On the relationship between the Pacific Decadal Oscillation and monsoon depressions over the Bay of Bengal

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This study investigates the relationship between inter-decadal variation in the number of monsoon depressions (MDs) over the Bay of Bengal (BoB) and the Pacific Decadal Oscillation (PDO). It is shown that there is an out-of-phase variation in the number of MDs over the BoB and the PDO, except during 1927–1945. Quantitative estimates of the relative contributions of individual environmental parameters show that the variation in the mid-tropospheric relative humidity over the BoB is the primary reason for the observed variation in the number of MDs. It is further postulated that the variation in the sea surface temperature in the western equatorial Indian Ocean associated with the PDO could be one of the reasons for the changes in the moisture advection over to the BoB and hence the variation in the number of MDs in inter-decadal timescale.

KEYWORDS
decadal variability, genesis potential index, Indian Ocean warming, monsoon depressions, Pacific Decadal Oscillation

1  INTRODUCTION

Pacific Decadal Oscillation (PDO), which is often described as long-lived El Niño like pattern in the tropical Pacific, is one of the dominant modes of climate variability in the North Pacific Ocean (Tanimoto et al., 1993; Mantua et al., 1997; Zhang et al., 1997; Mantua and Hare, 2002). Positive (negative) phases of the PDO are associated with warming (cooling) of the tropical Pacific Ocean (Mantua et al., 1997).

It is well known that the PDO modulates climate variability in various parts of the globe. For example, the temporal and spatial variance in multi-decadal drought frequency in the United States (McCabe et al., 2004) and the summer monsoon rainfall in south China (Chan and Zhou, 2005) are influenced by the PDO. Positive (negative) phases of the PDO are associated with the deficit (excess) Indian summer monsoon rainfall (ISMR) and they enhance (suppress) the teleconnection between ISMR and El Niño Southern Oscillation (ENSO; Krishnan and Sugi, 2003; Krishnamurthy and Krishnamurthy, 2013). Lupo and Johnston (2000) had suggested that the difference in the frequency of Atlantic cyclones between El Niño (fewer tropical cyclone) and La Niña (more tropical cyclone) years shows a decadal variability, which is related to the decadal variability in the Pacific Ocean. The frequency of tropical cyclones over the western North Pacific also shows a decadal variability associated with the PDO (Lee et al., 2012; Wang et al., 2015). It was also shown that the number of tropical cyclones over the Pacific, which undergo rapid intensification, is less (high) in the warm (cold) phases of the PDO (Wang et al., 2015).

Recently, Girishkumar et al. (2015a) had shown that the impact of ENSO on tropical cyclones over the BoB is significant only in the warm phase of the PDO.

It is well known that along with the northwards propagation of Intertropical Convergence Zone, the westwards propagations of synoptic-scale systems also significantly...
contribute to the total rainfall in India during the summer monsoon season (Yoon and Chen, 2005; Hurley and Boos, 2015; Vishnu et al., 2016). Synoptic-scale systems in the northern Indian Ocean during the summer monsoon season generally do not grow into cyclones due to unfavorable environmental conditions (Sikka, 1977). Hence, they are called as monsoon depressions (MDs), with two or three closed isobars at 2 hPa interval in the synoptic chart and wind speed 8.5–16.5 m/s at sea (Ajayamohan et al., 2010; India Meteorological Department, 2011). MDs which form over the Bay of Bengal (BoB) move westwards or northwesterly (Boos et al., 2015; Hunt and Parker, 2016; Boos et al., 2017) onto the Indian subcontinent and are associated with significant amount of rainfall (sometimes up to 300–400 mm) along its track (Sikka, 1977).

Some recent studies have reported that there are differences in the trend in the number of MDs extracted from the reanalysis data sets and traditional India Meteorological Department (IMD) data set (Cohen and Boos, 2014; Hunt et al., 2016). At the same time, Praveen et al. (2015) have shown that the number of low-pressure systems extracted from the reanalysis data, using conventional detection algorithm based on the closed isobars in the surface pressure field, is well matched with traditional IMD data set. Nevertheless, many studies did report that there is a decreasing trend in the number of MDs in the recent decades (Mandke and Bhide, 2003; Prageesh et al., 2013; Vishnu et al., 2016). Recently, Kumar and Dash (2001) had reported that there is a decadal variability in the number of MDs with a decreasing trend in the number of MDs in recent decades. A few studies have also shown that there are links between the variation on the relationship between the frequency of MDs and the sea surface temperature (SST) in BoB in decadal time scales (Rajeevan et al., 2000; Mandke and Bhide, 2003; Jadhav and Munot, 2009). Recently, Vishnu et al. (2016) found that the decreasing trend in the frequency of MDs over the BoB is mainly due to an epochal shift with less number of MDs in the recent epoch (1981–2010) compared to the earlier epoch (1951–1980).

In the recent years, there were some attempts to study the influence of ENSO on the monsoon disturbances (Krishnamurthy and Ajayamohan, 2010; Hunt et al., 2016). Even though these studies did not report any strong links between the ENSO and the frequency of monsoon disturbance (Krishnamurthy and Ajayamohan, 2010), monsoon disturbances are found to be stronger during the La Niña years (Hunt et al., 2016). On the other hand, the links between the PDO and MDs are yet to be explored. Because there are sufficient evidences suggesting that the intensity and frequency of the tropical cyclones are affected by the PDO and many MDs are directly or indirectly linked to the typhoons over the Pacific Ocean (Saha et al., 1981), we explore the possible links between the variation in the number of MDs in the decadal timescale and the PDO in this paper.

### DATA AND METHODS

The details of MDs over the BoB are taken from the website of IMD (http://www.rmcchennaiatlas.tn.nic.in, India Meteorological Department, 2011). Recently, Praveen et al. (2015) have derived the information on low-pressure systems from multiple reanalysis data sets using conventional detection algorithm based on the closed isobars in the surface pressure field. They showed that the newly derived data set matches very well with the data set on low-pressure systems prepared by a careful examination of the IMD surface pressure charts. Furthermore, because the IMD data are available for a longer period, this data set is more appropriate for analyzing the long-term (decadal time scale) variability in the number of MDs. PDO index used in this study is obtained from the Joint Institute for the Study of Atmosphere and Oceans (JISAO) at the University of Washington (http://jisao.washington.edu/the PDO/ the PDO/latest). The index of the PDO is defined as the first empirical orthogonal function (EOF) of SST anomalies in the extra-tropical northern Pacific Ocean (above 20°N) (Mantua et al., 1997). Monthly mean SST used in this study is taken from the Hadley Centre Global Sea Ice and Sea Surface Temperature version 2 (HadISST2) (Rayner et al., 2003). Monthly mean profiles of atmospheric temperature, horizontal wind, specific humidity, relative humidity and sea level pressure are used from various reanalysis data sets. Details of these reanalysis data sets are given in Table 1.

In order to understand the relative contributions of different environmental conditions to the variations in the frequency of MDs, we make use of genesis potential index (GPI) (Emanuel and Nolan, 2004), which is an empirical index to quantify the influence of environmental parameters associated with the genesis of synoptic-scale systems. Following Emanuel and Nolan (2004) and Li et al. (2013), the expression for GPI is

\[
\delta\text{GPI} = \alpha_1 \times \delta \left( \frac{H}{50} \right)^3 + \alpha_2 \times \delta \left| \frac{\bar{\nabla} \cdot \bar{v}}{H} \right|^2 + \alpha_3 \times \delta \left( 1 + 0.1 \frac{V_{\text{shear}}}{V_{\text{pot}}} \right)^2 + \alpha_4 \times \delta \left( \frac{V_{\text{pot}}}{70} \right)^3,
\]

where

| Data set   | Resolution | Period of record | Source                        |
|------------|------------|------------------|-------------------------------|
| ERA20      | 1 × 1°     | 1945–2010        | http://apps.ecmwf.int/datasets/data/era20cm-edmm |
| NCEP       | 2.5 × 2.5° | 1951–2010        | Kalnay et al. (1996)          |
| JRA55      | 2.5 × 2.5° | 1958–2014        | Ebita et al. (2011)           |
| ERA40      | 2.5 × 2.5° | 1958–2001        | Uppala et al. (2005)          |
| ERA-Interim| 0.7 × 0.7° | 1979–2013        | Dee et al. (2011)             |
\[
\alpha_1 = \frac{10^3 \eta^2}{(1 + 0.1 V_{\text{shear}})^2} \times \left(\frac{V_{\text{pot}}}{70}\right)^3,
\]
\[
\alpha_2 = \frac{H_{50}^3}{50} \times \frac{(1 + 0.1 V_{\text{shear}})^2}{V_{\text{pot}}^{1/3}} \times \left(\frac{V_{\text{pot}}}{70}\right)^3,
\]
\[
\alpha_3 = \frac{H_{50}^3}{50} \times 10^3 \eta^2 \times \left(\frac{V_{\text{pot}}}{70}\right)^3.
\]
\[
\alpha_4 = \frac{H_{50}^3}{50} \times 10^3 \eta^2 \times (1 + 0.1 V_{\text{shear}})^{-2},
\]

where \(H\) is the relative humidity (\%) at 600 hPa, \(\eta\) is the absolute vorticity at 850 hPa (s\(^{-1}\)), \(V_{\text{shear}}\) is the magnitude of the vertical wind shear (m/s) between 850 and 200 hPa and \(V_{\text{pot}}\) is the maximum tropical cyclone potential intensity (PI) (m/s).

In the above expressions, the horizontal bar indicates summer monsoon seasonal climatology and \(\delta\) represents seasonal anomaly of the individual parameter. While the GPI is generally used to study the relative influence of different environmental parameters in the genesis and intensification of tropical cyclones (Camargo et al., 2007; Li et al., 2013; Girishkumar et al., 2015b), Vishnu et al. (2016) have shown that the spatio-temporal variation in the GPI is in good agreement with the frequency of MDs and hence GPI is a good tool to study the role of different environmental parameters in the variation in the frequency of MDs also. We also used an alternative index for the genesis of MD proposed by Ditchek et al. (2016) to reconfirm the results obtained from the GPI analysis.

As the data sets used in this study have different data durations and contains multiple warm and cold phases of the PDO, individual terms of Equation (1) are regressed onto the PDO index to analyse the variations associated with the PDO in each of the parameters rather than computing the differences in the individual terms between warm and cold phases of the PDO. However, the regression analysis and the difference between warm and cold phases of the PDO show similar results (figures not shown). We computed the relative contribution of each terms in the right-hand side of the Equation (1) on the regression of the GPI (left-hand side of the equation). Statistical significances of the regression coefficients are determined by Student’s t test. This study is focused on the Indian summer monsoon season (June–September) and hence the inter-decadal variability is obtained from 9-year running averages of total values during the summer monsoon season. It may be noted that there is no significant difference between the results obtained using seasonal the PDO index and annual the PDO index (figures not shown).

3 | RESULTS AND DISCUSSIONS

3.1 | Relation between the PDO and MD

A time series of the index of the PDO shows that during the period 1901–2011, there were three warm spells (positive) (viz. 1905–1915, W1; 1927–1945, W2; and 1977–2001, W3) and three cold spells (negative) (viz. 1916–1926, C1; 1946–1976, C2; and 2002–2011, C3) in the PDO (Figure 1). Amplitude of W1 and C1 were smaller compared to the other warm and cold spells in the PDO. If we consider the period 1901–2011, the correlation coefficient between the PDO and the number of MDs over the BoB is −0.26 (\(p = .007\)). The out-of-phase relationship between the number of MDs and the PDO are clearly seen throughout the period except in the warm phase W2 (Figure 1). Chowdary et al. (2012) had reported that there were considerable gaps in the ocean/atm observations in this period, and it is possible that the ocean data in this period may not be representing the variability accurately. If we exclude the period W2 and compute the correlation between the index of the PDO and number of MDs, the correlation coefficient is significantly high (\(r = –0.62, p < .001\)). Hence, we restrict our analysis to the period 1946–2011 only. It may also be noted that in general the number of MDs have been decreasing during last several decades irrespective of the phase of the PDO.

Vishnu et al. (2016) had shown that this decreasing trend is mainly associated with anomalous warming of the western equatorial Indian Ocean (WEIO). However, if we remove this long-term decreasing trend in the number of MDs, there are clear episodes of higher/lesser number of MDs (Figure S1.1, Supporting Information). It may be noted that the detrended data of number MD clearly shows an out-of-phase relationship between the number of MDs and the PDO index (Figure S1.1). As the decadal variation of the PDO and the number of MDs over the BoB are strongly anti-correlated, it is important to understand the reasons behind this relationship.

It is well known that favorable low-level cyclonic vorticity, high mid-tropospheric relative humidity and suitable local SST are the necessary conditions for the genesis and intensification of MDs (Sikka, 1977). Therefore, an assessment of the variation in these environmental parameters associated with the PDO will give more insight into the observed MD–the PDO relationship. Regression of GPI onto the PDO index shows that the phases of the PDO and the GPI over the head BoB, where maximum number of MD genesis/intensification occurs are negatively correlated (Figure 2). While this relation is consistent across all the reanalysis data sets, in the ERA-40 data set, this significant relationship is slightly shifted westwards to the region where MDs generally cross over to the land.

In order to assess relative contributions of each of the environmental parameters on the PDO–MD relationship, regression of individual terms in the GPI equation (Equation (1)) onto the PDO are examined separately (Figure 2). Relative contribution (in percentage of total change in the GPI) averaged over the head of the BoB (15°–22.5°N, 80°–90°E) of each of the individual terms on the regression of GPI onto the PDO index are also given in Figure 3. It is clearly seen from the regression analysis that
the most dominant factor that influenced the out-of-phase relationship between number of MDs and the PDO index is the variation in the mid-level relative humidity over the BoB in all reanalysis data sets. However, the contribution from the PI term is also as strong as the relative humidity term in ERA-40 data set. It may, however, be noted that compared to the other reanalysis data sets, over the BoB, the region of negative regression coefficients of the GPI as well as the relative humidity are restricted to the eastern coast of India in ERA40 data set. At the same time, the regression coefficients of both these parameters over the eastern parts of the Bay are positive in this data set. These opposing characteristics within the basin could have reduced the average contribution of relative humidity term to the GPI in the ERA40 data set. It is also interesting to note that both in ERA-40 and ERA-Interim data sets, the contribution by wind shear term is negative, suggesting that the variations in the PDO index and the wind shear are in the same phase. The PI term computed from ERA-Interim data set is also negatively contributing to the GPI variation. However, it may be noted that the period of ERA-Interim is from 1979 to 2011 only and hence, it can resolve only the last cycle of the PDO (W3 and C3). Even though there are differences among different data sets in the relative contributions of each of the factors those influence the genesis of MDs over BoB, it is clear that the variation in the relative humidity is the most dominant factor that explains the PDO–MD link in all reanalysis data sets. Further, the dominant contribution of mid-tropospheric relative humidity on the observed PDO–MD link is evident from the strong spatial correspondence between the relative humidity term and the GPI (Figure 2).

The results from the GPI analysis show that the variation in the relative humidity is the most important factor that is responsible for the observed out-of-phase relationship between the MDs and the PDO. In a recent study, Ditchek et al. (2016) have proposed another index for the genesis of MDs (MDGI), in which dominant factors considered are total column water vapor, low-level absolute vorticity, estimated convective available potential energy and 600-hPa relative humidity. Because the MDGI proposed by Ditchek et al. (2016) is devised exclusively for the genesis of MDs, we used this method to confirm our findings based on the GPI analysis. The results from this analysis reconfirm that the variation in MDGI computed for the head Bay and the PDO are out-of-phase (Figure S2.1) and the variation in the relative humidity is the major factor responsible for this out-of-phase relation between the observed decadal variations in the number of MDs and the PDO (Table S2.1).

3.2 Plausible link between the PDO and MD

The regression of SST in Indo–Pacific basin onto the PDO index, shown in Figure 4, suggests a strong in-phase relation between the variation in the PDO and the SST in the WEIO. This is consistent with the findings of D’Arrigo and Wilson (2006) that positive phase of the PDO is associated with the warming of WEIO. It may be noted that the observed warming tendency in the WEIO associated with the global warming (Nieves et al., 2015; Roxy et al., 2015) may also enhance the relationship between the PDO and the SST in the WEIO. In order to avoid the influence of the global warming trend, we have regressed the SST on to the PDO index after removing the long-term linear trend in SST. The regression of SST, after removing long-term linear trend, onto the PDO index also shows a significant in-phase relationship between the PDO and the SST in the WEIO (Figure 4b). Krishnan and Sugi (2003) and Krishnamurthy and Krishnamurthy (2013) had shown that the link between the ENSO and the Indian Ocean variability is enhanced (suppressed) when the PDO and ENSO are in (out of) phase. Several recent studies have shown that variability in the Pacific Ocean can modulate the Walker circulation over the Indo–Pacific basin, with subsidence over the Maritime continents and generate low-level easterly anomalies over the equatorial Indian Ocean (Krishnamurthy and Krishnamurthy, 2013; Roxy et al., 2014). These easterly anomalies weaken the mean westerlies, which act as a favorable atmospheric forcing for the warming of WEIO (Vinayachandran et al., 2002). Even though the previous studies were focused on the inter-annual variation in the Indian Ocean associated with the PDO, there are relative warming (cooling) episodes in the WEIO associated with similar modulation of Walker circulation in the warm (cold) phase of the PDO (Figure S3.1a).
Regression of vertical wind over the Indian Ocean onto the PDO index shows suppression (enhancement) of Hadley circulation with anomalous upwards (downwards) movement over the equatorial Indian Ocean and anomalous downwards (upwards) movement over north Indian Ocean in the warm (cold) phase of the PDO (Figure S3.1b). This weakening of Hadley cell leads to the weakening (strengthening) of monsoon flow in warm (cold) phase of the PDO. Vishnu et al. (2016) had shown that the warming of WEIO reduces the moisture transport towards the BoB due to the enhanced convergence over the WEIO and hence decrease in the frequency of formation of MDs over the BoB. Here we postulate that a similar mechanism may be responsible for the variation in the mid-tropospheric humidity over the BoB which decrease (increase) the frequency of formation of the MDs over the BoB during the warm (cold) phases of the PDO. However, experiments with state-of-the-art numerical models are necessary to ascertain this hypothesis. We will attempt to address this problem in a future study.

FIGURE 2 Regression of the GPI (first column), relative humidity (second column), vorticity (third column), wind shear (fourth column) and PI (fifth column) on the PDO index for various reanalysis data sets such as (a) ERA20 (period: 1946–2010), (b) NCEP (period: 1951–2010), (c) JRA55 (period: 1958–2014), (d) ERA40 (period: 1958–2001) and (e) ERA-Interim (period: 1979–2013). Shaded are statically significant at 95% confident level using Student’s two tailed t-test. A 9-year running average of all data set is performed to extract the decadal variability.
In this study, we show that the number of MDs over the BoB has a strong out-of-phase relationship with the PDO, particularly in the past seven decades. A quantitative analysis of the environmental parameters responsible for the genesis and intensification of MDs shows that the variation in the availability in the relative humidity over the BoB is the major factor controlling the observed relationship between the PDO and number of MDs. It is hypothesized that the warming (cooling) of WEIO associated with the warm (cold) phase of the PDO weakens (strengthens) the moisture transport to the BoB and hence decreases (increases) the frequency of genesis of MDs over the BoB.

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