Forecasting Spring Runoff Pulses from the Sierra Nevada34S

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Cayan *et al* (this issue) have shown that the major spring runoff pulse during most years in the Merced River is part of a regional transition between low wintertime streamflow rates and high-flow springtime rates in snowmelt-dominated rivers of much of the western United States. In the Sierra Nevada, the runoff pulse is the last gasp of plentiful freshwater inflow to the Sacramento/San Joaquin Delta and San Francisco Bay prior to the long dry spell that is summertime in California. On the managed rivers of central California, the runoff pulse also is of interest as a turning point during which the last large reservoir inflows of the water year typically begin.

The large size of the region within which rivers yield runoff pulses at about the same time as the Merced River and the rapid rise in streamflows once they begin (see Cayan *et al*, this issue) suggest that the spring runoff pulse might be amenable to forecasting by using operational weather-prediction models. The pulse is evidently a response to almost simultaneous changes in temperatures over much of the western United States, and current weather-prediction models are best when forecasting large spatial scales. The pulses evidently follow the seasonal temperature change and current weather-prediction models provide more reliable forecasts of temperatures than of precipitation (mostly because precipitation depends and occurs on smaller spatial scales than do changing temperatures). Finally, unlike many hydrologic modeling exercises, forecasts of the timing of the spring runoff pulse with lead times of a week, or even a few days, could be useful for reservoir, resource, and flood managers. Current weather-prediction models provide temperature predictions on just such time scales.

Peterson *et al* (this issue) list a range of hydrologic models that could be applied for prediction of large and small pulses of snowmelt-induced runoff from the Sierra Nevada. The benefits of further developing some of the models could be somewhat academic, however, if available weather predictions were poorly suited, for some reason, for use as inputs to proposed hydrologic models of the spring pulse. In this note, an initial test of the hydrologic use of weather predictions of air temperature, with lead times of 0-14 days, is reported. One of the simplest statistical "models" in the menu of options proposed by Peterson *et al* is used here to relate streamflow rates in the Merced River to forecasted air temperatures. Although the model is too simple to successfully simulate some aspects of Merced River hydrographs, it is sufficient to test the usefulness of temperature forecasts with lead times of 0-14 days. The design of the test (including the choice of the hydrologic model) and the statistics presented in this note focus mostly on prediction of the timing of runoff pulses, but the general magnitude of runoff variations are predicted fairly well also.

Data and Methods

Daily streamflow was forecast at the Happy Isles Bridge gage on the Merced River (USGS gage 11264500), near the head of Yosemite Valley, for the springtime periods of March 1 through June 15 of 1996 and 1997. The spring 1997 forecasts were made in "real time" as each day's forecasts became available; the 1996 forecasts were made using archived weather predictions from NOAA's Climate Diagnostics Center. The weather predictions used were air temperatures at roughly 1.5 km above sea level (at the 850-millibar pressure level) in a 2.5°-latitude-by-2.5°-longitude grid box centered at 40°N and 120°W, as predicted each day by the NOAA National Center for Environmental Prediction's weather models. About 17 model predictions are made by NCEP each day — each from a slightly different estimate of the current weather. The average of this ensemble of temperature predictions for each day was used to predict runoff. Each day's temperature (and streamflow) predictions included forecasts for lead times of 0-14 days in the future.

The temperature forecasts were turned into streamflow forecasts by applying simple regression relationships that Peterson *et al* (1997) developed and in which, for example, the deviation of the streamflow on day 0 from a given spring's mean flow rate is estimated by

$$Flow = 1.7\,T_0 + 2.1\,T_{-1} + 0.8\,T_{-2} + 0.6\,T_{-3} + 0.8\,T_{-4}$$

where T_i is the deviation from the spring-mean temperature on day *i*, in °C, and where the flow is measured in cubic meters per second. The temperature series used in this simple relationship is an average of daily temperatures from four long-term weather stations in and around the central Sierra (Sacramento, Hetch Hetchy, Nevada City, and Tahoe City). The particular flow equation above is a best fit between streamflow and temperature deviations during spring 1956 and was used for all the predictions in this note. This simplification is possible because the equation above yields results similar in timing to the average of forecasts from flow equations fit to other years, and flow timing was the focus of this test. The magnitude of predicted flow fluctuations varied moderately, depending on the years used to fit the flow equation.

When forecasting flows, the spring-mean temperature and spring-mean flows for the year being forecast are not known in advance. To make the forecasts shown here, the long-term spring-mean temperature was used instead of the spring 1996 and 1997 mean temperatures (unknown, until later), and the spring-mean flows for those years were estimated, in advance, from snow-water content recorded during March 1 snow-course measurements. This forecast scheme was applied to springs between 1955 and 1993 in a simple "hindcast" experiment using observed temperatures as if they were temperature forecasts. Results were encouraging (and will be reported elsewhere). Consequently, the real-time forecasting experiment reported here was undertaken.

Finally, 850-millibar temperature forecasts available from NCEP had to be converted into the regional average of surface-air temperatures to which the regression equation above was fitted. A linear regression between historical daily 850-millibar temperatures (obtained from CDC) and the corresponding regional surface-air temperatures yielded a relation between the two series, with a resulting r-squared value (percent explained) of 95% overall and about 75-85% when only spring-time temperatures were kept. Using this relation, 850-millibar temperature forecasts from NCEP ensembles were converted into equivalent values of the surface-air temperatures. The resulting surface-air temperatures were transformed, in turn, into streamflow forecasts using the flow equation above, with results described in the next section.

Results

Actual 1997 streamflow rates (heavy solid curves) are compared to "nowcasts" (open circles) and forecasts at various leads (solid dots) in Figure 1. Nowcasts are streamflow estimates using the flow equation presented in the previous section and based on the actual (not forecast) 850-millibar air temperatures. Both early and late in the spring season, the simple flow-temperature relation tended to overestimate flow fluctuations (as indicated by discrepancies between actual flows and nowcasts). Early in the season, the snowpack was not primed to melt with every temperature rise; late in the season, the snowpack was depleted and limited the streamflow responses more than did air temperature. This pattern of errors also was found when the scheme was applied to temperature predictions from spring 1996 (not shown here). Despite these weaknesses in nowcast mode, the simple temperature-based flow model predicted the timing of most upturns and downturns. Considering that nowhere were the actual flow rates input to the model [unlike Kalman filters of Peterson *et al* (this issue)], even the flow magnitudes projected by the simple model, encouragingly, are quite similar to the observed flows.

Forecasts of streamflow variations shown in Figure 1 also capture the timing and magnitude of streamflow fluctuations fairly well for lead times of as much as 7 days. For lead times up to 5 days, the nowcasts and forecasts are very similar, which also indicates that the temperatures that went into nowcasts (actual temperatures) and forecasts (predicted temperatures) were similar. The spring 1997 relationship between nowcast 850-millibar temperatures and observed surface-air temperatures from the central Sierra Nevada was similar to the long-term relationship described in the preceding section, with about 80% of the variation of surface-air temperature also present in the 850-millibar temperatures. Thus, most of the discrepancies between actual flows and flows forecasted with lead times of up to 5 days (at least) came from the simple hydrologic model used here rather than from errors in the temperature forecasts themselves. At lead times greater than about 7 days, the nowcasts and forecasts start to deviate from each other, and by 13 days the forecasted flow variations become smaller and noisily parallel the long-term median flow series (shown as faint dotted curves in Figure 1); this pattern results from a tendency of the weather-prediction models to "revert to the norm" after a time as the influence of the predictions' initial conditions starts to decline. Similar success at shorter lead times and an even stronger reversion to the long-term median (climatological) condition at longer lead times were observed when the scheme was applied to spring 1996.

Some of these relationships between prediction accuracy and lead time are shown in Figure 2. Each curve in Figure 2 shows correlation coefficients between deviations of observed (or nowcast) flows from the long-term median daily flows shown in Figure 1 and deviations of forecasts at various lead times from the long-term median flows. (If median flows are not subtracted in each case, the apparent accuracy of the forecast is misleadingly high because the "expected" trend toward increasing spring-time flow adds substantially to the variance explained by the temperatures, whether actual or forecast.) The light curves in Figure 2 show correlations of observed flow fluctuations (around the medians) with forecasted flows. In both 1996 and 1997, the correlations decline for lead times greater than about 5 to 7 days. Forecasts of

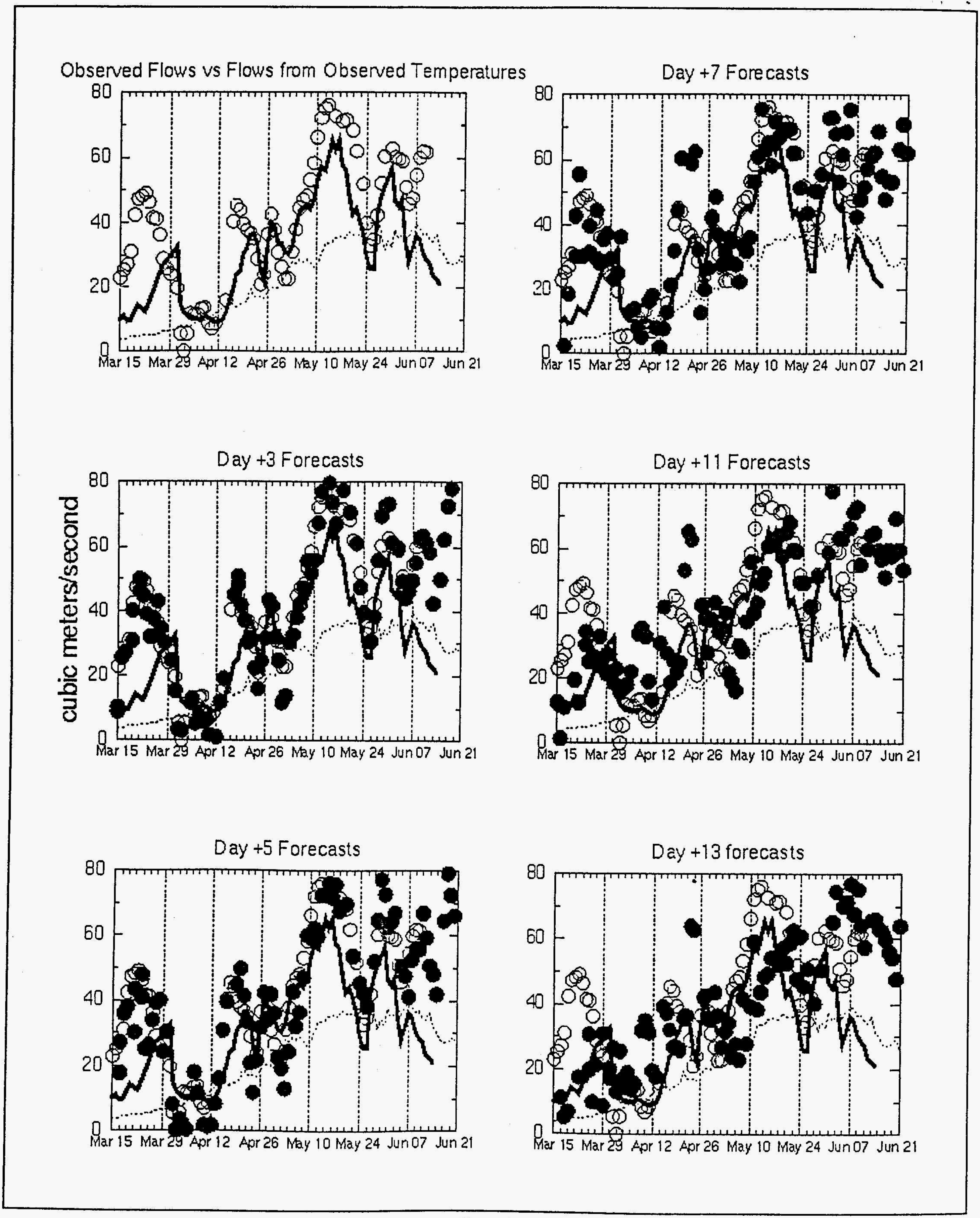

Figure 1
OBSERVED, 78-YEAR MEDIAN, NOWCAST, AND FORECAST STREAMFLOW,
MERCED RIVER AT HAPPY ISLES BRIDGE, SPRING 1997

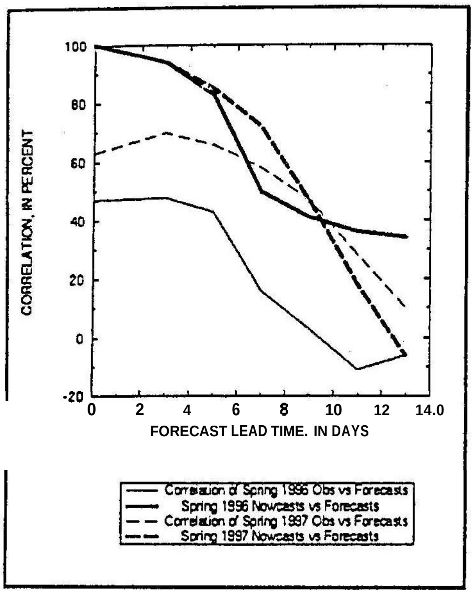

Figure 2
CORRELATION COEFFICIENTS BETWEEN OBSERVED FLOWS/FORECASTS AND NOWCAST FLOWS/FORECASTS FOR SPRING 1996 AND 1997
Correlations in all curves were calculated from deviations of daily streamflows from 78-year median daily flows.

flows in spring 1996 were somewhat less accurate (lower correlations) than those in spring 1997 at all lead times.

The heavy curves in Figure 2 show the correlations between nowcasts and forecasts of flow at various lead times and measure the similarities between actual temperatures and forecast temperatures at each lead time (because the hydrologic part of the scheme is linear). As in the comparison of observed and forecasted flows (light curves), correlations decrease for lead times greater than about 5-7 days. Differences between the correlations of nowcast and forecasts, on the one hand, and correlations of actual flows and forecasts, on the other, are mostly attributable to the inability of the hydrologic part of the scheme to turn actual temperatures into flows. Thus, because the shapes of the dashed curves are similar to each other, and the shapes of the solid curves are similar to each other, we see that the correlations to actual flows and nowcasts for a particular year differ in magnitude rather than shape. From this, we tentatively conclude that the breakdown in forecasts after about 5-7 days may be associated with the breakdown of temperature forecasts beyond these lead times. The actual flow curves (light) are broadly parallel to the corresponding nowcast curves (heavy) but about 20-40% lower (even at *day* 0), which suggests that the simple hydrologic model used here, together with the modest discrepancies between 850-millibar and surface-air temperatures, cause a decline in correlations of as much as 40% at the short lead times when temperature forecasts are good.

Conclusion

Although the results reported here are limited in scope (only these two spring seasons were available in the CDC archives), they are encouraging. Overall, they suggest that available temperature predictions could be used to make forecasts of the spring runoff surges from the Sierra Nevada as much as a week ahead of time. The principal limitation of the flow forecasts shown appears to be the simple hydrologic "model" used; the temperature-based forecasts worked as well as they did mostly because they were limited to spring runoff only and because the spring seasons used had little precipitation to complicate the snowpack/snowmelt processes. However, the simple flow/temperature relationship used is by no means the best model that could be made of snowmelt and runoff in the Merced River. Peterson et *al* (this issue) discuss options for improving our ability to model the hydrology of the Sierra Nevada. Recently, in fact, a spatially detailed, physically based hydrologic model of the Merced River basin has been constructed; that model is now being calibrated. Using a better hydrologic model would tend to raise the light curves in Figure 2 toward the level of the heavy curves so that more of the accuracy of weather forecasts (suggested by the heavy curves) would be translated into accurate surge prediction. With such improvements, available weather predictions offer opportunities for prediction of regional-scale, short-term events like the Sierra Nevada runoff pulse.

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