Long-Lead Streamflow Forecasting Using Ensemble Streamflow Prediction (ESP) Technique and Large-Scale Climate Signals

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ABSRACT

In this paper a new method for incorporating the information of large-scale climate signals in to a well-know advance hydrologic forecasting technique named Ensemble Streamflow Prediction (ESP) is investigated. Firstly, two of the most prominent known sources of interannual and interdecadal climate variability in the form of El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) are analyzed to assess their influences on Zayande-Rood streamflow. The results indicate a strong correlation between Apr-Sep streamflow and spring SOI and spring PDO of the same year. In order to consider the mixed effects of ENSO and PDO, four climate conditions are defined. Two forecast ensembles are then created, one of which consists of meteorological information of all the historical years prior to the forecast year, and the other consists of the information of the years of the climate group to which the forecast year belongs. The initialized hydrologic model is then driven for each forecast ensemble in each climate condition to produce the streamflow traces. Correlation coefficients of the median of the two ensemble forecasts and the observed value indicate the superiority of the categorical ensemble forecast, particularly for La Nina/-PDO forecast years. Using the proposed method, the forecast lead time has extended up to one year.

Keywords: Streamflow Forecasting, Ensemble Streamflow Prediction, El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO)

INTRODUCTION

Nowadays, effects of large-scale climate signals on world's water resources have been clearly proven and information about these phenomena such as El-Nino Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), etc have been successfully added to the forecaster's toolbox. Understanding ocean-atmospheric interactions that result in climate modes and identifying the effects of these phenomena on hydrological and meteorological parameters of different basins throughout the world is of great importance. In recent decades, many researchers have investigated the relationships between hydrological and meteorological variables of different basins with large-scale climate phenomena. In addition, it has been found that incorporating large-scale climate signals into forecasting models could greatly improve long-lead streamflow forecasting skills.

Hamlet and Lettenmaier (1999) devised a simple method to incorporate the ENSO and PDO climate signals into the extended streamflow forecasting approach. The results indicated the increase in the lead time and specificity of the forecasts [1]. Grantz et. al. (2003) has utilized large-scale climate information as a spring runoff predictor in a forecasting model to improve the skill and lead-time of the forecasts. The results demonstrated that the incorporation of this information, particularly the 500 mbar geopotential height index, improves the forecasts skills at longer lead times when compared with forecasts only based on snowpack information [2, 3]. Optiz-Stapleton et al. (2007) developed and examined an ensemble streamflow forecasting model incorporated with the Pacific North American (PNA) pattern for the Yakima River Basin. The results showed a significant correlation between the PNA and the spring runoff at the Yakima Basin [4]. Araghinejad (2005) used ENSO and NAO data, as well as the climate predictors of seasonal streamflow in his model. The results indicated a significant improvement in the long-term streamflow [5].

These studies reveal the great importance of investigation and incorporation of the large-scale climate signals impacts in hydrological forecasting. In this research, influences of the changes in the pressure and temperature patterns of the Pacific Ocean, in the form of ENSO and PDO, on the streamflow of two of the major tributaries in Zayande-Rood River Basin have been firstly investigated. As the second step, considering the mixed effects of ENSO and PDO, we have utilized a non parametric method called Ensemble Streamflow Prediction (ESP) to produce more precise streamflow forecasts. Ensemble Streamflow Prediction (ESP) - part of the US National Weather Service River Forecasting System (NWSRFS) is a well-known advanced hydrological forecasting technique that considers the forecast uncertainty in terms of occurrence probability and provides probabilistic forecast information rather than deterministic. This probabilistic approach, together with large-scale climate information could beneficially lead us to more accurate hydrological forecasts with longer lead times.

BASIN DESCRIPTION

Zayandeh-rood River Basin is located in the central plateau of Iran with an approximate area of 41,500 km2. The water supply in the Zayandeh-rood Basin is allocated for the irrigation, domestic and industrial uses. The main river of the basin, Zayandeh-rood River is about 350 km long which originates from Zagros Mountains in the western part of Iran.

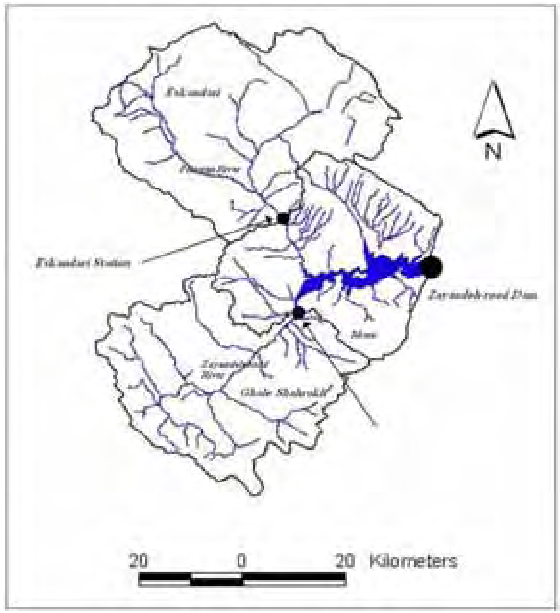

Figure 1. Subbasins and main tributaries of Zayande-Rood River Basin

CORRELATION ANALYSIS

ENSO is one of the most prominent known sources of inter-annual climate variability that is the result of a cyclic warming and cooling of the surface of the central and eastern Pacific Ocean. This region of the ocean is normally colder than its equatorial location, mainly due to the influence of northeasterly trade winds. The condition would be vice versa in the opposite phase.

PDO is a pattern of Pacific climate variability that shifts phases on inter-decadal time scale, usually about 20 to 30 years and is detected as warm or cool surface waters in the Pacific Ocean. During a "warm (positive)" phase, the west Pacific becomes cool and part of the eastern ocean warms; while during a "cool (negative)" phase, the opposite pattern occurs.

Since El Niño and La Niña Phases of ENSO generally develop around September or October [6], it is more convenient to start a water year from October. Thus, four seasons are defined as follows: 1) Fall: October – December, 2) Winter: January – March, 3) Spring: April – June and 4) Summer: July – September. Regarding different aspects of water management including water allocation for different sectors, flood controlling, environmental considerations etc., the April through September (Apr-Sep) Streamflow was considered as the general descriptor of the available water in each water year. This period covers the snow accumulation season and snowmelt period of a water year [6, 7].

In this research, inter-annual and inter-decadal climate variability in the form of ENSO and PDO are analyzed to assess the impacts of these large-scale climate patterns on streamflow of the main tributary in Zayandeh-rood River Basin, one of the major river basins in the central plateau of Iran. For this purpose, seasonal and annual cross correlation coefficients of Southern Oscillation Index (SOI) and Pacific Decadal Oscillation Index with the historical streamflow records with different lag have been determined.

In order to investigate the influences of ENSO and PDO on the streamflow of Zayande-Rood river, cross correlation of the Apr-Sep streamflow with the seasonal SOI and PDO indices were analyzed at 95% confidence level. As it is shown in Figure 2, the most significant cross correlations for Zayande-Rood river is with the spring SOI and spring PDO of the same year. In addition, fall and summer PDO of the same year has shown a significant relation with Zayande-Rood river streamflow. The interesting point is that the Apr-Sep streamflow is inversely related to the SOI index, i.e. by the increment (decrement) of SOI and nearing the La Niña (El Niño) phase, the streamflow volume decrease (increase). On the other hand, the positive correlation of Apr-Sep streamflow volume and the PDO index indicates the direct relation.

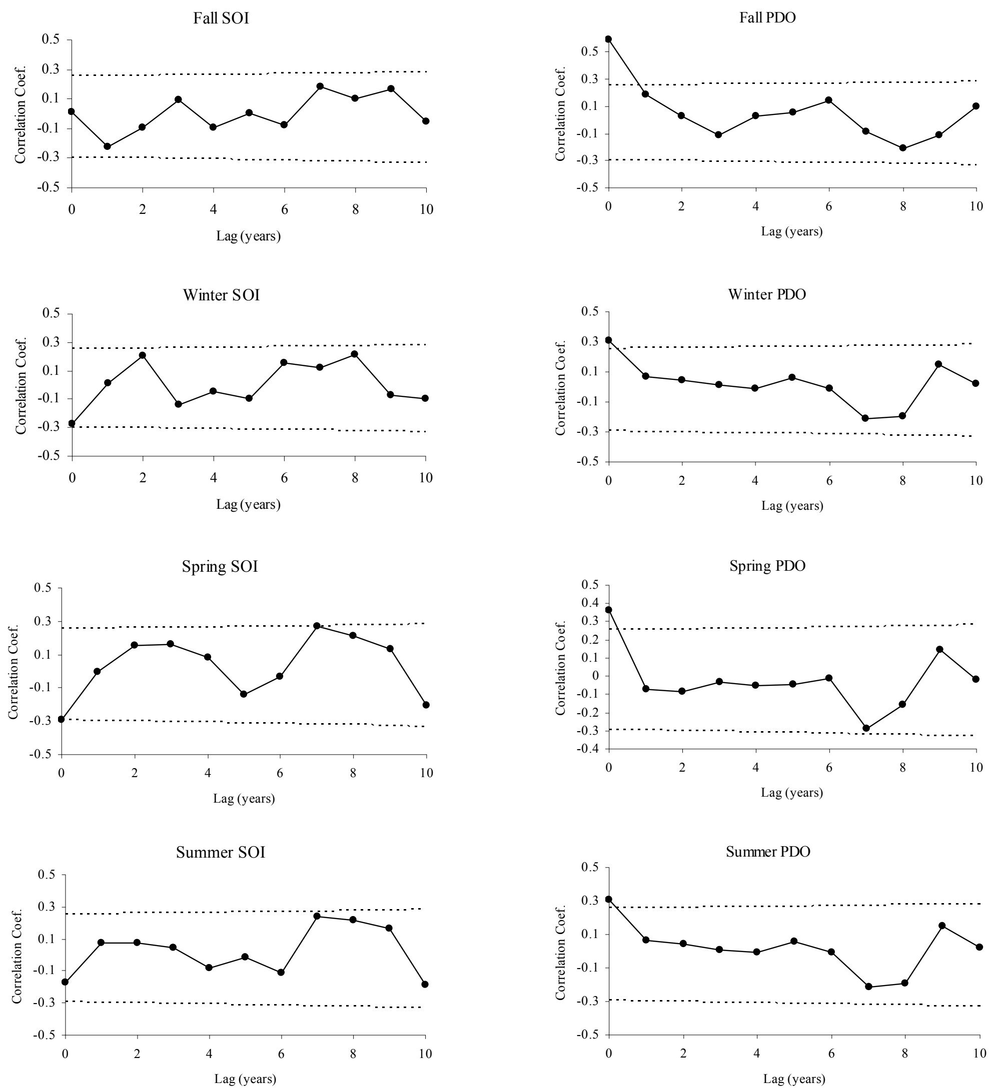

Figure 2. Cross correlation function of the Apr-Sep streamflow of Zayande-Rood River and seasonal SOI and PDO index

Considering this preliminary analysis, which indicates the strong correlation between streamflow of Zayandeh-Rood river and ENSO and PDO, we could then incorporate these large-scale climate signals in our forecast approach to reach more precise forecasts with longer lead times.

FORECAST METHODOLOGY

In order to more accurately consider the influences of ENSO and PDO in streamflow forecasting, four different climate conditions are created using the warm and cold phases of these phenomena. Using the Trenberth method (1997), the El Niño and La Niña years are defined. According to his method, a water year is called an El Niño (La Niña) year, when the winter NINO3.4 index (December-February) value exceeds more than 0.5 standard deviation above (below) the long term mean value. Otherwise, the water year is considered as a neutral year [6]. Table 1 lists the water years of different phases of ENSO events.

To determine the years of the warm and cold phases of PDO, Mantua (1997) stated that when the averaged October – March PDO index exceeds more than 0.5 standard deviation above (below) the long term mean value, the warm (cold) phase of the PDO would be predominant. Using the Mantua method, it is found that water years 2006 and 2007 were also in the warm phase of PDO. Now, water years in Table 1 could be further grouped according to the water years of different phases of PDO (Table 2) [6, 8]. Neutral condition includes years which are neither in the El Niño phase of ENSO, nor in the La Niña phase, irrespective to the predominant phase of the PDO.

Table 1. El Niño, La Niña and Neutral years

El Niño	Neutral	La Niña
1973	1979	1971
1977	1981	1972
1978	1982	1974
1980	1990	1975
1983	1991	1976
1987	1993	1984
1988	1994	1985
1992	1997	1986
1995	2002	1989
1998	2004	1996
2003		1999
2005		2000
2007		2001
		2006

Table 2. Climate Conditions (CC) resulted from the combination of ENSO and PDO phases

Positive PDO		Negative PDO	
El Niño (CC1)	La Niña (CC2)	El Niño (CC3)	La Niña (CC4)
1977	1984	1970	1971
1978	1985	1973	1972
1980	1986		1974
1983	1989		1975
1987	1996		1976
1988	2006		1999
1992			2000
1995			2001
1998			
2003			
2005			
2007			

It should be noted that the El Niño/-PDO (CC3) climate condition was omitted due to the lack of data in this group. There is only a one year data of inflow volume for this group which belongs to the year 1973.

In our forecasting approach, using meteorological data from the previous year or a water year similar to the forecasting year, the hydrologic model is initialized for each climate condition. Considering the ENSO forecasts, which are now available up to six month, and the predominant phase of the PDO, the climate condition for the coming water year is determined. We will then run the initialized rainfall-runoff model twice and consequently, two forecast hydrographs will be produced for that year.

In the first run, information (Precipitation, Potential Evapotranspiration, etc) of all the years prior to the forecasting year is considered as the model input. Thus, equaling the number of the input years, different hydrographs will be produced. The ensemble mean of these hydrographs is considered as the forecast hydrograph. In the second run, only the information of the years in the climate condition of the forecast year is considered as the input of the model, and thus less number of hydrographs will be produced, which equals to the number of the years in the chosen climate condition. This means that in the second run we only the consider those years which have characteristics similar to the forecasting year and thus we could expect less deviation of the simulated streamflow from the observed data, which might be due to the years not similar to the forecasting year.

The hydrologic model (HyMOD) used in this study is a 5 parameter rainfall-runoff model which has its origins in the probability distributed moisture model. HyMOD consists of a nonlinear rainfall excess model which is connected in series with three quick-flow tanks in parallel with a slow-flow tank. More information about the HyMOD could be found in the work of Moradkhani et al. (2005) [9].

FORECAST VERIFICATION

To evaluate our approach, correlation coefficient of the median of the two ensemble forecast and the observed value for water years 2001, 2005 and 2006 have been determined [2, 3]. The result shows the improvement of the forecast capability. The acquired correlation coefficients indicate that when only information of the years in the climate condition of the forecasting year, rather than all the years, is used as model input, more accurate results are obtained. The total available information for this study was 34 years. If more information is available, better results are acquired.

years	Obs vs Ens. Mean1 (all years)	Obs vs Ens. Mean2 (CC years)
2004 (CC4)	0.911	
2001 (CC1)	0.792	
2006 (CC2)	0.896	

The results also indicate that our forecasting approach gives better results when the forecast year is in the fourth climate condition (La Nina/-PDO). Authors of the paper have previously found that La Nina/-PDO is a dry climate group, in which we will face below normal precipitation and above normal temperature patterns that result in the increment of the inflow volume to Zayande-Rood Dam [10]. Considering these pints, we can conclude that the proposed forecasting technique is more powerful for dry years.

Table 3. Correlation coeficient of the median of the two ensemble forecast and the observed value for water years 2001, 2005 and 2006

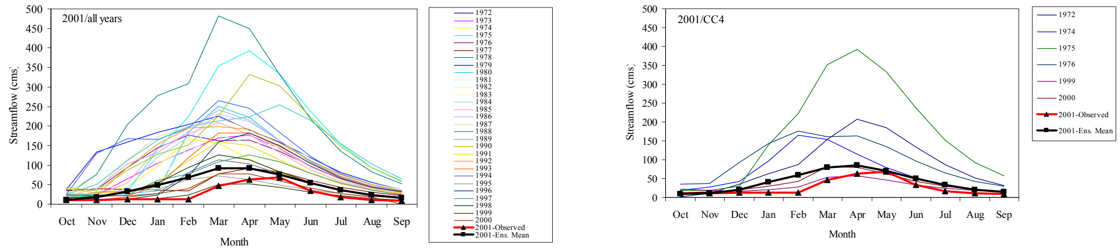

Figure 3. Ensemble Traces for Water year 2001 (Left: All Years, Right: Years of CC4)

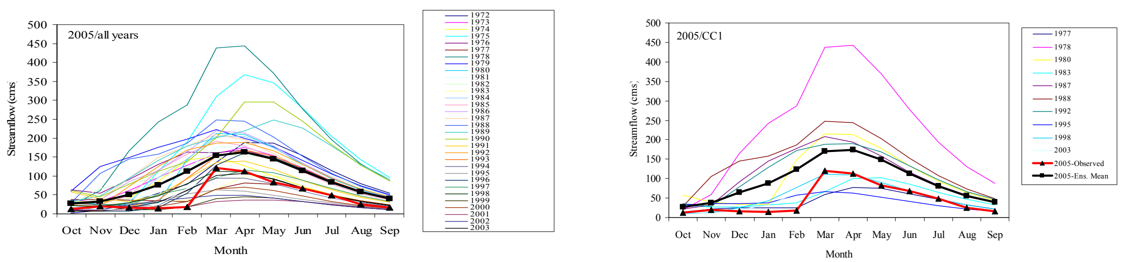

Figure 4. Ensemble Traces for Water year 2005 (Left: All Years, Right: Years of CC1)

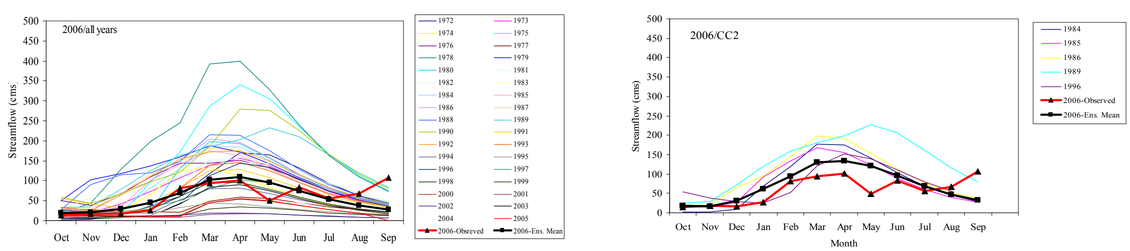

Figure 5. Ensemble Traces for Water year 2006 (Left: All Years, Right: Years of CC2)

In order to give a physical justification to the results, just assume a water year which is a dry year. If we omit the wet years or extreme wet years, in which heavy precipitation have occurred, and use the meteorological information of the other years as the model input, we could expect less deviation of simulated streamflow from the observed data.

But, considering information of all the historical years mean that irrespective to the characteristics of the forecasts year, any of the historical meteorological condition of each year is possible to occur. While we can define different years as wet, normal and dry years, the above assumption, does not consider any difference between variable water years with different climate conditions and meteorological patterns. Therefore, we can easily understand the advantages of the proposed categorical forecasting approach.

CONCLUSION

In this paper a new method for incorporating the information of large-scale climate signals in to a well-know advance hydrological forecasting technique named Ensemble Streamflow Prediction (ESP) was investigated. As the first step, influences of two of the most prominent know sources of climate variability named El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) on the streamflow of Zayande-Rood river were investigated. The results indicated a strong correlation between Apr-Sep streamflow and spring SOI and spring PDO of the same year. In addition, while Apr-Sep streamflow is inversely related to the SOI, it is directly related to the PDO index.

As the second step, considering the mixed effects of ENSO and PDO, we have utilized the non parametric Ensemble Streamflow Prediction (ESP) method to produce streamflow traces. The results show a considerable improvement in streamflow forecasting accuracy, as well as the extension of the forecast lead time up to a year. In addition, the results indicate that the proposed approach gives better results for La Nina/-PDO forecast years. This result is consonant with the previous findings of the author in Zayande-Rood River Basin [10].

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