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Key Points:
- Low-intensity rainfall is a major driver of groundwater recharge in India
- Low-intensity rainfall controls groundwater recharge in north central and northwest India
- SST in Pacific and Atlantic Oceans controls the year-to-year variability in low- and high-intensity rainfall in India

Supporting Information:
- Supporting Information S1

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Strong Linkage Between Precipitation Intensity and Monsoon Season Groundwater Recharge in India

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Abstract Groundwater is a lifeline for millions of people in India, which is affected by the year-to-year variability of precipitation amount and characteristics (low and high intensity). Precipitation intensity has been observed and projected to change in India. However, the crucial impact of precipitation intensity on groundwater recharge in India remains unknown. Here we use in situ data from more than 5,800 groundwater wells to show that precipitation intensity is strongly linked with groundwater recharge in India. In the northwest and north central India, the monsoon season groundwater recharge is linked with the low-intensity precipitation, while in South India high-intensity precipitation is a major driver of groundwater recharge. Observed long-term changes in precipitation characteristics show a decline in the low-intensity rain in the northwest and north central India that are strongly driven by sea surface temperature over the Pacific Ocean. Increases in the high-intensity precipitation in South India are linked with the sea surface temperatures in the Atlantic Ocean. Our results highlight the importance of precipitation intensity for the monsoon season groundwater recharge in India, which can provide insights to sustainably manage rapidly declining groundwater resources in India.

Plain Language Summary Sustainable management of groundwater resources in India is vital for ensuring food and water security for millions of people. Groundwater storage in India has declined due to excessive pumping for irrigation and decreased summer monsoon rainfall. There are efforts to enhance the groundwater recharge in India. However, the role of precipitation intensity for groundwater recharge remains unclear. We provide the first ever assessment of the linkage between groundwater recharge and precipitation intensity in India using observed data from more than 5,800 wells. We show that low-intensity precipitation is vital for groundwater recharge in the heavily irrigated North India. In South India, high-intensity rainfall is a major driver of groundwater recharge in comparison to low-intensity precipitation. Our findings can provide insights for management of groundwater recharge in India.

1. Introduction

Groundwater plays a vital role in ensuring food and freshwater security in many water-scarce countries, including India (Shah, 2017). More than 60% of irrigation and 80% of drinking water supply in India are sourced from groundwater (World Bank, 2012). As in many other water-stressed regions in the world (Wada et al., 2010), groundwater depletion has become widespread in India during the recent decades (Asoka et al., 2017; Gleeson et al., 2012; Rodell et al., 2009; Tiwari et al., 2009; Wada et al., 2010). This rapid decline in groundwater storage has been attributed to excessive withdrawal for irrigation (Rodell et al., 2009) as well as changes in the monsoon season precipitation (Asoka et al., 2017). Most previous studies document significant declines in groundwater storage and water table elevations in India (Macdonald et al., 2016; Rodell et al., 2009; Tiwari et al., 2009) and attribute this to pumping for irrigation. However, the linkage between precipitation characteristics and groundwater recharge (Jasechko & Taylor, 2015; Tashie et al., 2016; Taylor et al., 2013), which is essential for a complete understanding of groundwater sustainability and food security, remains unexplored in India.

Substantial changes have been observed in the amount and characteristics of the Indian summer monsoon season precipitation during the recent decades (Mishra et al., 2012; Roxy et al., 2015; Singh et al., 2014). The most notable change has been the decline in the monsoon season precipitation over the Indo-Gangetic Plain (Mishra et al., 2012; Roxy et al., 2015). This decline in the monsoon season precipitation over the Indo-Gangetic Plain affected ground and surface water resources (Asoka et al., 2017; Mishra et al., 2016) and has been attributed to rising in sea surface temperature (SST) over the Indian Ocean (Mishra et al.,

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2012; Roxy et al., 2015) and atmospheric aerosols (Bollasina et al., 2011). Singh et al. (2014) reported changes in the characteristics of extreme wet and dry spells in the post-1950 period with an increased frequency of dry spells over the South Asian monsoon region. More recently, Roxy et al. (2017) found a significant increase in extreme precipitation over central India, which is projected to increase further under warming climate (Mukherjee et al., 2018). Despite these observed changes in the monsoon season precipitation, their role in groundwater recharge in India remains largely unrecognized. Here we use observed precipitation and groundwater level data from 5,874 groundwater wells to establish the linkage between precipitation intensity, monsoon season groundwater recharge, and SSTs for the observed climate.

2. Materials and Methods

We used groundwater level data from Central Groundwater Board (CGWB) for 1996–2016. The CGWB monitors monthly groundwater levels four times in a year (January, May, August, and November) in India, which are available from the Water Resources Information System of India (http://india-wris.nrsc.gov.in/wris.html). We used groundwater level observations that are available for more than 20,000 wells. However, after the quality checks and postprocessing, data from 5,874 wells that have long-term records were selected for the analysis.

We used the median of maximum (of observations for four months: January, May, August, and November) well levels from 1996 to 2016. The water table fluctuation method (Asoka et al., 2017) was used to estimate groundwater recharge during the monsoon season (June to September). The difference between the premonsoon (May) and the postmonsoon (November) groundwater levels is considered as the water table fluctuation. We estimated total groundwater recharge during the monsoon season by multiplying specific yield of an aquifer and fluctuation in groundwater table as described in Asoka et al. (2017). Specific yields of the 14 major aquifers in India are estimated using the long-duration pumping tests for the aquifer material that is within the cone of depression created during the pumping test. To reduce uncertainty in the estimates of specific yield, there have been more than 30,000 pumping tests conducted by the CGWB (based on personal communication with Dipankar Saha, Ex Chairman CGWB). Since long-duration pumping tests may lead to uncertainty in the specific yield estimation in hard-rock aquifers, dry season groundwater balance method has been used. More information on the estimation of specific yield can be obtained from the Report of the Groundwater Resource Estimation Committee (2017; Central Groundwater Board, 2017; GEC-2015: http://cgwb.gov.in/Documents/GEC2015_Report_Final%2030.10.2017.pdf) and Maréchal et al. (2006). For each aquifer, CGWB provides the range of specific yield along with the recommended values (Table S1 in the supporting information). We used recommended values of specific yield (Figure S1 and Table S1) as mentioned in Asoka et al. (2017).

The monsoon season precipitation is a significant contributor of groundwater recharge in India (Figure S2). Using the data provided by the CGWB (http://www.cgwb.gov.in/documents/Ground%20Water%20Year%20Book%202013-14.pdf), we find that the other sources (e.g., canals, ponds, and return flow from irrigation) contribute less than 20% of the groundwater recharge during the monsoon season (Figure S2). The norms adopted for recharge estimation from other sources are mentioned in Central Groundwater Board (2009). Even though this recharge component accounts for the withdrawal and irrigation return flow, here we assume that the major contribution comes from the monsoon season precipitation (Figure S2).

Daily gridded precipitation and air temperature data were obtained from the India Meteorological Department (IMD) for the 1951–2016 period. Gridded (0.25°) precipitation data (Pai et al., 2014) from IMD were developed using station-based observations, which have been used in the many previous studies related to hydrology and drought assessments (Asoka et al., 2017; Shah & Mishra, 2014). The gridded air temperature data from IMD (Srivastava et al., 2009) are available at 1° spatial resolution, which were regrided at 0.25° spatial resolution using bilinear interpolation. We categorize daily precipitation into three classes based on precipitation amount, the sum of daily precipitation above 1 mm (total precipitation: PPT_{Total}), the sum of low-intensity (less than the 90th percentile and above 1 mm: PPT_{Low}), and high-intensity (more than the 90th percentile: PPT_{High}) daily precipitation. The 90th percentile was fixed for each grid cell based on the daily precipitation for the monsoon season for the reference period of 1971–2000. The selection of the 90th percentile to define precipitation intensity is based on guidelines from the World Meteorological Organization (2015). We find that about 60% of the total monsoon season precipitation falls as low-intensity precipitation (Table S2 and Figure S3).

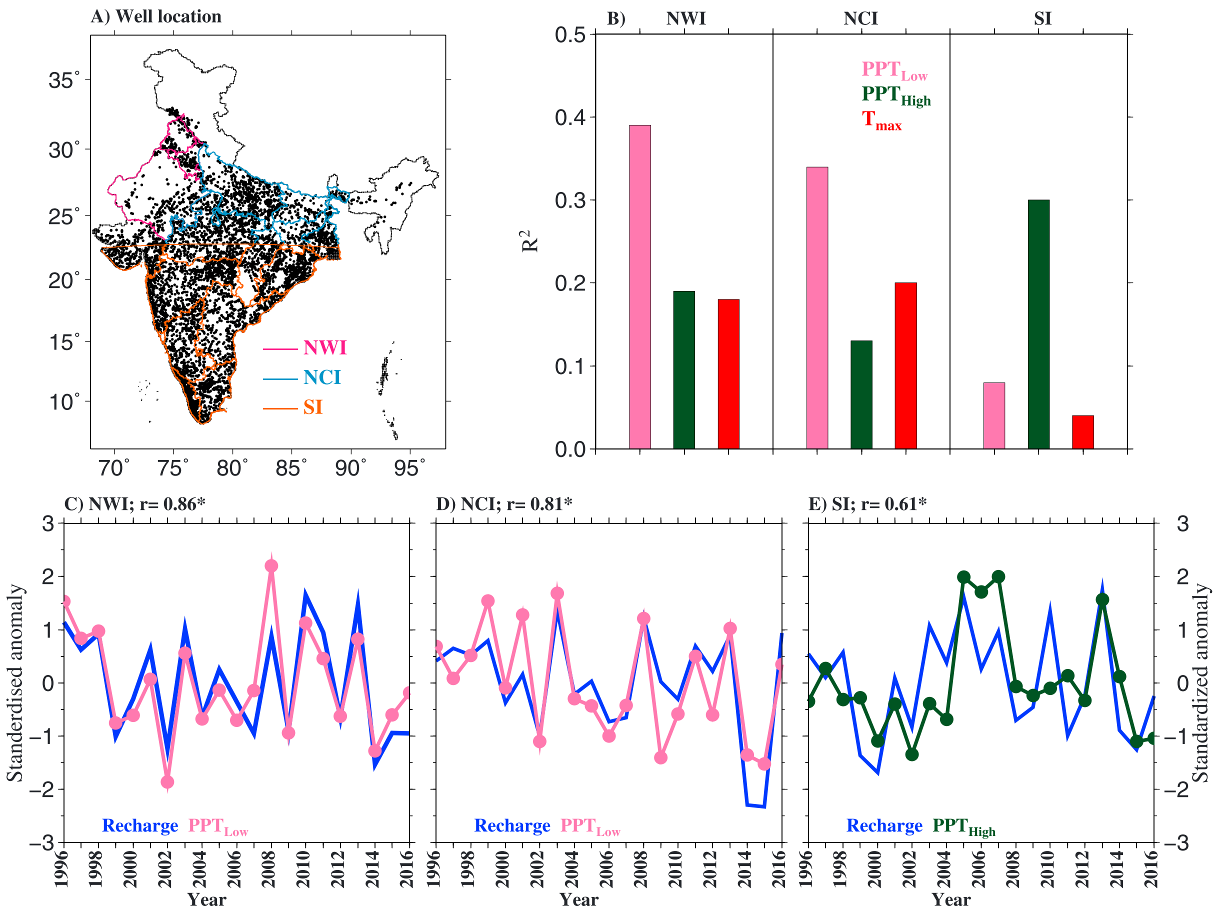

Figure 1. Importance of low- and high-intensity precipitation for groundwater recharge in India. (a) Location of the selected groundwater wells (5,874) that were used for the analysis. The groundwater well data were obtained from the Central Groundwater Board for the period 1996–2016. (b) The relative importance (estimated using coefficient of determination R^2) of low-intensity precipitation (PPT_{Low}), high-intensity precipitation (PPT_{High}), and maximum temperature (Tmax) for groundwater recharge for the northwest (NWI), north central (NCI), and South India (SI). (c–e) Standardized anomalies of groundwater recharge and precipitation (June to October) for NWI, NCI, and SI.

Other than the percentile-based threshold, we used the binning technique (Alter et al., 2015; Groisman et al., 2004) to distribute the monsoon season precipitation according to precipitation intensity as per the guideline (http://imd.gov.in/section/nhac/termglossary.pdf) provided by IMD (Table S2). We find that all the three regions (northwest [NWI], north central [NCI], and South India [SI]) receive most (~50%) of the total monsoon season for daily precipitation intensity between 7.5 and 35.5 mm (Table S2). We used daily intensity of 35.5 mm to decide low- (intensity less than 35.5 mm) and high- (intensity more than 35.5 mm) intensity precipitation in India. The contribution from low-intensity precipitation is 72.4, 64.5, and 62.3% of the total monsoon season precipitation in NWI, NCI, and SI, respectively (Table S2).

We use precipitation (PPT_{Total}, PPT_{Low}, and PPT_{High}) and daily maximum temperature (T_{max}) to understand the linkage between climate and groundwater recharge in India. Climate data for each well were assigned based on the nearest neighboring grid cell. For the regional analysis, we used area averaged time series (precipitation and recharge) for NWI, NCI, and SI. These three regions were selected based on the changes in the groundwater storage and climate characteristics as explained in Asoka et al. (2017). We finally used 139, 712, and 3,838 (total 5,874) number of groundwater wells in NWI, NCI, and SI for the analysis (Figure 1). Since we used the precipitation for the grid (0.25°) in which groundwater observation well is located, lesser number of groundwater wells in NWI is unlikely to affect the relationship between groundwater recharge and precipitation intensity.

We fitted multiple linear regression for recharge with precipitation (PPT_{Total}, PPT_{Low}, and PPT_{High}) and T_{max} as predictors. The multicollinearity among the predictors was evaluated using cross-correlation matrix and

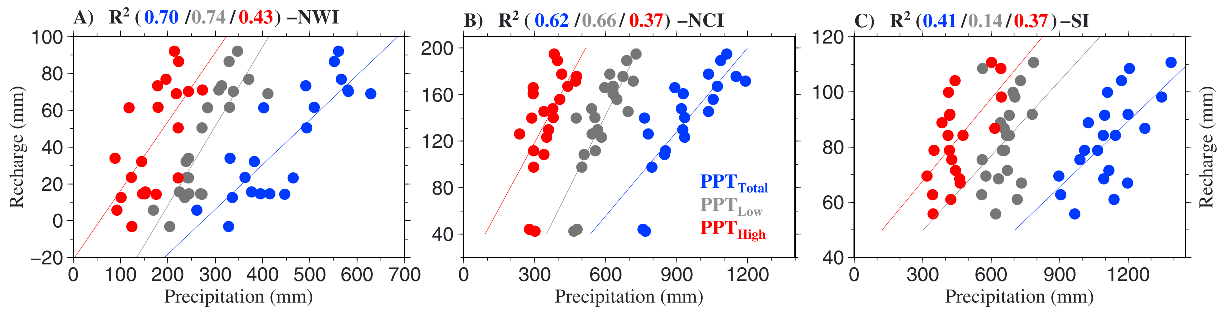

Figure 2. Relationship between groundwater recharge (mm) and precipitation amounts due to total (PPT_{Total}; blue), low (PPT_{Low}; gray), and high (PPT_{High}; red) intensity precipitation in northwest India, NWI (a), north central India, NCI (b), and South India, SI (c). Coefficient of determination (R^2) of the regression relationship for PPT_{Total}, PPT_{Low}, and PPT_{High} are given in blue, gray, and red colors.

variance inflation factor (VIF). The predictors with VIF more than four were dropped, and the final regression model was selected using Akaike information criterion (AIC), AIC corrected, and Bayesian information criterion. We estimated the relative importance (Silber et al., 1995; R^2: coefficient of determination) of the predictors for the three regions (NWI, NCI, and SI) at 95% confidence level after applying a bootstrapping of 1,000 runs.

We obtained precipitation, evapotranspiration (ET), and total runoff (TR: baseflow + surface runoff) simulated from the Variable Infiltration Capacity land surface model at 0.25° for 1980–2012, which is well calibrated and validated for the Indian subcontinental river basins (Shah & Mishra, 2016). The Variable Infiltration Capacity model simulated ET and TR were used to analyze the water budget in the three (NWI, NCI, and SI) regions. Trends in climate variables were estimated using the nonparametric Mann Kendall (Kendall, 1975; Mann, 1945) trend test and Sen's slope method (Sen, 1968). To evaluate the linkage between climate variability and PPT_{Low}/PPT_{High}, we used maximum covariance analysis (MCA) and empirical orthogonal function (EOF) analysis as described in Mishra et al. (2012). The analysis was performed using the SST departure and total amount of low/high-intensity precipitation in each monsoon season. Monthly SST data were obtained from National Centers for Environmental Information's Extended Reconstructed SST (Huang et al., 2014; ERSSTv4). The SST departure was estimated by removing the monthly mean global SST from each grid cell (Mishra et al., 2012). EOF analysis on the monsoon season's low/high-intensity precipitation for the period of 1951–2016 was performed to obtain the dominant modes of variability irrespective of the variations in SST. The corresponding principal components (PCs) were used to understand the linkage between variability in precipitation and SST. We performed MCA (Bretherton et al., 1992) to obtain coupled patterns of precipitation and SST for the period of 1951–2016.

3. Results and Discussion

We first analyze linkages between precipitation characteristics and groundwater recharge in India using data from more than 5,800 observation wells for the period of 1996–2016 (Figure 1a). Since the linkage between groundwater storage levels and accumulated precipitation is driven by year-to-year rates of groundwater recharge and pumping (Taylor et al., 2013), we examine the role of PPT_{Low} and PPT_{High} on annual groundwater recharge (Figure S4). Contribution (mm/year) from the PPT_{Low} and PPT_{High} was estimated for the June to October period for each year, and its relationship with groundwater recharge was established. We find that in the majority of India, low-intensity precipitation contributes to more than 60% of the total precipitation (Figure S3 and Table S2).

Annual groundwater recharge was estimated using the difference in well levels for the May and November months (see methods for details). The relative importance of PPT_{Low}, PPT_{High}, and *T*max for annual groundwater recharge was estimated using 95% bootstrap confidence intervals (Figures 1b and S4 and Table S3). Results for relative importance demonstrate the dominant role of PPT_{Low} in groundwater recharge in NWI (correlation = 0.86) and NCI (r = 0.81). However, the importance of PPT_{High} for groundwater recharge in SI (r = 0.61) is substantially higher than PPT_{Low} (Figures 1c–1e and S4). We also note that the relative importance of *T*max was higher in NWI in comparison to NCI or SI (Figures 1b and S5). We evaluated the regression relationship between groundwater recharge and PPT_{Total}, PPT_{Low}, and PPT_{High} (Figure 2). We find that PPT_{Low}

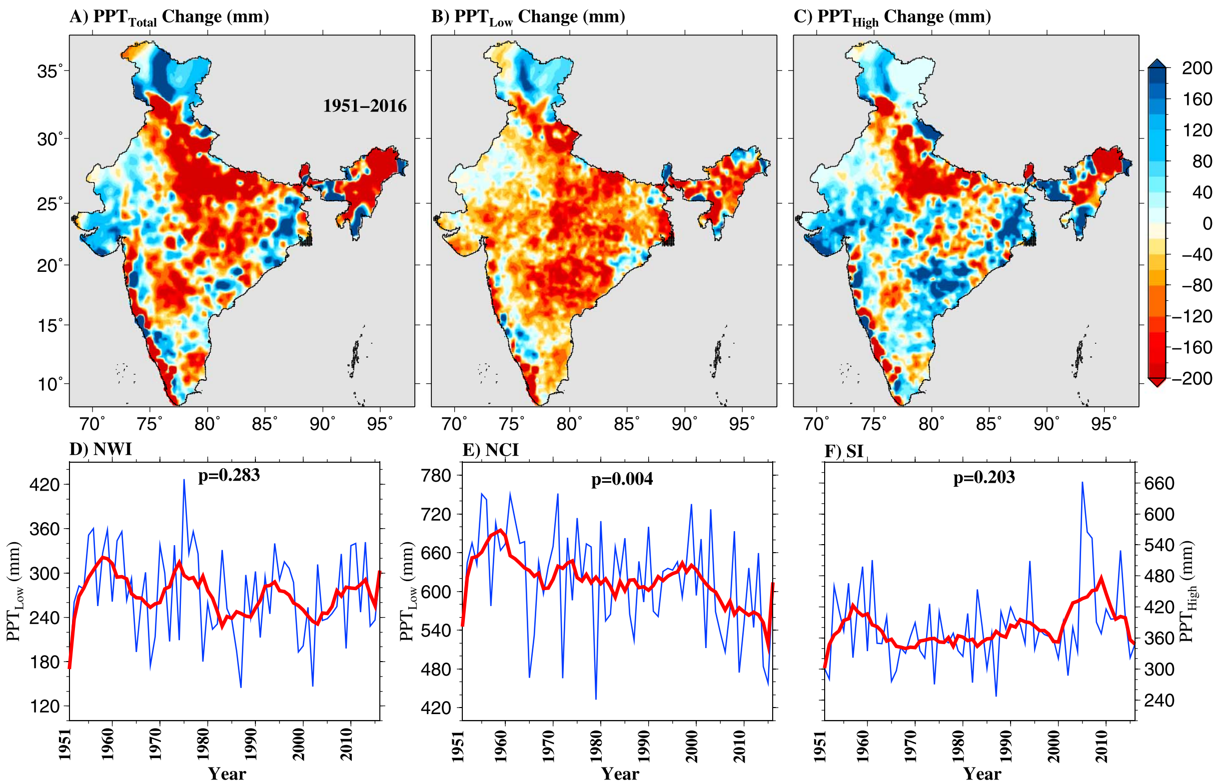

Figure 3. Observed changes in precipitation characteristics over India (1951–2015). (a) Observed changes (mm) in PPT_{Total}, (b) PPT_{Low}, and (c) PPT_{High}. (d and e) Area averaged changes in PPT_{Low} for northwest India, NWI and north central India, NCI, and (f) area averaged changes in PPT_{High} in SI. All changes were estimated using the nonparametric trend test and Sen's slope method for the period of 1951–2016. Statistical significance was tested at 5% significance level and *p* value (in d–f) less than 0.05 indicates trends were significant.

explains a higher variance in groundwater recharge (R^2 = 0.74 and 0.66) than PPT_{Total} (R^2 = 0.70 and 0.62) for NWI and NCI (Figure 2 and Table S4). However, for SI, PPT_{High} explains higher variance (R^2 = 0.37) in groundwater recharge than PPT_{Low} (R^2 = 0.14). In SI, the total explained variance by PPT_{Total} is slightly higher (R^2 = 0.41) than that of PPT_{High} (R^2 = 0.37; Figure 2 and Tables S4 and S5). We also evaluated lagged correlations between 1- and 4-year accumulated monsoon season precipitation and groundwater recharge (Table S6). We find that the monsoon season groundwater recharge is strongly related with the monsoon season precipitation in the same year and contribution from the previous monsoon season precipitation is lower except for the NWI (Table S6).

We find that our results based on percentile and fixed (binning) thresholds for PPT_{Low} and PPT_{High} are consistent (Table S5 and Table S7). These results further confirm the importance of PPT_{Low} for groundwater recharge in India. These differences in groundwater recharge with PPT_{Low} and PPT_{High} are most likely related to the prevalence of alluvial and hard-rock aquifers present in the North and South India, respectively (Asoka et al., 2017; Fishman et al., 2011; Macdonald et al., 2016). We evaluated the differences in water budget in the three regions and found that NWI receives the lowest (436.30 mm) monsoon season precipitation followed by SI (970.51 mm) and NCI (998.16 mm; Table S8 and Figure S6). Monsoon season ET is the highest (61% of precipitation), and TR is the lowest (26% of precipitation) in NWI. Since ET (36%− NCI, 42%− SI) and TR (51%− NCI, 43%− SI) fractions of the monsoon season precipitation are similar for NCI and SI, the differences in groundwater recharge in these regions are most likely linked with the aquifer characteristics (Table S8).

After evaluating the relative importance of PPT_{Low}, PPT_{High}, and T_{max}, we used multiple linear regression to model groundwater recharge using precipitation characteristics (low and high intensity) and T_{max} after estimating cross-correlation and VIFs (Table S4 and S9). Our regression results based on AIC, AIC corrected, and Bayesian information criterion show that PPT_{Low} can be used to estimate groundwater recharge in the NWI and NCI (Table S4) while for SI, both PPT_{Low} and PPT_{High} are predictors of groundwater recharge. Consistent

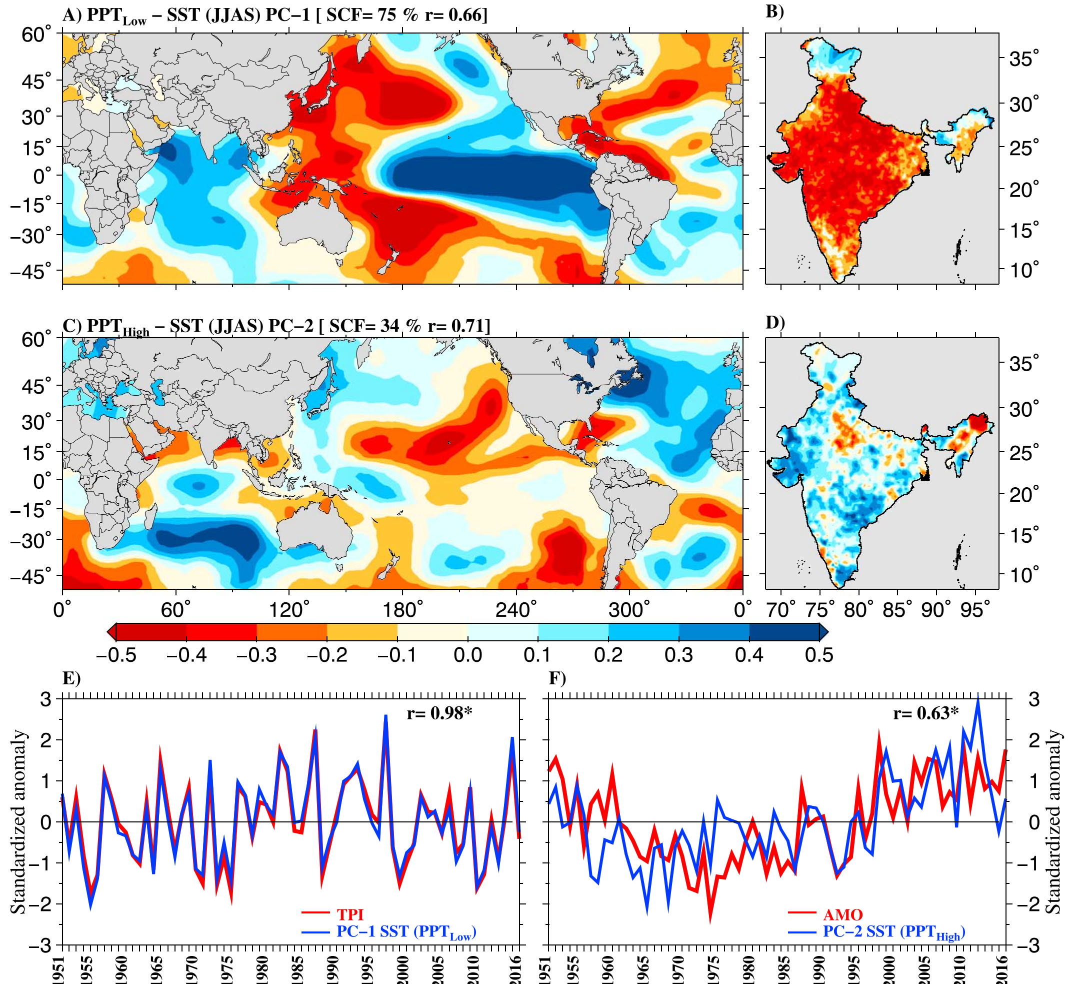

Figure 4. Major drivers of the low- and high-intensity precipitation in India during the period of 1951–2016. (a, b) Heterogeneous correlation maps of the leading mode obtained using the maximum covariance analysis between PPT_{Low} and sea surface temperature (SST) for the monsoon (June to October) season. (c, d) Same as (a) and (b) but for the second mode of the maximum covariance analysis performed on PPT_{High} and SST for the monsoon season. (e) Relationship (r = 0.98, significant) between PC-1 of SST (for PPT_{Low}) and the Tripole Pacific Index and (f) relationship (r = 0.63, significant) between PC-2 of SST and Atlantic Multidecadal Oscillation (AMO). For both the leading modes correlation coefficient (r) and squared covariance fraction (SCF) were estimated.

with the analysis of relative importance (Figure 1b), the regression analysis shows that PPT_{Low} explains 74% (R^2 = 0.74, p value <0.001) and 66% (R^2 = 0.66, p value <0.001) of the total variance in groundwater recharge in NWI and NCI (Table S4). Groundwater recharge in SI is less well explained (R^2 = 0.43, p value <0.001), but PPT_{Total} is the predictors. Based on the regression analysis and relative importance, we find that PPT_{Low} plays a vital role in groundwater recharge in the NWI and NCI, while in SI, PPT_{High} is the major contributor (Figure 1 and Table S7).

Since precipitation characteristics play a significant role in groundwater recharge in different regions in India, we estimate long-term (1951–2016) changes in PPT_{Total}, PPT_{Low}, and PPT_{High} in India using gridded observations (0.25°) from IMD (Figure 3). Our results show a substantial decline in PPT_{Total} and PPT_{Low} across India (Figures 3a and 3b) that might have affected the long-term groundwater recharge. This decrease in PPT_{Low} during the summer monsoon is more widespread than previously reported declining trend in precipitation that was mainly centered over the Indo-Gangetic Plain (Mishra et al., 2012; Roxy et al., 2015). Moreover, we find a high spatial variability in the trends of PPT_{High} over India from 1951 to 2016 (Figure 3b). For instance, PPT_{High} has increased in the western and peninsular India while declined in the Indo-Gangetic Plain (Figure 3b). Our analysis reveals a nonsignificant (p value =0.28) declining trend in low-intensity precipitation in NWI, while a significantly declining trend (p value = 0.004) in NCI (Figures 3c and 3d). We also find a nonsignificant (p value =0.20) increasing trend in high-intensity precipitation in SI (Figure 3e). A significant increase in PPT_{High} was found in SI during the post-2000 period (Figure 3e). Overall, our results show that the Indo-Gangetic Plain in NCI experienced a significant decline in the both PPT_{Low}, and PPT_{High} (Figures 3a and 3b).

Next, we established the role of large-scale climate variability on the year-to-year fluctuation of PPT_{Low} and PPT_{High} (Figure 4), which remains unexplored in the previous studies (Asoka et al., 2017; Mishra et al., 2012; Roxy et al., 2015). This analysis was conducted on a longer time period of 1951–2016 using the gridded precipitation observations from IMD and SST (Huang et al., 2014) data from National Centers for Environmental Information. To diagnose the role of climate variability on the changes in PPT_{Low} and PPT_{High}, we conducted EOF and MCA (Bretherton et al., 1992). The first mode of variability from the EOF analysis of PPT_{Low} and PPT_{High} resembled trend patterns (Figures S7a, S7b, 2b, and 2c). Moreover, the corresponding PCs from the leading modes of the EOF analysis show changing characteristics in precipitation over India from 1951 to 2016 (Figures S7c and S7d).

To understand the coupled modes of variability, the MCA was conducted using PPT_{Low} and PPT_{High} and SST departure field. We find that the leading mode obtained from the MCA for PPT_{Low} exhibits a similar spatial pattern that was obtained from the trend analysis (Figures 3a, 3b, and 4b), indicating that the SST variability over the Pacific Ocean has a strong influence on the year-to-year variability of PPT_{Low} over India (Figures 4a and 4b and Table S10). The correlation analysis ($r = 0.98$) between the PC (for SST) obtained from the MCA and oceanic indices (Table S10) shows that the spatial pattern obtained from MCA resembles with the Tripole Pacific mode (Figure 4e). This signifies that a positive Tripole Pacific Index (Henley et al., 2015) results in a decline in PPT_{Low}, which is strongly coupled with groundwater recharge in a major part (NWI and NCI) of India (Figure 1 and Table S10). The MCA of the SST departure field and PPT_{High} results in a correlation pattern, which is similar to the changes in high-intensity precipitation (Figures 4d and 3b). We find that Atlantic Multidecadal Oscillation is coupled ($r = 0.63$) with the year-to-year variability and changes in high-intensity precipitation (Figures 4c, 4d, 4f, and S8 and Table S11). Two key features, which remained previously unexplored, govern the variability of the characteristics of precipitation and have a strong influence on groundwater recharge variability over India.

4. Conclusions

A large population of India depends on groundwater for food and fresh water availability (Shah, 2017), which has rapidly depleted (Asoka et al., 2017; Rodell et al., 2009; Tiwari et al., 2009) and posing a threat for water security (Famiglietti, 2014). Both groundwater pumping for irrigation (Rodell et al., 2009) and the monsoon season precipitation (Asoka et al., 2017) play an important role in groundwater storage changes in India. A balance between groundwater withdrawal and recharge is essential for sustainable management of groundwater resources in India. While the amount of monsoon season precipitation plays a vital role on recharge (Asoka et al., 2017), the role of precipitation intensity and its influence on groundwater recharge was previously unexplored over India. Our analysis shows that the groundwater recharge in India in the past is strongly linked with the precipitation characteristics. In the NWI and NCI, which are dominated by the alluvial aquifers, groundwater recharge is driven by the low-intensity precipitation. However, in South India, which is dominated by hard-rock aquifers, groundwater recharge is mainly driven by high-intensity and total precipitation.

The year-to-year variability of low- and high-intensity precipitation is largely governed by the ocean temperatures in the Pacific and Atlantic Ocean regions. The role of large-scale climate variability, especially SST anomalies in the Pacific and Atlantic Oceans, shows a potential to predict year-to-year variability in groundwater recharge in India. Moreover, the relationship between precipitation amounts (due to the total, low, and high intensity) and groundwater recharge can be used for the prediction of groundwater storage in India. It is worth noting that groundwater recharge estimates may have uncertainty primarily due to uncertainty in specific yields. Notwithstanding specific yields for the major aquifer are estimated based on a large number of pumping tests, these may have uncertainties because of aquifer types (bedrock or alluvial) and the methods used (long-term pumping test and groundwater budget for the dry season). Despite these limitations, our results provide important insights for sustainable management of groundwater resources. For instance, the regions that have experienced declines in the low-intensity precipitation (NCI and NWI) and experience significant groundwater withdrawal for pumping need additional and efficient mechanism for groundwater recharge.

Acknowledgments
Data used in this study are available from the following sources: precipitation and temperature from IMD (http://www.imd.gov.in/Welcome%20To%20IMD/Welcome.php), groundwater levels from India-WRIS (http://www.india-wris.nrsc.gov.in/), and SST from NCEI (https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.v4.html). Authors appreciate suggestions from Tom Gleeson, two anonymous reviewers, and the Editor. The funding for this work from ITRA-Water program is greatly appreciated.

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