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Examination of PDO-ENSO Adjustment Impact in the Maritime Continent

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Abstract

The precipitation regime in the Maritime continent is largely driven by changes in sea surface temperature (SST) in the Pacific and Indian Oceans. The SST anomalies induced by the cycles of Pacific Decadal Oscillation (PDO) and El Niño–Southern Oscillation (ENSO) have a large impact on precipitation regime in the Maritime Continent. Based on long-term observational datasets, this study demonstrates that in-phase occurrence of ENSO and PDO creates a statistically different pattern of precipitation and SST anomalies compared to ENSO cycle accompanied by neutral PDO. The results show that in-phase positive events produce weaker dry anomalies, especially in SON when the amount of precipitation increases by 5-12% of the seasonal norm. In-phase negative events produce stronger dry anomalies in JJA and SON with the amount of precipitation increasing by 3-12% of the seasonal norm relative to ENSO event with neutral PDO. The ENSO-PDO modulation effect leads to rapid changes in precipitation regime in the Maritime continent associated with PDO phase change. Understanding the role of the PDO cycle in the precipitation regime can improve estimates of precipitation trends and lead to better climate change projections.

Keywords: Post gastric bypass hypoglycemia; Late-dumping; Glp-1 receptor expression; 68Ga-dota-exendin-4; Glp-1 receptor imaging

Introduction

The Maritime Continent is a region of Southeast Asia consisting of thousands of islands, including Indonesia, the Philippines, Papua, and Malaysia. The Maritime Continent is located within the Indo-Pacific warm pool, a region characterized by high sea surface temperatures (SST) exceeding 28°C. The meteorological regime of the Maritime Continent is dominated by coastal land-sea interactions, with the diurnal cycle being dominant both in the rainy and dry seasons [1]. SSTs play a crucial role in governing precipitation and dry-wet anomalies in the Maritime Continent. SST anomalies, in turn, are driven by large-scale oceanic oscillations: The Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO) (Figure 1).

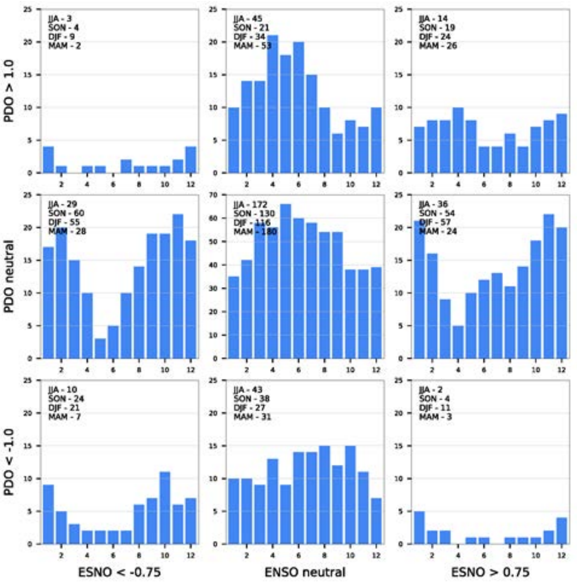

Figure1: The number of months with a specific ENSO/PDO phase combination per month.

The precipitation regime of the Maritime Continent is characterized by high internal and decadal variability. A large part of the internal variability is explained by ENSO. During the positive (warm) phase of ENSO, the cooler SST in the Maritime Continent suppresses rainfall and leads to drier conditions. During the negative (cold) ENSO phase, the Maritime Continent, on average, experiences an increase in precipitation. However, the effect depends on location, especially during the rainy season. Increased precipitation intensity during the negative ENSO phase causes more floods and landslides in many regions of the Maritime Continent [2].

Another major factor affecting the climate regime in the Maritime Continent is the decadal oscillation in the Pacific Ocean commonly quantified by the Pacific Decadal Oscillation (PDO) index or Inter decadal Pacific Oscillation (IPO) index.This oscillation is characterized by a reoccurring large-scale SST anomaly in the mid-latitude Pacific. The PDO index is defined as the leading Empirical Orthogonal Function (EOF) amplitude of SST anomalies in the Pacific north of 20°N. The IPO was initially defined as the second EOF of SST in the Pacific Ocean, or in later studies as the first EOF of defriended low-pass filtered SST over 50°S-50°N, 100°E-70°W. The IPO is symmetrical around the equator and usually considered to be a long-period component of ENSO, while the PDO demonstrates more independent behavior and has a known physical connection to ENSO via an atmospheric bridge and oceanic coastally trapped waves [3].

Historical data for both PDO and IPO show alternating cold and warm periods, each with duration of 20 to 30 years with similar phase changes in 1945, 1976/7, and 1998/9. The PDO cold/warm phases have a significant impact on climate variables globally, such as air temperature, SST,

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and tropical cyclone activity. The PDO phase change of 1976 has led to several significant environmental impacts that are well documented in the scientific literature as summarized by [4-6]. For example, rapid changes in Pacific Ocean SST have resulted in dramatic changes in Alaskan salmon production and anchovy and sardine populations in the Pacific Ocean. While the regime shift of 1976 is the most studied one, studies point to similar changes in ocean ecosystems after other PDO shifts in 1925, 1947, and 1998. Similarly, the IPO has been shown to modulate interannual ENSO-related climate variability over Australia. Our recently published article provides statistical evidence of the PDO phase change of 1976 being the mechanism behind the found precipitation regime shift change in the northern hemispheric part of the Maritime Continent, resulting in an increased number of dry days.

On a global scale, the PDO magnifies the wet-dry anomalies caused by ENSO when their phases align, whereas the effect is much smaller when the PDO and ENSO are in counter-phase. Multiple studies demonstrate that the PDO can have a modulating effect on teleconnections in many parts of the world, such as North America, South America, and Australia [7]. In East Asia, the PDO modulation effect has been shown to affect the East Asian winter monsoon and tropical cyclone rapid intensification. The purpose of the present study is to determine the influence of phase combinations of the ENSO and PDO on the precipitation regime and SST anomalies in the Marine Continent using multiple long-term observational datasets. Specifically, it is investigated to what extent the PDO phase modulation of ENSO can explain the observed precipitation regime shift of 1976.

Methods and Data

To isolate the effect of the PDO on ENSO precipitation and SST anomalies in the Maritime Continent, we compare the anomalies for ENSO and PDO in-phase events with the anomalies for ENSO and neutral PDO phase events. An extended period of observations is necessary to compare the effect of ENSO in different PDO phases because all data must cover at least one cold and one warm PDO phase. Historical monthly data (1901-2018) for ENSO (Nino-3.4) and PDO were obtained from the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer. To minimize the influence of climate change in the ENSO data, we use the relative Nino 3.4, where the average SST for 20S-20N is subtracted to remove the climate change signal [8].We separate historical precipitation data into months associated with different phase combinations of ENSO and PDO. All months in 1901-2018 are assigned qualitative values of ENSO and PDO indices: positive, negative, or neutral. The threshold values separating neutral values from positive or negative ones are defined as the 68th percentile of the absolute values of the index [9]. For ENSO, the threshold values are ±0.75 °C, the values between -0.75 °C and +0.75°C are considered as neutral. For PDO, the threshold is index values above or below ±1 the PDO index is unitless.We distinguish nine phase combinations – positive ENSO and positive PDO, positive ENSO and neutral PDO, etc. For convenience, we refer to the phase combinations where ENSO and PDO are both positive/negative as an in-phase positive/negative event to distinguish from an ENSO positive/negative event accompanied by neutral PDO conditions [10] (Figure 2).

For each phase combination, we calculate the mean values of the anomalies of seasonal precipitation. In order to simplify the analysis, precipitation anomalies are expressed as a percentage from the monthly mean.For precipitation, we use monthly total values from the CRU TS4 dataset – a gridded observations-based time-series dataset with 0.5 resolution maintained by the UK National Centre for Atmospheric Science.This dataset is chosen because of the long period of available observations, namely 1901-2018. A dataset is required to stretch back to at least two phases to the 1976 regime shift, ideally to the beginning of the 20th century, to include two cold and warm phases [11].

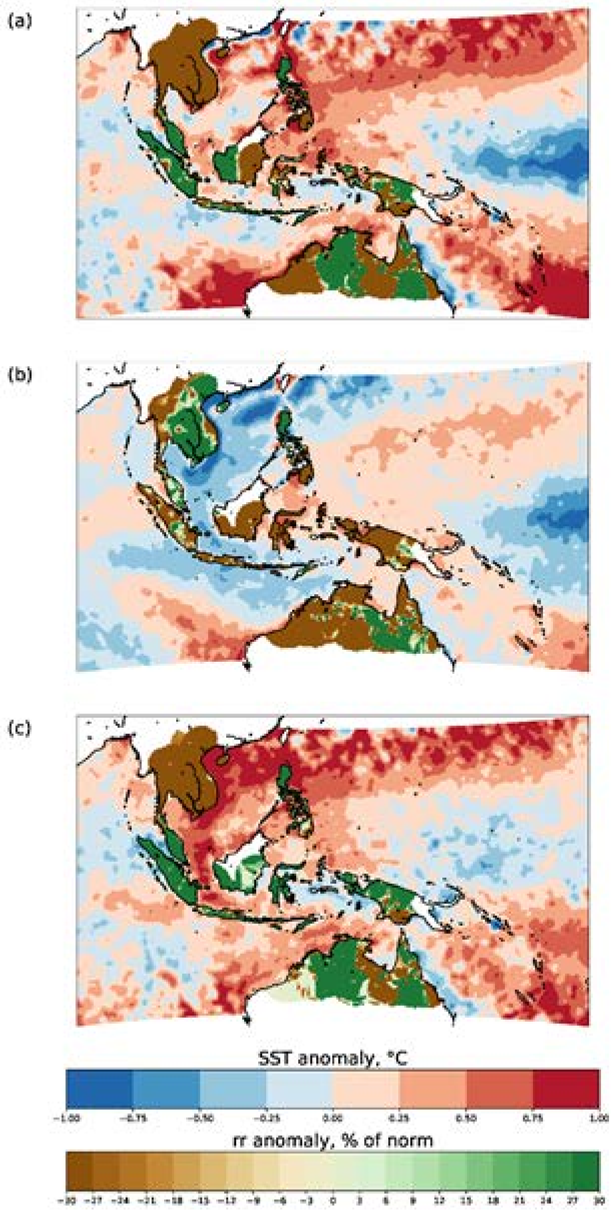

Figure 2: Difference between in-phase negative ENSO and typical ENSO events during MAM data from high-resolution dataset 1981-2017. Maps show seasonal precipitation anomalies expressed as a percentage of the seasonal mean (shown over land) and seasonal SST anomalies in C (shown over the sea) calculated from the long-period datasets for ENSO negative months (Nino 3.4 < -0.75) for (a) – MAM, negative PDO (PDO >1); (b) MAM, neutral PDO; (c) difference.

In addition, we calculate SST anomalies to investigate the mechanisms behind the precipitation anomalies. Daily SST data are obtained from the NOAA Extended Reconstructed Sea Surface Temperature (ERSST. v5) at 2 resolution and temporal coverage from 1881 to 2020. While reconstructed SST datasets such as ERSST.v5 suffer from high uncertainties, especially before the satellite era, no alternative offers a perspective into long-term climatological changes. While we are not focusing specifically on analyzing changes in SSTs, investigating these changes helps to verify the significance of precipitation anomalies and improves our understanding of the underlying processes.

The precipitation and SST anomalies for each of the nine ENSO/PDO phase combinations are calculated using the following procedure. The monthly precipitation and SST anomalies are calculated for a 1901-2018 monthly climatology. Then the data are split into nine discontinuous data series, one for each specific ENSO/PDO phase combination. The resulting dataset is further aggregated into seasons – DJF (December-February), MAM (March-May), JJA (June-August), SON (September-November).Mean values and standard deviations are calculated for each series. The result is a mean anomaly field for precipitation and SST for each of the nine combinations of ENSO and PDO values for each of the four seasons (Table 1).

Due to limited resolution, long-period datasets do not allow for meaningful regional-level analysis. To analyze regional level effects, we reproduce the analysis described above using daily high-resolution datasets NOAA OISST v2 for SST and SACA&D for precipitation. These high-resolution datasets only cover the period from 1981 to 2017, but the much shorter temporal resolution is compensated by improved spatial resolution 0.5° for SST and 0.25° for precipitation [12].

		JJA	**SON**	**DJF**	**MAM**
Positive ENSO	Brunei	2.07(13.71)*	-6.94(3.25)*	-25.84(2.09)*	-18.31(-4.29)*
	Indonesia	-18.20(-2.18)*	-7.67(5.55)	-3.03(-2.86)	-1.58(1.61)
	Malaysia	-1.82(7.83)	-3.17(-4.68)	-14.24(-2.90)*	-15.77(-4.53)
	Philippines	-0.22(-2.93)	-13.26(5.91)	-17.31(12.16)	-38.43(-16.12)
	Papua New Guinea	-8.23(-0.66)*	-2.71(12.40)	1.28(0.89)*	-4.37(-1.49)*
	Timor-Leste	37.53(48.61)	1.46(12.70)	-3.81(1.88)*	-0.02(2.48)*
	Whole MC	-12.44(-0.56)*	-6.96(5.58)	-5.20(-0.60)*	-7.69(-1.52)
	MC, NH only	-2.34(4.36)	-5.65(1.01)*	-12.79(0.69)*	-18.66(-5.69)
	MC, SH only	-18.53(-3.53)	-7.75(8.33)	-0.65(-1.37)	-1.07(0.99)
	Australia(Lat > -25°)	-30.17(-17.59)	-6.10(11.51)	-5.45(3.05)	12.90(18.51)
	Laos	1.40(4.20)	-19.65(-8.05)	23.79(24.36)	-22.31(-20.18)
	Cambodia	-3.66(-2.49)	-8.49(2.58)	22.61(32.34)	-17.51(-13.30)
	Thailand	-6.17(-3.53)	-11.37(1.01)*	13.95(32.74)	-26.08(-22.32)
	Vietnam	-1.40(-0.04)*	-11.13(-5.74)	3.56(-4.51)	-12.90(-18.77)
		JJA	**SON**	**DJF**	**MAM**
Negative ENSO	Brunei	13.91(-0.35)*	8.88(2.34)*	35.44(6.87)*	10.46(-5.91)*
	Indonesia	13.37(5.62)	15.88(5.36)	0.97(-1.75)	-0.59(-4.38)
	Malaysia	10.63(-2.61)*	2.78(1.95)*	19.80(1.90)*	11.42(-1.79)*
	Philippines	-0.23(5.41)	13.15(0.85)*	20.45(-9.03)	33.61(31.64)
	Papua New Guinea	11.29(12.32)	9.10(1.81)*	0.58(0.45)*	3.27(-0.52)*
	Timor-Leste	-40.23(-2.88)*	13.20(-16.92)	-2.97(-5.18)	-23.39(-39.57)
	Whole MC	10.89(5.68)	13.05(3.78)	5.15(-1.80)	5.00(0.27)*
	MC, NH only	8.28(2.58)	6.05(0.63)*	15.39(-1.98)*	15.64(8.92)
	MC, SH only	12.46(7.54)	17.26(5.67)	-0.98(-1.69)	-1.41(-4.94)
	Australia (Lat > -25°)	13.84(10.87)	41.93(28.59)	26.62(16.70)	19.86(-15.92)
	Laos	19.80(19.19)	6.32(6.90)	-18.42(-20.58)	-4.51(11.48)
	Cambodia	7.36(8.01)	12.47(13.47)	-15.36(-24.07)	-5.53(7.67)
	Thailand	19.31(11.64)	6.82(6.58)	-25.10(-38.63)	3.80(20.97)
	Vietnam	1.37(-0.47)*	2.69(2.69)	-5.32(0.11)*	-13.35(11.34)

Table 1: Precipitation anomalies during ENSO-PDO in-phase events as a percentage of the seasonal mean. In brackets – the difference from typical ENSO events. * - the difference is not significant on 1% level according to the t-test.

Statistically significant differences between mean values of different ENSO-PDO phase combinations are verified using Welch's unequal variances t-test. This test is an adaptation of the Student's t-test that is more robust when samples have unequal sizes or variability. The t-statistics with p-values below 0.01 are considered to be statistically significant. As there is not enough data to calculate meaningful statistics per every cell, we evaluate statistical significance on a country level as a workaround.

Results

Long period data

The number of occurrences of each of the nine ENSO/PDO phase combinations in 1901-2018 for each calendar month and season. Of the nine phase combinations, the most common combination is neutral, occurring in 47% of the months from 1901-2018. Precipitation and SST anomalies in these neutral situations are close to average (i.e., zero). This is to be expected: both because of their prevalence and because neutral ENSO and PDO are states with minor SSTs anomalies by definition.The non-neutral ENSO most commonly occurs from October to February. However, in-phase positive events are distributed much more evenly over the year than the rest of ENSO positive events [13].

High resolution data

For the recent period 1981-2018, we have access to high-resolution data of both SST and precipitation. However, this period contains only one incomplete PDO cycle. Both PDO and IPO indexes identify a phase change in 1998 (IPO) and 1999 (PDO), which allows us to perform the analysis presented in the previous section but with high-resolution datasets. The number of days for each of the phase combinations is presented. The figure shows that the frequency of occurrence of each of the nine-ENSO/PDO phase combinations for 1981-2018 is similar to that of the long period dataset [14].

By switching to a shorter period dataset, we are sacrificing the option to analyze the average of multiple PDO cycles, but we gain many spatial details. Results from high- resolution dataset generally confirm patterns from the long-period dataset for the seasons and phase combinations with a sufficient amount of data. During in-phase positive ENSO, SON and JJA demonstrate the same general patterns as in the long-period dataset: SST is warmer during in-phase events, and dry anomalies are weaker, especially during SON. High-resolution data clearly shows the difference between the Southern and Northern hemispheres, and an equatorial line is visible in the precipitation anomalies. But the primary reaction to in-phase events is similar for both hemispheres [15].

SST anomalies are stronger during in-phase negative events than typical ENSO negative events, which match the result from the long-period dataset. Precipitation anomalies, however, often show large differences and even opposite signs compared to results from the long-period dataset. Due to the lower natural variability of SST, a small amount of data is enough to produce the same patterns observed in the long-period dataset. For precipitation, however, the natural variability is much higher, and 30-300 days of data is not enough to calculate the average [16] (Figure 3).

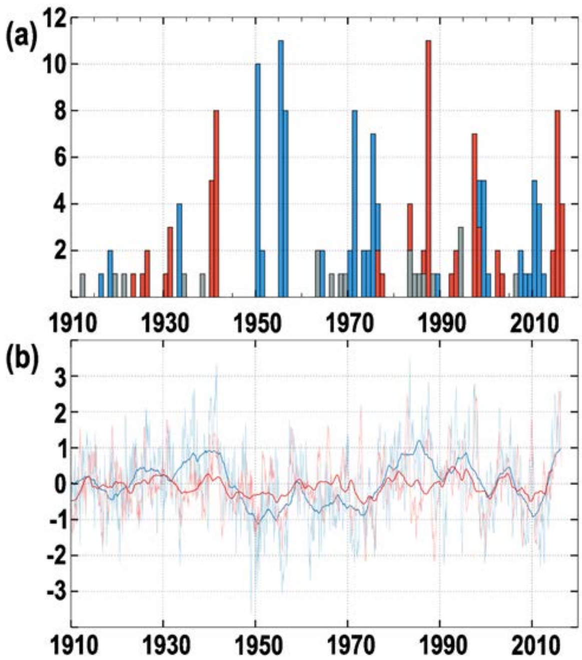

Figure 3: (a) Number of months classified as in-phase positive (Nino 3.4 > 0.75 and PDO > 1) in red, in-phase negative (E Nino 3.4 <- 0.75 and PDO < -1) in blue, counterphase ((Nino 3.4 > 0.75 and PDO < -1) or (Nino 3.4 < -0.75 and PDO > 1)) in grey; (b) – PDO historical monthly data in blue, ENSO historical data in red, bold lines represent 5 years running mean.

Discussion

This study contributes to a growing amount of evidence demonstrating the impact of PDO/ENSO interactions on the global climate by filling in details for the Maritime Continent. The PDO cycle appears to impact the rate of global near-surface temperature increase through changes in ocean heat uptake and vertical redistribution of ocean heat content. The influence of the PDO helps to explain the so-called global warming hiatus. Warm PDO phases from 1925 to 1947 and 1976 to 1998 correspond to periods with a rapid increase in global temperature, while cold PDO phases correspond to periods with relatively stable global temperatures [17].

The impact of the PDO cycle on global climate and the precipitation regime in the Maritime Continent has important implications for climate predictions on a 20 to 30year timescale. Based on an expected PDO cycle length of 20-30 years, we can expect the next phase to change from negative to positive between 2020 and 2030. The current data suggest that this change might already have happened, but we need more data to confirm this. The new regime, associated with the positive PDO phase, will increase the frequency of in-phase positive events and reduce the frequency of in-phase negative events. In recent history, long-lasting in-phase positive conditions were observed in 1987, 1997, and 2016 three years associated with strong precipitation and temperature anomalies, both positive and negative, as well as dramatic economic impacts from floods and droughts.

A previous study of the influence of PDO-ENSO modulation on global wet-dry anomalies suggests that on a global scale, in-phase events intensify typical wet-dry anomalies associated with ENSO. However, our study demonstrates that precipitation on the scale of the Maritime Continent does not always follow this simple pattern. The analysis of long-period datasets reveals that impacts of in-phase events on precipitation and SST anomalies in the Maritime Continent often lead to the weakening of precipitation anomalies in contrast to the global pattern. Analysis of a high-resolution dataset exposes the spatial and seasonal complexity of the impacts of the in-phase event. While some patterns are present in both the long-period and the high-resolution dataset, as well as earlier publication, a lot of regional details are different. The high spatial resolution dataset uses daily observations to delineate different phase combinations more precisely, making differences between different phase combinations more noticeable. Unfortunately, the temporal coverage of the data available in high resolution is not sufficient. It is difficult to conclude which different details are related to the higher quality of the dataset and which are just statistical anomalies caused by insufficient temporal coverage [18].

Conclusion

We have shown that the PDO phase significantly impacts ENSO-related precipitation and SST anomalies in the Maritime Continent in 1901-2018. In-phase ENSO/PDO events produce a distinct pattern of precipitation anomalies compared to typical ENSO events. In contrast to global patterns presented by, in-phase positive ENSO events weaken dry anomalies in the Maritime Continent. Conversely, in-phase negative ENSO demonstrates stronger wet anomalies compared to typical ENSO, which agrees with global patterns.

In most Maritime Continent, both positive and negative in-phase events produce wetter conditions in JJA and SON than typical ENSO/PDO-neutral events. However, during DJF, both in-phase positive and negative events produce small or statistically insignificant precipitation anomalies throughout the Maritime Continent except in the Philippines.

The SST is 0.25 C to 0.75C warmer during in-phase positive events, while in-phase negative has a ±0.25°C difference with typical ENSO events.

High-resolution data reveal the full extent of spatial and season complexity of the ENSO-PDO modulation effect. The sharp contrast in precipitation anomalies around the equator is visible, but the differences between in-phase and typical events are usually more spatially coherent. High-resolution SST data show a complex pattern of local bathymetry and ocean currents that can help explain some of the regional differences in precipitation.

The analyzed in-phase negative events mainly occur during cold PDO phases, and the in-phase positive events occur exclusively during warm PDO phases. The domination of in-phase positive events during warm PDO phases produces a precipitation regime significantly different from that observed during the PDO cold phase. We observe more precipitation during both in-phase positive and negative events, leading to weaker dry anomalies and stronger wet anomalies. Increase in precipitation leads to stronger anomalies during the negative PDO phase since both ENSO positive and negative anomalies are stronger than the in-phase positive ENSO. This effect is consistent with the results presented. We demonstrate evidence of a shift around 1976 to fewer dry days in the Maritime Continent after the PDO phase changing from negative to positive. Although this is a very general pattern and for some regions, our results demonstrate different behavior, we conclude that overall, the regional results for different seasons and nine ENSO/PDO phase combinations are robust.

The source code used to produce the results and additional materials not included in this publication is available on GitHub (https://github.com/kokorev/ENSO-PDO_modulation).

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