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# USE OF SEASONAL CLIMATE FORECAST FOR WATER RESOURCES MANAGEMENT IN THE TENNESSEE RIVER

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## 1. INTRODUCTION

Over the past decades, important progress has been made towards understanding and predicting ENSO-related climate variability. Seasonal climate forecasts are now available through the use of empirical and dynamical models. How can these forecasts be utilized by the various sectors of the society? This study aims at examining the feasibility of using seasonal climate forecasts for water resources management.

One central issue of using seasonal climate forecasts for managing water resources is the specificity of the climate forecasts. Are they provided with enough accuracy and spatial resolution to be of practical value? To address the issue of spatial resolution, we use a regional climate-hydrology modeling system to downscale dynamical seasonal climate forecasts provided by the NCEP Global Spectral Model (GSM) to produce ensembles of regional climate and streamflow forecasts. To determine the usefulness of the streamflow forecasts, a reservoir model and a multi-objective optimization routine will be applied to the Clinch River of the Tennessee River Basin to assess the values of seasonal forecasts under operating rules that balance flood control and hydropower production.

This paper reports the ongoing progress to achieve our objectives. In the sections below, we will discuss the evaluation of regional climate and hydrologic simulations in the region encompassing the Tennessee River, analyze the ENSO streamflow anomalies, and examine the impacts of water operations with perfect seasonal forecasts on various water management objectives.

## 2. REGIONAL CLIMATE SIMULATIONS FOR THE EASTERN U.S. NUMERICAL EXPERIMENTS

To test the performance of downscaling, a Regional Climate Model (RCM) (Leung and Ghan 1999) based on the Penn State/NCAR Mesoscale Model (MM5) (Grell et al. 1993) has been used to perform a simulation for October 1991 through December 1998 over the eastern U.S. at 60-km spatial resolution. The simulation was driven by large-scale conditions from the NCEP/NCAR reanalysis and has been evaluated using a half-degree temperature and precipitation dataset from the Climate Research Unit (New et al. 1999).

Figure 1 shows the RCM model domain, surface elevation, and a region in the eastern U.S. where analyses have been performed. Figure 2 shows the observed and simulated monthly mean precipitation averaged over the region shown in Figure 1. The RCM simulation captures the seasonal cycle and interannual variability very well except for some larger negative biases in a few summer seasons. The NCEP reanalyzed precipitation persistently shows unrealistically larger summer precipitation peak not found in the observations.

To further evaluate model skill in simulating interannual variability, Figure 3 shows the observed and simulated ENSO precipitation anomaly of 1997/98. The wetter and dryer than normal precipitation pattern near the Appalachians and southeast Texas are well simulated by both the RCM and the NCEP reanalyses.

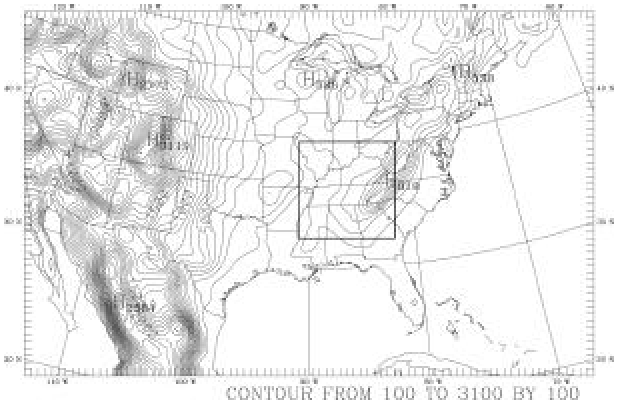

Figure 1. Domain and surface elevation used in the regional model. Analyses were performed over the region shown in the square over the eastern U.S.

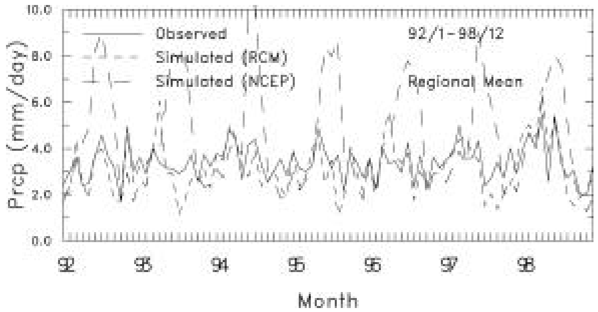

Figure 2. Regional averaged monthly mean precipitation as observed and simulated by the RCM and NCEP reanalyses for 1992-98.

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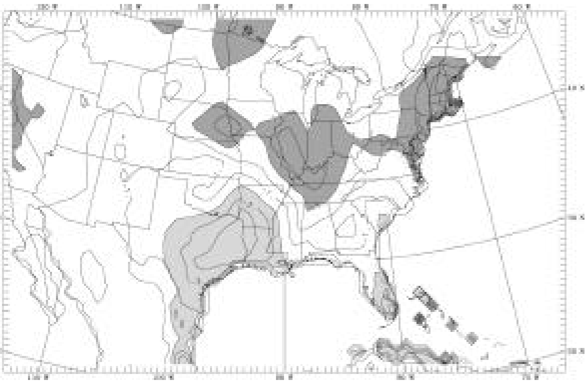
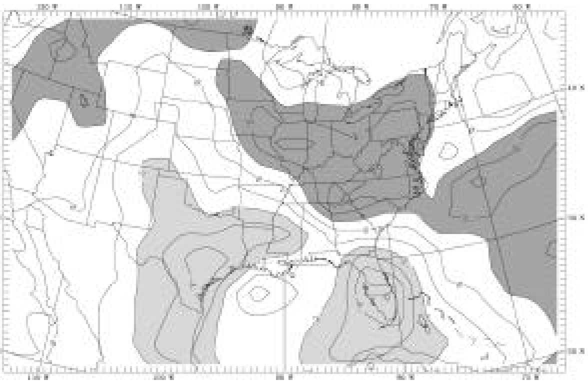
(a) Observation



(b) NCEP Reanalyses



(c) RCM Simulation

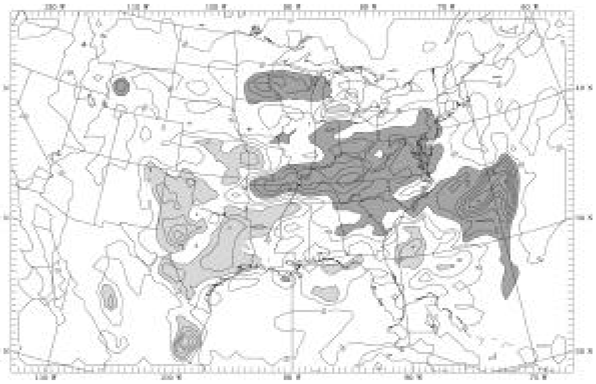


Figure 3. Averaged April-June precipitation anomaly (1998 minus 1997) based on (a) observation, (b) NCEP reanalyses, and (c) RCM simulation. Light shading corresponds to area where negative (dry) anomaly is ≤-2 mm/day; dark shading corresponds to area where positive (wet) anomaly is ≥1 mm/day.

Global simulations have been performed with the NCEP Global Spectral Model (GSM) driven by observed sea surface temperature for October 1996 through May 1997, and October 1997 through May 1998. There are 10 ensemble simulations for each period. These simulations are being used to drive the RCM to examine the value of downscaling on predicting the ENSO hydroclimate signal. Both the GSM and RCM simulations will be used to drive a hydrology model of the Tennessee River to determine how well the modeling system simulates the ENSO streamflow signal.

## 3. HYDROLOGIC MODELING AND ANALYSES

Hydrologic processes are highly affected by the ENSO events at the Tennessee River. An analysis has been performed using observed streamflow data at the Clinch River above Tazewell to understand the effects of ENSO on annual flow volume. Table 1 shows the number of years and the corresponding averaged annual flow volume by climate classification between 1949-1995. During the 46 years, there is a much higher likelihood of high flow volume during La Nina years as evident from the larger number of events in the highest 10 and 5 percentiles of streamflow. The opposite is true for El Nino years when typically lower streamflow conditions are found (lowest 10 and 5 percentile).

Figure 4 shows the temperature, precipitation, and streamflow during El Nino, La Nino, and Normal years at the Clinch River. The decrease in streamflow during winter (January through March) is as large as 25% during El Nino years. Reduced precipitation in January and February is responsible for the lower flows. Furthermore, colder winter temperature may be responsible for a delay in the streamflow peak from March to April.

Table 1. Number of Years and Corresponding Average Annual Flow Volume by Climate Classification for Clinch River Above Tazewell: 1949-1995.

| | **El Nino** | **Normal** | **La Nina** |
|---|---|---|---|
| Upper 50 Percent | | | |
| Observed | 4 (549) | 10 (581) | 9 (604) |
| Simulated | 4 (540) | 10 (616) | 9 (630) |
| Highest 10 | | | |
| Observed | 2 (594) | 3 (658) | 5 (667) |
| Simulated | 0 | 4 (685) | 6 (682) |
| Highest 5 | | | |
| Observed | 0 | 1 (710) | 4 (674) |
| Simulated | 0 | 2 (718) | 3 (736) |
| Lower 50 Percent | | | |
| Observed | 11 (397) | 5 (366) | 7 (398) |
| Simulated | 11 (413) | 5 (412) | 7 (398) |
| Lowest 10 | | | |
| Observed | 4 (328) | 3 (325) | 3 (348) |
| Simulated | 5 (351) | 2 (334) | 3 (342) |
| Lowest 5 | | | |
| Observed | 2 (279) | 2 (305) | 1 (337) |
| Simulated | 2 (311) | 2 (334) | 1 (309) |

Note: For each climate/flow classification (e.g., Upper 50 Percent, Observed El Nino) the number of years is given first, followed by the average annual flow volume (mm) for those years in parenthesis.

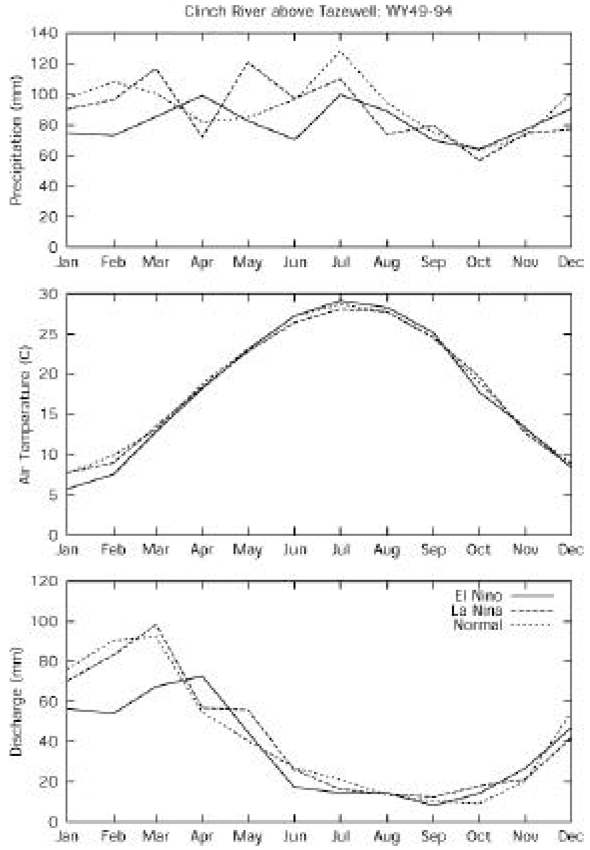


Figure 4. Observed precipitation, temperature, and discharge at the Clinch River during El Nino, La Nina, and Normal years between 1949-1994.

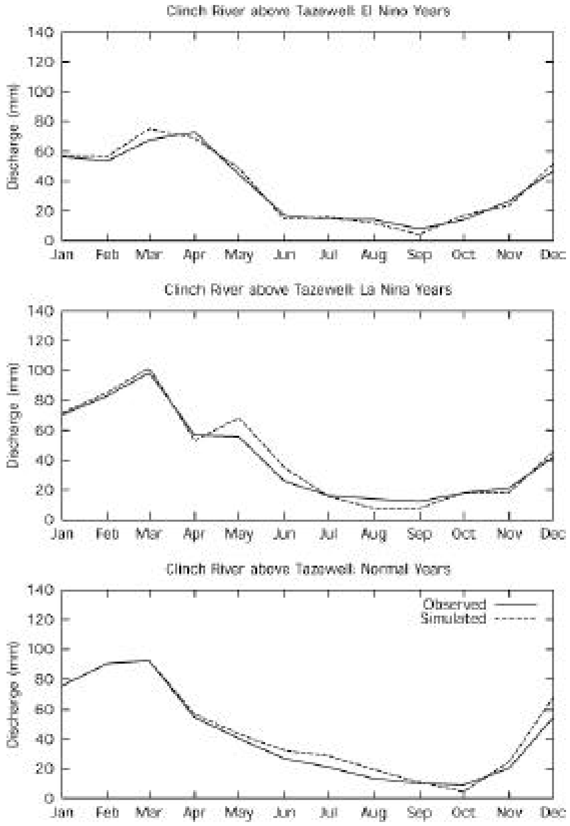


Figure 5. Comparison of observed and simulated streamflow during El Nino, La Nina, and Normal years from 1949-1994.

To determine how well the ENSO streamflow anomalies can be represented by hydrologic modeling, we used a distributed hydrology model to simulate the streamflow conditions at the Clinch River. The hydrology model used in this study is the Distributed-Hydrology-Soil-Vegetation Model (DHSVM) (Wigmosta et al. 1994). DHSVM has been enhanced to operate either on the original square-grid domain or a more generic subbasin or channel representation that allows direct application at the appropriate Hydrologic Unit Code (HUC) level. Support utilities have been developed to subdivide each subbasin or HUC into elevation bands with a simplified representation of subband topography. Each band may be mapped to the appropriate US EPA River Reach(s). The new HUC representation is found to significantly cut down on CPU and memory requirements while maintaining a similar level of skill in simulating hydrologic processes in river basins.

DHSVM has been applied to the Norris Watershed upstream from the Norris Reservoir. The 3,820 km$^2$ Clinch River basin above Tazewell, Tennessee, has been modeled using four subbasins, each with twenty elevation bands. The model was driven at a 3-hour time step using observed meteorology from Water Years 1949 through 1995. Figure 5 shows the comparison between the mean observed and simulated streamflow during El Nino, La Nina, and Normal years. The model simulates realistically the variability associated with the ENSO events. Table 1 also shows the simulated streamflow for each flow and climate regime classification. The simulation matches the observations very well both in terms of the number of events and mean flows.

DHSVM will be used to provide streamflow forecasts for the Tennessee River based on downscaled RCM simulations driven by the NCEP GSM ensemble simulations discussed above. The streamflow forecasts will be used to assess the value of improved streamflow forecasts for reservoir management.

## 4. RESERVOIR MANAGEMENT

The Norris Reservoir is used as a baseline reservoir design for this study. Norris Reservoir currently provides 1,922,000 acre-feet of useful controlled storage and 101 megawatts (electric) of hydropower capacity. Its operations provide for both local and system flood control. A reregulating reservoir about 2 miles downstream of Norris moderates the downstream flow fluctuations resulting from peak load hydropower operations. Peaking operations are not considered in this study.

The reservoir is represented with a simple mass balance module with a daily time step and neglects any hydraulics within the reservoir. Releases are prescribed by the "rule curve" given the current storage and the forecasted inflows. The current reservoir storage is assumed to be known perfectly. In each iteration of the analysis process, a genetic algorithm provides a new "rule curve" that optimizes the various management objectives. Flood damages are expressed as a non-linear function of flow. Firm power is expressed as the probability of meeting total monthly generation targets with daily generation expressed as a nonlinear function of head and storage.

Riverside Technology, Inc. has provided an ensemble of Extended Streamflow Prediction (ESP) traces for the inflow to Norris. The ESP method uses calibrated hydrologic and hydraulic models with estimates of "current conditions" used as initial conditions. The method assumes that the historical climate record represents an ensemble of equally feasible future climates. An ensemble of streamflow traces is generated from each year of the historic record. The traces were provided on a moving month basis and are based on historic data for 1955 through 1994. ESP represents an inflow forecast reliability baseline. The value of extended climate forecasts should be compared to this baseline since this represents the current standard in streamflow forecasting. It is assumed that the extended climate forecasts will augment (or possibly replace) the ESP streamflow forecasts, if significant improvement is shown.

An analysis framework has been established to assess the value of improved inflow forecasts in reservoir management. The simple mass-balance model of the Norris Reservoir is combined with historical inflow measurements (which are treated as perfect forecasts), the ESP forecasts, and a pareto genetic algorithm. The pareto genetic algorithm defines the tradeoff relationship between two reservoir management objectives by defining pareto optimal "rule curves" for reservoir releases. Reservoir releases are assumed to be a function of the reservoir's current storage and inflow forecasts for multiple lead times. Currently, objectives for baseload hydropower and flood control are being evaluated. The optimization algorithm employs PGAPack, developed at the Argonne National Laboratory, to allow rapid restructuring of the reservoir operating rule representation.

Before actual inflow forecasts become available through the regional climate-hydrologic modeling system, inflow forecasts are estimated by corrupting the historical inflows with a forecast reliability function. A series of reliability functions will be utilized ranging from perfect forecast reliability for the entire forecast period down to the baseline of the ESP forecasts. The tradeoff curves based on the perfect forecasts and the ESP forecasts should provide the upper and lower bounds for the extended forecasts that utilize seasonal climate predictions.

An initial testing of this framework has been performed. Reservoir releases were simulated using three simple operating rules where reservoir release is a linear function of storage 1) without forecast correction; 2) with one month perfect forecast correction (i.e., based on historical inflows); and 3) with one month ESP forecast correction. An example of reservoir storage and release is shown in Figure 6 for 1967 with the three simple operating rules.

The reservoir spills are 1.4%, 3.3%, and 3.3% of the storage, respectively, for perfect forecasts, no forecasts, and ESP forecasts. Therefore, in terms of spill management, results showed that the one-month ESP correction scheme is only slightly better than that without any correction; the perfect forecast scheme shows considerable improvement over the no forecasts scheme. Once actual streamflow forecasts are produced using the regional climate-hydrology models, they will be compared with the three schemes described above.

In the next steps, reservoir releases will be assumed to be a function of the reservoir's current storage and inflow forecasts for multiple lead times. Operating rules will be developed to maximize hydropower, minimize flood damages, and minimize number of days violating minimum flow criteria for recreation purposes. The optimization algorithm based on PGAPACK will allow rapid restructuring of the reservoir operating rule representation. The value of the extended forecast will be expressed as a shift in the tradeoff curves for the specified level inflow forecast reliability. An example is shown in Figure 7 for the

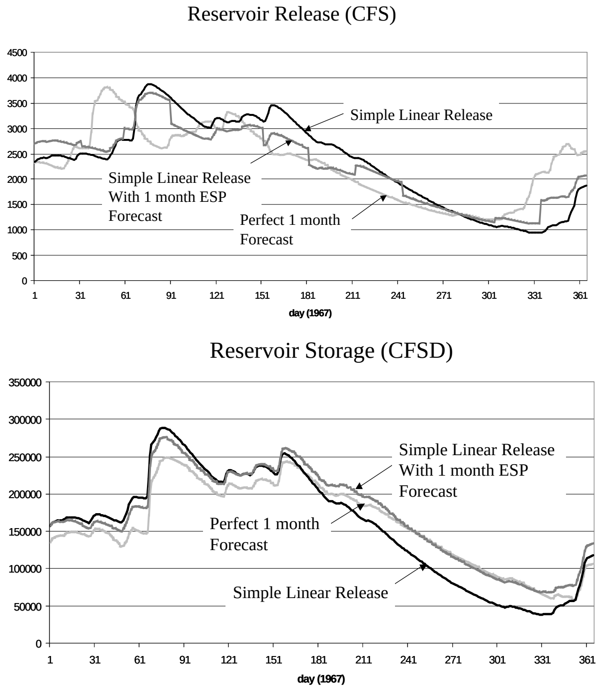


Figure 6. Reservoir release (top) and storage (bottom) simulated using simple linear functions with and without forecast correction.

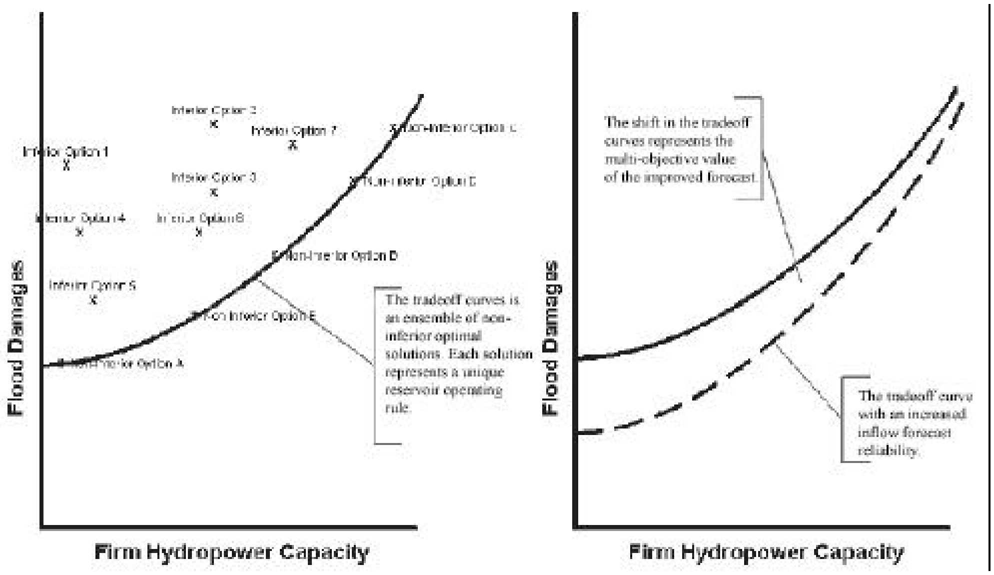


Figure 7. Illustration of multi-objective tradeoff curves for hydropower production and flood control. The figure on the left shows the ensemble of non-inferior reservoir operating solutions obtained through optimization. The figure on the right shows a hypothetical shift in the multi-objective tradeoff curves with improved inflow forecasts.

multi-objective tradeoff curve between flood protection and hydropower production. The tradeoff curve is an ensemble of non-inferior solutions each representing a unique reservoir operating rule. The value of seasonal climate forecasts will be indicated as a shift in the tradeoff curve as a result of improved inflow forecasts. This remains to be demonstrated as progress is made in the near future.

## 5. CONCLUSIONS

This paper reports progress towards examining the value of seasonal climate forecasts for managing water resources in the Tennessee River. A regional climate-hydrology modeling system is being used for downscaling seasonal forecasts or simulations provided by the NCEP GSM. The modeling system was shown to realistically simulate regional climate and hydrologic conditions of the Tennessee River region when driven by observed or analyzed conditions. An analysis framework has been developed to assess the usefulness of climate forecasts under optimized operating rules. It compares non-inferior multi-objective tradeoff curves generated by inflow forecasts based on the ESP method, the use of seasonal climate forecasts and regional modeling, perfect forecasts (historical flows), and no forecasts. Tradeoff curves provide a way to communicate the values of various types of inflow forecasts without the need to reduce multiple objectives into a single metric.

## 6. REFERENCES

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