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Hydroclimatic influence of large-scale circulation on the variability of reservoir inflow

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Abstract:

In this study, the nature of basin-scale hydroclimatic association for Indian subcontinent is investigated. It is found that, the large-scale circulation information from Indian Ocean is also equally important in addition to the El Niño-Southern Oscillation (ENSO), owing to the geographical location of Indian subcontinent. The hydroclimatic association of the variation of monsoon inflow into the Hirakud reservoir in India is investigated using ENSO and EQUatorial INdian Ocean Oscillation (EQUINOO, the atmospheric part of Indian Ocean Dipole mode) as the large-scale circulation information from tropical Pacific Ocean and Indian Ocean regions respectively. Individual associations of ENSO & EQUINOO indices with inflow into Hirakud reservoir are also assessed and found to be weak. However, the association of inflows into Hirakud reservoir with the composite index (*CI*) of ENSO and EQUINOO is quite strong. Thus, the large-scale circulation information from Indian Ocean is also important apart form the ENSO. The potential of the combined information of ENSO and EQUINOO for predicting the inflows during monsoon is also investigated with promising results. The results of this study will be helpful to water resources managers due to fact that the nature of monsoon inflow is becoming available as an early prediction. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS Hydroclimatic association; ENSO; EQUINOO; Monsoon; Reservoirs inflow; India; Prediction

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INTRODUCTION

It has been inferred recently that the temporal structure of the hydrologic time series are significantly influenced by the large-scale coupled atmospheric-oceanic circulations (Jain and Lall, 2001). The association between hydrologic events and the large-scale circulation phenomena, which are widely separated (planetary scale) across the globe, is referred as 'hydroclimatic teleconnection'. The hydroclimatic teleconnection between the large-scale coupled atmospheric-oceanic circulations and the basin-scale hydrologic variables is required to be determined for efficient management of water resources. For Indian subcontinent, owing to its geographical location, nature of the hydroclimatic teleconnection is significantly different from that for the rest of the world. The combined information of large-scale circulation phenomena from tropical Pacific Ocean and that from tropical Indian Ocean is salient in this regard (Gadgil *et al*., 2004; Maity and Nagesh Kumar, 2006). *Gadgil et al*. (2004) have shown an association of summer monsoon rainfall with both ENSO and EQUINOO. In fact, the extremes of the summer monsoon rainfall for last couple of decades are statistically associated with favorable (unfavorable) phases of ENSO or EQUINOO or both (Gadgil *et al*., 2004). Maity and Nagesh Kumar (2006) have established that the best prediction performance of monthly rainfall over India is obtained by considering both ENSO and EQUINOO as compared to that considering them individually. However, these studies deal with a large-spatial scale (continental scale) compared to river basin scale. For river basin scale, the responses of 'basin-scale' hydrologic variables such as, rainfall, surface runoff, reservoir inflow etc. to the 'large-scale' circulation phenomena are yet to be adequately established.

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HIRAKUD RESERVOIR

Hirakud reservoir is located on Mahanadi River in the state of Orissa in India, having a catchment area of 83,400 sq. km. (Figure 1). Hirakud reservoir is a multipurpose reservoir used for irrigation, flood control and hydropower generation. It provides water for irrigation of 1556·35 sq. km. of Kharif crop and 1083·85 sq. km. of Rabi crop. The water released for power production rejoins the river and irrigates further area of 4360 sq. km. in Mahanadi delta. The installed capacity of power generation is 307·5 MW through its two power houses. Besides, it provides flood protection for 9500 sq. km. of delta area (Patri, 1993). Thus, the operation policy of Hirakud reservoir plays an important role on the agricultural aspect, hydropower generation and flood control over downstream area. Annual variation of inflows into Hirakud reservoir is a very important factor for deciding its operation policy.

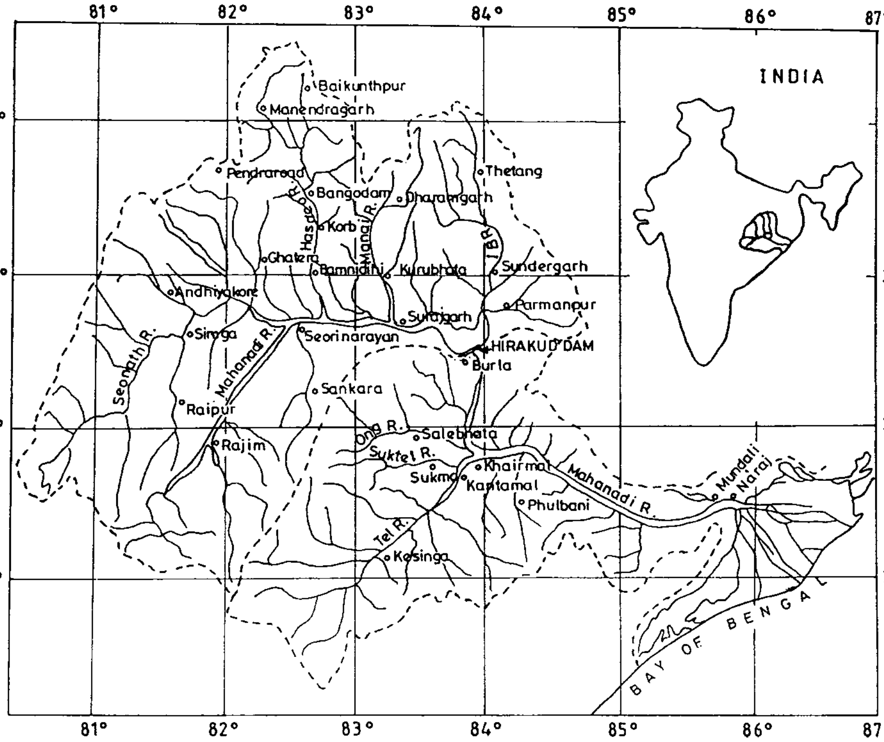

Figure 1. Location map of Hirakud reservoir and its catchment in Mahanadi Basin

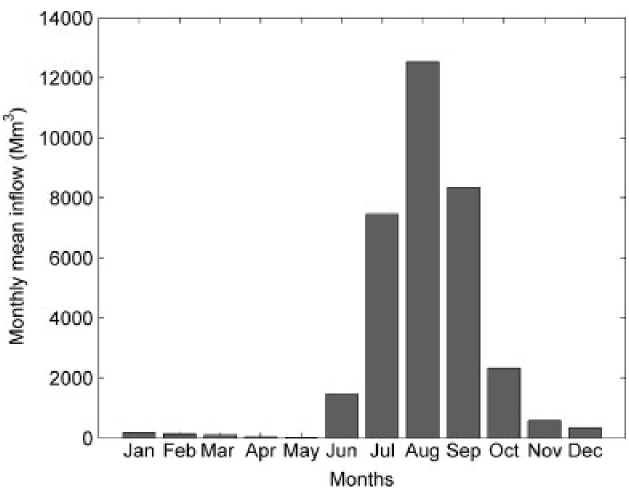

Figure 2. Monthly mean inflows into Hirakud reservoir

Mahanadi River is a rain fed river. The rain water during the monsoon season (June through September) is its main source. More than 80% of the annual inflow into Hirakud reservoir occurs during the months of June through September. However, inflow in the month of October is also considerable because the catchment remains wet immediately after the monsoon season and subsurface flow also contributes to the streamflow. Thus, the streamflow during June through October constitutes most of the annual inflow into Hirakud Reservoir as can be seen from Figure 2. When compared to the traditional approaches for inflow modeling (e.g., Mujumdar and Nagesh Kumar, 1990), in this study, association of reservoir inflows with the large-scale coupled atmospheric-oceanic circulations is investigated.

EL NIÑO-SOUTHERN OSCILLATION (ENSO) AND HYDROLOGIC VARIABLES

El Niño-Southern Oscillation (ENSO) is the coupled ocean-atmosphere mode of tropical Pacific Ocean (Cane, 1992). El Niño (La Niña) is the large-scale anomalous oceanic warming (cooling) of the tropical eastern Pacific region. El Niño (La Niña) is normally accompanied by a lower than normal (higher than normal) pressure in the eastern part and higher than normal (lower than normal) pressure in the western part of the Pacific Ocean. This see-saw variation of the pressure field is known as the Southern Oscillation. Acting together, the El Niño-Southern Oscillation (ENSO) is one of the main sources of interannual variation in weather and climate around the world (Kiladis and Diaz, 1989).

The association of ISMR (Indian summer monsoon rainfall) with ENSO is established long back (Rasmusson and Carpenter, 1983; Khandekar and Neralla, 1984; Mooley and Paolino, 1989). About the teleconnection mechanism between ISMR and ENSO events, Rasmusson and Carpenter (1983) inferred that, 'episodes of above normal Sea Surface Temperatures (SST) over the eastern and central equatorial Pacific are associated with a low SOI (Southern Oscillation Index), i.e., negative pressure anomalies in the southeast Pacific, and positive anomalies over the Indian Ocean region, a weaker than normal southwest monsoon over the Arabian Sea, and below normal rainfall over India'. According to Krishna Kumar *et al.* (1999), during the El Niño event, the rising limb of Walker circulation (the circulation of air in zonal direction near equator and its proximity, identified by Gilbert Walker) is shifted towards the central

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or eastern part of tropical Pacific Ocean and an anomalous subsidence exists over the Indian subcontinent. This subsidence, suppressing the convection and precipitation over Indian region, results in lower than normal rainfall. However, contrary to the long recognized negative correlation between the ISMR and El Niño events, India received slightly above normal rainfall in 1997 (Li *et al.*, 2001) when El Niño was observed in the Pacific Ocean. On the other hand, in 2002 the failure of Indian summer monsoon was completely unanticipated, although it was a weak El Niño year. No model could predict such a large deficit in Indian summer monsoon for 2002 (Gadgil *et al.*, 2003). According to Kane (1998), the relationship between ISMR and ENSO is not uniform for all the El Niño events. According to him "..... in some years, some other factors might be playing important roles......". Krishna Kumar *et al.* (1999) have shown that the historical relationship has been broken after 1970. These unanticipated experiences suggest that the response of monsoon to El Niño is not yet assessed adequately (Gadgil *et al.*, 2004) or more importantly that there are some other climate forcing events which are also influencing the Indian rainfall concurrently.

After the recent discovery of Indian Ocean Dipole (IOD) (Saji *et al.*, 1999; Webster *et al.*, 1999), it is established that relationship between ISMR and ENSO is modulated by IOD (Ashok *et al.*, 2001). Gadgil *et al.* (2004) have established that ISMR is linked to equatorial Indian Ocean oscillation (EQUINOO) which is the atmospheric part of Indian Ocean Dipole (IOD) mode. A brief description of EQUINOO is presented in the next section.

EQUATORIAL INDIAN OCEAN OSCILLATION (EQUINOO)

EQUINOO is the atmospheric component of the IOD mode (Gadgil *et al.*, 2003, 2004). During summer monsoon season (June-September), the convection over the Eastern part of the Equatorial Indian Ocean (EEIO, 90°–110 °E, 10 °S–0°) is negatively correlated to that over the Western part of the Equatorial Indian Ocean (WEIO, 50°–70 °E, 10 °S–10 °N). The anomalies in the sea level pressure and the zonal component of the surface wind along the equator are consistent with the convection anomalies. When the convection is enhanced (suppressed) over the WEIO, the anomalous surface pressure gradient is towards the west (east) so that the anomalous surface wind along the equator becomes easterly (westerly). The oscillation between these two states is called the EQUINOO (Gadgil *et al.*, 2003, 2004). EQuatorial zonal Wind INdex (EQWIN) is considered as an index of EQUINOO which is defined as the negative of the anomaly of the zonal component of surface wind in the equatorial Indian Ocean region (60°–90 °E, 2·5 °S–2·5 °N). The association of ISMR with EQUINOO is due to the association of the monsoon rainfall over the Indian region with the northward propagation of convective system generated over the Indian Ocean region (Gadgil *et al.*, 2004).

SCOPE AND ORGANIZATION OF THIS PAPER

As mentioned earlier, the summer monsoon rainfall over India is not only associated with ENSO, but also with EQUINOO. However, such association at basin-scale and its use in hydrologic forecasting is yet to be explored. Earlier studies for assessment of the hydroclimatic association between ENSO and the basin-scale streamflow in South Asian countries, indicated the necessity to establish the link with Indian Ocean circulation pattern apart from ENSO (Douglas *et al.*, 2001; Chowdhury, 2003; Zubair, 2003; Chowdhury and Ward, 2004). Thus, while investigating the hydroclimatic association between the basin-scale hydrologic variables of India and the large-scale atmospheric circulation, ENSO alone may not be sufficient. The circulation pattern from Indian Ocean region is equally important and is therefore to be considered additionally.

In this paper, the hydroclimatic teleconnection between the variation of inflow into Hirakud reservoir during monsoon and the large-scale circulations from both the Pacific Ocean and Indian Ocean regions has been investigated. The potential of the large-scale circulations information for predicting the inflow into Hirakud reservoir is also investigated.

The rest of the paper is organized as follows. The data used in this study is explained in section 2. In section 3, the individual association of ENSO & EQUINOO index with inflow into Hirakud reservoir is investigated. The association of inflow into Hirakud reservoir with ENSO and EQUINOO individually is discussed in section 4. In section 5, a composite index of ENSO and EQUINOO is developed and its association with the inflow into Hirakud reservoir is investigated. The association of inflow into Hirakud reservoir with the composite index (CI) of ENSO and EQUINOO is examined in section 6. In section 7, the performance of the composite index in predicting the inflow into the Hirakud reservoir is investigated. Finally, conclusions are presented in section 8.

DATA

The intensities of El-Niño events are generally assessed on the basis of the average SST over the different Niño regions in the Pacific Ocean, widely known as Niño 1 (10 °S–5 °S, 90 °W–80 °W), Niño 2 (5 °S–0°, 90 °W–80 °W), Niño 3 (5 °S–5 °N, 90 °W–150 °W), Niño 3·4 (5 °S–5 °N, 170 °W–120 °W) and Niño 4 (5 °S–5 °N, 160 °E–150 °W). It is also found that the summer monsoon rainfall over India is best correlated with temperature anomaly from Niño 3·4 region, which overlaps between Niño 3 and Niño 4 regions as can be noticed from their latitude-longitude limits.

Oceanic Niño Index (ONI) is used to represent the ENSO event. ONI is the three months running mean of Extended Reconstructed Sea Surface Temperature (ERSST, Smith and Reynolds, 2003) anomalies in the Niño 3·4 region (5 °S–5 °N, 120°–170 °W). Smith and Reynolds (2003) produced a global, extended reconstruction of sea surface temperature. Apart from other improvements, compared to the earlier analysis of SST, they include additional data from a new version of the Comprehensive Ocean–Atmosphere Data Set (COADS) release 2 (Slutz *et al.*, 1985; Woodruff *et al.*, 1998). This is a monthly data set with a spatial resolution of 2° by 2° with the gird intersections located at 88 °S, 86 °S, ..., 88 °N by 0°, 2 °E, ..., 2 °W. The grids are offset by 1° from original grids used in COADS so as to obtain better information of equatorial signals, such as ENSO (Smith and Reynolds, 2003).

As stated before, ONI (Oceanic Niño Index) is the three months running mean of sea surface temperature anomalies in the Niño 3·4 region (5 °S–5 °N, 120°–170 °W). To obtain the monthly anomaly values, the climatological values are subtracted from observed values. The climatological values are the long term means of the observed data for the period 1971–2000. The range of ONI values is −2·5 to +2·5. The data of ONI is obtained for the period 1958 to 1992 from the website of National Weather Service, Climate Prediction Centre of NOAA (http://www.cpc.noaa.gov/).

The monthly data of surface wind over the equatorial Indian Ocean region, for the period January 1958 to December 2003, is obtained from National Center for Environmental Prediction (http://www.cdc.noaa.gov/Datasets) to compute the EQWIN, which is the measure of EQUINOO as mentioned earlier. The EQWIN values are also obtained in a similar way as those of ONI. The climatological values of zonal wind over equatorial Indian Ocean region (60°–90 °E, 2·5 °S–2·5 °N) are subtracted from observed monthly values to obtain the zonal wind anomaly. The negative (multiplied by −1) of these values (according to the definition, as stated before, refer Gadgil *et al.*, 2004) are known as EQWIN. The range of EQWIN values is −3 to +3.

Monthly inflow data into the Hirakud reservoir, for the period 1958–1992, is obtained from the project report of Department of Irrigation, Government of Orissa (Patri, 1993). The data set from 1993 onwards is not available to us. So we had to restrict our analysis till that period. To our knowledge, there are no special extreme events that may affect the performance of overall analysis undertaken in this study. The time series of annual inflow into Hirakud reservoir is shown in Figure 3. The large interannual variation in the inflows is an important aspect for water resource management and for deciding the operation policy for the reservoir. As mentioned earlier, most of the annual inflow occurs in the monsoon period. Hence total inflow, for the period June through October, is considered as 'monsoon inflow'. The monsoon inflows are log transformed prior to analysis.

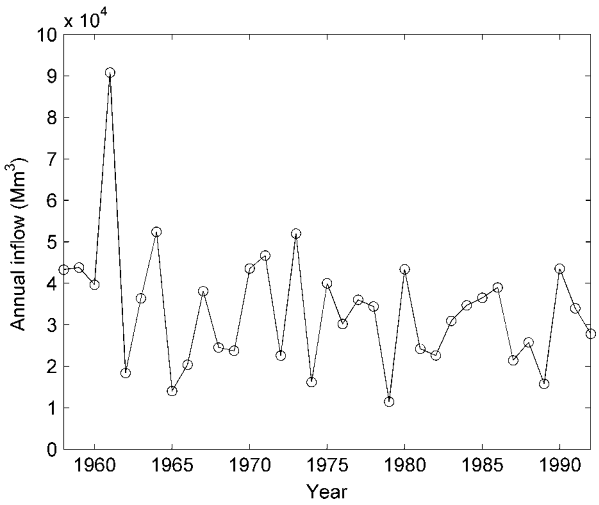

Figure 3. Time series of annual inflow into Hirakud reservoir

INDIVIDUAL ASSOCIATION OF ENSO & EQUINOO INDEX WITH THE INFLOW INTO HIRAKUD RESERVOIR

The association of ENSO with the inflow into Hirakud reservoir is investigated by composite pictures of SST from Niño 3·4 region for low as well as high flow years. From the composite analysis, a mild La Niña is observed for the lowest flow years whereas a mild El Niño is observed for the highest flow years. This observation contradicts the usual expectation (usually El Niño is associated with lower than normal ISMR and vice versa), which may be due to spatially non-uniform association of ENSO and summer monsoon rainfall over India.

The relationship of monsoon inflow into Hirakud reservoir with ENSO index (ONI) and with EQUINOO index (EQWIN) is investigated individually using lagged correlation analysis. Correlation coefficient, r_{xy} between two random variables, X and Y (samples being x_i and y_i, $i = 1, \cdots, n$) is calculated as

$$r_{xy} = \frac{1}{(n-1)} \sum_{i=1}^{n} \frac{(x_i - \overline{X})(y_i - \overline{Y})}{S_{XX} S_{YY}} \tag{1}$$

where $\overline{X}$ and $\overline{Y}$ are the means and S_{XX} and S_{YY} are the standard deviations of x_i and y_i respectively.

The partial correlation coefficient between two random variables X and Y after removing the effect of another random variable Z is calculated as

$$r_{xy/z} = \frac{r_{xy} - r_{xz} r_{yz}}{\sqrt{\left(1 - r_{xz}^2\right)\left(1 - r_{yz}^2\right)}} \tag{2}$$

where r_{xy}, r_{xz} and r_{yz} denote correlation coefficients between the variables, indicated by the suffixes. It may be noted that the correlation coefficient is the measure of linear association between two variables. This is irrespective of the effect from other variables on either of the two variables for which correlation coefficient is measured, whereas the partial correlation coefficient is the measure of linear association between two variables, after

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removing the effect of other variables on the association between two variables for which correlation coefficient is measured. Further, it may also be noted that the Normal distribution function is generally employed to check the significance levels as used in this study.

The correlation coefficients between the monsoon inflow into Hirakud reservoir and ONI and those between the monsoon inflow into Hirakud reservoir and EQWIN for different premonsoon periods were computed and presented in Table I. It is observed that ONI for the period December (previous year) through February (current year) is maximum correlated (0·207) with monsoon inflow. Similarly EQWIN, averaged over the period January (current year) through March (current year), is highest correlated (−0·245) with the monsoon inflow. It can also be observed that the correlation coefficients with EQWIN are always negative whereas those with ONI are mostly positive. A negative correlation between EQWIN and inflow indicates the out-of-phase relationship between them. The reason could be that the convective activity increases over the western part of Indian Ocean. Being located in the eastern part of India, the rainfall might be lower-than-normal over the Mahanadi basin, which eventually causes the decreased inflow into the Hirakud reservoir. On the other hand, for the ENSO it is opposite, i.e., it is positively correlated in most of the cases. This contradicts the overall negative correlation with ENSO and rainfall over India. Even though an obvious reasoning is not possible to be adduced, it may be attributed to the spatial non-homogenity of the association between ENSO and rainfall over different parts of India.

These correlation coefficients are not statistically significant at 95% significance level (p-values 0·235 are 0·157 respectively). However, considering ONI and EQWIN from these periods, a partial correlation coefficient of 0·36 is obtained between the monsoon inflow and ONI (after removing the effect of EQWIN) using eqn (2). Similarly, a partial correlation coefficient of −0·38 is obtained between the monsoon inflow and EQWIN (after removing the effect of ONI). These correlation coefficients are statistically significant at 95% significance level (p-values are 0·033 and 0·024 respectively).

Thus, although the correlation coefficients between the monsoon inflow and ONI as well as monsoon inflow and EQWIN are not statistically significant, the partial correlation coefficients between monsoon inflow and ONI (EQWIN) after removing the effect of EQWIN (ONI) are statistically significant. This indicates that both the climate indices are jointly associated with the monsoon inflow into Hirakud reservoir. Before investigating their combined influence, their individual association is investigated.

Table I. Correlation coefficients of monsoon inflow into Hirakud reservoir with ONI and EQWIN for different premonsoon periods

Period	Correlation Coefficient with ONI	Correlation Coefficient with EQWIN
Dec*, Jan, Feb	0·207	−0·194
Jan, Feb, Mar	0·153	−0·245
Feb, Mar, Apr	0·053	−0·239
Mar, Apr, May	−0·040	−0·077

* Month of previous year.

ASSOCIATION OF INFLOW INTO HIRAKUD RESERVOIR WITH ENSO AND EQUINOO INDIVIDUALLY

The conditional probabilities of low, medium and high inflows are investigated for different ranges of ENSO and EQUINOO indices. Inflow value, lower than the mean minus 0·5 times standard deviation, is categorized as low inflow; inflow value, within the range of ±0·5 times standard deviation from the mean, is categorized as medium inflow; and the inflow value, higher than mean plus 0·5 times standard deviation, is categorized as high inflow. The total ambit of each index is divided into three approximately equal ranges to investigate nature of inflows in different ranges of indices. These ranges are classified as lower, middle and upper 1/3rd range of the indices. The number of occurrences of category wise inflows in different ranges of ONI and EQWIN are shown in Tables II and III respectively. The corresponding conditional probabilities are mentioned in parentheses in these tables. Even though the number of observations is small, it may be observed that, in general, the inflows are not so well associated with the different ranges of both these indices, except that the high

Table II. Number of low, medium and high inflow events and their conditioned probabilities (in parentheses) for different ranges of Oceanic Niño Index (ONI) for the period Dec*, Jan, Feb

ONI range	NL (CP)	NM (CP)	NH (CP)
<−0·8 (Lower 1/3rd)	2 (0·40)	2 (0·40)	1 (0·20)
−0·8 to 0·8 (Middle 1/3rd)	8 (0·35)	5 (0·22)	10 (0·43)
>0·8 (Upper 1/3rd)	3 (0·43)	2 (0·285)	2 (0·285)

NL—Number of occurrence(s) of low inflow (lower than the mean inflow minus 0·5 times the standard deviation)
NM—Number of occurrence(s) of medium inflow (within the range of ±0·5 times the standard deviation from mean inflow)
NH—Number of occurrence(s) of high inflow (higher than the mean inflow plus 0·5 times the standard deviation)
CP—Conditional probability

Table III. Number of low, medium and high inflow events and their conditional probabilities (in parentheses) for different ranges of equatorial zonal wind index from Indian Ocean region (EQWIN) for the period Jan, Feb, March

EQWIN range	NL (CP)	NM (CP)	NH (CP)
<−0·6 (Lower 1/3rd)	0 (0·00)	1 (0·17)	5 (0·83)
−0·6 to 0·6 (Middle 1/3rd)	12 (0·46)	7 (0·27)	7 (0·27)
>0·6 (Upper 1/3rd)	1 (0·33)	1 (0·33)	1 (0·33)

NL, NM, NH, CP are as described below Table II.

inflows are well associated with low values of EQWIN (conditional probability being 0·83). It may be noted that 35 years of data is used for this analysis and for most of the cases both the indices fail to be well associated with the inflows.

It is worthwhile to investigate when and why the indices fail, to get at more insight. The ENSO index, corresponding to low and high inflow years are averaged. It is found that average ENSO index is 0·17 for high inflow years and −0·18 for low inflow years. This suggests that a positive (negative) ENSO index is mostly associated with high (low) inflows. This is true for only 7 out of 13 high inflow events, whereas, for other 6 events, this relation does not hold good. Thus, ENSO index fails approximately for 46% cases. Next, the EQUINOO index is investigated in a similar way. It is found that, the average EQUINOO index is −0·27 for high inflow years and 0·04 for low inflow years. It is interesting to notice that, all the 6 events for which discrepancies were observed between ENSO index and inflow category, EQUINOO index is negative. Now, the question is reversed to find the number of high inflow years when EQUINOO index is negative. It is observed that 7 out of 13 cases match. Thus, again, EQUINOO index fails for 46% cases. However, it is also noticed that, out of these 7 years, ENSO index is negative for 6 years. Thus, if the observations for high inflow years are summarized, it is observed that high inflow years are associated with either positive ENSO index in conjunction with positive EQUINOO index (6 years) or negative EQUINOO index in conjunction with negative ENSO index (6 years). However, there is one high inflow year for which this relationship doesn't hold good (i.e., ENSO index and EQUINOO index are not of the same sign). Thus, 12 out of 13 high inflow years are associated with the combined information of both the indices. Similar investigation for the low inflow years shows that 9 out of 13 low inflow years are associated with the combined information of both the indices (ENSO index and EQUINOO index are opposite in sign). Thus both the indices fail for significant number of cases when considered individually. However, combined information of both the indices is able to explain most of the cases. This observation motivates to combine the indices and check the association of the combined index with the inflow into Hirakud reservoir.

COMPOSITE INDEX OF ENSO AND EQUINOO AND ITS ASSOCIATION WITH THE INFLOW INTO HIRAKUD RESERVOIR

ENSO and EQUINOO indices are linearly combined by least square technique. The linearly combined index is named composite index (*CI*) of ENSO and EQUINOO indices. Thus,

$$CI = \alpha.EN + \beta.EQ \tag{3}$$

where, *EN* is ENSO index (ONI), *EQ* is EQUINOO index (EQWIN) and α, β are the multiplying coefficients, which are obtained by minimizing the summed square errors,

$$S = \sum_{i=1}^{n}[IA_i - (\alpha.EN_i + \beta.EQ_i)]^2 \tag{4}$$

where IA_i is the i^{th} inflow (log transformed) anomaly, n is data length. To obtain the estimates of α and β, the sum of square errors, S, is minimized with respect to $\hat{\alpha}$ and $\hat{\beta}$, where $\hat{\alpha}$ and $\hat{\beta}$ are the estimates of α and β respectively. The obtained estimates of α and β are 0·366 and −0·577 respectively. In a statistical sense, these estimates are known as partial effects. Thus, the obtained equation for the composite index (*CI*) is

$$CI = 0{\cdot}366\ EN - 0{\cdot}577\ EQ \tag{5}$$

The correlation coefficient obtained between the composite index (*CI*) and the monsoon inflow into Hirakud reservoir is statistically significant at 95% significance level (0·435, p value 0·0084). Thus, even though the individual indices of ENSO and EQUINOO are poorly associated with monsoon inflow, their composite index is well associated with it.

It is relevant to mention here, that both ENSO and EQUINOO are two independent large-scale atmospheric circulation phenomena (Saji *et al*., 1999; Webster *et al*., 1999) and their effects are likely to be additive. In fact, it was established by researchers (Ashok *et al*., 2001; Gadgil *et al*., 2004) that the relationship between ENSO and ISMR is significantly modulated by IOD mode (EQUINOO is the atmospheric component of IOD mode). Thus, the ISMR is influenced by both the large-scale atmospheric circulations (ENSO and EQUINOO). The monsoon inflow into Hirakud reservoir is also associated with ISMR. So, the monsoon inflow into Hirakud reservoir is necessarily influenced by both ENSO and EQUINOO. Statistical evidence of this fact is that, even though the individual correlations between inflow and ONI (ENSO index) and those between inflow and EQWIN (EQUINOO index) are not strong, the partial correlation coefficients between inflow and ONI (EQWIN) after removing the effect of EQWIN (ONI) are statistically significant at 95% significance level, as mentioned earlier. These correlation coefficients indicate that both the climate indices influence the monsoon inflow into Hirakud reservoir and that ONI (EQWIN) is suppressing the partial effect of EQWIN (ONI). After establishing the linear combination of ONI and EQWIN, their partial contribution towards the variation of inflow into the Hirakud reservoir is examined. As a consequence, the correlation coefficient between composite index (*CI*) and monsoon inflow is statistically significant as shown earlier.

ASSOCIATION OF INFLOW INTO HIRAKUD RESERVOIR WITH THE COMPOSITE INDEX (CI)

To investigate the association between inflow into Hirakud reservoir and composite index (*CI*), the conditional probabilities of high, medium and low inflows,

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Table IV. Number of low, medium and high inflow events and their conditional probabilities (in parentheses) for different ranges of composite index (*CI*)

CI range	NL (CP)	NM (CP)	NH (CP)
<−0·3 (Lower 1/3rd)	5 (0·71)	2 (0·29)	0 (0·0)
−0·3 to 0·3 (Middle 1/3rd)	5 (0·30)	5 (0·30)	7 (0·40)
>0·3 (Upper 1/3rd)	3 (0·27)	2 (0·18)	6 (0·55)

NL, NM, NH, CP are as described below Table II.

conditioned on different ranges of *CI*, were computed along with the number of their occurrences and presented in Table IV. The classification of high, medium and low inflows is the same as adopted earlier. Different ranges of *CI* values are classified as lower, middle and upper 1/3rd of its full range. It can be observed from Table IV that, the probabilities of low, medium and high inflows, conditioned on lower 1/3rd range of *CI* value (i.e., $CI < -0{\cdot}3$), are 0·71, 0·29 and 0·00 respectively. Similarly, the probabilities of low, medium and high inflow, conditioned on upper 1/3rd range of *CI* value (i.e., $CI > 0{\cdot}3$), are 0·27, 0·18 and 0·55 respectively. It is worthwhile to mention that the unconditional probabilities of low and high inflow are equally probable both being 0·37. Thus, it is clearly observed that low inflows are highly associated with low values of composite index, whereas high inflows are highly associated with high values of composite index in contrast to their unconditional probabilities. In the case of middle range of *CI*, the probabilities of different categories of inflows are more or less equally probable. However, for water resources management, low and high inflows (high deviations) are more important than normal inflows (small deviations) as decisions are critical in former cases from the water management point of view.

PERFORMANCE OF THE COMPOSITE INDEX IN PREDICTING INFLOW INTO HIRAKUD RESERVOIR

It is observed in the previous section that the conditional probabilities of low and high inflows, conditioned on composite index (*CI*), are much higher than their unconditional probabilities. In view of the observed higher dependence, the composite index can be used to predict the inflow into Hirakud reservoir which will significantly help the water resource management. A linear regression analysis is performed between log transformed monsoon inflows and composite index (*CI*). Data for the period 1958 to 1980 is used to find out the regression relationship and the model performance is tested for the period 1981–1992. The predicted inflow values (log scale) are back transformed to obtain the actual monsoon inflows. A plot of the observed and the predicted monsoon inflows is presented in Figure 4. The difference between the observed and the predicted values are shown on this figure as errors. The magnitude of errors (in percentage) with respect to climatological (long term) mean are also shown within parentheses.

As the predictions are made with a couple of months lead-time, it may be proper to categorize the predictions with 10% error (with respect to long-term mean) as excellent; with 10–20% error as good; with 20–30% error as satisfactory; and with >30% error as poor. Thus, it can be observed from the Figure 4 that, the predictions for the years 1983, 1985, 1986 and 1991 are within 10% error; predictions for the years 1981, 1987 and 1992 are within 10–20% error; predictions for the years 1982 and 1989 are within 20–30% error and predictions for the years 1984, 1988 and 1990 are poor, the errors being more than 30%. Thus, the predictions are made with reasonable accuracy for 75% cases (9 out of 12) of the

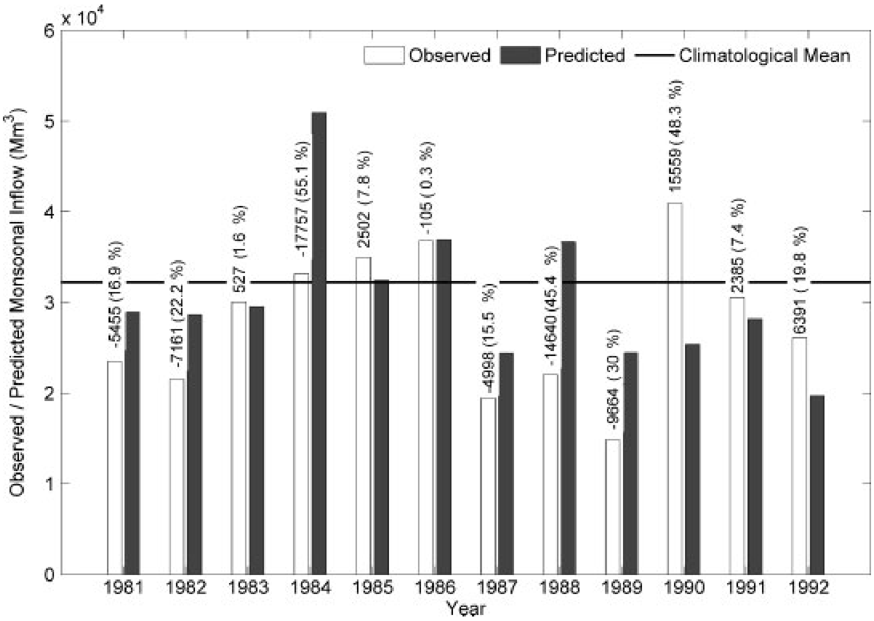

Figure 4. Plot of observed and predicted monsoon inflows into Hirakud reservoir using composite index (CI). The difference between the observed and the predicted values are shown as errors. The magnitude of errors (in percentage) with respect to climatological (long term) mean is also shown within parentheses

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testing period. Among the poor performance years, it is observed that monsoon inflow is under-predicted for the year 1990 and over-predicted for the years 1984 and 1988. It may be observed that, except for these years, better information compared to the climatological mean is obtained. Thus, the natural variation of inflow, to a great extent, is effectively captured. It is obvious that if more data length is available the model performance would be even better.

The performance of the model using only ONI and only EQWIN is also investigated keeping the model development period and testing period same as that of combined index, each index being used one at a time. While using only ONI, the predictions for the year 1991 is within 10% error; predictions for the years 1981 and 1984 are found to be within 10–20% error; predictions for the years 1982, 1985, 1986, 1989 and 1990 are within 20–30% error and predictions for rest of the years (1983, 1987, 1988 and 1992) are poor, the errors being more than 30%. Similarly, while using only EQWIN, the predictions for the year 1983, 1985, 1986 and 1991 are within 10% error; predictions for the years 1981, 1987 and 1992 are within 10–20% error; prediction for the year 1982 is within 20–30% error and predictions for rest of the years (1984, 1988, 1989 and 1990) are poor, the errors being more than 30%. Thus, the overall performance reveals that for both the cases (using only ONI and only EQWIN), reasonable accuracy is obtained in 66·7% cases (8 out of 12), errors being within 30%. Moreover, the tendency of larger errors in individual years, as compared to those in the case of using combined index, was also observed.

It may be noted that the composite index is obtained from the circulation indices (ENSO and EQUINOO) well before the monsoon season. In particular, the predictions are available at the end of March for the ensuing season (June through October). Thus, the information of the large-scale circulations, being used to predict monsoon inflows, provides a warning time of a few months before the ensuing monsoon period. Such early prediction of the inflows for the ensuing monsoon season will be a valuable input to the water resources managers for agricultural and socio-economic decision making. A couple of months', time would be sufficient to decide the agricultural strategies with respect to the predicted status of the ensuing monsoon season and calculate the irrigation requirements. For other decisions, such as, reservoir operation, flood control, etc. the availability of the information, a couple of months in advance, would be very useful for the water resources decision maker.

CONCLUSIONS

In this study, the association of large-scale atmospheric circulations with the basin-scale hydrologic variable, namely inflow into Hirakud reservoir in India is investigated. El Niño-Southern Oscillation (ENSO) was used in different parts of the world for this purpose and its association with the hydrologic variable was convincingly established. However, for Indian subcontinent, owing to its geographical location, the large-scale circulation information from Indian Ocean is also equally important, in addition to the ENSO. This issue is explored in this paper and it is established that the combined information of large-scale circulation information from Pacific Ocean and Indian Ocean yields better performance. It is observed that the monsoon inflow into Hirakud reservoir is associated with the combined influence of El Niño-Southern Oscillation (ENSO) from tropical Pacific Ocean and Equatorial Indian Ocean Oscillation (EQUINOO) from tropical Indian Ocean region. The available pre-monsoon information of both the circulation phenomena is used to investigate their association with the monsoon (June through October) inflows into Hirakud reservoir. It is observed that though the association between the ENSO and monsoon inflows into the reservoir as well as EQUINOO and monsoon inflows into the reservoir are poor, their combined association with annual inflows into the reservoir is significantly high. A composite index (*CI*) of ENSO and EQUINOO has been developed by least square technique. It is observed that there exists a stronger association of inflow into Hirakud reservoir with this *CI* than those with either ENSO or EQUINOO individually. Thus, the stronger predictive skill of the composite index of ENSO and EQUINOO, as compared to their individual potentials, is established for the extreme inflow values. It is also observed that the conditional probabilities of low and high inflow, conditioned on composite index (*CI*), are much higher than their unconditional probabilities. A linear regression analysis shows that the variation of inflow can be captured to a great extent by using the composite index. It is also important to mention here that the association between large-scale circulation patterns and basin-scale hydrologic response is not spatially uniform. Thus, the association may vary from one basin to another and also from one location to another. However, the same procedure can be followed to investigate such association. The developed equation to obtain combined index may be different in terms of the multiplying coefficients (α & β) depending on the location of the catchment.

An important aspect of this approach is that it does not use the rainfall information over the catchment. Most of the catchments in developing countries are not well gauged, which creates a bottleneck for developing a real-time alarm system for the extreme phenomena, such as, droughts and floods. The present approach provides the information of monsoon inflows well before the ensuing monsoon period. Thus, the consequent higher prediction lead-time helps in better planning of utilization of the expected water resources by providing early alert, giving an opportunity for early decision making.

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REFERENCES

Ashok K, Guan Z, Yamagata T. 2001. Impact of Indian Ocean dipole on the relationship between the Indian monsoon rainfall and ENSO. *Geophys. Res. Lett.*, **28**: 4499–4502.

Cane MA. 1992. "Tropical Pacific ENSO models: ENSO as a mode of the coupled system." *Climate System Modeling*, KE Trenberth, Ed., Cambridge University Press: 583–689.

Chowdhury MD. R. 2003. The El Niño-Southern Oscillation (ENSO) and seasonal flooding—Bangladesh. *Theor. Appl. Climatol.* **76**: 105–124, DOI: 10·1007/s00704-003-0001-z.

Chowdhury MD. R, Ward N. 2004. Hydro-Meteorological Variability in the Greater Ganges–Brahmaputra–Meghna Basins. *Int. J. Climatol.*, **24**: 1495–1508, DOI: 10·1002/joc.1076.

Douglas WW, Wasimi SA, Islam S. 2001. The El Niño—Southern oscillation and long-range forecasting of flows in the Ganges. *Int. J. Climatol.*, **21**: 77–87.

Gadgil S, Vinayachandran PN, Francis PA. 2003. Droughts of the Indian summer monsoon: Role of clouds over the Indian Ocean. *Current Science*, **85**(12): 1713–1719.

Gadgil S, Vinayachandran PN, Francis PA, Gadgil S. 2004. Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation. *Geophys. Res. Lett.*, **31**: L12213, DOI: 10·1029/2004GL019733.

Jain S, Lall U. 2001. Floods in a changing climate: Does the past represent the future? *Water Resour. Res.*, **37**(12): 3193–3205.

Kane RP. 1998. Extremes of the ENSO phenomenon and Indian summer monsoon rainfall. *Int. J. Climatol.*, **18**: 775–791.

Khandekar ML, Neralla VR. 1984. On the relationship between the sea surface temperatures in the equatorial Pacific and the Indian monsoon rainfall. *Geophys. Res. Lett.*, **11**: 1137–1140.

Kiladis GN, Diaz HF. 1989. Global climatic anomalies associated with extremes in the Southern Oscillation. *J. Climate*, **2**: 1069–1090.

Krishna Kumar K, Rajagopalan B, Cane MA. 1999. On the weakening relationship between the Indian Monsoon and ENSO. *Science*, **284**: 5423, DOI: 10·1126/science.284·5423·2156.

Li T, Zhang YS, Chang CP, Wang B. 2001. On the relationship between Indian Ocean sea surface temperature and Asian summer monsoon. *Geophys. Res. Lett.*, **28**: 2843–2846.

Maity R, Nagesh Kumar D. 2006. Bayesian dynamic modeling for monthly Indian summer monsoon rainfall using El Niño-Southern Oscillation (ENSO) and Equatorial Indian Ocean Oscillation (EQUINOO). *J. Geophys. Res.*, **111**: D07104, DOI: 10·1029/2005JD006539.

Mooley DA, Paolino DA. 1989. The response of the Indian monsoon associated with the change in sea surface temperature over the eastern south equatorial Pacific. *Mausam*, **40**: 369–380.

Mujumdar PP, Nagesh Kumar D. 1990. Stochastic models of streamflow—Some case studies. *Hydrological Sciences Journal*, **35**(4): 395–410.

Patri S. 1993. *Data on flood control operation of Hirakud dam*, Report, Dept. of Irrigation, Gov. of Orissa, India, [Available from Executive Engineer, Main Dam Division, Dept. of Irrigation, Gov. of Orissa, P.O.—Burla, Sambalpur, Orissa, India].

Rasmusson EM, Carpenter TH. 1983. The relationship between eastern equatorial Pacific sea surface temperature and rainfall over India and Sri Lanka. *Mon. Wea. Rev.*, **111**: 517–528.

Saji NH, Goswami BN, Vinayachandran PN, Yamagata T. 1999. A dipole mode in the tropical Indian Ocean. *Nature*, **401**: 360–363.

Smith TM, Reynolds RW. 2003. Extended reconstruction of global sea surface temperatures based on COADS data (1854–1997). *J. Climate*, **16**: 1495–1510.

Slutz RJ, Lubker SJ, Hiscox JD, Woodruff SD, Jenne RL, Joseph DH, Steurer PM, Elms JD. 1985. COADS: Comprehensive Ocean–Atmosphere Data Set. *Release* **1**: 262 pp.

Webster PJ, Moore AM, Loschnigg JP, Leben RR. 1999. Coupled oceanic-atmospheric dynamics in the Indian Ocean during 1997–98. *Nature*, **401**: 356–360.

Woodruff SD, Diaz HF, Elms JD, Worley SJ. 1998. COADS Release 2 data and metadata enhancements for improvements of marine surface flux fields. *Phys. Chem. Earth*, **23**: 517–527.

Zubair L. 2003. Sensitivity of Kelani streamflow in Sri Lanka to ENSO. *Hydrol. Process.*, **17**: 2439–2448.

Web Refrences: http://www.cpc.noaa.gov/; http://www.cdc.noaa.gov/Datasets.