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Linkage between global sea surface temperature and hydroclimatology of a major river basin of India before and after 1980

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Abstract

The frequent occurrence of flood and drought worldwide has drawn attention to assessing whether the hydroclimatology of major river basins has changed. The Mahanadi river basin (MRB) is the major source of fresh water for both Chattisgarh and Odisha states (71 million people approximately) in India. The MRB (141 600 km^2 area) is one of the most vulnerable to climate change and variations in temperature and precipitation. In recent years, it has repeatedly faced adverse hydrometeorological conditions. Large-scale ocean–atmospheric phenomena have a substantial influence on river hydroclimatology. Hence global sea surface temperature (SST) linkage with the precipitation and surface temperature of the MRB was analyzed over the period 1950–2012. Significant changes in seasonal correlation patterns were witnessed from 1950–1980 (PR-80) to 1981–2012 (PO-80). The correlation was higher during PR-80 compared to PO-80 between the El Niño region SST versus the maximum temperature (T_{max}) in all seasons except the pre-monsoon season and the minimum temperature (T_{min}) in all seasons except the monsoon season. However, precipitation correlation changes are not prominent. Like the SST, the correlation patterns of sea level pressure with precipitation, T_{max} and T_{min} shifted conspicuously from PR-80 to PO-80. These shifts could be related to change in Pacific decadal SST patterns and anthropogenic effects. Fingerprint-based detection and attribution analysis revealed that the observed changes in T_{min} (pre-monsoon and monsoon season) during the second half of the 20th century cannot be explained solely by natural variability and can be attributed to an anthropogenic effect.

1. Introduction

Global warming is unequivocal and is mostly the major cause for the recent increase in magnitude and frequency of extreme events (Seneviratne *et al* 2012). Hence, it is important to determine the impact of climate change on various sectors because of its scientific and societal importance. Extensive scientific research and evidence has revealed that the average earth surface temperature increased significantly during 20th century and continues to have a substantial impact on hydroclimatological variables such as precipitation, evapotranspiration, etc (IPCC 2013). The rate of increase in the minimum temperature (T_{min}) was higher than the maximum temperature (T_{max}) over the last three decades of the 20th century in India (Sonali and Nagesh Kumar 2013), leading to prominent changes in climate, similar to that on a global scale (Easterling *et al* 1997). The changes in seasonal T_{min} over India during the second half of the 20th century were not part of its natural variability (Sonali and Nagesh Kumar 2016).

The sea surface temperature (SST) impacts the hydrological cycle, the key components of which are surface air temperature and precipitation. Warm (El Niño) and cool (La Niña) phases of the El

Niño–Southern Oscillation (ENSO) have measurable influences on regional and global climate. ENSO influences the temperature and precipitation of India significantly (Panda and Kumar 2014, Panda *et al* 2014, Dwivedi *et al* 2015). Dwivedi *et al* (2015) found that ENSO weakens (strengthens) the Indian summer monsoon rainfall through shortening (lengthening) the length of the rainy season, respectively, in El Niño and La Niña years over India.

Water availability and food security in most of Asia's major river basins are imperiled by climate change (Immerzeel *et al* 2010). Per capita water availability in India has lessened and will continue to decrease in the future, resulting in existing water issues such as disputes for the inter-state water transfer and hindrances to the socio-economic growth of the country. Spatio-temporal variation of temperature and precipitation specifies the climate of each region and effects water resources. There is little research in India at river basin scale on the long term changes in temperature and precipitation and their linkage with large-scale atmospheric circulation, even though it would reflect several interesting changes more than that would have occurred circumstantially as a part of natural internal variability (Mondal and Mujumdar 2012). Five recent consecutive floods in Mahanadi (years: 2001, 2003, 2006, 2008, and 2011) motivated us to analyze climate change and variability impact on the hydroclimatology of this basin.

Mahanadi is a major river basin and is a recognized climatically vulnerable region of India located in the east-central region. This basin is characterized by tropical monsoon. The water availability undergoes large seasonal fluctuations. The average annual rainfall is 1572 mm, 70% of which occurs during the southwest monsoon. The total basin area is about 1.42×10^5 km^2 and is located between longitudes 80° 25' and 87°E, and latitudes 19°15' and 23°35'N (figure 1(*a*)). The river flows eastwards and debouches into the Bay of Bengal. Because of its location (adjacent to the northwest Bay of Bengal), this basin is vulnerable to extremes and can be considered as a good case study as an Asian monsoon region. Hence, a detailed assessment of the spatial and temporal variation of hydroclimatology of the Mahanadi river basin (MRB) is indispensable.

Owing to this sensitivity in hydroclimatic conditions, various studies using general circulation models were conducted over the MRB (Asokan and Dutta 2008, Ghosh *et al* 2010). Chakrapani and Subramanian (1990) found that the geology, smaller upstream tributaries and water discharge of the MRB are the main reasons behind the bulk annual transportation of sediment to the Bay of Bengal. The rate of change of surface temperature is higher (during 1901–1980) over this basin compared to the overall India trend (Rao 1993). Gosain *et al* (2006) suggested that the MRB will experience a higher level of rainfall and water yield in future. Panda *et al* (2013) used gridded data sets on a daily scale of precipitation and stream flow for the MRB to evaluate the hydroclimatology and impact of the Niño index (Niño3.4). Close connections were established for Mahanadi precipitation and stream flow with the Niño3.4 index. Jena *et al* (2014) investigated changes in heavy precipitation and floods over Mahanadi basin and suggested that an increase in extreme rainfall in the middle reaches could have caused the high floods.

Very few climatic studies have been conducted for this important basin. Keeping in view the research lacuna, it is pertinent to analyze the impact of climate change and variability on river hydroclimatology. Climate change can affect river flows not only due to a change in the magnitude of precipitation, but also due to changes in temperature. Most of the earlier studies investigated the spatio-temporal changes in precipitation and stream flow over this basin. Hence this present study considers temperature (T_{max} and T_{min}) along with precipitation to analyze the effects of climate change and variability. The present work aims at characterizing the hydroclimatology of the MRB by assessing long term changes and linking these with the large-scale atmospheric circulation during a 63 year period (1950–2012). The worldwide prominent climate change signature and concurrent significant changes in the Pacific SST pattern around the mid-1970s propelled us to divide the considered data set into two parts, 1950–1980 (PR-80) and 1981–2012 (PO-80) and to assess the important changes in the climatic patterns of the MRB, which may not be possible to identify in a single long-term time series. At least a record of 30 years is necessary to understand the climatic shift.

2. Data and methods

This study used a daily gridded precipitation data set at $1° \times 1°$ resolution developed by the Indian Meteorological Department (IMD) (Rajeevan *et al* 2005). Monthly gridded precipitation data sets were computed by averaging daily estimates over 1950–2012. The IMD does not have temperature data sets for the considered time span. Hence, observed T_{max} and T_{min} monthly data from the Climate Research Unit (CRU), University of East Anglia, version 3.22 at $0.5° \times 0.5°$ resolution (covering 52 grid points as shown in figure 1(*a*)), covering the period 1901–2012 was used for the present analysis (Harris *et al* 2014). The CRU data set is highly and significantly correlated with the IMD temperature data for India except for a few locations, mainly in the Western Himalayas and Northeast India. Monthly data sets of T_{max} and T_{min} from CRU3.22 showed a better correlation with the IMD data than the National Center for Environmental Prediction (NCEP) reanalysis data sets (Sonali and Nagesh Kumar 2016).

The monthly global SST for the period 1950–2012 was obtained from the Centennial Observation-Based Estimates of SST version 2 (i.e. COBE-SST2) at a

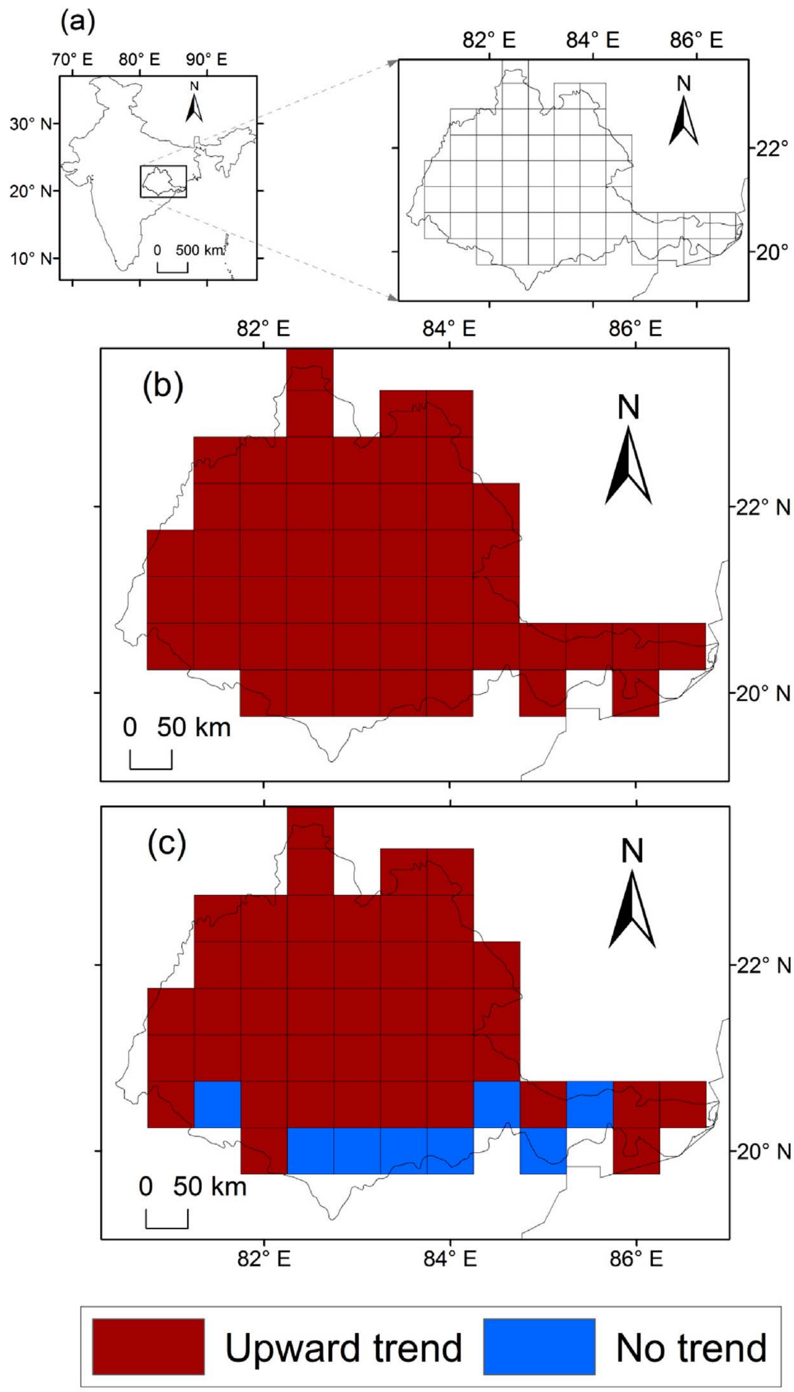

Figure 1. The MRB of India with considered grid points (*a*), trend in T_{max} (*b*) and T_{min} (*c*) in post-monsoon season, during 1950–2012.

resolution of 1° × 1°. Descriptions of COBE-SST2 can be found in Hirahara *et al* (2014). The COBE-SST2 data was obtained from www.esrl.noaa.gov/psd/in. For additional analysis, monthly re-analyses of sea level pressure (SLP), vertical pressure velocity at 500 hPa (Omega_500 hPa) and zonal wind (U-wind) data sets at 2.5° spatial resolution were obtained from NCEP (www.esrl.noaa.gov/psd/data/gridded/).

Niño1+2 (90°W–80°W, 10°S–0°), Niño3 (150°W–90°W, 5°S–5°N), Niño4 (160°E–150°W, 5°S–5°N) and Trans Niño indices were considered to understand their association with the MRB hydroclimatology along with Niño3.4 (170°W–120°W, 5°S–5°N).

Niño indices were calculated as the area-averaged SST anomalies for the specified Niño region. The Southern Oscillation is the atmospheric component of El Niño. The Southern Oscillation Index (SOI) is based on SLP differences between Tahiti and Darwin. It represents the intensity of El Niño and La Niña events. The SOI data for the considered time frame was obtained from the National Climatic Data Center (NCDC) (www.ncdc.noaa.gov/teleconnections/enso/indicators/soi/). The Indian Ocean dipole (IOD) is a coupled ocean and atmosphere phenomenon in the equatorial Indian Ocean (Saji *et al* 1999). The oceanic component of the IOD is measured by the dipole mode index (DMI). The DMI is the difference between SST anomalies in the western (50°E–70°E, 10°S–10°N) and eastern (90°E–110°E, 10°S–0°S) equatorial Indian Ocean. Equatorial Indian Ocean oscillation is the atmospheric component of the IOD and evaluated by the equatorial zonal wind index (EQWIN). EQWIN can be defined based on either outgoing longwave radiation (OLR) or surface zonal wind (Francis and Gadgil 2013). As OLR data is not available for the considered time period, EQWIN based on surface zonal wind (averaged over central equatorial Indian Ocean (60°E–90°E, 2.5°S–2.5°N) was used for the present analysis. DMI, EQWIN and SOI climatic indices were also considered in this study along with Niño indices.

Non-parametric approaches are distribution free and more resistant to outliers and missing values, unlike the parametric approaches. The non-parametric Mann–Kendall (MK) test statistically assesses the presence of monotonic upward or downward trend in the time series. However, this test does not consider the effect of serial correlation, which may conduce spurious conclusions (Sonali and Nagesh Kumar 2013). Hence, the modified version of the MK test (MMK) proposed by Yue and Wang (2004) was used here to investigate the possible trends in precipitation, T_{max} and T_{min}. The MMK approach corrects the variance in the MK test statistics in order to consider the effect of serial correlation that could be present in the time series. The MMK test indicates the presence of a statistically significant trend but does not quantify its magnitude. Hence Sen's slope approach was used to assess the trend magnitude (Sen 1968). As mentioned earlier, the time series was divided into sub-periods to assess the changes in correlation of SST with precipitation and temperature, and to detect abrupt changes in the time series. For this purpose the Wilcoxon rank sum test (Wilcoxon 1945) was employed. The Wilcoxon rank sum test is a non-parametric test that compares the equality of two time series. To investigate the relation between the global SST and the MRB hydroclimatology, non-parametric Spearman rank correlation was used.

A region-based (spatially averaged over the entire basin) and a grid-based trend detection study were conducted at seasonal and sub-seasonal (monthly) scales. Seasonal division of year was based on the conventional meteorology such as winter (January–February), pre-monsoon (March–May), monsoon (June–September) and post-monsoon (October–December). Using these available data sets, the connection between the MRB hydroclimatology and the global SST was established by determining correlations. This identified the most influential SST variations for the MRB hydroclimatology. This was achieved by computing the correlation of global SST with precipitation, T_{max} and T_{min} separately for different seasons and time slots. Hydroclimatic teleconnection was established between the large-scale atmospheric circulation phenomena (different climatic indices) and hydroclimatology of the MRB.

3. Results and discussion

Data pertaining to monthly temperature (T_{max} and T_{min}) and precipitation for 63 years (1950–2012) were considered. First, the Kolmogorov–Smirnov test was employed to check the normality and it was found that none of the considered time series followed a normal distribution. Hence, the non-parametric MMK approach was used instead of least-square linear regression. The statistical significance of the trend was evaluated at the 5% level. Unseen local changes in precipitation, T_{max} and T_{min} over MRB were extracted by analyzing both grid-based and region- based data sets. Significant changes in precipitation, T_{max} and T_{min} were examined for the first half of the 20th century and only a few significant changes were detected, unlike for the 1950–2012 time period. Hence, the first half of the 20th century was not analyzed further and the present study focused mainly on the 1950–2012 time period.

In the mid-1970s, the effect of a significant shift in the tropical Pacific SST was noticed and the climate change signals were found to be prominent both at global and continental scales (Meehl *et al* 2009). Hence, as discussed, the two main periods (PR-80 and PO-80) were set according to the changing circumstances. Table 1 depicts the trends of seasonal precipitation, T_{max} and T_{min} for different time slots.

The following represents an overview of the region-based and grid-based trend analyses (table 1).

- Significant downward trends in monsoon precipitation were observed during PR-80.
- Precipitation in non-monsoon seasons (i.e. winter and pre-monsoon) has significant upward trend during 1950–2012. Panda *et al* (2013) reported similar behavior in stream flow and rainfall during non-monsoon seasons in the period 1972–2007.
- Trends seen in T_{min} during winter and post-monsoon seasons are high in magnitude (increasing tendency of 0.22 °C per decade in the winter T_{min}) and statistically significant during 1950–2012 is that T_{min} exhibits a significant trend of 0.18 °C per decade during the PO-80 period.
- Results indicate an increasing tendency of 0.16 °C per decade in the T_{max} time series during the post-monsoon season and a significant decreasing trend in the pre-monsoon season during 1950–2012.
- Grid-based trend analysis shows that there is no significant trend in post-monsoon precipitation during 1950–2012 but a decrease is noticeable over some region of the study area.
- All the fifty-two grids for T_{max} (figure 1(*b*)) and about 85% for T_{min} (figure 1(*c*)) showed a significant

Table 1. Trend detection results for the MRB T_{max}, T_{min} and precipitation in different seasons, using the MKK approach in different periods, viz. 1950–2012, 1950–1980 and 1981–2012. In the table, '0' indicates no trend, '1' upward positive trend and '−1' downward trend. Results from the Wilcoxon rank sum test. The sign '≠', indicates that two time series are significantly different.

Presence of significant trend				
Time slot			1950–2012	
Seasons	Winter	Pre-monsoon	Monsoon	Post-monsoon
Variables				
T_{max}	0	−1	0	1
T_{min}	1	0	0	1
Precipitation	1	1	0	0
Time slot			1950–1980	
Season	Winter	Pre-monsoon	Monsoon	Post-monsoon
Variables				
T_{max}	0	0	0	0
T_{min}	0	0	0	0
Precipitation	0	0	−1	0
Time slot			1981–2012	
Seasons	Winter	Pre-monsoon	Monsoon	Post-monsoon
Variables				
T_{max}	0	0	0	0
T_{min}	0	0	0	1
Precipitation	0	0	0	0
Time series significantly different (≠) from 1950–1980 to 1981–2012 period				
Season	Winter	Pre-monsoon	Monsoon	Post-monsoon
Variables				
T_{max}				≠
T_{min}	≠			≠
Precipitation				

upward trend in the post-monsoon season during 1950–2012

- T_{min} increased significantly during all the months except April, May and June. T_{max} showed a positive trend during July to December and negative trend in January, whereas change in precipitation is seen in only two months, increasing in December and decreasing in July.
- Inspection of grid-based analyses shows that the total number of grids with significant trend is greater during the PO-80 period compared to the PR-80 period for both T_{max} and T_{min} in the post-monsoon season.

T_{max} and T_{min} are characterized by an increased tendency in most parts of the MRB over the entire period (i.e. 1950–2012). Post-monsoon T_{max} over this basin showed significant warming trends with relatively higher magnitude compared to other seasons. Both region-based and grid-based analyses revealed the rate of change in temperature is higher compared to precipitation. Significant positive trends in T_{max} and T_{min} indicate an obvious warming over the recent three decades, suggesting local climate change impact (human-induced effect) on the MRB. The consequences of the climate change phenomena can be alarming. Regional climate change affects various components of the hydrological cycle such as evapotranspiration, stream flow and soil moisture. A few studies have already shown the vulnerability of the MRB to climate change (Asokan and Dutta 2008, Gosain *et al* 2006). The mean total cloud cover has decreased significantly in most parts of India at a seasonal scale except for over the Indo-Gangetic plains and the north-east region (Jaswal 2017). Regional analyses by Warren *et al* (2007) also indicated significant decreasing trends of total cloud cover in India. Cloudiness is strongly associated with both T_{max} and T_{min}, which partially explains the reason behind the significant changes in temperature. There is a huge impact on urbanization (which induces warming) in regional climatic trends (mainly temperature).

Fingerprint-based detection and attribution targets whether observed climate changes are still consistent with the range of natural climate variations or an indication of anthropogenic climate change. So far, detection and attribution studies over the MRB have mainly referred to precipitation and streamflow. Mondal and Mujumdar (2012) reported that the observed changes in monsoon precipitation and streamflow in the MRB are clearly distinguishable from natural internal climate variability. Mondal and Mujumdar (2012) have already conducted a change detection and attribution study considering precipitation. Hence, the present study focused on temperature. A fingerprint-based detection and attribution technique was applied to assess the changes in observed temperature (T_{max} and T_{min}) during different seasons. Climate model simulations of different experiments were obtained from CMIP5 archives (Taylor *et al* 2012, Sonali *et al* 2016) and details are shown in table S1. Details about the fingerprint-based detection and attribution technique, their application and subsequent results and discussions are presented in the supplementary information available at stacks.iop.org/ERL/12/124002/mmedia. Results indicated the observed changes in the case of T_{min} during pre-monsoon and monsoon seasons and T_{max} during post-monsoon season are significantly different from natural internal climate variability (at the 5% significance level) (table S2). However, the changes in T_{min} during pre-monsoon and monsoon seasons can be attributed confidently to human-induced climate change effects (mainly because of anthropogenic GHGs, aerosols and urbanization) (figures S1 and S2).

Trend analysis indicates a probable abrupt change in temperature in the MRB around 1980. The Wilcoxon rank sum test results indicated that during the months of May and August to December, T_{max} changed significantly (step change) from PR-80 to PO-80. Similarly, in the months of February, August, September, November and December step changes were detected in T_{min}. T_{min} increased from PR-80 to PO-80 during all months, but the changes are not statistically significant every month. Greater skew and outliers in precipitation data are seen compared to T_{max} and T_{min} data sets. Analysis showed that monthly mean precipitation has lessened from the PR-80 to PO-80 periods. However, the changes in precipitation from the PR-80 to PO-80 periods are significant only during May. At seasonal scale, T_{max} changed significantly during post-monsoon and annually from PR-80 to PO-80. T_{min} changes are substantial during winter and post-monsoon along with the annual scale in the same time frame. However, precipitation did not change in any of the seasons. Annual cumulative precipitation remains approximately the same for both the PR-80 and PO-80 periods. This analysis has provided convincing evidence that one of the India's major river basins, Mahanadi, experienced an altered hydroclimatic condition after 1980. Additional analysis is required to interpret the test results.

In order to ascertain the significance of the variability obtained from the PR-80 to PO-80 periods, statistical bootstrapping was performed. Based on the observed data set (i.e. 1950–2012), 1000 bootstrapped samples were generated. The Wilcoxon rank sum test (a rank-based nonparametric statistical test to detect the step change in a time series) was applied and test statistics were computed for all bootstrapped samples along with observed data. It was found that the observed test statistic was more significant compared to all test statistics obtained from the bootstrapped samples. Hence, the changes in the hydroclimatological conditions of the MRB from the PR-80 to PO-80 periods are statistically significant and not random.

The climate of the MRB is strongly influenced by the surrounding oceans. The correlation between the SST (grid-based, globally) and T_{max}, T_{min} and precipitation in Mahanadi during PR-80 and PO-80 were computed for all seasons. Some of the important findings are depicted in figures 2 and 3. Contrasting patterns of correlation are observed during PR-80 and PO-80 (majorly in the cases of T_{max} and T_{min}). Figure 2 illustrates the correlation of T_{max} (figures 2(*a*) and (*b*)), T_{min} (figures 2(*c*) and (*d*)) and precipitation (figures 2(*e*) and 2(*f*)) with the global SST during PR-80 and PO-80 in monsoon season. Correlations of T_{max} and T_{min} are prominent with the Niño region SST (figures 2(*a*) and (*c*)) compared to precipitation during PR-80 in monsoon season (figure 2(*e*)). As discussed, the MRB is characterized by the southwest monsoon (June–September) but significant changes in mean precipitation between the PR-80 and PO-80 periods do not subsist during monsoon season. This may be one of the prominent reasons for the shift in correlation patterns seen in T_{max} and T_{min} rather than precipitation. Similarly, in the post-monsoon season, correlation of precipitation, T_{max} and T_{min} with the Niño region SST is stronger, and the shift in the patterns (PR-80–PO-80) is prominent compared to other seasons (figures 3(*a*)–(*f*)). Differences in the correlation from the PR-80 to PO-80 periods extend mainly over the region 110°E–80°W and 50°S–40°N (figures 3(*a*) and (*c*)). In the case of precipitation, the shift is distinct during monsoon and post-monsoon seasons. The precipitation contribution in non-monsoon seasons to the MRB is insignificant. However, there is an increase in mean precipitation from the PR-80 to PO-80 periods during non-monsoon seasons (but changes are not statistically significant). During PO-80, the SSTs of the surrounding ocean (local SST) are highly correlated with the MRB hydroclimatology in monsoon seasons (figures 2(*b*) and (*d*)). During post-monsoon season, local SST effects are dominant in both the PR-80 and PO-80 periods (figures 3(*a*)–(*d*)). Shifts in the correlation patterns are mainly witnessed in most of the portions extending from 60°S to 60°N. This change in the MRB hydroclimatology (flood and drought) is notable because of the disturbances over the surrounding ocean and Niño region SSTs in addition to the local climate change effect. Local/regional climate change is possibly because of the amplified T_{min} (which indicates anthropogenic effects), changing irrigation patterns, land use and land cover changes, decadal population growth rate (around 20%), and urbanization (Panda *et al* 2013). The start of this shift coincided with the strong decadal shift in the tropical Pacific Ocean.

It is important to understand the linkage between atmospheric circulation and the MRB hydroclimatology. This can also help in understanding the reason behind the significant shift in SST correlation patterns from the PR-80 to PO-80 periods. To gain insight into the atmospheric counterpart of the driving mechanism, atmospheric circulation features such as SLP and Omega_500 hPa. and their correlations with precipitation, T_{max} and T_{min} during all seasons were investigated. However, the results are shown for monsoon and post-monsoon seasons (figures S3, S4, S5 and S6), which were found to be significant. Omega_500 hPa is important for operational meteorology and a crucial parameter for understanding tropical convection. For SLP, most of the changes in correlation from the PR-80 to PO-80 periods are significant during the post-monsoon season and more prominent in T_{max} and T_{min} compared to precipitation. These changes are similar to changes witnessed in the case of the SST. Differences in correlations of precipitation with the SLP from PR-80 to PO-80 during monsoon season are

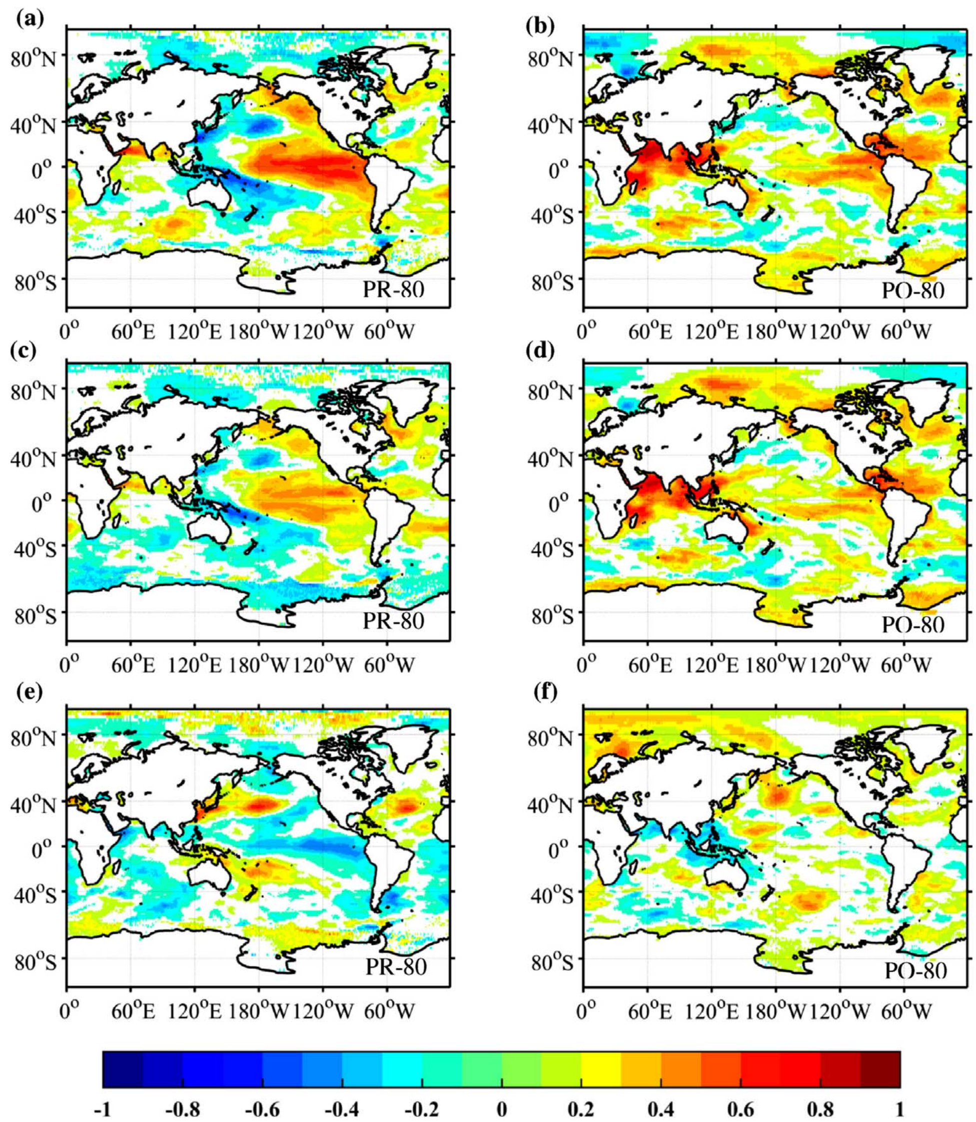

Figure 2. Correlations between the global SST and Mahanadi T_{max} (*a*) and (*b*), T_{min} (*c*) and (*d*), and precipitation (*e*) and (*f*) in monsoon season during the PR-80 and PO-80 time slots.

extended from the surrounding ocean regions of the MRB to Australia. Changes in the correlation between the SLP and precipitation are significant in most of the portions over 20°N–55°S during monsoon and (more prominently) in post-monsoon seasons. The difference in correlations of SLP with T_{max} and T_{min} from the PR-80 to PO-80 periods are more prominent during post-monsoon season and covers most of the portions between 30°N and 30°S (figure S4). In the case of Omega_500 hPa, correlation patterns are not continuous like SST and SLP. This may be because Omega_500 hPa is not a direct but a derived parameter and, hence, it is more noisy compared to SST and SLP. However, the shift in correlation patterns from the PR-80 to PO-80 periods in the case of T_{max} and T_{min} with Omega_500 hPa is still visualized and is prominent during post-monsoon season (figure S6). This additional analysis showed that changes in the hydroclimatology of the MRB in the 1980s are most likely to be contributed by both oceanic and atmospheric field, and majorly because of the well-known decadal shift in the Pacific.

To bring out the lead–lag relationship, concurrent lead (1–2 seasons) and lag (1–2 seasons) correlations of large-scale circulation indices (Niño indices, DMI, EQWIN, SOI, western and eastern equatorial Indian Ocean SST (IOD_E_Box, IOD_W_Box)) with T_{max}, T_{min} and precipitation on a seasonal scale were obtained. Table S3 and table S4 present the positive (▲) and negative (▼) correlations (lag-2, lag-1, lag-0, lead-1 and lead-2) at the 5% significance level, respectively, for the PR-80 and PO-80 periods. This analysis helped in understanding the linkages with large-scale circulation indices. The most obvious difference from PR-80 to PO-80 is the extent of association of the MRB hydroclimatology with all Niño indices. During PR-80, associations of the MRB hydroclimatology with all Niño indices (not Niño 3.4 alone), namely Niño1+2, Niño3, Niño3.4, Niño4, Trans-Niño and SOI are significant in most of the season

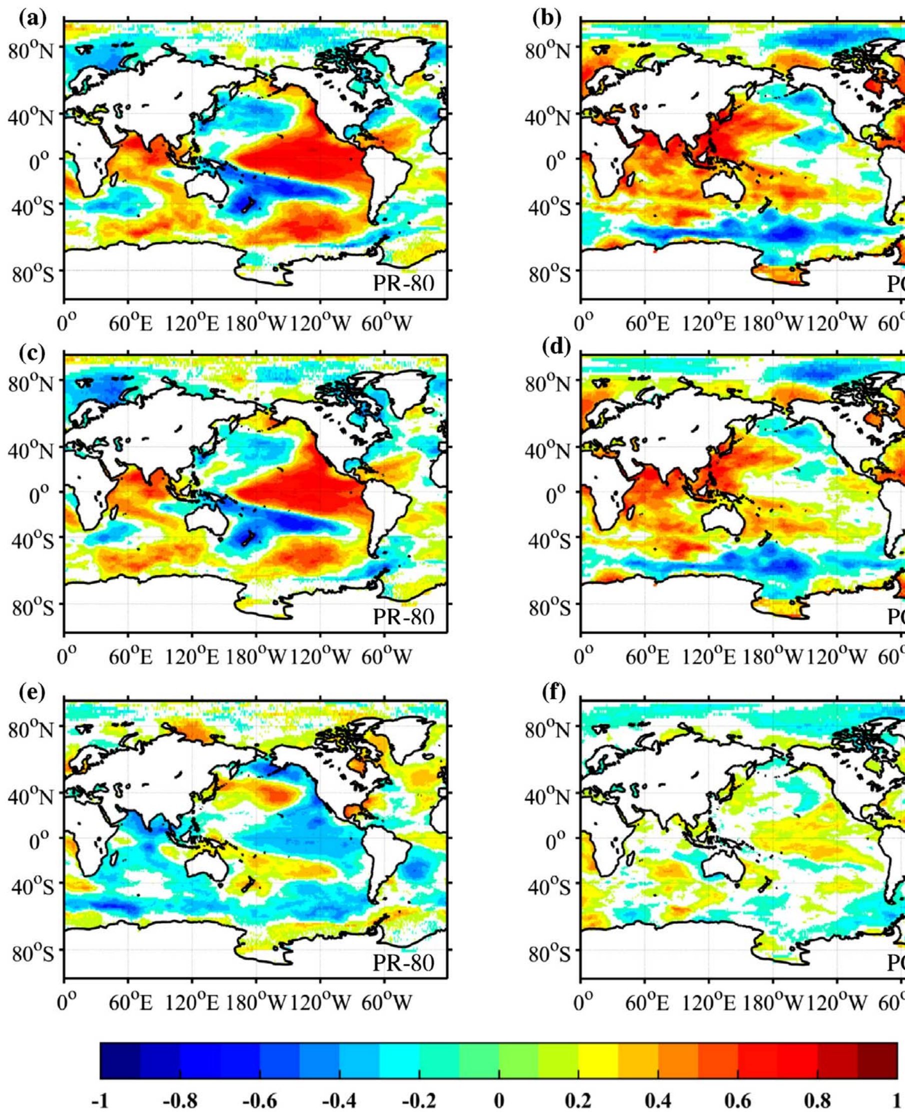

Figure 3. Correlations between the global SST and Mahanadi T_{max} (*a*) and (*b*), T_{min} (*c*) and (*d*), and precipitation (*e*) and (*f*) in post-monsoon season during the PR-80 and PO-80 time slots.

(except pre-monsoon). The number of significant correlations is higher for T_{max} and T_{min} compared to precipitation. Eastern and western equatorial Indian Ocean SSTs (IOD_E_Box, IOD_W_Box) are better associated with the MRB hydroclimatology than the DMI (table S4) and the EQWIN (table S3) indices. During PR-80, a significant association of precipitation with Niño3.4, Niño1+2, Niño3, Niño4 indices are witnessed (table S3). Further investigation may help to collaborate this link better.

Panda *et al* (2013) studied the influence of Niño3.4 and the DMI on the Mahanadi basin precipitation and stream flow during 1972–2005. They found a direct correspondence of Mahanadi stream flow and precipitation with ENSO and a decline in discharge at a rate of 3388×10^6 m^3 $decade^{-1}$. However, in this study, the global SST with all the Niño indices and the SST of whole Indian Ocean region were considered. The findings from this study provide strong evidence for abrupt changes in the MRB hydroclimatology in 1980. In the recent three decades, hydroclimatology was triggered more by the SST of equatorial Indian Ocean than ENSO effects. One of the main causes behind the shift could be the decadal shift in the tropical Pacific SST extending globally in the mid-1970s (Meehl *et al* 2009). Pacific SSTs and the Indian monsoon are associated through an interaction between the regional monsoon Hadley circulation and the Walker circulation, either at interdecadal or at interannual time scales (Krishnamurthy and Goswami 2000). Kosaka and Xie (2013) found the major cause behind the recent global warming hiatus to be the anomalous cool eastern Pacific SST and unprecedented strong Pacific trade winds. The impact of ENSO and IOD on the hydroclimatology of the MRB is found to be dominant in post-monsoon season. This suggests that the influence of ENSO on the Mahanadi temperature is different in respective seasons.

On the whole, it can be concluded that the MRB is sensitive to both climate change and variability, and was altered with respect to the considered time periods and seasons. This study has brought out several interesting features about the changing characteristics of the Mahanadi basin temperature and precipitation from the PR-80 to PO-80 periods. The mapping of the observed temperature and precipitation changes and their parallelism to the large-scale circulation modes (such as ENSO and IOD) are anticipated to aid the policy makers to manage various strategies.

4. Conclusions

Climate change and variability assessment of the MRB reflected several interesting features. The observed trends in the post-monsoon T_{max} and T_{min} were significant over the MRB during 1950–2012. Fingerprint-based detection and attribution analysis revealed that the observed pre-monsoon and monsoon T_{min} were consistent with the climate simulations, which include anthropogenic effects, and inconsistent with the natural external factors (solar and volcanic activities). It also indicated that the post-monsoon T_{max} change is not because of natural internal variability. A marked increasing trend was detected in precipitation of non-monsoon season during the same period. Significant change was observed in T_{min} during the recent three decades (PO-80) in post-monsoon season. Anthropogenic effects probably caused the recent changes in T_{min}.

The MRB hydroclimatology characteristics and its association with the global SST and SLP were obtained from seasonal correlation patterns. Post-monsoon season exhibited strong correlation patterns (for precipitation, T_{max} and T_{min}) compared to other seasons and a major shift in correlation patterns was witnessed around 1980. This shift from PR-80 to PO-80 is the most conspicuous change where the reversal of correlations from strongly positive to negative occurred over most of the Niño regions (post-monsoon T_{max} and T_{min} being dominant).

Global and regional temperature variability was influenced by the ENSO phenomenon (Kiladis and Diaz 1989). Lead-lag and concurrent correlations of different climatic indices (all Niño indices, SOI, DMI and EQWIN) with precipitation, T_{max} and T_{min} in different seasons were also obtained. Strong connections with all Niño indices and SOI were found during PR-80. The SST in the western equatorial Indian Ocean (IOD_W_Box) was highly correlated with post-monsoon T_{max} and T_{min} compared to DMI and EQWIN during PO-80. The Indian Ocean SST played a more important causative role compared to the Niño region SST during PO-80. The most striking feature of this study is the shifting of observed signals after 1980. More analysis is required to unveil the plausible cause behind this shift. Both climate change and variability are likely to impact the overall hydroclimatological changes in future. Hence this analysis will help to predict better the likelihood of occurrence of future events and in decision making about the potential effect of natural climate variability. It needs to be checked whether the effect is similar on the inflow of the Hirakud dam located in the MRB and should be a topic of future study.

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