In Period II, the intensity of the Aleutian Low increased significantly, becoming stronger than the climatology (Figure 3c). Therefore, the main difference between Periods II and I, as shown in Figure 3e, is an intensification of the Aleutian Low. It is notable that the Subtropical High was weaker than the climatology during both periods, which is indicated by the negative deviations in the subtropics shown in Figures 3b and 3c. During Period III, the Subtropical High strengthened as revealed in Figure 3d with the positive SLP deviations

centered around 25°N and 160°W. The Aleutian Low during this period was also somewhat stronger than the climatology but not very different than it was during Period II. Therefore, the main difference between Periods III and II, as shown in Figure 3f, was an intensification of the Pacific Subtropical High. The Subtropical High not only intensified but also expanded northward toward 40°N. The mean trade winds during Period III were also enhanced over the eastern subtropical Pacific (not shown). The stronger the background trade winds, the stronger the wind-evaporation-SST feedback [Xie and Philander, 1994], which explains why the MM coupling was strongest during Period III.

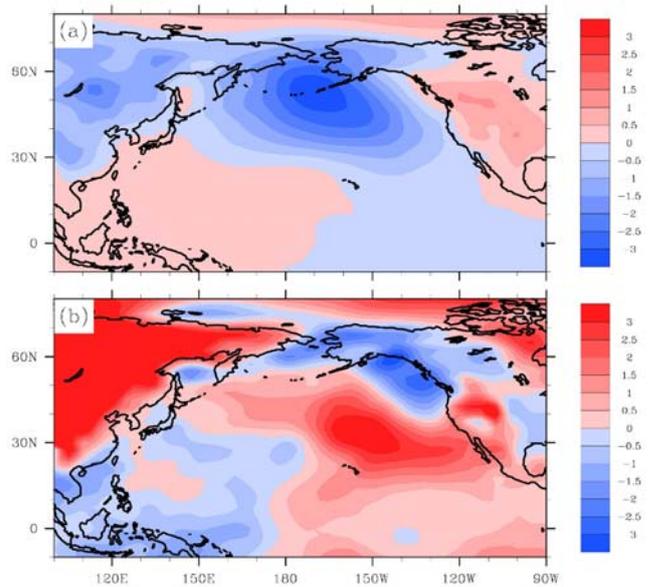


Figure 4: (a) SLP regressed onto the six-year low-pass filtered PDO index. (b) as in (a), but for the AMO index.

Our analyses have indicated that the decadal variations in the MM coupling strength were associated with an intensification of the Aleutian Low around 1976 and an intensification of the Subtropical High around 1993. What could be the causes for these decadal SLP changes? On decadal timescales, the Pacific Decadal Oscillation (PDO; Mantua *et al.*, 1997) and Atlantic Multidecadal Oscillation (AMO; Kerr, 2000; Enfield *et al.*, 2001) are two major modes of variability that are capable of influencing global climate. Here, we explore the possible connections between them and the decadal MM variations. Figure 4 shows the boreal winter SLP anomalies regressed onto the decadal components (6-year lowpass filtered) of the PDO and AMO. The largest regressions with the PDO (Figure 4a) occur over the Aleutian Low and have negative values, which indicates that the positive phase of the PDO is associated with an intensification of the Aleutian Low, and vice versa. As for the AMO, the regressed SLP anomalies are largest in the region of the Pacific Subtropical High near 30°-40°N and have positive values, which indicates that the positive phase of the AMO is associated with an

intensification of the Subtropical High. Figure 4, therefore, suggests that the PDO has a strong influence on the SLP variations within the Aleutian Low while the AMO has a strong influence on variations in the strength of the Subtropical High. It should be mentioned that a similar influence of the AMO on Pacific SLPs was uncovered in the modeling study of Zhang and Delworth [2007], although the positive SLP anomalies in their model appear at higher latitudes of the North Pacific.

We show the phases of the PDO and AMO in Figure 2 for Periods I, II, and III. It is clear from the figure that the PDO switches from a negative (blue) to a positive (red) phase sometime around 1976, which happens to be the year that separates Periods I and II of the decadal MM variations and also the time after which the Aleutian Low was intensified. As for the AMO, its phase switch occurred around 1995, which is close to the year 1993 that separates Periods II and II of the decadal MM variations. The AMO was in a negative phase throughout 1995, which according to Fig. 4b should be associated with a weaker-than-normal Subtropical High. During Period III, the AMO switched to a positive phase, which is consistent with the fact that the Subtropical High intensified during that period. Therefore, Figures 2 and 4 together suggest that decadal variations in the MM coupling strength during the past four decades are a result of the changing and joint influences of the PDO and AMO.

#### 4. Conclusion

In this study, we have examined the decadal variations in the MM with a specific focus on changes in its atmosphere-ocean coupling strength. We show that the MM coupling strength has increased during the past four decades. The enhancement of the coupling occurred in a step-wise manner with two distinct steps. The coupling strength was first increased around 1976 when the PDO switched from a negative to positive phase and the Aleutian Low intensified. The intensified low can displace the tropospheric jetstream equatorward and intensify the extratropical influence on the subtropical Pacific Ocean to enhance the MM. The second increase in MM coupling strength occurred around the early-to-middle 1990s when the AMO switched from a negative to positive phase and intensified the Pacific Subtropical High. The intensified high elevated the MM coupling strength to its strongest level in the past four decades, which is consistent with the increased occurrence of the CP El Niño observed since 1990 (*Yu et al.*, 2012).

Since it is known that El Niño was mostly dominated by the EP type before 1970 and by the CP type after the 1990s (e.g., *Yu and Kim*, 2012), our results suggest that the change in the El Niño type can be linked to combined phases of the PDO and AMO. El Niño is likely to be predominately of the EP type during periods when these two decadal oscillations are both in their negative phases (such as Period I), but predominantly of the CP type when both the oscillations are in their

positive phases (such as Period III). Thus, the selection of the El Niño type is determined not only by mean state changes within the Pacific but also by state changes in the Atlantic.

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