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THE INDIAN SOCIETY FOR HYDRAULICS
JOURNAL OF HYDRAULIC ENGINEERING

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# REVIEW OF HYDROCLIMATIC TELECONNECTION BETWEEN HYDROLOGIC VARIABLES AND LARGE-SCALE ATMOSPHERIC CIRCULATION PATTERNS WITH INDIAN PERSPECTIVE

by

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## ABSTRACT

Hydroclimatic teleconnection between hydrologic variables and large-scale atmospheric circulation phenomena is being studied worldwide and gaining more and more interest in recent years due to its potential use in hydrologic time series analysis and forecasting. In this paper a review of such related work is presented. First, characteristics of major large-scale atmospheric circulation phenomena from tropical Pacific Ocean and Indian Ocean region are explained. El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) mode from tropical Pacific Ocean and Indian Ocean respectively are selected and their global influences on hydrologic variables through hydroclimatic teleconnection are elaborated. Potential predictive power of such large-scale indices for hydrologic variables is explained based on the established research work across the world. Research opportunities, in this direction, are then explained in Indian perspective. A preliminary analysis is also presented in this regard. Predictive potential of such large-scale indices is of immense use to water resources community.

**KEY WORDS :** El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Equatorial Indian Ocean Oscillation (EQUINOO), Hydroclimatic teleconnection, Monsoon rainfall.

## INTRODUCTION

Natural variability of different hydrologic variables, such as, rainfall, streamflow etc., is of importance to the socio-economic status of an agriculture-based country like India. Extremes of these variables cause significant economic loss. Though reliable

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**Note :** Written discussion of this paper will be open until 30th June 2007.

prediction of hydrologic variables is scientifically challenging, it is essential for planning and devising agricultural strategies and for better management of water resources of the country.

Hydrologic variables are significantly linked with the atmospheric circulation. Such links can be modeled in two different ways - a) Simulation through general circulation models (GCMs) and b) Analysis of statistical relationship between hydrologic variables and atmospheric/oceanic variables from different parts of the world. Such relationship is known as 'hydroclimatic teleconnection'.

Simulation through general circulation models (GCMs) indicates a potential climate change effect on hydrology and water resources. However, potential skill of GCM drastically decreases a) from continental or hemispheric spatial scale to local subgrid scale, b) from free tropospheric variables to surface variables, c) from climate related variables i.e., wind, humidity, pressure, temperature etc. to precipitation, runoff. soil moisture etc. while the later, in each case, is more important for hydrologic regime. Macroscale hydrological modeling, dynamic downscaling and statistical downscaling techniques of GCM output to regional scale are widely used to narrow the gap between GCM ability and hydrologic requirements (Xu, 1999). Some work has been done towards this direction in India (Gosain et al., 2003; Ghosh and Mujumdar, 2006). However, macroscale hydrological models deal with large river basins ($10^4$ km$^2$ or more) to continental scale. 'Downscaling' refers to the calculation of spatially distributed grided data at higher resolution from its lower resolution. Two different ways to downscale GCM output are statistical and dynamic. Statistical invariance is the basic assumption of any statistical downscaling technique which is questionable under the climate change scenario. Dynamic downscaling includes the regional climate models (RCMs) which still fail to meet the scale of hydrologic system and thus the downscaling techniques still needed for the output from these models (Xu, 1999). Another way to asses the impact of atmospheric circulation on 'basin-scale' hydrologic variables is to investigate the hydroclimatic teleconnection between them which is the interest of this paper. It may be worth noting here that the significant association between hydrologic events and large-scale atmospheric circulation patterns, which are widely separated (planetary scale) on the globe is referred as 'hydroclimatic teleconnection'. It is recently being understood that temporal structure of hydrologic time series is significantly forced by large-scale atmospheric circulation patterns through hydroclimatic teleconnection (Jain and Lall, 2001).

In this paper, such research work is reviewed and research opportunities in Indian perspective are explored. Future research scope in this direction is also outlined as hydrology is linked closely to the vagaries of monsoon over the Indian region. A preliminary analysis is presented about the hydroclimatic teleconnection between all India monthly rainfall and large-scale atmospheric circulation patterns from tropical

Pacific and Indian Ocean. Before discussing the hydroclimatic teleconnection, large-scale atmospheric circulation phenomena, such as El Niño-Southern Oscillation (ENSO) from Pacific Ocean, and Indian Ocean Dipole (IOD) mode from Indian Ocean are briefly discussed here.

## El Niño-Southern Oscillation (ENSO)

El Niño Southern Oscillation (ENSO) is the coupled Ocean-atmosphere mode of tropical Pacific Ocean (Cane, 1992). In normal years, sea surface temperature of the western part of equatorial Pacific Ocean remains warmer than that of the eastern part. But in some anomalous years this situation changes drastically. Sea surface temperature of the eastern part of equatorial Pacific Ocean becomes warmer-than-normal which is known as El Niño. A contrary situation is known as La Niña. El Niño is normally accompanied by a change in the sea surface pressure field, between eastern and the western parts of the Pacific Ocean. In normal years, pressure at the eastern part of Pacific Ocean is higher than that of western part, but in the years of El Niño, the pressure field is reversed, i.e., the anomalous pressure in the eastern part of the Pacific Ocean becomes lower than that of western part. This sea-saw variation of the pressure field, between eastern and western parts of Pacific Ocean, is called the Southern Oscillation. Acting together, the oceanic and atmospheric parts are jointly known as El Niño-Southern Oscillation (ENSO).

## Impact of ENSO and Recent Changes

ENSO is one of the main sources of interannual variability in weather and climate around the world (Kiladis and Diaz, 1989). The global pattern of hydro-climatological responses to ENSO is the result of physical alterations in the Ocean-atmosphere system. These responses clearly contrast between El Niño and La Niña events and they are completely opposite to each other in some cases. According to Allan et al. (1996) 'the El Niño phase is dominated by the rainfall deficiencies (dry and drought conditions) over Africa, the Indian subcontinent, northern China, Australia, northern South America and the Caribbean. Dry or drought conditions also lead to low river discharge in the Nile (Egypt), Senegal (Senegal), Orange (South Africa), Krishna (India), Murray-Darling (Australia) and Amazon (Brazil) river system.' Surplus rainfall, as a result of El Niño events, is observed over much of the western Europe, parts of eastern Africa, the Western Cape of South Africa, Vietnam, central China to southern Japan, the South Island of New Zealand, the Grate Basin and Gulf regions of the United States and northern Mexico, central Chile and southeastern Argentina. The La Niña phase shows almost the opposite configuration of response to the El Niño. Enhanced rainfall patterns tend to dominate over Africa, the Indian subcontinent, northern China, Australia and northeastern South America. River discharge is high in major river systems of the Nile, Senegal, Orange, Krishna, Murray-Darling and

Amazon. Monsoonal/tropical-linked summer rainfall is enhanced over southern Africa and India, and prominent cloud band influences lead to rainfall surplus regions over southern Australia and southern Africa.

For Indian subcontinent, general impact of an El Niño event, as broadly stated above, is shown to be a lower-than-normal rainfall and opposite in case of a La Niña (Rasmusson and Carpenter, 1983; Khandekar and Neralla, 1984; Ropelewski and Halpert, 1987; Mooley and Paolino, 1989). It is quantified by Selvaraju (2003) that El Niño costs India about $US 800M while a La Niña provides a gain of $US 400M. However, it is recently observed that the relationship is not unique for all the El Niño events (Kane, 1998). According to Kane (1998), "..... in some years, some other factors might be playing important roles......". Kumar et al. (1999) have speculated that the historical relationship has been broken after 1970. However, the droughts in 2002 and 2004 suggest that this linkage may still be strong (Gadgil et al., 2005)

## Indian Ocean Dipole (IOD) Mode

A dipole is referred to a combination of two distinct points with opposite characteristics. Indian Ocean Dipole (IOD) mode is a pattern of internal variability with anomalously low sea surface temperatures off Sumatra and high sea surface temperatures in the western Indian Ocean, with accompanying wind and precipitation anomalies (Saji et al., 1999). Large changes in equatorial zonal wind (70° E - 90° E, 5° S - 5° N) field, seasonal phase locking and strong empirical evidence for coupling between SST and the wind field through the precipitation field are typical characteristics of IOD mode (Saji et al., 1999).

Dipole Mode Index (DMI) is a measure of IOD mode. It is defined as the difference in SST anomaly between the tropical western Indian Ocean (50° E - 70° E, 10° S - 10° N) and the tropical south-eastern Indian Ocean (90° E - 110° E, 10° S - 0°). It may be noted that ENSO and IOD are independent to each other (Saji et al., 1999).

Equatorial Indian Ocean Oscillation (EQUINOO) is the atmospheric component of the IOD mode (Gadgil et al., 2003; 2004). During the 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 Equatorial Indian Ocean Oscillation (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).

### Impact of IOD mode

IOD mode has important implications on climate variability in the regions surrounding the Indian Ocean like east Africa and Indonesia. Positive dipole event causes high rainfall over east Africa and drought in Indonesia and vice versa. However, statistical correlation of the DMI with precipitation over the Asian monsoon regime does not yield a significant relationship. Therefore the relationship of the DMI to the Indian summer monsoon rainfall (ISMR) variability is not clear (Saji et al., 1999). However, Ashok et al. (2001) have shown that the IOD plays an important role as a modulator of the ENSO-ISMR relationship. In fact whenever the ENSO-ISMR correlation is low (high), the IOD-ISMR correlation is high (low) (Ashok et al., 2001). Gadgil et al. (2003) had shown that the Indian summer monsoon rainfall is not only associated with ENSO, but also with EQUINOO. They suggested that an educated guess could be made about the Indian summer monsoon rainfall by knowing the prior EQUINOO status.

Apart from ENSO and IOD, several large-scale atmospheric circulations phenomena, such as, North Atlantic Oscillations (NAO) and Pacific/North America (PNA) pattern, are widely studied.

## STUDIES ON HYDROCLIMATIC TELECONNECTION ACROSS THE WORLD

Hydroclimatic teleconnection between hydrologic variables and large-scale atmospheric circulation is being studied in United States (Kahya and Dracup, 1993; Dracup and Kahya, 1994; Jain and Lall, 2001), Australia (Verdon et al, 2004), New Zealand (Moss et al., 1994; McKerchar et al., 1998), Egypt (Eltahir, 1996), Sri Lanka (Zubair, 2003) and Bangladesh (Chowdhury and Ward, 2004) to explore statistical relationship between different hydrologic variables and large-scale climate indices. In this section, few established works are briefly reviewed.

Redmond and Koch (1991) statistically analyzed the nature and magnitude of the relationship of precipitation, temperature and streamflow in the western United States to Southern Oscillation Index (SOI) and Pacific/North America (PNA) pattern. They observed that October-March precipitation is strongly correlated with SOI, averaged over the July-November period. It is also observed by using split sample analysis that precipitations are significantly different (statistically) for extremes of the SOI. Strong association was observed between precipitation and temperature in the Pacific northwest with PNA pattern also. Kahya and Dracup, (1993) examined the relationship between El Niño events and streamflows over United States. Strong and consistent relationship in four core regions, namely the Gulf of Mexico, the Northeast, the North Central and the Pacific Northwest was identified. Dracup and Kahya, (1994) followed a similar approach to investigate the influence of La Niña on streamflow in aforementioned four core regions of streamflow in United States. Their study shows strong signals in streamflow data for both the El Niño and La Niña phases of ENSO. An Index Time Series was developed and statistical investigation is done using Hypergeometric distribution. However, the study does not explain the extremes of streamflow which are not associated with El Niño or La Niña. Moss et al. (1994) has used Southern Oscillation Index (SOI) as a predictor of the probability of low streamflow in Clutha River basin in New Zealand. They used Bayesian analysis of the conditional probability and showed that the unconditional probability of summer lake-inflow (SLI) above a threshold value of 360 $m^3/s$ is 0.17, whereas, probability of SLI, conditioned on different values of SOI of preceding season, differs significantly. Thus, significant relationship between the preceding season's SOI and summer lake inflows is established, though these two series are weakly related by ordinary linear regression. Eltahir (1996) analyzed the association of ENSO index with natural annual variability of streamflow of Nile River at Aswan Dam in Egypt. This study reflects the existence of a significant relationship between mean flow of Nile River and SST of Pacific Ocean. In fact, it is shown that 25% of natural variability in the annual flow is associated with El Niño. The hypothesis of Hurst phenomenon: variability of mean annual flow process in the Nile River with time, following ENSO, is established in this study. McKerchar et al. (1998) investigated the dependency of summer lake inflows and precipitation on spring SOI at South Island, New Zealand. Box plot comparisons were used to show the dependency for different ranges of SOI (<-5, -5 to 5 and >5). They observed that the variance of inflows and precipitation appeared to be dependent on the magnitude of the SOI. Summer inflows and precipitation tend to be less in years when the spring SOI is positive (La Niña). It was inferred from the analysis that relative absence of La Niña conditions for the period 1976-1994 may be partially responsible for a significant increase in mean lake inflows over the period 1978-1994. Jain and Lall (2001) used the ENSO and PDO indices to model the stream flow of Similkameen River in Washington State, USA. They concluded that streamflow values are teleconnected with these large-scale climate indices, which can be used as exogenous inputs to the prediction model. Zubair (2003) analyzed the influences of ENSO on streamflow and rainfall in the upper catchment of the Mahaweli River in Sri Lanka. El Niño conditions are shown to be associated with lower average rainfall and streamflow and La Niña with the converse. By correlation analysis, he showed that the seasonally averaged streamflow for the period January to September is significantly correlated with ENSO index for concurrent period. However, correlation coefficient is insignificant for the period October to December. A moderate Heidke skill score of 15 is reported on the basis of a contingency table for the association of NINO3.4 with aggregate January to September streamflow between 1943 and 1993.

Chowdhury and Ward (2004) studied the hydro-meteorological aspect of greater Ganges - Brahmaputra - Meghna (GBM) basin. Large-scale Oceanic factors behind hydro-meteorological variability are also investigated in this study. It was observed that the seasonal correlation between the SST with rainfall (India) and streamflow (Bangladesh) in the greater Ganges basin are highly correlated to: (i) the negative SST anomaly in the domain of the Niño 3.4 region and the Indian Ocean region and (ii) the positive SST anomaly over some parts of the western Pacific Ocean region. However, this correlation does not exist for upstream rainfall for Brahmaputra and Meghna. The flow in Brahmaputra River is influenced by a combination of local causes and SST anomalies that are positive in the domain of the Indo-Pacific region. Having briefly outlined the research work on hydroclimatic teleconnection for different parts of world, related research work in this direction for Indian subcontinent and future scope is outlined in the next section.

## INDIAN PERSPECTIVE OF HYDROCLIMATIC TELECONNECTION STUDIES

Association of Southern Oscillation and Indian summer monsoon rainfall (ISMR) was recognized long back (Walker, 1923; 1924; Normand, 1953). Significant negative correlation between ENSO and ISMR was discovered in eighties (Pant and Parthasarathy, 1981; Rasmusson and Carpenter, 1983). Research is still going on to use the ENSO information as a predictor for ISMR. Nageswara Rao (1997) statistically linked basin-scale precipitation for Godavari River basin with SOI. Douglas et al. (2001) has shown a significant relationship between natural variability of annual flow of River Ganges and ENSO. However, in a recent study, Gadgil et al. (2003) has stated that relation between El Niño and ISMR is not yet understood properly. Some studies have shown that the historical relationship has been broken after 1970 (Kumar et al., 1999) as stated earlier.

After the discovery of Indian Ocean Dipole (IOD) mode in 1999 (Saji et al., 1999), researchers are trying to investigate its impact on ISMR. It is established that IOD mode modulates the relationship between ISMR and ENSO (Ashok et al., 2001). Hydroclimatic teleconnection between global sea surface temperature and monthly rainfall over different subdivisions of India is investigated in a recent study (Maity and Nagesh Kumar, 2006a). It is shown that sea surface temperature anomaly from Indian Ocean region plays a significant role on monthly variation of subdivisional rainfall in India. Gadgil et al. (2004) had established the hydroclimatic teleconnection between seasonally averaged ISMR and a linearly combined index of ENSO and EQUINOO. Thus, both ENSO and EQUINOO are to be necessarily considered while investigating the hydroclimatic teleconnection in the Indian perspective. However, the impact of such 'large-scale' atmospheric circulations (both ENSO and EQUINOO) on comparatively smaller 'basin-scale' hydrologic variables is yet to be explored for smaller temporal resolutions, which is all the more essential in hydrology and water resources development and management.

## A Preliminary Investigation

A preliminary analysis is presented here to investigate the possible teleconnection between monthly all India rainfall and large-scale atmospheric circulation indices from Pacific Ocean and Indian Ocean region. A somewhat similar analysis was performed by Gadgil et al. (2004) for seasonal all India rainfall during June to September, considering both ENSO index and EQWIN averaged over the same period. However, monthly analysis is considered in the present analysis where as Gadgil et al. (2004) considered seasonal analysis. Lagged relationship is considered in the present analysis where as Gadgil et al. (2004) considered simultaneous relationship. Thus, present analysis considers monthly rainfall anomaly during monsoon months and their lagged relationship with ENSO index and EQWIN. Even though the spatial scale is much larger than hydrologic requirement, the temporal scale is reduced to monthly level, compared to the earlier analysis where temporal scale was seasonal. For smaller spatial scale further analysis in this direction is needed.

## Data

Sea surface temperature anomaly (SSTA) data from Niño 3.4 region (5° S - 5° N, 120° - 170° W) is used as ENSO index. Monthly SST data is obtained from the website of National Weather Service, Climate Prediction Centre of NOAA [http://www.cpc.noaa.gov/data/indices/] for the period, January 1958 to December 2003. Equatorial zonal wind index (EQWIN, described earlier) is used to represent EQUINOO (Gadgil et al., 2004). Monthly surface wind data (Kalnay et al., 1996) is obtained from National Center for Environmental Prediction [http://www.cdc.noaa.gov/Datasets] for the period, January 1958 to December 2003. All India monthly rainfall data (Parthasarathy et al., 1995) is obtained from the website of Indian Institute of Tropical Meteorology, Pune, India [http://www.tropmet.res.in/data.html] for the period, January 1958 to December 2003.

Standardized monthly anomaly values, for the above datasets, are calculated as follows:

$$a_{i,j} = \frac{X_{i,j} - m_j}{S_j} \qquad (1)$$

where, $a_{i,j}$ is the standardized anomaly value for $j^{th}$ month of $i^{th}$ year, $X_{i,j}$ is the observed value for $j^{th}$ month of $i^{th}$ year and $m_j$, $S_j$ are mean and standard deviation for $j^{th}$ month, respectively.

Monthly rainfall anomalies for four monsoon months (June through September) are considered and their association with large-scale atmospheric circulation indices is investigated for different lags.

## Observations and discussions

Correlation coefficients and partial correlation coefficients between monthly rainfall anomaly during monsoon months and lagged circulation indices (both ENSO index and EQWIN) is presented in Table 1. Partial correlation coefficients are computed using Eqn. (2).

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

where $r_{xy/z}$ is the partial correlation coefficient which implies the correlation coefficient between x and y after removing the effect of z. Cross correlation coefficients are denoted as $r_{xy}$, $r_{xz}$ and $r_{yz}$ between the variables as shown in suffixes.

### TABLE-1
### CORRELATIONS BETWEEN ALL INDIA MONTHLY RAINFALL ANOMALY AND CIRCULATION INDICES

| | | Lag (in months) between rainfall anomaly and circulation indices (both ENSO index and EQWIN) | | | | |
|---|---|---|---|---|---|---|
| **Statistics** | **Series considered** | **0** | **1** | **2** | **3** | **4** |
| Correlation coefficient | Rainfall anomaly and ENSO Index | -0.319 | -0.295 | -0.278 | -0.202 | -0.064 |
| | Rainfall anomaly and EQWIN | 0.285 | 0.305 | 0.032 | -0.009 | -0.053 |
| Partial Correlation coefficient | Rainfall anomaly and ENSO Index after removing the effect of EQWIN | -0.347 | -0.310 | -0.279 | -0.202 | -0.053 |
| | Rainfall anomaly and EQWIN after removing the effect of ENSO Index | 0.316 | 0.319 | 0.040 | 0.006 | -0.039 |

It is observed from Table 1, that the correlation coefficients are more or less equal for zero lag and one month lag. As the lag increases, the correlation coefficients decrease. Correlation coefficient between rainfall anomaly and EQWIN drops drastically from lag 2 onwards. However, for lag zero and one, all the correlation coefficients are statistically significant at 95% confidence level. This indicates that both the climate indices are influencing the monthly rainfall anomaly during monsoon months.

June through September monthly anomalies of all Indian rainfall are plotted in phase plane of monthly ENSO index and EQUINOO index for different lags (figure 1). Size of each circle represents the amount of departure of rainfall anomaly from zero. Larger the size of circles, greater is the amount of departure from zero. Shades of the circles are for distinguishing the positive and negative anomalies. Light circles are representing the positive anomaly and dark circles are representing the negative anomaly.

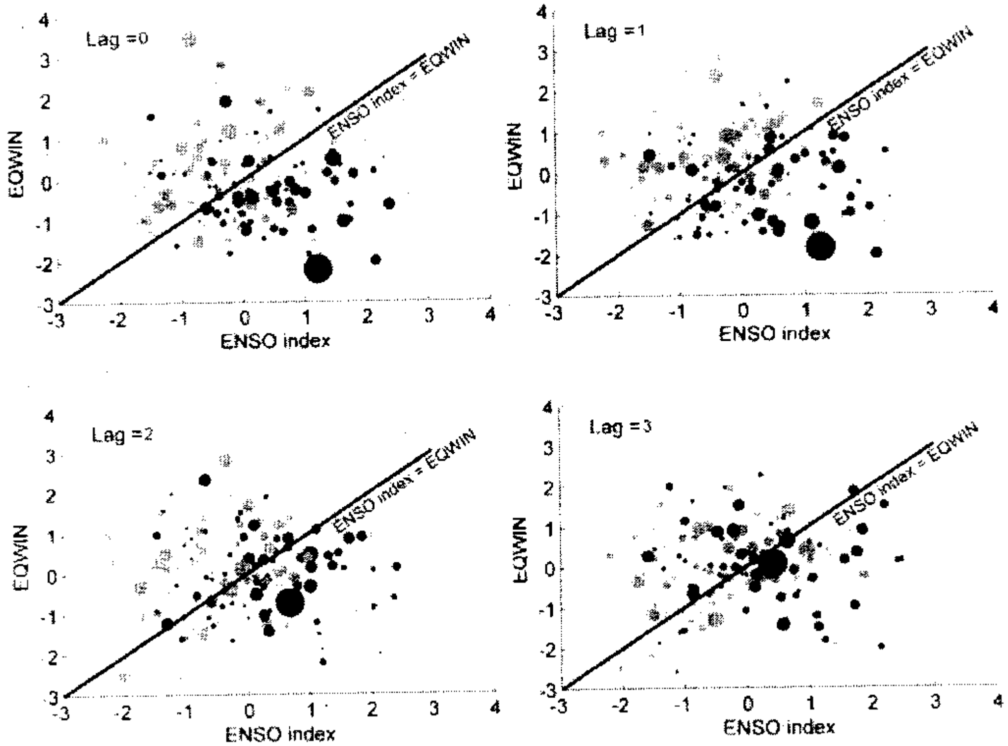

FIG. 1 PLOT OF MONTHLY ALL INDIA RAINFALL ANOMALIES IN PHASE PLANE OF MONTHLY ENSO INDEX AND EQUINOO INDEX (EQWIN) FOR DIFFERENT LAGS

It is observed that, most of the extreme positive anomalies are located in the region where $ENSO\ index < EQWIN$ and the extreme negative anomalies are located in the region where $ENSO\ index > EQWIN$. Thus, a separation between the extreme positive and negative anomalies is observed at a lag of one month, the separation line being $ENSO\ index = EQWIN$. This observation motivates to investigate the conditional probability of monthly anomaly, conditioned on relative magnitude of ENSO index and EQWIN, i.e. either $ENSO\ index < EQWIN$ or $ENSO\ index > EQWIN$. Conditional probabilities are shown in Table 2 for different lags between rainfall anomaly and circulation indices. It is observed that, probability of low rainfall anomaly (< 90% of Standard Deviation) is much higher than that of high rainfall anomaly (> 90% of Standard Deviation) if ENSO index is greater than EQWIN. On the other hand, probability of high rainfall anomaly is much higher than that of low rainfall anomaly if EQWIN is greater than ENSO index. Probabilities are more or less equal for the lags of 0 and 1 month, indication of which may also be observed from figure 1. However, from prediction point of view, lag 1 is preferable. It can also be observed that as the lag increases, difference between probabilities of low and high rainfall anomalies decreases.

**TABLE-2**
**CONDITIONAL PROBABILITIES OF ALL INDIA RAINFALL ANOMALIES**

| Condition | Monthly rainfall anomaly | Lag (in months) between rainfall anomaly and circulation indices (both ENSO index and EQWIN) | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 1 | 2 | 3 | 4 |
| NINO > EQWIN | Low | 0.298 | 0.294 | 0.235 | 0.200 | 0.196 |
| | Medium | 0.617 | 0.630 | 0.633 | 0.680 | 0.608 |
| | High | 0.085 | 0.076 | 0.133 | 0.120 | 0.196 |
| EQWIN > NINO | Low | 0.067 | 0.076 | 0.128 | 0.167 | 0.171 |
| | Medium | 0.656 | 0.641 | 0.640 | 0.583 | 0.671 |
| | High | 0.278 | 0.283 | 0.233 | 0.250 | 0.159 |

Another observation is that, the probabilities of low or high rainfall anomalies are always less than that of medium rainfall anomalies. Still, observations from this study help to have a prior information about the chances of high or low rainfall for the ensuing month. For example, if it is observed that ENSO index is greater than EQWIN, it is most likely, with probability 0.924 (0.294+0.630, refer Table 2 at one month lag), that medium (normal) or low rainfall is likely to occur whereas chance of high rainfall is very less (probability being 0.076) and vice versa.

## FUTURE RESEARCH SCOPE

It is mentioned earlier, that the impact of 'large-scale' atmospheric circulations (ENSO and EQUINOO) on 'basin-scale' hydrologic variables is yet to be fully explored for required temporal scale of hydrologic study. Further investigation is also needed to develop a methodology to incorporate climate information for forecasting hydrologic variables. However, following major issues are involved in the research in this direction.

1. The basin-scale hydrologic time series, being significantly influenced by the large-scale atmospheric circulation phenomena, is likely to be nonstationary in nature. While stationarity is a common assumption in most hydrologic modeling approaches, it is necessary to model nonstationary temporal structure of hydrologic time series expected under climate change scenario.
2. Dynamic nature of cause-effect relationship, under the recent climate change scenario, creates difficulties in robust and consistent prediction of hydrologic variables. Thus, the dynamic relationship between hydrologic time series and large-scale circulation is to be captured.
3. It is also important to consider the uncertainty associated with the forecasted values which is an important factor. Thus, probabilistic prediction of hydrologic variables, using the information of large-scale circulation, is another important issue to be addressed. It will provide the information about the uncertainty associated with the predicted values.
4. Research in this direction has been recently performed for monthly all India rainfall prediction (Maity and Nagesh Kumar, 2006b). However, further research is required for smaller spatio-temporal scale. It will help to tackle the extreme hydrologic phenomena, such as, droughts and floods at basin scale.

## CONCLUSIONS

In this paper, hydroclimatic teleconnection between large-scale atmospheric circulation patterns and hydrologic variables is reviewed. Characteristics of El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) mode are discussed with their general impacts on hydrologic variables. It is observed from established research work that large-scale atmospheric circulations are linked with hydrologic variables through hydroclimatic teleconnection. Feasibility of using the information of such indices, in advance, to forecast hydrologic variables is being investigated with alluring results.

For Indian subcontinent, teleconnection between large-scale atmospheric circulation and hydrologic variables like, precipitation, streamflow etc. is not yet established fully. Efforts are being made to identify the statistical relationship between recently identified IOD mode and Indian summer monsoon rainfall. Combined influence of seasonally averaged ENSO and atmospheric part of IOD mode, EQUINOO, on ISMR has also been investigated in recent studies. Analysis presented in this study, indicates dependence of monthly all India rainfall on relative dominance of ENSO and EQUINOO indices.

Further study is needed to investigate the responses of 'basin-scale' hydrologic variables like rainfall, surface runoff, streamflow etc. to 'large-scale' atmospheric circulations. It is needed to develop a modeling framework for probabilistic prediction of hydrologic time series using the information of large-scale atmospheric circulations.

## ACKNOWLEDGEMENT

This work is partially supported by Department of Science and Technology, Government of India, through a project with reference ES/48/010/2003.

## ABBREVIATIONS

| | |
|---|---|
| ENSO | El Niño-Southern Oscillation |
| EQUINOO | Equatorial Indian Ocean Oscillation |
| IOD | Indian Ocean Dipole |
| GCM | General Circulation Models/Global Climate Model |
| RCM | Regional Climate Models |
| OTCZ | Oceanic Tropical Convergence Zone |
| DMI | Dipole Mode Index |
| EEIO | Eastern part of the Equatorial Indian Ocean |
| WEIO | Western part of the Equatorial Indian Ocean |
| EQWIN | Equatorial zonal wind index |
| ISMR | Indian summer monsoon rainfall |
| NAO | North Atlantic Oscillations |
| PNA | Pacific/North America pattern |
| SOI | Southern Oscillation Index |

## REFERENCES

Allan, R., Lindesay, J. and Parker, D. (1996). El Niño Southern Oscillation and Climatic Variability. CSIRO Publishing, Australia.

Ashok, K., Guan, Z. and Yamagata, T. (2001). Impact of Indian Ocean Dipole on the Relationship between the Indian Monsoon Rainfall and ENSO. Geophysical Research Letters, Vol. 28, pp. 4499-4502.

Cane, M. A. (1992): Tropical Pacific ENSO Models: ENSO as a Mode of the Coupled System. Climate System Modeling, K. E. Trenberth (Ed.), Cambridge University Press, pp. 583-689.

Chowdhury, M. R. and Ward, N. (2004). Hydro-Meteorological Variability in the Greater Ganges - Brahmaputra - Meghna Basins. International Journal of Climatology, Vol. 24, pp. 1495-1508.

Douglas, W. W., Wasimi, S. A. and Islam, S. (2001). The El Niño - Southern Oscillation and Long-Range Forecasting of Flows in the Ganges. International Journal of Climatology, Vol. 21, pp. 77-87.

Dracup, J. A. and Kahya, E. (1994). The Relationship between U. S. Streamflow and La Niña Events. Water Resources Research, Vol. 30, No. 7, pp. 2133-2141.

Eltahir, E. A. B. (1996). El Niño and the Natural Variability in the Flow of the Nile River. Water Resources Research, Vol. 32, No. 1, pp. 131-137.

Gadgil, S., Rajeevan, M. and Nanjundiah, R. S. (2005). Monsoon Prediction - Why Yet Another Failure? Current Science, Vol. 88, No. 9, pp. 1389-1400.

Gadgil, S., Vinayachandran, P. N. and Francis, P. A. (2003). Droughts of the Indian Summer Monsoon: Role of Clouds over the Indian Ocean. Current Science, Vol. 85, No. 12, pp. 1713-1719.

Gadgil, S., Vinayachandran, P. N., Francis, P. A. and Gadgil, S. (2004). Extremes of the Indian Summer Monsoon Rainfall. ENSO and equatorial Indian Ocean oscillation, Geophysical Research Letters, Vol. 31, No. L12213, doi:10.1029/2004GL019733.

Ghosh, S. and Mujumdar, P. P. (2006). Future Rainfall Scenario over Orissa with GCM Projections by Statistical Downscaling. Current Science, Vol. 90, No. 3, pp. 396-404.

Gosain, A. K., Rao, S. and Basura, D. (2003). Assessment of Vulnerability and Adaptation for Water Sector. NATCOM - V&A workshop on Water Resources, Coastal Zones and Human Health, New Delhi.

Jain, S. and Lall, U. (2001). Floods in a Changing Climate: Does the Past Represent the Future? Water Resources Research, Vol. 37, No. 12, pp. 3193-3205.

Kahya, E. and Dracup, J. A. (1993). U. S. Streamflow Patterns in Relation to the El Niño/Southern Oscillation. Water Resources Research, Vol. 29, No. 8, pp. 2491-2503.

Kalnay, E., et al. (1996). The NCEP/NCAR 40-year Reanalysis Project. Bulletin of the American Meteorological Society, Vol. 2, pp. 437- 471.

Kane, R. P. (1998): Extremes of the ENSO phenomenon and Indian summer monsoon rainfall, International Journal of Climatology, Vol. 18, pp.775 - 791.

Khandekar, M. L. and Neralla, V. R. (1984): On the relationship between the sea surface temperatures in the equatorial Pacific and the Indian monsoon rainfall, Geophysical Research Letters Vol. 11, pp.1137-1140.

Kiladis, G. N. and Diaz, H. F. (1989): Global climatic anomalies associated with extremes in the Southern Oscillation, Journal of Climate, Vol. 2, pp.1069-1090.

Kumar K. K., Rajagopalan, B. and Cane, M. A. (1999): On the weakening relationship between the Indian monsoon and ENSO, Science, Vol. 284, No. 5423, pp.2156-2159, doi: 10.1126/science.284.5423.2156.

Maity, R. and Nagesh Kumar, D. (2006a): Hydroclimatic teleconnection between global sea surface temperature and rainfall over India at subdivisional monthly scale, Hydrological Processes, In print.

Maity, R. and Nagesh Kumar, D. (2006b): Bayesian dynamic modeling for monthly Indian summer monsoon rainfall using ENSO and EQUINOO, Journal of Geophysical Research, Vol. 111, D07104, doi:10.1029/2005JD006539.

McKerchar, A. I., Pearson, C. P. and Ftzharris, B.B. (1998): Dependency of summer lake inflows and precipitation on spring SOI, Journal of Hydrology, Vol. 205, No. (1-2), pp.66 - 80.

Mooley, D. A. and Paolino, D. A. (1989): The response of the Indian monsoon associated with the change in sea surface temperature over the eastern south equatorial Pacific, Mausam, Vol. 40, pp.369 - 380.

Moss, M. E., Pearson, C. P. and McKerchar A. I. (1994): The Southern Oscillation index as a predictor of the probability of low flows in New Zealand, Water Resources Research, Vol. 30, No. 10, pp.2717 - 2723.

Nageswara Rao, G. (1997): Interannual variation of monsoon rainfall in Godavari river basin connections with the Southern Oscillation, Journal of Climate, Vol. 11, pp.768 - 771.

Normand, C. (1953): Monsoon seasonal forecasting, Quarterly Journal of the Royal Meteorological Society, Vol. 79, pp. 463 - 473.

Pant, G. B., and B. Parthasarathy (1981), Some aspect of an association between the summer oscillation and Indian summer monsoon, Archives for Meteorology, Geophysics, and Bioclimatology, Vol. 89, pp. 179 - 195.

Parthasarathy B., Munot, A. A. and Kothawale D. R. (1995): All India monthly and seasonal rainfall series: 1871-1993. Theoretical and Applied Climatology, Vol. 49, pp. 217-224.

Rasmusson, E. M. and Carpenter, T. H. (1983). The Relationship between Eastern Equatorial Pacific Sea Surface Temperature and Rainfall over India and Sri Lanka. Monthly Weather Review, Vol. 111, pp. 517-528.

Redmond, K. T. and Koch, R. W. (1991). Surface Climate and Streamflow Variability in the Western United States and their Relationship to Large-Scale Circulation Indices. Water Resources Research, Vol. 27, No. 9, pp. 2381-2399.

Ropelewski, C. F. and Halpert, M. S. (1987). Global and Regional Scale Precipitation Patterns Associated with the El Niño/Southern Oscillation. Mon. Weather Rev., Vol. 115, pp. 1606-1626.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N. and Yamagata, T. (1999). A Dipole Mode in the Tropical Indian Ocean. Nature, Vol. 401, pp. 360-363.

Selvaraju, R. (2003). Impact of the El Niño Southern Oscillation on Indian Foodgrain Production. International Journal of Climatology, Vol. 23, pp. 187-206.

Verdon, D. C., Wyatt, A. M., Kiem, A. S. and Franks, S. W. (2004). Multidecadal Variability of Rainfall and Streamflow: Eastern Australia. Water Resources Research, Vol. 40, W10201, doi:10.1029/2004WR003234.

Walker, G. T. (1923). Correlation in Seasonal Variations of Weather. III: A preliminary study of world weather, Memo. Indian Meteorological Department, Vol. 24, pp. 75-131.

Walker, G. T. (1924). Correlation in Seasonal Variations of Weather. IV: A further study of world weather, Memo. Indian Meteorological Department, Vol. 24, pp. 275-332.

Webster, P. J., Moore, A. M., Loschnigg, J. P. and Leben, R. R. (1999). Coupled Oceanic-Atmospheric Dynamics in the Indian Ocean during 1997-98. Nature, Vol. 401, pp. 356-360.

Xu, C. Y. (1999). Climate Change and Hydrologic Models: A Review of Existing Gaps and Recent Research Developments. Water Resources Management, Vol. 13, pp. 369-382.

Zubair, L. (2003). El Niño - Southern Oscillation Influences on the Mahaweli Streamflow in Sri Lanka. International Journal of Climatology, Vol. 23, pp. 91-102.

**Referred URLs:**

http://www.cpc.noaa.gov/data/indices/
http://www.cdc.noaa.gov/Datasets
http://www.tropmet.res.in/data.html