Improving Predictability in the Colorado River Basin – Value of combining winter synoptic patterns with Sea Surface Temperature (SST) states

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ABSTRACT

Predicting wet or dry climate with sufficient lead time (3 months) for a season (especially winter) in the Colorado River Basin is a challenging scientific problem. The typical approach taken to predicting winter climate is based on using climate indices and climate models to predict precipitation or streamflow in the Colorado River Basin (CRB). In addition to these approaches which may have a long lead time, forecasts are also made based on current observations by the river forecast center. Recently the effects of coupled atmospheric-ocean phenomena such as ENSO over North America, and atmospheric circulation patterns at the 500 mb pressure level, which make the CRB wet or dry, have been studied separately. In the current work we test whether combining climate indices and circulation patterns improve predictability in the CRB. To accomplish this, the atmospheric circulation data from the Earth System Research Laboratory (ESRL) and climate indices data from the Climate Prediction Center were combined using logical functions. To quantify the skill in prediction, statistics such as the hit ratio and false alarm ratio were computed. The results from using a combination of climate indices and atmospheric circulation patterns suggest that there is an improvement in the prediction skill with hit ratios higher than 0.8, as compared to using either predictor individually (which typically produced a hit ratio of 0.6). Based on this result, there is value in using this hybrid approach when compared to a black box statistical model, as the climate index is an analog to the moisture availability and the right atmospheric circulation pattern helps in transporting that moisture to the basin.

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LIST OF ACRONYMS

AMO	Atlantic Multidecadal Oscillation
B	Bias
CAP	Central Arizona Project
CBRFC	Colorado Basin River Forecast Center
CFS	Climate Forecast System
CRB	Colorado River Basin
ENSO	El Nino Southern Oscillation
ESRL	Earth System Research Laboratory
FAR	False Alarm Ratio
GFDL	Geophysical Fluid Dynamics Laboratory
GPH	Geopotential Height
H	Hit Ratio
MERRA	Modern-Era Retrospective Analysis for Research and Applications
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
PC	Proportion Correct
PDO	Pacific Decadal Oscillation
RFC	River Forecast Centers
SNOTEL	SNOw TELemetry
SST	Sea Surface Temperatures
SVM	Support Vector Machines
USGS	United States Geological Survey
USBR	United States Bureau of Reclamation

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INTRODUCTION

Predicting wet or dry climate with sufficient lead time (3 months) for a season (especially winter) in the Colorado River Basin is a challenging scientific problem. The bulk of the streamflow generated in the Colorado River Basin is due to winter precipitation (snowfall) and spring snowmelt (Christensen et al., 2004) and hence the interest in predicting winter climate. Having accurate predictions of winter climate will help with water resources management and planning, especially if a water user such as the CAP is reliant on its allocation of water from the Colorado River to supply its customers in central Arizona.

The typical approach taken to predicting winter climate maybe summarized in the following categories: 1) identify climate indices (e.g. ENSO, PDO, NAO etc.) that correlate well with a hydrologic variable (e.g. streamflow, precipitation) within your basin of interest and then use this relationship to make future predictions (e.g. Kalra et al. 2013; Lamb et al. 2011; Switanek and Troch 2011; Salas et al. 2011; Kalra and Ahmed 2009); and 2) use climate model ensembles to predict medium to long term moisture availability (e.g. The North American Mutli-Model Ensemble). Typically the first approach is adopted for operational use due to its relatively simple mathematical formulations, and the short time required for conducting the analysis. The disadvantage of this approach is that even though it may have statistical power, it doesn't show physical causality.

In addition to the two approaches stated above a third approach, which is probably used extensively by water managers, is the water supply forecast for the season provided by the RFCs (CBRFC 2014). The river forecast centers typically start publishing forecasts in January for the future three months (February-April) and updates this forecast monthly till June. They typically use a statistical model that relates observations from weather stations, SNOTEL stations for snow, USGS streamflow, and USBR reservoir observations to predict water supply at various forecast points within the basin. Since these forecasts are directly based off observations, they should not be accepted to be accurate as it has been shown that the errors are higher (approximately 30-40%) in January and improve as more observations become available as the season progresses into April (CBRFC 2014).

Over the last couple of decades, from in situ observation, using climate models and satellite observations have allowed us to gain a better understanding of the dynamics of the climate system. For example, the effects of ENSO on global climate, especially over North America, are relatively well understood (NOAA 2014). Figure 1 illustrates how ENSO modulates storm tracks (circulation patterns); which are eventually responsible in transporting moisture. In addition to understanding the influence of ENSO on climate, we also have gained an (significant though not complete) understanding of the physical mechanisms responsible for the ENSO phenomena (e.g. McPhaden 1999). Apart from ENSO

Figure 1. Position of the jet stream based on different SST conditions. Source: http://www.srh.noaa.gov/jetstream/tropics/enso_impacts.htm

numerous other ocean and atmospheric phenomena have been discovered; such as PDO, NAO, AMO, etc., and quantified in terms of indices, though the physical mechanism causing them may not be understood.

OBJECTIVE

The objective of this study is to test whether combining climate indices and circulation patterns improve predictability in a basin. The hypothesis being, climate indices provide information on moisture availability and circulation patterns channel this moisture to a region of interest. The method will help predict if a region of interest will be wet or dry for a season (winter). This approach has a simplistic statistical formulation (as presented below), but the added advantage of showing physical causality in terms of the final prediction.

METHODS

Datasets

The method developed as part of this research, uses a combination of multiple climate indices (viz. ENSO and PDO) with atmospheric circulation patterns to predict if a given winter season is wet or dry and hence it is referred to as a hybrid method. The hybrid methodology builds on work by Changnon et al. 1993 (hereafter referred to as C93) who identified seven synoptic weather patterns over the Colorado River Basin that explain the annual snow patterns in the region. Only a brief explanation of their method is presented below, for a thorough understanding please refer to C93. The method of C93 involved analyzing the frequency of occurrence of weather types over the Colorado River Basin for the period 1951-1985 and its correlation with data from meteorological stations in the basin to identify weather types that caused it to be wet (meaning more precipitation than average) or dry (meaning less precipitation than average). In their technique they used the 500 mb geopotential height (gph) which shows air circulation patterns at the 500mb pressure level. They showed that nearly 90 percent of the annual wet or dry patterns were explained by the frequency of seven 500-mb winter synoptic patterns. The seven circulation patterns identified by C93 are presented in Table 1 along with their potential precipitation distribution. It should be noted that the seven circulation patterns identified by C93 are only a subset of all the circulation patterns observed in the basin. The reason to focus only on the seven patterns is because they could be correlated to wet and dry conditions in the Colorado River Basin. Two out of the seven patterns identified by C93 are of particular importance to the current study viz. the ridge winter synoptic pattern and the trough winter synoptic pattern which are shown below in Figure 2. While the two patterns presented here are most important in terms of identifying wet and dry years, the remaining five circulation patterns are also useful for predictive purposes.

The method of C93 involves frequency counts of occurrence of the synoptic patterns of interest, such as the trough (SWT) and ridge (DR) patterns. To facilitate this process of frequency counting, a Matlab tool was developed that automatically downloads the historical synoptic pattern for the entire U.S. and displays the 500 mb geopotential height synoptic pattern. Figure 3 provides a screenshot of the Matlab tool developed. The tool displays the 500mb circulation pattern for any day input by the user past Jan 01, 1948, since the NCEP reanalysis product used in this study only goes back to 1948. The source of the atmospheric data (primarily the 500 mb gph) used in this study is the NOAA reanalysis data (ESRL, 2015) and the reference is Kalnay et al., 1996. Details about using the Matlab tool are provided in Appendix I.

Table 1. Synoptic circulation patterns and their potential precipitation distribution

Synoptic Circulation Pattern	Abbreviation	Potential Precipitation Distribution
Ridge Pattern	DR	Dry
Meridional Northwest	NWM	Dry: San Juan River Basin
West Northwest	NWW	Dry: San Juan & Upper Colorado River Basin
Zonal Pattern	NWZ	Dry: San Juan & Upper Colorado River Basin
Trough Pattern	SWT	Wet
Split Flow	SWS	Wet: San Juan River Basin
Cutoff Pattern	SWC	Wet: San Juan & Upper Colorado River Basin

Note: This table is based on Changnon et al., 1993. Dry/Wet means dry/wet for the entire Colorado River Basin above Lees Ferry. Dry/Wet: specific river basin (e.g. San Juan) only means that specific basin is dry/wet and does not imply the rest of the Colorado River Basin is opposite of the specific basin state.

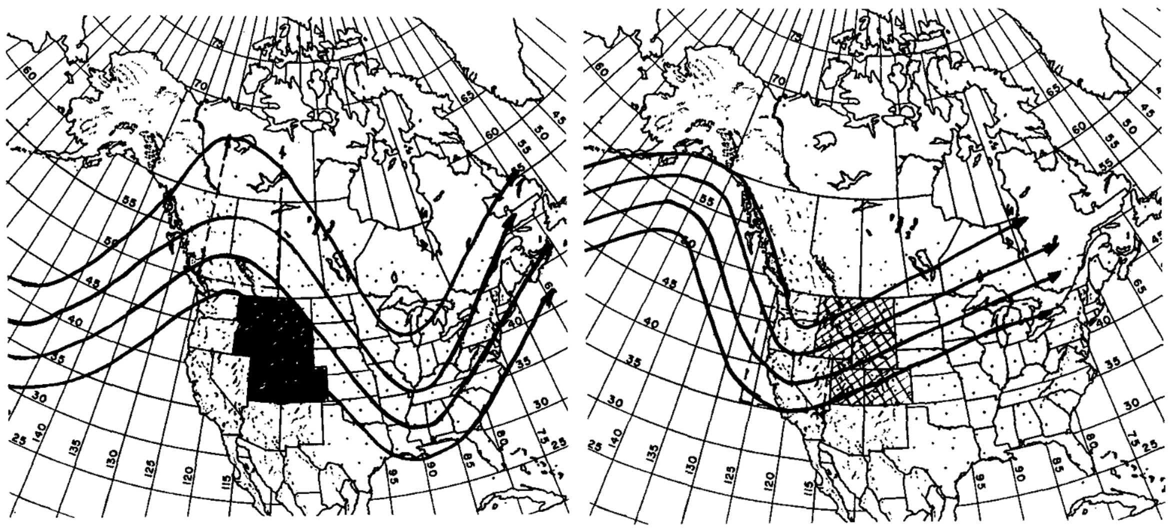

FIG. 8. The ridge (DR) winter synoptic pattern. Crosshatched lines represent areas in the five-state region where opportunities for precipitation exist, while shaded areas represent locations of little or no opportunity for precipitation.

FIG. 12. The trough (SWT) winter synoptic pattern. Crosshatched lines represent areas in the five-state region where opportunities for precipitation exist, while shaded areas represent locations of little or no opportunity for precipitation.

Figure 2. Two synoptic patterns, left the ridge pattern (DR) associated with dry conditions and right the trough patterns (SWT) associated with wet conditions over the Colorado River Basin identified by Changnon et al., 1993

As stated above, the method also uses SSTs in addition to circulation patterns to enhance the prediction. In this study, two indices were used; ENSO and PDO. The source of the ENSO index is CPC, 2015 and the source of the PDO index used in this study is the University of Washington (Washington, 2015). The forecast tool developed as part of this research also downloads the latest SST indices and displays them in the lower panel of the tool (Figure 3).

The circulation patterns and the SST states are the predictor variables used to predict if it is wet or dry in the Colorado River Basin, but we still need a method to know if the prediction is accurate. We use the annual streamflow observation as a proxy to evaluate if a given year is wet or dry in the Colorado River Basin. Since the Colorado River is highly regulated, we use the naturalized flows at Lees Ferry provided by the USBR to avoid the effects of depletion. The naturalized streamflow provides a good proxy for climate since it is an aggregator of all the hydro-meteorological processes upstream of Lees Ferry. The alternative to using the naturalized streamflow would be to evaluate all the climate stations that fall within the Colorado River Basin. While doing this may be more rigorous, due to time constraints on the project a simpler approach of using naturalized streamflow as a proxy was chosen. To predict a wet or dry year we compare the annual naturalized streamflow to the long term average (15 million ac-ft) for the Colorado River (Figure 4).

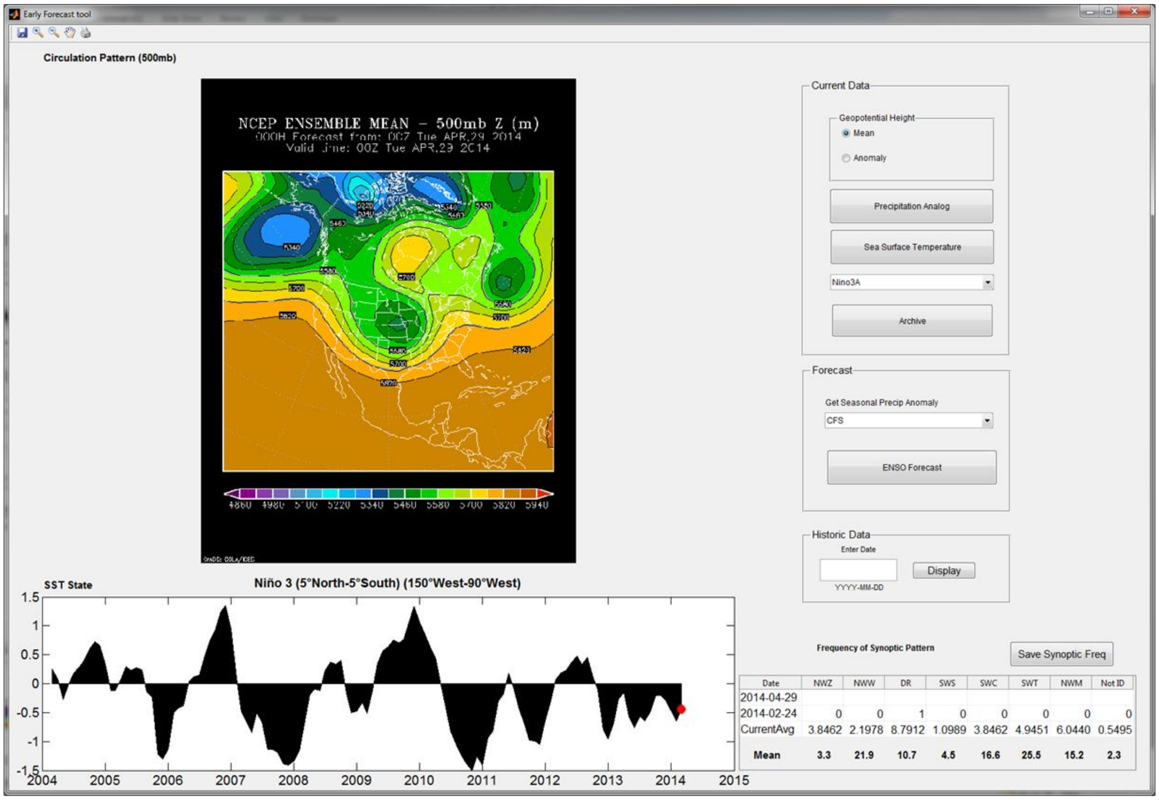

Figure 3. Screenshot of the Early Forecast Tool. Details of this tool can be found in Appendix I

Techniques

To understand how one may use circulation pattern information along with SST indices to predict if the Colorado River Basin is wet or dry, let us focus on a sample dataset presented in Table 2. This table provides data for three years (1954, 1985, 2010 - picked randomly) and shows the frequency of the seven circulation patterns for the chosen years during the October-1 to March-31 period of the water year. Also shown are the average SST index values for that period and the condition of the Colorado River Basin using the streamflow threshold approach described in the previous section.

As described in the introduction, one could make a forecast of a wet or dry winter in the Colorado River Basin using either the circulation patterns or SST index separately, or one can combine this information logically into the hybrid method to make a prediction. Here we use all three approaches and quantify the improvement in prediction due to the hydrid approach by computing statistical measures such as the hit ratio, and false alarm ratio.

Prediction Based Solely on Circulation Pattern:

Using only the circulation pattern, one can make a logical function to predict the chance of a wet or dry year if the following conditions are satisfied:

IF {Yearly Frequency (SWT) > Long Term Mean (SWT)} TRUE then Wet

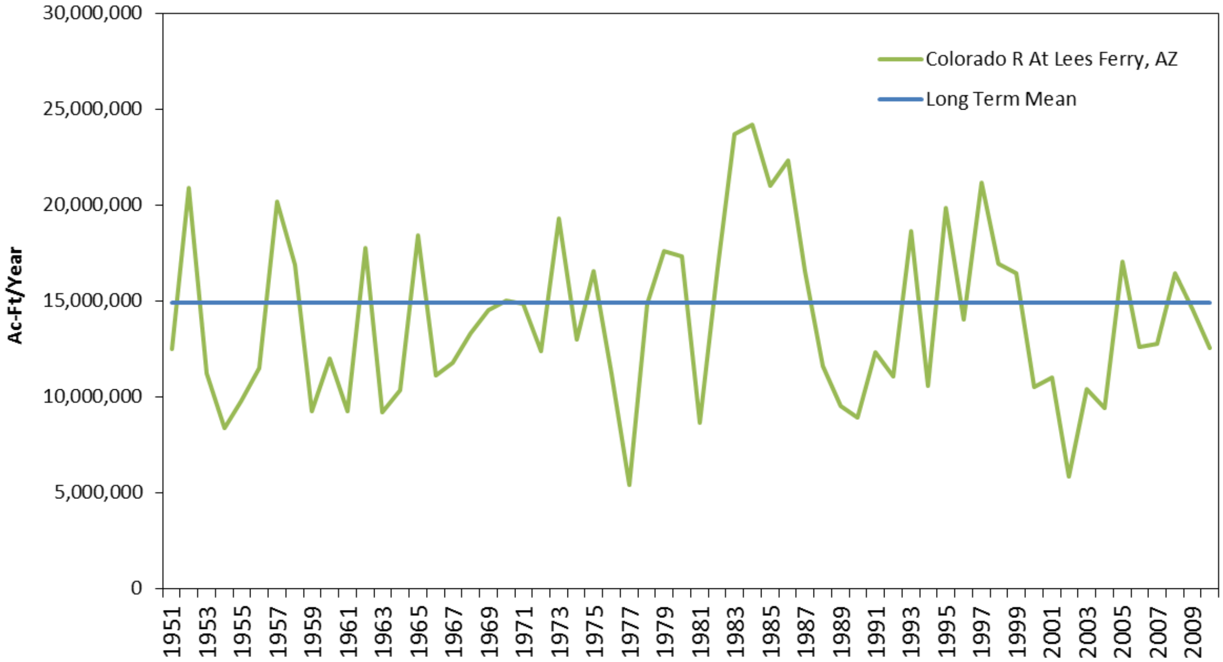

Figure 4. Naturalized streamflow for Lees Ferry, Arizona and the long term mean streamflow used to distinguish wet and dry years

The logical condition to be tested for a dry year is slightly more complicated than presuming that if it were not a wet year then it must be a dry year. The reason for the additional check is due to the fact that in some years even though the frequency of the DR pattern (associated with dry conditions) maybe higher than the long term mean, so is the frequency of the SWT pattern. The logical condition to be tested for a dry year is as follows:

IF {Yearly Frequency (DR) > Long Term Mean (DR) AND Yearly Frequency (SWT) < Long Term Mean (SWT)} TRUE then Dry

Prediction based solely on SST index:

One can make predictions of wet or dry conditions in the Colorado River Basin based on ENSO and PDO indices. In this approach we use both the indices in a logical function to predict a wet or dry year. The value for the ENSO index used to predict a wet year had to exceed a value of 0.28 and the PDO index should be positive (meaning > 0). While the choice of these threshold are arbitrary and could be revised as the sample data size increases, the logic of defining it is due to the fact that all El Nino years do not make it wet in the Colorado River Basin, only strong values (defined here as > 0.28) and a positive PDO lead to wet winters. The logical function used to predict wet years is as follows:

IF {OR (ENSO>0.28, PDO>0)} TRUE then Wet

The logical function used to predict dry years is as follows:

IF {AND (ENSO<0, PDO<0)} TRUE then Dry

Prediction based on hybrid method:

The hybrid method combines the circulation pattern frequency and the SST indices in a logical function to predict if it is wet or dry in the basin. The logical function used to predict wet years is:

IF {OR (SWT>SWTmean, ENSO>0, PDO>0)} AND

IF {OR (SWC>SWCmean, DR<DRmean)} TRUE then Wet

The logical function used to predict dry years uses different thresholds than the ones used to predict wet years. The reasoning being, by default a year that is not wet automatically does not get classified as dry, hence different threshold values have to be used along with certain other criteria that have to be met. These are defined in the logical function below:

IF {OR (DR>DRmean, ENSO<-0.3, PDO<-0.4) AND IF {SWC<SWCmean} TRUE then Dry

Forecast Verification Metrics:

To verify the forecast, the following evaluation statistics recommended by Wilks (1995) were computed:

$$PC = (a+d)/n \tag{1}$$

$$B = (a+b)/(a+c) \tag{2}$$

$$FAR = b/(a+b) \tag{3}$$

$$H = a/(a+c) \tag{4}$$

Where a = number of hits, b = number of false alarms, c = number of misses, d = number of correct rejections and n = a+b+c+d. The proportion correct (PC) is an accuracy statistic, while B is a measure of bias, the false alarm ratio (FAR) is a measure of reliability and the hit rate (H) is a measure of discrimination.

The ideal value for indicator PC = 1 as this indicates a perfectly accurate estimator. An unbiased estimator will have B=1 since B >1 indicates that the forecast overestimates more years as being wet than what was observed. While B < 1 indicates that the forecast is biased towards low occurrence. A good estimator will produce a FAR close to 0 and a hit ratio close to 1.

RESULTS

Table 3 shows the results from applying the logical functions to the three different techniques of prediction. While the truth tables presented for each year in Table 3 may not be useful by itself, its purpose is to evaluate the logical function that produced the values. Table 4 computes the evaluation statistics of the prediction.

From Table 4 we observe that the evaluation statistic such as PC and H are always higher than 0.5. Also observed was that the values of PC and H are comparable (approximately 0.6) for the methods that employ only one predictor variable; i.e. a synoptic pattern or SST index by itself. We noticed the improvement in both PC and H for the hybrid method, which has values of approximately 0.8 in comparison to the single predictor method. The goal of the logical function is not only to predict the PC and H of wet/dry years but also to minimize the FAR of years that were predicted incorrectly. Again the hybrid method achieves this goal by producing the lowest FAR of the three different techniques of prediction (see Table 4).

DISCUSSION

Predicting wet or dry climate for a season (especially winter) in the Colorado River Basin is a challenging scientific problem. As a baseline one could argue that it is similar to predicting the outcome of a coin toss. The probability of predicting this outcome correctly is approximately even, meaning there is a 0.5 probability that one would make the right guess. In the case of predicting a wet or dry climate, if one were to randomly make a guess without any other information, we can expect the prediction to be correct about half the time. This means that any additional information should improve the predictive skill.

Table 2. Sample of data used in the analysis

	Frequency of seven 500mb circulation patterns							**SST index Average**		**Colorado Basin Condition**	
Year	NWZ	NWW	DR	SWS	SWC	SWT	NWM	NINO3A	PDO	Wet	Dry
1954	2	30	5	1	12	21	27	-0.02	0.75	0	1
1985	3	9	5	14	23	29	15	-0.93	0.82	1	0
2010	4	35	7	4	13	25	11	0.96	0.34	0	1
min	0	9	1	0	9	17	4				
mean	3	22	11	5	17	26	15				
max	11	35	38	14	34	41	27				
std	2	7	8	3	6	5	6				

Note: min, mean, max, std are based on frequency count data from 1951-1985. In the column Wet/Dry a value of 0 means false and a value of 1 means true.

Table 3. Truth tables of predictions based on the logical functions for each technique

Year	Based on Streamflow		Prediction based on Synoptic Pattern		Prediction based on SST Indices		Prediction based on Hybrid Method	
	Wet	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**
1951	F	T	F	T	F	T	F	T
1952	T	F	T	F	T	F	T	F
1953	F	T	F	T	F	T	F	T
1954	F	T	F	T	F	T	F	T
1955	F	T	F	T	F	T	F	T
1956	F	T	F	T	F	T	F	T
1957	T	F	F	T	F	T	F	T
1958	T	F	F	T	T	F	T	F
1959	F	T	T	F	F	F	T	F
1960	F	T	F	T	T	F	F	T
1961	F	T	F	T	T	F	F	T
1962	T	F	T	F	F	T	T	F
1963	F	T	F	T	F	T	F	T
1964	F	T	T	F	T	F	T	T
1965	T	F	T	F	F	T	T	T
1966	F	T	F	T	T	F	F	T
1967	F	T	T	F	F	T	T	T
1968	F	T	T	F	F	T	T	T
1969	T	F	T	F	T	F	T	T
1970	T	F	F	T	T	F	T	F
1971	T	F	F	T	F	T	F	F
1972	F	T	F	T	F	T	F	F
1973	T	F	T	F	T	F	T	F
1974	F	T	T	F	F	T	T	T
1975	T	F	T	F	F	T	T	F
1976	F	T	T	F	F	T	T	F
1977	F	T	F	T	T	F	F	T
1978	T	F	F	T	T	F	T	F
1979	T	F	T	F	F	T	T	F
1980	T	F	F	T	T	F	T	F
1981	F	T	F	T	T	F	F	T
1982	T	F	T	F	T	F	T	F
1983	T	F	F	T	T	F	T	F
1984	T	F	F	T	T	F	T	F
1985	T	F	T	F	T	F	T	F

Note: T: True; F: False.

We observe from Table 4 that there is an improvement in the predictive skill for PC and H values for the three techniques tested in this study and all are consistently higher than 0.5, which means that there is additional information in the synoptic patterns and SST indices that improves the predictive skill. However, the improvement in skill is only approximately 20 percent when either the synoptic patterns or the SST indices are used separately as is evidenced by the PC and H values of ~0.6. Notice that the improvement in prediction is more than 60 percent for the hybrid method which has a PC and H value of approximately 0.8 or higher. The hybrid method not only improves the PC and H but also lowers the FAR. From a lay perspective this could be viewed as the hybrid method producing predictions that are accurate about 80 percent of time and only producing a false prediction between 20 to 30 percent of the time.

This is an important finding since one usually either used circulation patterns (Changnon et al., 1993) or SST indices separately to improve predictive skill. To our knowledge, this is the first time these two methods have been combined into a single predictive model and they statistically show an improvement in predictive skill.

LIMITATIONS

One of the primary limitations of this approach is that the weather types identified by Changnon et al., 1993 that are associated with wet and dry conditions in the Colorado River Basin are based on historical analysis and may not correspond with recent circulation patterns that make the basin wet or dry. In this study we assumed that the patterns identified by C93 are valid for the recent years (2000-2014) studied. Another limitation of this study is related to the weather types identified by C93 and its correspondence with the weather type on a given day, which may sometimes lead to misclassification for the frequency count. A third limitation of this method is that while it accounts for atmospheric circulation patterns and climate indices, it does not explicitly account for precipitation in the basin.

Table 4. Evaluation statistics for the prediction made using the three different techniques

		PC	B	FAR	H
Based on Synoptic Patterns Alone	Wet	0.60	0.88	0.40	0.53
	Dry	0.60	1.11	0.40	0.67
Based on SST Alone	Wet	0.66	1.00	0.35	0.65
	Dry	0.63	0.94	0.35	0.61
Based on Hybrid Method	Wet	0.77	1.24	0.29	0.88
	Dry	0.83	1.00	0.17	0.83

Note: PC: Percent Correct (1); B: Bias (1); FAR: False Alarm Ratio (0); H: Hit Ratio (1). Ideal value shown in parenthesis.

POTENTIAL IMPROVEMENTS

While working on developing and evaluating the hybrid method, it was recognized that a good extension of the current hybrid approach would be to pursue a logistic regression. This is a statistical technique capable of predicting a binary outcome. Logistic regression is a valuable approach since it will give us insight into what the model is exactly doing to produce a certain outcome (e.g. wet/dry conditions), which is not the case with other black box algorithms such as Support Vector Machines (SVM).

The goal of the logistic regression will be to evaluate the various factors that may influence the Colorado River Basin to be wet or dry. From the present research we have identified at least two factors, namely synoptic circulation patterns and SST indices. While these two predictors provide improvement in skill, the logistic regression does not need to be limited to them. One could potentially include other predictor variables such as snow cover extent, water vapor, and precipitation variables from reanalysis products such as the new NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA) product to refine the prediction.

SUMMARY AND CONCLUSIONS

This work presents a novel method by combining both synoptic circulation patterns at the 500mb geopotential height level with SST indices (ENSO, PDO) to improve the prediction of wet or dry conditions in the Colorado River Basin. We show that the improvement in predictive skill is substantial with a percent correct and hit ratio value of 0.8 or greater, which is a significant improvement over using a predictor in isolation. While the technique uses logical functions and statistics to make predictions and evaluations, one can intuitively provide a physical mechanism to why it works. One plausible explanation for the causal mechanism is that the SST index provides a metric of how much moisture is available in the atmosphere and the synoptic circulation pattern provides a means for this moisture to either be funneled to the basin or not. While we acknowledge that there are limitations to the current approach, we also think that there is value in using this approach compared to a black box statistical model that may give you a prediction similar to the current approach but there is no way of understanding the underlying cause of the prediction.

REFERENCES

CBRFC,2014, http://www.cbrfc.noaa.gov/arc/verif/verif.php?column=January

Changnon D, McKee T.B., Doesken N.J., 1993, Annual snowpack patterns across the Rockies: long-term trends and associated 500-mb synoptic patterns, Monthly Weather Review, Vol 121, 633-647.

Christensen N.S., Andrew W. Wood, Nathalie Voisin, Dennis P. Lettenmaier and Richard N. Palmer, 2004. The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin, Climatic Change 62: 337–363

CPC, 2015 http://www.cpc.ncep.noaa.gov/data/indices/ersst3b.nino.mth.81-10.ascii

ESRL, 2015 http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.pressure.html

Kalra A, William P. Miller, Kenneth W. Lamb, Sajjad Ahmad and Thomas Piechota, 2013, Using large-scale climatic patterns for improving long lead time streamflow forecasts for Gunnison and San Juan River Basins, Hydrol. Process. 27, 1543–1559, DOI: 10.1002/hyp.9236

Kalra, A., and S. Ahmad (2009), Using oceanic-atmospheric oscillations for long lead time streamflow forecasting, Water Resour. Res., 45, W03413, doi:10.1029/2008WR006855.

Lamb K.W., Thomas C. Piechota, Oubeidillah A. Aziz, and Glenn A. Tootle, 2011, Basis for Extending Long-Term Streamflow Forecasts in the Colorado River Basin, Journal of Hydrologic Engineering, Vol. 16, No. 12, DOI: 10.1061/(ASCE)HE.1943-5584.0000153

Mantua, N.J. and S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis,1997: A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society, 78, pp. 1069-1079.

McPhaden, M. J., 1999, Genesis and Evolution of the 1997-98 El Niño, Science 283, 950; DOI: 10.1126/science.283.5404.950

NOAA, 2014, http://www.pmel.noaa.gov/tao/elnino/impacts.html#part2

Switanek, M. B., and P. A. Troch (2011), Decadal prediction of Colorado River streamflow anomalies using ocean-atmosphere teleconnections, Geophys. Res. Lett., 38, L23404, doi:10.1029/2011GL049644

Salas J D, Chongjin Fu, and Balaji Rajagopalan, 2011, Long-Range Forecasting of Colorado Streamflows Based on Hydrologic, Atmospheric, and Oceanic Data, Journal of Hydrologic Engineering, Vol. 16, No. 6, DOI: 10.1061/(ASCE)HE.1943-5584.0000343

The North American Mutli-Model Ensemble, available at http://www.cpc.ncep.noaa.gov/products/NMME/; US National Academies report "Assessment of Intraseasonal to Interannual Climate Prediction and Predictability

Washington, 2015 http://research.jisao.washington.edu/pdo/PDO.latest

Wilks D. S., 1995, Statistical methods in the atmospheric sciences, second edition, International Geophysics Series, Vol 59, Academic Press, 464pp. ISBN-10: 0127519653. ISBN-13: 978-0127519654

Zhang, Y., J.M. Wallace, D.S. Battisti, 1997: ENSO-like interdecadal variability: 1900-93. J. Climate, 10, 1004-1020.

APPENDIX I: SHORT GUIDE TO USING THE MATLAB FORECAST TOOL

To aid the data collection effort of this study a MATLAB Forecast Tool was developed. This tool was developed in MATLAB version R2013b. The executable requires that one install the MATLAB Runtime which is freely available on the Mathworks webpage and does not require a license to enable the execution of compiled MATLAB applications. The name of the executable is forecast_tool.exe and to start the application one simply needs to double click the application. This application was developed primarily for Microsoft Windows 7. The zipped folder that contains the executable also contains shapefiles of the Upper and Lower Colorado River Basin, which are used primarily for visualization and it contains a Microsoft Excel worksheet that is used as a database for recording the frequency of synoptic patterns.

Once the executable is run, the program appears as shown in Figure 3 and it contains four panels on the right with different functions/purpose. The current data panel as the name suggests helps acquire and visualize the current, meaning today’s/recent, data. The primary purpose of the current data panel is to help visualize the current 500 mb gph mean and anomaly graphs which is displayed on the left panel. In addition to this functionality it also helps the user by displaying information on precipitation when the precipitation analog button is pressed. Since the hybrid method also relies on sea surface temperatures (SST) there is a button with a drop down menu to display various SSTs such as Nino3A and PDO which is displayed in the left bottom panel. The archive button is used to create a copy of the graph being displayed into the directory where the executable resides.

The forecast panel is used to acquire and visualize the forecasts based on the multiple climate models run to predict precipitation for the future three months. The drop down menu has options for selecting multiple climate models such as the Climate Forecast System (CFS) and the Geophysical Fluid Dynamics Laboratory (GFDL). When the user selects a particular climate model, its future three month forecast will be displayed in the left top panel.

The historic data panel helps with collecting data for dates entered by the user. The hybrid method requires daily frequency counts of 500 mb gph circulation patterns, but if the user has to take time off from work or due to a holiday misses entering some days of data, the historic data panel will help gap fill data in the excel database. Another reason this panel can be used is to help the user enter data for a historic year (e.g. 1990). It should be noted that when the user starts to enter data for a historic year, the tool first has to download this information. Since the file size of the download can be typically high (~ 150 MB) for the first time that the user queries a historic year, the program may behave slowly, but this is because the file is being downloaded in the background. The downloaded file will be placed in the directory where the executable is placed. The filename typically has the format hgt.YEAR.nc where YEAR corresponds to the year being queried and the nc refers to a netcdf file format.

The frequency of synoptic patterns panel is where the user can record the synoptic pattern by entering the pattern for the current day in the top row. The second row of the panel is where the most recent record in the excel database is stored. The third row simply updates the percentage of occurrence of various synoptic patterns until the most recent record. For reference, the long term mean is displayed in the fourth row of the panel.