Using Climate Forecasts for Drought Management

ANNE C. STEINEMANN

Department of Civil and Environmental Engineering, Evans School of Public Affairs, and The Water Center, University of Washington, Seattle, Washington

(Manuscript received 12 August 2005, in final form 31 January 2006)

ABSTRACT

Drought hazards, and the ability to mitigate them with advance warning, offer potentially valuable applications of climate forecast products. Yet the value is often untapped, owing to the gap between climate science and societal decisions. This study bridged that gap; it determined forecast needs among water managers, translated forecasts to meet those needs, and shaped drought decision making to take advantage of forecasts. NOAA Climate Prediction Center (CPC) seasonal precipitation outlooks were converted into a forecast precipitation index (FPI) tailored for water managers in the southeastern United States. The FPI expresses forecasts as a departure from the climatological normal and is consistent with other drought indicators. Evaluations of CPC seasonal forecasts issued during 1995–2000 demonstrated positive skill for drought seasons in the Southeast. In addition, using evaluation criteria of water managers, 88% of forecasts for drought seasons would have appropriately prompted drought responses. Encouraged by these evaluations, and the understandability of the FPI, state water managers started using the forecasts in 2001 for deciding whether to pay farmers to suspend irrigation. Economic benefits of this forecast information were estimated at \$100–\$350 million in a state-declared drought year (2001, 2002) and \$5–\$30 million in the other years (2003, 2004). This study provides four main contributions: 1) an investigation of the needs and potential benefits of seasonal forecast information for water management, 2) a method for translating the CPC forecasts into a format needed by water managers, 3) the integration of forecast information into agency decision making, and 4) the economic valuation of that forecast information.

1. Introduction

Improvements in climate forecasts have created the potential to improve seasonal to interannual water resources management. This potential remains largely untapped, however, because forecasts are not frequently used in actual decision making. Barriers to forecast use, as noted in prior studies, include user difficulties in understanding, applying, evaluating, and trusting the forecasts (Hartmann et al. 2002; Pulwarty and Redmond 1997; Schneider and Garbrecht 2003; Callahan et al. 1999; Nicholls 1999; Stern and Easterling 1999; Lins and Stakhiv 1998; Briggs and Wilks 1996; Pagano et al. 2001; Agrawala et al. 2001; Wernstedt and Hersh 2002; Carbone and Dow 2005).

Despite considerable attention to identifying barriers, relatively little attention has gone to developing remedies. One reason is that remedies are not unilateral; they depend on both forecasters and users. This, in turn, often requires a communicator who works with and between those two groups. In this process, forecast products are developed to meet user needs, and decision-making processes are developed to take advantage of forecast information. Another reason is that remedies often require more than just better forecasts. Improving forecast accuracy and demonstrating forecast benefits are important but not sufficient conditions for the actual use of forecasts. In addition to climate-scientific factors, social-scientific factors influence forecast adoption.

This article reports on a 4-year study of the use of the climate forecasts for drought management in the state of Georgia. This study is significant because it represents a successful transition of climate forecasts into decision-making procedures of a public agency. In addition, this study assesses the economic benefits of forecast information and provides broader lessons on bridging the gap between forecasts and their potential and beneficial uses.

Corresponding author address: Anne C. Steinemann, Department of Civil and Environmental Engineering, University of Washington, Seattle, WA 98195-2700.
E-mail: acstein@u.washington.edu

2. Survey of forecast uses, needs, applications, and potential benefits

The southeastern United States is recovering from one of its most severe droughts on record (1998–2002), causing tens of billions of dollars in damages (National Climatic Data Center 2006). Growing water demands, limited supplies, and allocation controversies such as the "water wars" among Georgia, Alabama, and Florida (Apalachicola–Chattahoochee–Flint River Basin Commission 2002) bring increased concern about future droughts and increased interest in the potential of climate forecasts. Indeed, strong teleconnections between ENSO and the southeastern United States have enabled skillful forecasts for the Southeast up to a year in advance, and they provide an opportunity for longer-lead drought planning.

To investigate this potential, the author conducted a formal survey and set of interviews with 25 water resources decision makers, representing federal, state, and local agencies and stakeholders in the southeastern United States who had primary responsibilities for water management. The survey and interviews, conducted from 1999 to 2000, sought to determine the forecast information that would be most useful, the decisions and decision makers that would use the forecasts, and the ways in which forecast information could be tailored to water management and operations. Specific questions were asked about the seasonal outlooks produced by the National Oceanic and Atmospheric Administration Climate Prediction Center (CPC), given their potential for long-lead drought forecasting, their advances in forecasting techniques (Barnston et al. 1994, 2000), and their attention in recent studies on forecast use (e.g., Hartmann et al. 2002; Schneider and Garbrecht 2003).

Of the 25 water managers surveyed, 21 had seen the CPC forecast products but only 2 had ever used them in decision making. Reasons for nonuse include difficulties in understanding the forecasts, in assessing their accuracy and potential benefits, and in applying them to the types of decisions that concern drought management (Table 1). Forecast products were also frequently misinterpreted. For instance, on the CPC seasonal outlook maps, the probability anomaly from the most-favored tercile was commonly misinterpreted as the change in total precipitation relative to the climatological normal.

For drought management, water managers stated that the greatest need was for precipitation forecasts, for 3-month periods, with lead times varying from 2 weeks to 1 yr in advance (Table 2). These forecasts would be most important for the winter months (in particular, January–March) and summer months (in particular, June–August), corresponding to peak rainfall and peak demands, respectively (Tables 3 and 4).

TABLE 1. Most frequently mentioned reasons, from the survey and interviews, for lack of use of CPC forecast information, given in response to the question, "If you have seen, but have not used, any of the CPC forecasts in decision making, why not?"

- Difficulties in understanding and assessing
  - Forecasts and forecast information—the forecast maps, the meaning of the probability anomaly, the tercile probabilities, the probability of exceedance curves, the meaning of skill, and the assessments of skill
  - How the CPC generated the forecasts
  - How to judge the accuracy of forecasts
  - How to find needed forecasts on the CPC Web page
  - The CPC's explanations about forecasts
  - The potential benefits of the forecasts, such as improvement over climatological probabilities
  - The uncertainty associated with forecasts
  - The CPC's calculations of skill, and what skill means
  - How to apply a forecast to a smaller area
- Need for a forecast/forecast information that is
  - Easily understood, interpreted, and applied to decision making
  - Proven to be more accurate than using climatological probabilities
  - Relevant to a smaller geographic area, such as county or watershed
  - Relative to historic conditions, such as a percentile or analog
  - Trustworthy; forecasts "dry" (not "wet") for future drought conditions
  - Easily integrated with existing information, such as drought indicators
- Need for better explanation about
  - How forecasts were generated
  - How to understand and use the forecasts
  - How to interpret forecast accuracy and uncertainty
  - How to determine relative benefits of using forecasts

Of interest is that the desired climate forecasts were already being produced, albeit not in the formats that water managers needed (Table 5). Water managers also needed assessments of forecast accuracy, but the CPC's reported skill was not meaningful to them; they wanted to evaluate other aspects of forecasts. For instance, traditional measures of skill may not be able to distinguish between 1) a wet season that was forecast to be dry and 2) a dry season that was forecast to be wet—if differences between forecasts and observations were the same. From a management perspective, however, the two forecasts would be different because case 1 would pose fewer risks than case 2, as will be detailed later in this paper.

Thus, the surveys and interviews revealed a paradoxical but not uncommon result. Despite the high potential value of forecasts, they had low actual use. The next phase of the study sought to address the barriers to

Table 2. Climate forecast information needed, specifying forecast variable, temporal scale, lead time, and spatial scale, given in response to the question, "What types of climate forecasts would be the most useful to have? Specify (a) type of forecast (temperature, precipitation, etc.), (b) temporal scale of forecast (30 days, 90 days, etc.), (c) lead time (1 month in advance, 3 months in advance, 1 yr in advance, etc.), and (d) spatial scale (river basin level, county level, climate division level, etc.)."

Type	Temporal scale	Lead time	Responses
Precipitation	30 days	0	1
	45 days	15 days	1
	60 days	30 days	1
	3 months	15 days to 12 months	12
	6 months	1–3 months	1
	12 months	3 months	1
	3 months year-round	15 days to 12 months	6
	5 yr		1
Temperature	3 months	30 days	1

Spatial scale	Responses
Basin/watershed	13
County	8
Climate division (nine in GA)	4
CPC forecast division (three in GA)	0

forecast use by providing forecast information and integrating it into decision-making processes important to water managers.

3. The forecast precipitation index: Translating the CPC seasonal outlooks for water managers

The CPC provides its forecasts in two main formats: 1) probability anomalies for terciles and 2) a probability of exceedance function. The tercile probabilities can be extracted from the maps for "seasonal outlooks" (available online at the time of writing at http://www.cpc.ncep.noaa.gov/products/predictions/90day/) and can be obtained for each forecast division from data files in the "forecast for tercile probability" section within the "probability of exceedance (POEs) of CPC's long-lead seasonal forecasts for temperature & precipitation . . ." Web page (available online at the time of writing at http://www.cpc.ncep.noaa.gov/pacdir/NFORdir/HUGEdir2/hut.html). This page is also referred to as "probability density functions." From that same page, using the "current month precipitation" link, "forecast precipitation percentiles" report the forecast and climatological mean, the forecast and climatological standard deviation, the power values (for normalizing the precipitation forecast distribution), the estimated high-frequency skill, and the exceedance threshold values for a range of percentile levels. The CPC uses the empirically derived relationships among tercile probability anomalies, the climatological probability density function, and the estimated forecast skill to derive the probability of exceedance function (D. Unger, CPC, 2002, personal communication).

The forecast precipitation index (FPI) was developed, in this study, to provide forecast information to meet the primary needs of water managers. Specifically, water managers wanted a forecast anomaly from the climatological normal rather than from the boundary of the most-favored tercile; a single forecast value in terms of percentiles, consistent with other state drought indicators; a seasonal precipitation forecast with lead times

Table 3. Season most important for precipitation forecast, given in response to the question, "For precipitation forecasts, which consecutive 3-month period would be most important, and why?" (The sum of responses adds to more than 25 because respondents were permitted to check more than one 3-month period if they were equally important. The sum of reasons may not be equal to the number of responses because not all respondents provided a reason and some respondents provided more than one reason.)

Three-month period	Respondents ranking this period as most important	Reasons
Jan–Mar	9	Rainiest months (4); reservoir refill (3); planning for summer months (2)
Feb–Apr	5	Rainy months (1); reservoir refill (2)
Mar–May	3	Lowest reservoir elevations (2); agricultural growing season (1)
Apr–Jun	2	Agricultural growing season (1)
May–Jul	3	High water demands (2); agricultural growing season (1)
Jun–Aug	9	Highest water demands and consumption peaks (5); greatest impact if lack of precipitation (2)
Jul–Sep	5	Highest water demands and consumption peaks (2); streamflows critical (2)
Aug–Oct	2	High water demands (2)
Sep–Nov	2	Reservoir inflows lowest (1); low-flow period (1); greatest potential for draw down (1)
Oct–Dec	0	
Nov–Jan	2	High water demands (1)
Dec–Feb	2	Rainiest months (2); reservoir refill (1); groundwater recharge (2)

TABLE 4. Lead time (months) needed for seasonal precipitation forecast, given in response to the question, "For 3-month precipitation forecasts, how much lead time would be needed, and why?" (The sum of responses adds to more than 25 because respondents were permitted to check more than one 3-month period if they were equally important. The sum of reasons may not be equal to the number of responses because not all respondents provided a reason and some respondents provided more than one reason.)

Lead time	Responses	Reasons
0.5	4	Factor precipitation into short-term planning (1); use on-site reservoirs for storage buffers (1); manage weekly demands (1); consider implementing drought measures (1)
1.5	10	Increase public communication and education (3); implement water use restrictions and water management strategies (2); determine water budget for year (1); maximize revenue and resources (2)
2.5	5	Plan for summer months (1); provide information to public through one billing cycle (60 days) (1); maximize revenue and resources (2); increase public communication and education (3)
3.5	5	Implement drought plan measures (2); increase public communication and education (3); develop provisions to protect supplies through low-flow periods (1)
4.5	2	Implement more severe drought measures (1); influence draw-down decisions (1)
6.5	2	Consider more severe drought measures (1)
12.5	1	Plan for multiyear droughts (1)

from 2 weeks to 1 yr; and other criteria as noted in Table 5. In accord with these criteria, the FPI represents the shift of the forecast mean relative to the climatological distribution for the period and region of the seasonal precipitation outlook. This anomaly is translated into percentiles on the normalized climatological cumulative distribution function, using aforementioned statistical information provided by the CPC. The FPI can then be calculated as FPI $= \Phi_c(Z_{\mathrm{FPI}})$, where Φ_c is the cumulative probability on the normalized climatological distribution, Z_{FPI} = FPI standardized anomaly $= [(y^*)^p - (\mu_X)^p]/\sigma_X$, y^* = forecast value (unpowered) reported by CPC $= \mu_{X|Y}$ = conditional forecast mean, μ_X is the climatological mean (unpowered), p is the deskewing power, σ_X = climatological (unconditional) standard deviation (of powered values) $= \sigma_{X|Y}(1 - \rho^2)^{-1/2}$, $\sigma_{X|Y}$ is the forecast (conditional) standard deviation (of powered values), and ρ is the Pearson product-moment correlation between observations and forecasts and is also the CPC's reported high-frequency skill. For example, consider a seasonal precipitation forecast for CPC forecast division 56 (north Georgia), month 12 (forecast issued in December), and lead time of 3 (technically 2.5 months), which is a forecast for March–May 1998. The forecast-for-tercile-probability product reports probability values of PrA = 0.274, PrB = 0.393, and PrN = 0.333 for above-normal, below-normal, and near-normal terciles, respectively, and PrAB = −5.97 for the probability anomaly of the most-favored tercile (percentage points by which and direction in which the distribution is shifted away from an even distribution across the A, B, and N categories).

TABLE 5. Most frequently mentioned forecast communication needs, from the survey and interviews, given in response to the question, "How would forecast information need to be communicated in order for you to use it for drought management?"

Provide in terms relative to historic conditions
Make consistent with other drought indicators and triggers
Make applicable to regional and local scales
Provide improvement over use of climatological probabilities
Give "best guess"—most likely amount
Provide easy-to-understand measures of accuracy and uncertainty
Assess forecast performance in the context of drought events

These tercile probabilities are what water managers extract from the outlook maps and are what they have difficulty interpreting. To convert the tercile probability forecast to the FPI, the databases for the probability density function (or probability of exceedance) yield the information $y^* = 13.38$, $\mu_X = 13.9$, $\sigma_X = 2.0407$, $p = 0.878$, $\sigma_{X|Y} = 2.0201$, and $\rho = 0.14$, giving $Z_{\mathrm{FPI}} = -0.1627$ and FPI = 43.54%, using the above definitions. Using this approach, the CPC forecasts for total 3-month precipitation were transformed into FPI values for forecast division 56. This division was selected for its coverage of the Atlanta, Georgia, metropolitan area and its headwaters, which is a focus of the "tristate water wars," and its relatively high number of nonclimatological forecasts ventured (111) for the 6-yr period of study (December 1994–December 2000), with 13 lead times and 12 target months (the center of the 3-month period). In addition, the observed amount of precipitation was translated into an equivalent FPI value, termed here the observed precipitation index (OPI). The FPI and OPI values are compared in Figs. 1 and 2, showing that the range of FPI anomalies is smaller than OPI anomalies, considering the 12 target months and 13 lead times. These FPI and OPI values were used for the verification exercises described in the following section.

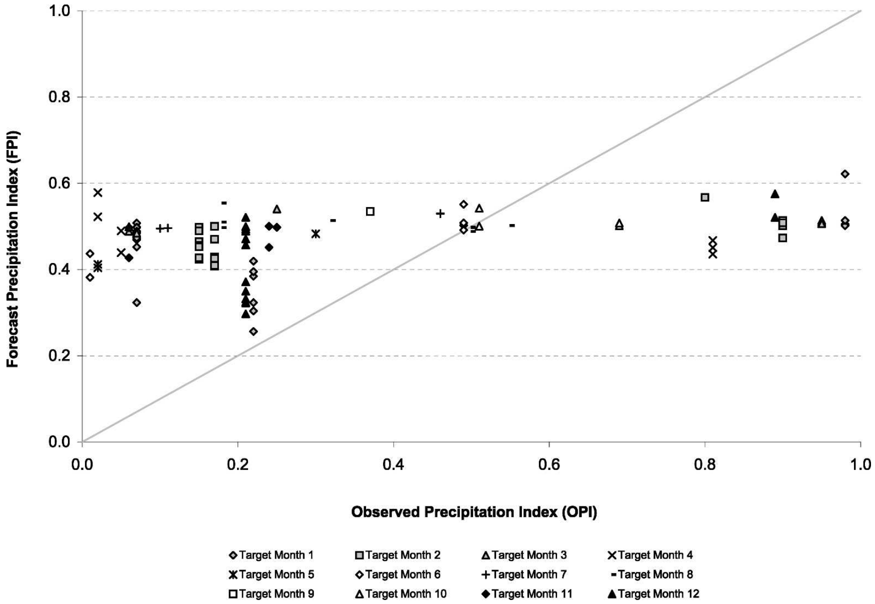

FIG. 1. Comparison of the FPI and OPI by target month for forecast division 56.

In an operational setting, the FPI can help to determine whether to invoke, revoke, or maintain a certain level of drought restrictions (Table 6). The levels represent the percentile scales, triggering criteria, and responses used in the drought management plan for Georgia (Department of Natural Resources 2003). The FPI was designed for use with other drought indicators, each of which were transformed to percentiles and which include precipitation, groundwater levels, streamflows, and reservoir storage (Steinemann 2003a).

Conceptually, this approach is novel in its transformation of a forecast into a drought indicator. Drought indicators are typically retrospective, based on antecedent conditions, whereas the FPI is prospective, providing advance warning of potentially progressing or receding drought conditions. Both retrospective and prospective triggers can be used together to determine the timing and staging of drought restrictions.

The FPI/OPI values are also similar to a common drought indicator, the 3-month standardized precipita-

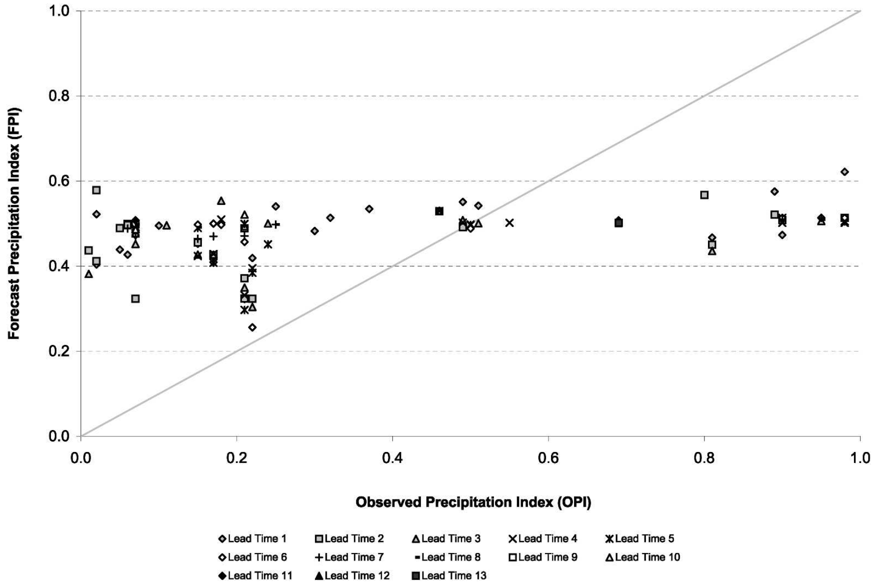

FIG. 2. Comparison of the FPI and OPI by lead time for forecast division 56.

TABLE 6. Drought response levels, with percentile ranges for indicators. An example of drought response (outdoor residential water use restrictions) for each level is as follows—level 1: water on allowed days, from 0000 to 1000 and from 1600 to 0000 LT; level 2: water on allowed days, from 0000 to 1000 LT; level 3: water on allowed weekend day, from 0000 to 1000 LT; level 4: complete outdoor water use ban.

Category	Percentile (%)
Level 0	35–50
Level 1	20–35
Level 2	10–20
Level 3	5–10
Level 4	0–5

tion index (SPI; McKee et al. 1993), which is the observed precipitation anomaly over the prior 3 months relative to the climatological mean. A difference is that the FPI/OPI uses a power-transformed Gaussian distribution, whereas the SPI uses a gamma distribution. Also, the FPI/OPI is expressed in terms of cumulative probability relative to the normalized climatological distribution, whereas the SPI is expressed as a Z score from the center of the climatological distribution. Algebraically, the FPI corresponds to the second month of the 3-month season and the SPI corresponds to the third month. Also, the FPI is prospective, whereas the SPI is retrospective.

Water managers noted that the FPI anomalies were not as great as the OPI anomalies, and it would be difficult to determine the severity of a potential drought forecast based on the size of the anomaly. Most below-normal FPI values fell in the level-0 category (0.35–0.50), so that range of 15-percentiles was discretized further for operational use with other drought triggers. For instance, the FPI categories of level 0 were used as an indicator for level-1 drought, using the lower forecast percentile as an upper drought-level percentile. This approach uses these indicator thresholds, or triggers, for invoking or revoking each level of the drought plan (Steinemann 2003b; Department of Natural Resources 2003).

4. Evaluation of forecasts and the FPI for drought management

Central to forecast use and acceptance is forecast verification, but verification criteria used by forecasters may be different than the criteria that are important to water managers. Each type can complement the other, and each was determined in this study. First, forecast skill was calculated based on three measures of accuracy (Wilks 1995): 1) mean absolute error (MAE), 2) root-mean-square error (RMSE), and 3) linear error in probability space (LEPS; Potts et al. 1996; Ward and Folland 1991). Among this set of 111 forecasts, the highest skill for all measures was for the target month of December and for the lead time of 4.5 months (Table 7), with positive skill for most of the critical months and lead times identified in the surveys.

TABLE 7. Aggregate forecast skill for forecast division 56, by target month and lead time. Skill values here are multiplied by 100 for ease of comparability.

Target month	Count	S_{MAE}	S_{RMSE}	S_{LEPS}
1	22	11.52	6.85	15.80
2	23	8.50	7.25	10.14
3	8	0.63	1.14	0.91
4	7	−4.48	−3.83	−6.30
5	3	11.00	11.27	17.33
6	6	7.42	10.62	12.45
7	5	−7.58	−0.33	−8.78
8	9	−7.59	−6.00	−8.48
9	1	−25.45	−25.45	−26.14
10	6	0.26	1.99	0.32
11	6	5.76	5.87	6.60
12	16	25.44	20.31	27.97
Lead time	**Count**	S_{MAE}	S_{RMSE}	S_{LEPS}
0.5	22	9.49	8.14	11.77
1.5	19	10.32	6.47	13.50
2.5	17	8.79	6.72	10.60
3.5	13	10.49	7.38	12.02
4.5	9	15.11	9.35	18.13
5.5	11	7.67	3.99	9.76
6.5	10	4.00	3.64	5.04
7.5	4	1.15	1.15	1.50
8.5	2	1.39	0.99	1.74
9.5	2	−0.90	0.11	−0.99
10.5	1	−1.26	−1.26	−1.80
11.5	1	0.72	0.72	0.78
12.5	1	0.78	0.78	0.84

Water managers were encouraged by the results but wanted to evaluate forecasts in two additional dimensions. First, how often did the forecast offer improvement over using climatological probabilities? This is calculated as the percentage of correct directional forecasts (i.e., in the same direction, above normal or below normal, as observations) relative to total number of forecasts. Second, how often did the forecast provide forewarning of severe (level 3) or extreme (level 4) droughts? This is calculated as the percentage of below-normal forecasts relative to the total number of level-3 or level-4 drought events.

For improvement (Table 8), 78% of the forecasts were in the same direction as observations. For the other 22%, water managers were interested in the type of directional difference: 1) below-normal forecast and above-normal observation or 2) above-normal forecast and below-normal observation. The first case was of less concern than the second case.

TABLE 8. Forecast direction relative to observations.

	Total forecasts	Same direction	Different direction	Below-normal forecast and above-normal observation	Above-normal forecast and below-normal observation
1995	7	1 (14%)	6 (86%)	3 (43%)	3 (43%)
1996	—	—	—	—	—
1997	20	18 (90%)	2 (10%)	2 (10%)	—
1998	26	22 (85%)	4 (15%)	2 (7.5%)	2 (7.5%)
1999	45	33 (73%)	12 (27%)	—	12 (27%)
2000	13	13 (100%)	—	—	—
Total	111	87 (78%)	24 (22%)	7 (6.5%)	17 (15.5%)

In case 1, which was viewed as a false alarm, restrictions may be continued or increased in severity, even if dry conditions did not persist or develop. This type represented 29% (7/24) of the forecasts that differed in direction, or approximately 6.5% of all forecasts. Adverse impacts would include the potential diminishment of forecast and agency credibility and losses resulting from water use restrictions, yet these impacts were regarded as being less critical than those of the second case.

In case 2, which was viewed as a false assurance, restrictions may be discontinued or decreased in severity, when drought conditions would be developing or persisting. This case represents 71% (17/24) of the forecasts that differed in direction, or approximately 15.5% of all forecasts. Adverse impacts would include direct and indirect losses resulting from drought, increased strain on available water supplies, potential diminishment of agency and forecast credibility, and political consequences for water managers.

For forewarning (Table 9), of the observed level-3 or level-4 seasons with forecasts issued, 88% were below-normal forecasts, thus providing an element of advance warning for drought. Of the forecasts ventured for level-3 or level-4 seasons, 12% of these were above normal, which are of the most concern, because drought restrictions might have been rescinded or not implemented.

As a water manager explained, “If the forecast said dry, and it is wet, I do not see us being blamed for anything. If we call it wet, and it turns very dry, they [the water users] could be very upset with us.” Another explained, “At early stages of drought, the consequences are not that severe, in either case. But at later drought stages [level 3 and level 4], it is important to be conservative. If we were going to have a drought, it would be OK for a dry forecast to turn out to be wet, but the other way around would cause severe impacts.”

Presented with these evaluations, and with the FPI as a translation of forecasts into a drought indicator, water managers started to use this information in 2001 for decision making. The next section details one statewide application and the benefits that resulted from forecast use.

5. Use and valuation of forecasts for drought management

Georgia’s Flint River Drought Protection Act (FRDPA; Department of Natural Resources 2000) is a state program that compensates farmers who voluntarily suspend agricultural acreage from surface water irrigation during a possible drought year. By 1 March of each year, the state needs to make the decision on whether to implement this program, based on whether they think it will be a severe or extreme drought year. That determination is, in turn, based on drought indicators, both prospective (climate forecasts) and retrospective.

The CPC seasonal climate forecasts, which were converted into the FPI as forecast indicators, are the primary decision criterion for the state, followed by hydrologic indicators. These indicators are considered as follows. For the target months of April (March–May), May (April–June), and June (May–July) for CPC forecast divisions 56 and 69, if the FPI is negative for any of those six cases, then the state will consider implementing the FRDPA. If all of the FPI values are positive (or indicate climatological probabilities), then the state will determine the retrospective drought indicators of streamflows, groundwater, and precipitation for the months of January and February for Georgia climate divisions 4 and 7 (see Fig. 3). If any indicator is severe or extreme, then the state will consider implementing the FRDPA. Although state water officials attest that the most important factor in the decisions is the climate forecasts, they will also consult with the state climatologist, the state geologist, and other officials before taking action.

The state implemented the FRDPA in 2001 and in 2002 but not in 2003 or in 2004. State officials felt that they “called it right each year” and that the forecasts were primary determinants in the decision. The valua-

TABLE 9. Forecast for observed level 3 and level 4 of drought.

	Total forecasts	Total seasons forecast	Seasons with observed level 3 or 4	Seasons without forecast for observed level 3 or 4	Seasons with forecast for observed level 3 or 4	Total forecasts for observed level 3 or 4	Total forecasts for observed level 3 or 4	
							Same direction	Different direction
1995	7	4	1	0	1 (100%)	2	0	2 (100%)
1996	0	0	—	—	—	—	—	—
1997	20	5	3	3 (100%)	0	—	—	—
1998	26	8	5	2 (40%)	3 (60%)	5	5 (100%)	0
1999	45	11	7	6 (86%)	1 (14%)	10	9 (90%)	1 (10%)
2000	13	8	5	1 (20%)	4 (80%)	7	7 (100%)	0
Total	111	36 (50%)	21	12 (57%)	9 (43%)	24	21 (88%)	3 (12%)

tion of these forecasts for possible decision outcomes is as follows. 1) For a drought year, when the FRDPA is implemented, the net benefits range from $100 million to $350 million in terms of mitigated agricultural losses. 2) For a drought year, when the FRDPA is not implemented, agricultural losses could reach nearly $1 billion. Moreover, the state felt their credibility in drought management would be damaged. 3) For a nondrought year, when the FRDPA is implemented, the state could lose up to $30 million in implementation costs, although the farmers would receive this windfall. 4) For a nondrought year, when the FRDPA is not implemented, the state saves between $5 million and $30 million in implementation costs. This valuation focused on primary agricultural and implementation costs, and estimates were determined through interviews and surveys with state officials. Note that additional benefits and costs would accrue in each decision outcome, considering impacts on streamflows, habitat, hydroelectric power, and other water uses. Future work would consider these factors in a more detailed economic evaluation. At the time of this writing, the forecasts were still being used for this decision.

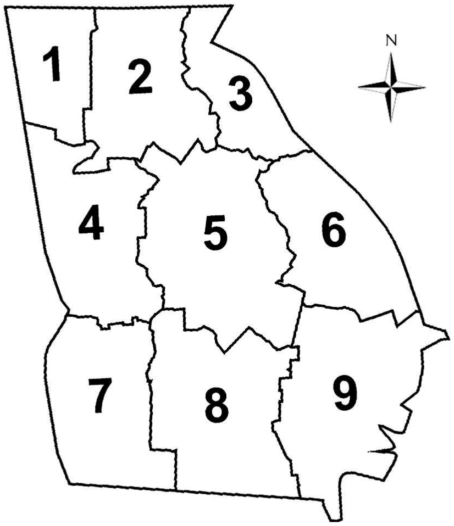

FIG. 3. Georgia's climate divisions.

6. Conclusions

This study demonstrates the usefulness and actual use of climate forecasts for drought management. The CPC forecasts were translated into a prospective indicator, the forecast precipitation index, and were used by water managers to make decisions concerning drought. In the application detailed, the benefits of using the forecasts ranged from $30 million to $350 million per year to the state of Georgia.

In addition, forecast evaluation criteria extended traditional measures used by forecasters. Water managers were interested primarily in the context of forecasts versus observations rather than differences between the two values, and in the frequency of improvement and forewarning offered by the forecasts. Of the 111 forecasts issued, 78% offered improvement over use of climatological values; for seasons with severe or extreme drought conditions, 43% had forecasts issued, and 88% of those forecasts would have appropriately invoked drought responses.

This study also provides some broader lessons. First, decision makers often view forecasts and accuracy differently than do forecasters. Probabilistic information may not be used in its entirety or may need to be converted into a form that is used and understood. In this application, water managers tended to view forecasts as being either "right" or "wrong" rather than as one possible outcome among a range of possible outcomes with associated probabilities. Second, public-sector applications differ from private-sector applications, and one way that they can differ is in operational goals. In this case, water managers were concerned primarily with "not making mistakes" rather than profit maximization.

For instance, concern about a type-I error (taking action on a forecast that turns out to be less accurate than existing information) appeared greater than concern about a type-II error (not taking action on a forecast that was more accurate than existing information, even though it could have prompted valuable drought mitigations and responses). Thus, it is important to understand when forecasts offer sufficient justification for deviating from standard operating procedures. Last, the forecast adoption process takes time. The process of working with stakeholders, understanding institutional and individual decision-making processes, and developing trust and relationships can take many months if not years. An important area of future work is training and promoting the role of communicators that can work between both groups—forecasters and users—to promote the successful migration of climate science to society.

Acknowledgments. I thank Jeanne Schneider and David Unger for their helpful reviews and comments, Luiz Cavalcanti for his valuable research assistance, Dan Ribeiro for his careful editing and preparation of the manuscript, and the water managers who participated in this study. David Unger also provided forecast data and interpretations throughout the project. This research received support from the National Science Foundation under Grant CMS 9874391 and from the Georgia Department of Natural Resources. Any opinions, findings, or conclusions are those of the author and do not necessarily reflect the views of the organizations that provided support.

REFERENCES

Agrawala, S., K. Broad, and D. H. Guston, 2001: Integrating climate forecasts and societal decision making: Challenges to an emergent boundary organization. *Sci. Technol. Human Values,* **26,** 454–477.

Apalachicola–Chattahoochee–Flint River Basin Commission, 2002: ACF allocation formula agreement. Apalachicola–Chattahoochee–Flint River Basin Draft Proposal, 60 pp.

Barnston, A. G., and Coauthors, 1994: Long-lead seasonal forecasts—Where do we stand? *Bull. Amer. Meteor. Soc.,* **75,** 2097–2114.

——, Y. He, and D. A. Unger, 2000: A forecast product that maximizes utility for state-of-the-art seasonal climate prediction. *Bull. Amer. Meteor. Soc.,* **81,** 1271–1279.

Briggs, W. M., and D. S. Wilks, 1996: Estimating monthly and seasonal distributions of temperature and precipitation using the new CPC long-range forecasts. *J. Climate,* **9,** 818–826.

Callahan, B., E. Miles, and D. Fluharty, 1999: Policy implications of climate forecasting for water resources management in the Pacific Northwest. *Policy Sci.,* **32,** 269–293.

Carbone, G. J., and K. Dow, 2005: Water resource management and drought forecasts in South Carolina. *J. Amer. Water Resour. Assoc.,* **41,** 145–155.

Department of Natural Resources, cited 2000: Flint River drought protection. Georgia Department of Natural Resources, Environmental Protection Division, 16 pp. [Available online at http://www.gaepd.org/Files_PDF/rules/rules_exist/391-3-28.pdf.]

——, cited 2003: Georgia drought management plan. Georgia Department of Natural Resources, 23 pp. [Available online at http://www.georgiaplanning.com/watertookkit/Documents/WaterConservationDrougthManagement/DroughtMgtPlanFinal03.pdf.]

Hartmann, H. C., T. C. Pagano, S. Sorooshian, and R. Bales, 2002: Confidence builders: Evaluating seasonal climate forecasts from user perspectives. *Bull. Amer. Meteor. Soc.,* **83,** 683–698.

Lins, H. F., and E. Z. Stakhiv, 1998: Managing the nation's water in a changing climate. *J. Amer. Water Resour. Assoc.,* **34,** 1255–1264.

McKee, T. B., N. J. Doesken, and J. Kleist, 1993: The relationship of drought frequency and duration to time scale. Preprints, *Eighth Conf. on Applied Climatology*, Anaheim, CA, Amer. Meteor. Soc., 179–184.

National Climatic Data Center, cited 2006: Billion dollar U.S. weather disasters. [Available online at http://lwf.ncdc.noaa.gov/oa/reports/billionz.html.]

Nicholls, N., 1999: Cognitive illusions, heuristics, and climate prediction. *Bull. Amer. Meteor. Soc.,* **80,** 1385–1397.

Pagano, T. C., H. C. Hartmann, and S. Sorooshian, 2001: Using climate forecasts for water management: Arizona and the 1997-2001 El Niño. *J. Amer. Water Resour. Assoc.,* **37,** 1139–1153.

Potts, J. M., C. K. Folland, I. T. Jolliffe, and D. Sexton, 1996: Revised "LEPS" scores for assessing climate model simulations and long-range forecasts. *J. Climate,* **9,** 34–53.

Pulwarty, R., and K. T. Redmond, 1997: Climate and salmon restoration in the Columbia River Basin. *Bull. Amer. Meteor. Soc.,* **78,** 381–397.

Schneider, J. M., and J. D. Garbrecht, 2003: Regional utility of NOAA/CPC seasonal climate precipitation forecasts. *Proc. Symp. on Watershed Management and Restoration, World Water & Environmental Resources Congress,* Philadelphia, PA, Environmental and Water Resources Institute of the ASCE, 370.

Steinemann, A., 2003a: Drought indicators and triggers: A stochastic approach to evaluation. *J. Amer. Water Resour. Assoc.,* **39,** 1217–1234.

——, cited 2003b: Drought indicators and triggers. Georgia Drought Management Plan, Georgia Department of Natural Resources, 19–22. [Available online at http://www.georgiaplanning.com/watertoolkit/Documents/WaterConservationDroughtManagement/DroughtMgtPlanFinal03.pdf.]

Stern, P. C., and W. E. Easterling, 1999: *Making Climate Forecasts Matter*. National Research Council, National Academy Press, 175 pp.

Ward, M. H., and C. K. Folland, 1991: Prediction of seasonal rainfall in the north Nordeste of Brazil using eigenvectors of sea-surface temperature. *Int. J. Climatol.,* **11,** 711–743.

Wernstedt, K., and R. Hersh, 2002: Climate forecasts in flood planning: Promise and ambiguity. *J. Amer. Water Resour. Assoc.,* **38,** 1703–1713.

Wilks, D. S., 1995: *Statistical Methods in the Atmospheric Sciences*. Academic Press, 467 pp.