IMPROVING HYDROLOGICAL FORECASTS FOR IJC LAKE ONTARIO - ST. LAWRENCE RIVER STUDY

(HYDROLOGY AND HYDRAULICS TECHNICAL WORKING GROUP)

PROJECT 2: FORECASTING REVIEW - T.E. Croley, II

PROJECT 2 — REVIEW OF GREAT LAKES FORECASTING METHODOLOGIES

In FY2002, the Great Lakes Environmental Research Laboratory (GLERL) and the US Army Corps of Engineers (USCOE), as US members of the Hydrology and Hydraulics Technical Working Group subcommittee on Investigation of Forecasting for Use in Operation Decisions, participated with their Canadian counterparts in the following areas: user needs assessment, monitoring review, and forecasting review. A user needs assessment, undertaken by the Canadians, was needed to gain a clearer understanding of how improved hydrological and weather applications can be used to improve Lake Ontario system regulation, forecasting, and prediction. A workshop was held by the Meteorological Service of Canada—Ontario, of Environment Canada. The US helped to build the workshop agenda, to prepare summary reports for the workshop, and to make presentations at the workshop. A monitoring information assessment and review, undertaken by the Canadians, were necessary to clearly identify the hydrometeorological and related networks and data products (e.g., weather radar, quantitative precipitation forecasts) that are available to hydrological forecasting of the Lake Ontario—St. Lawrence Study. Recommendations for monitoring information optimization are also to be developed. The US provided the GLERL—USACE hydrometeorological station directory, developed under the auspices of the International Coordinating Committee for Great Lakes Hydraulic and Hydrological Data, to initialize the monitoring information assessment.

The US undertook the forecasting review, reported here. A review of hydrological and weather forecasting methodologies was done to assess the status of current capabilities and the key improvements necessary for the most suitable methodologies to be applied for improved Lake Ontario forecasting. The US provided a risk assessment demonstration, illustrating the use of forecasting in regulation decisions to allow consideration of risk associated with decisions. Risk assessment was considered in operational Lake Ontario decision-making through the incorporation of hydrological forecasting techniques into the decision-making process and is reported here. Also reported here are three case studies illustrating the use of probabilistic hydrological forecasts to Great Lakes water level management and decision-making. This approach's benefits, the unresolved technical and institutional issues, and recommendations are also presented.

METHODOLOGY

The US reviewed existing operational net basin supply (NBS) and lake level forecast methods on the Laurentian Great Lakes above Cornwall, consisting of the Corps of Engineers (Detroit District) arithmetic moving average, trend, and multiple correlation methods, the Corps of Engineers (Buffalo District) Lake Ontario and downstream water level heuristic methods, the Canadian historical NBS Monte Carlo analysis, the US-Canadian coordinated, and GLERL's Advanced Hydrologic Prediction System (AHPS). Conceptual descriptions of each are provided herein. The US reviewed extended weather forecasting, pertinent to use in Great Lakes water level forecasting. This review describes them in sufficient detail for operational use. It considers NOAA and EC extended forecasts and describes their bases conceptually. The US evaluated the relative impacts (worth) of near real time data availability (initial conditions) and weather forecasts on hydrological forecasts by building forecasts with and without their use and assessing agreement with observations over recent data periods. The US explored (evaluated) all existing operational NBS and lake level forecast methods on the Great Lakes above Cornwall by inter-comparing them and their "goodness of forecast." They used deterministic comparisons for the most part since all but the Canadian, the Coordinated, and AHPS are deterministic only. They did perform some probabilistic analyses for these latter three as well as deterministic.

EXISTING GREAT LAKES FORECASTS (ABOVE CORNWALL)

Extreme Great Lakes water levels cause extensive flooding, erosion, and damage to shorelines, shipping, and hydropower. Knowledge of even near-normal level expectations is important to riparian people, recreational users, shippers, fishers, and many others. While forecasts of meteorology, riverine flooding, and water level fluctuations have long been available for periods of several hours to several days, the Great Lakes community requires water resource forecasts over large areas and time periods. Fortunately (for forecasters), the Great Lakes possess tremendous capacities for storage of mass and energy and respond slowly to changes in meteorology, making them amenable to hydrological forecasting. Products must include nowcasts and 1-day to 6-month probabilistic forecasts of lake supplies, lake levels, and connecting channel flows. Though desirable, longer forecast timeframes cannot be realistically supported since weather and operating conditions are insufficiently known that far into the future.

US Upper Great Lakes Water Level Forecasts

Great Lakes forecasters include the former US Lake Survey of the US Army Corps of Engineers, which began 6-month lake level forecasts in 1952. Since 1975, the Detroit District of the Corps has continued on a monthly basis. They first forecast net basin supply, defined as the algebraic sum of over lake precipitation, runoff to the lake from bordering watersheds, and lake evaporation. (The Corps estimates historical net basin supplies with a water balance from records of connecting channel flows, lake levels, and diversions.) For the last several years, the Corps has been making three deterministic forecasts of these water supplies each month for each of the upper Great Lakes based on: 1) multiple linear regressions, 2) extrapolations of recent supply trends (superposition of seasonal cycles onto recent supplies), and 3) their use of the Great Lakes Environmental Research Laboratory's (GLERL's) Advanced Hydrologic Prediction System (AHPS), covered subsequently. The multiple linear regressions relate future supplies to past supplies, air temperatures, and precipitation, as determined from historical records. The Corps also adjust their regression supply forecast to consider air temperature and precipitation estimates for the coming month. They estimate the coming month's values as the historical quantiles associated with the meteorological probabilities forecast by the National Oceanic and Atmospheric Administration's (NOAA's) Climate Prediction Center (CPC). The general regression equation for each month and for each lake as used by the Corps is:

$$NBS_j = \sum_{i=j}^{j-6} a_i Q_i + \sum_{i=j}^{j-1} b_i T_i + \sum_{i=j-1}^{j-3} c_i NBS_i \tag{1}$$

where NBS_i, Q_i, and T_i are net basin supply, total precipitation, and average air temperature, respectively, for month i, and a_i, b_i, and c_i are regression coefficients for month i. The regression is revised about every five years. Antecedent net basin supplies are estimated as the residual in a water balance from recorded inflows, outflows, and water levels (change of storage). The Corps uses its regression only for a one month forecast.

The extrapolation of recent supply trends up to 12 months into the future is accomplished with the "Trend Model," which comprises four components: long-term trends, inter annual cycle, seasonal variation, and random fluctuation. The trends component describes the long-term rise or decline of water supplies and is evaluated in two parts. Primary trend represents fluctuations over the most recent 30-35 years and secondary trend is over the last 18 months, with emphasis on the last six months. The inter annual cycle occurs over a long period of time, but is not uniform in time, duration or amplitude. Seasonal variation over the annual cycle is estimated from historical net basin supplies averaged for each month of the year.

The Corps also use meteorological forecasts from NOAA's CPC and from Environment Canada (EC), as well as prevailing basin and supply conditions, as guidance in choosing among or weighting of the three supply forecasts they generate (regression, trend, and AHPS). The probability range, or the 5% (wet) and 95% (dry) scenarios, is estimated from the coordinated (1900-1989) set of net basin supplies and are used to make a lake level forecast.

US Lake Ontario Water Level Forecasts

The US Army Corps of Engineers (Buffalo District) generally makes the Lake Ontario forecast during the last Friday of each month or, sometimes, in the first week of the new month (see Appendix I). They coordinate current initial condition estimates and forecast start and end dates with Environment Canada. Lake Ontario initial conditions come from the weekly Lake Ontario regulation (made each Thursday) and monthly mean Lake Michigan-Huron and Erie water levels are also computed as initial inputs. Generally, for forecasts beginning during December through March, the end date is taken as the last week of June, which corresponds closely to the peak Ontario water level. Forecasts beginning during April through August generally end the last week of December, corresponding to the closing of the St. Lawrence Seaway. Forecasts beginning during September through November generally end the last week of March, corresponding to the opening of the St. Lawrence Seaway.

Forecast computations include computer code for water supply computation, pre-project conditions, and Lake Ontario regulation. First, long-term average supplies to each of the Great Lakes are found with an upper lakes model (the Lake Superior regulation model), producing the long-term Lake Erie outflow for each month of the forecast period. The long-term net basin supply to Lake Ontario is computed from 1900—2002 recorded data and added to Lake Erie outflow to produce total basin supply to Lake Ontario over the forecast period. The Corps then adds a randomly generated component to estimate 5%, 50%, and 95% exceedance probability quantiles. Forecast monthly supplies are then pro-rated for each week of the forecast period.

Second, "pre-project" Lake Ontario levels and outflows are computed for each week of the forecast period, corresponding to conditions existing before the International St. Lawrence Seaway project was built. These conditions are best approximated by:

$$O = 57.710\left(L - 69.485\right)^{1.5} c_i \qquad (2)$$

where O = pre-project outflow from Lake Ontario (m^3s^{-1}), L = Oswego water level (m), and c_i = an ice factor (1 under open water conditions and < 1 with ice). The pre-project outflow is used as the following weeks' outflow if the generated levels from the regulation plan (described next) exceed the upper limit of 75.15 m or fall below the lower limit of 74.28 m. The following week's water supply is subtracted and the difference added to the pre-project level to estimate water level. The procedure is repeated for all weeks of the forecast period.

Third, Lake Ontario weekly regulation (Plan 1958-D) is simulated over the forecast period. The regulation procedure consists of a supply indicator, two basic rule curves, a seasonal adjustment and a maximum and minimum outflow limit. The two basic rule curves are seasonally based (one for August to January inclusive and the other for February to July inclusive). Using the end-of-week level and an "adjusted supply indicator", the following week's outflow can be derived from one of the two basic rule curves. The resultant outflow is called the basic rule outflow and is compared to the four maximum limits and three minimum limits in Plan 1958-D. The regulation outflow is taken as the basic rule outflow, limited to allowable from Plan 1958-D.

Canadian Great Lakes Water Level Forecasts

The Canadian Hydrographic Service (CHS) of the Department of Fisheries and Oceans began publishing monthly forecasts of levels in 1973. Now, the Great Lakes - St. Lawrence Regulation Office of Environment Canada generates the Canadian forecasts and the CHS publishes them. They produce monthly six-month water level forecasts for the Great Lakes and St. Lawrence River at the beginning of each month. These include levels forecast for each of the Great Lakes and for Montreal Harbor. These forecasts are coordinated with the Corps of Engineers. They also produce a set of six-month forecast levels for six locations on the St. Lawrence River from Kingston to Pointe Claire each month during the recreational boating season. It is coordinated and published by the U.S. Army Corps of Engineers, Buffalo District as part of the "Monthly Water Level Bulletin – Saint Lawrence River".

Starting with beginning-of-month water levels on each of the lakes, Environment Canada forecasts net basin supplies to each lake and St. Lawrence River tributary inflows below Cornwall in several manners. The supplies are then routed through the system to produce forecasts of levels and flows. The first method uses the historical net basin supply record to simulate possibilities for the future. In this method, appropriate six-month segments of NBS to each Great Lake and Lake St. Louis, for each year of 1900—present, are routed through the Great Lakes system to generate series of monthly levels and outflows. Lake Superior Regulation Plan 1977-A, in combination with its associated routing model for the unregulated lakes are used to produce water levels and flows for the system downstream to Lake Erie. The Lake Erie outflows are then routed through Lake Ontario Regulation Plan 1958-D (along with Lake Ontario NBS sequences and expected deviations from the regulation plan) and a St. Lawrence River model to produce water levels and outflows for Lake Ontario and the St. Lawrence River. (The ice and weed retardations in the connecting channels, and major diversion rates, are taken as long-term averages over various periods of record in order to represent the present hydraulic regime). The resulting sample of six-month lake-level and outflow scenarios enables calculation of frequency distributions at selected locations for each month of the period. From the frequency distribution, the 5% (wet), 50% (average), and 95% (dry) exceedance probability results are selected to form the forecast. This method uses real sequences of NBS, preserving actual serial correlations and cross-correlations of NBS from basin to basin. The only real-time data required are initial lake levels. This method is based on an extensive historical database, using recorded extremes. It is a simple method that uses minimal resources. However, it ignores antecedent basin hydrologic conditions (e.g. initial snow pack, soil moisture conditions, lake temperatures, ice pack) and available weather outlooks. This method also fails to take into account the initial storage conditions and particular regulation conditions of the Ottawa River, which affect Montreal area levels.

The second method is older and is supplanted now by the above. It assumes that standardized NBS for each month of the forecast is normally distributed and estimates exceedance quantiles from the historical record. It is only used now to support the “most probable” forecast of inflows to the St Lawrence River in the Montreal area. The six-month 50% exceedance probability NBS sequences are routed through each lake and, along with the one Ottawa River flow forecast produced by the Ottawa River Regulation Planning Board, are used to estimate the “most probable” inflows to the St Lawrence River in the Montreal area.

Additional methods account for antecedent basin conditions, available weather forecasts, and snow survey data. Beginning the spring of 2001, Environment Canada generates in-house forecasts using GLERL’s AHPS to determine two scenarios: one using as many readily available weather-related climatological outlooks as possible, and one using none (i.e., “climatology”). They also consider GLERL’s own AHPS forecast, posted each workday on their Web site. This method does not include the Ottawa River or the other St. Lawrence River tributaries. Environment Canada each spring (since 2000), estimates the “most probable” spring NBS on both the Lake Superior and Lakes Michigan-Huron basins with snow survey results. The method is based on regression equations that estimate April and May NBS from monthly basin precipitation and March and April snow water equivalent data from the Ontario Power Generation snow survey. Incorporation of this approach can improve the “most probable” forecasts for the spring since near real-time snow data improves the estimation of spring NBS during this usually high supply period of the year when snowmelt makes up a large part of the runoff.

Each month, Environment Canada combines the above forecasts in a subjective selection based on the forecaster’s experience. Typically, he uses the first method initially define the 5%, 50% and 95% forecast Great Lake levels and adjusts by up to a few centimeters based on results and assumptions from the other methods, after scrutinizing unreasonable values. Finally, accepted values are coordinated with the U.S. Army Corps of Engineers, Detroit District. Weighting the first method 10—30% and the second method 70—90% for the first three months of the six-month forecast produces Montreal Harbor levels “most probable” forecast and the forecast for Lake St. Louis. However, the first month of the Montreal Harbor forecast may be adjusted by the forecaster in consideration of the one-month 50% forecast from Canadian Hydrographic Service, Fisheries and Oceans Canada, Quebec Region. The fourth through six months of the “most probable” forecast are usually taken as the forecast produced using the first method. The first method is also used to estimate the 5% “wet” and 95% “dry” levels for Lake St. Louis and Montreal Harbour, subjectively taking into account the relative differences between the two methods in the 50% case.

Great Lakes Advanced Hydrologic Prediction System

GLERL adapted runoff models to estimate supplies in 1982, identified weak evaporation estimates in 1985, added improved one-dimensional evaporation models in 1990, altered deterministic outlooks, added probabilistic outlooks, and identified meteorological outlooks as the weakest component in 1993. In 1995, they defined AHPS for the Great Lakes, incorporating NOAA meteorological outlook probabilities available only since the start of that year. From 1996 through 1998 they expanded AHPS to use mixed meteorological outlook event probabilities and most-probable events and in 1999 they added new ways of combining these meteorological outlooks in making derivative hydrological outlooks. GLERL installed their forecast package for the US Army Corps of Engineers on Lake Superior in 1983, for the National Weather Service (NWS) Northeast River Forecast Center on Lake Champlain in 1984, for 3 Corps offices on all Great Lakes for their evaluations in 1987, 1996, 1997, and 2001, for the New York Power Authority and Ontario Hydro in 1988, 1995, 1997, and 2001, for the Midwest Climate Center in 1994, 1996, and 1997, and Environment Canada in 2001. GLERL evaluated AHPS, US, and Canadian lake level outlooks in 1997 and, more recently, they converted AHPS code to the Windows platform, documented the system, developed multimedia tutorials, and reevaluated AHPS, US, and Canadian lake level outlooks as experience mounted.

GLERL developed, calibrated, and verified conceptual model-based techniques for simulating hydrological processes in the Laurentian Great Lakes (including Georgian Bay and Lake St. Clair, both as separate entities). GLERL integrated the models into a system to estimate water and energy balances, whole-lake heat storage, and lake levels (Croley, 1990, 1993a,b; Croley and Hartmann, 1987, 1989; Croley and Lee, 1993; Hartmann, 1990). These include models for rainfall-runoff, evapotranspiration, and basin moisture storage [121 daily watershed models (Croley, 1983a,b)], over lake precipitation (a daily estimation model), one-dimensional (depth) lake thermodynamics [7 daily models for lake surface flux, thermal structure, evaporation, and heat storage (Croley, 1989a,b, 1992; Croley and Assel, 1994)], net lake supplies, channel routing [4 daily models for connecting channel flow and level, outlet works, and lake levels (Hartmann, 1987, 1988; Quinn, 1978)], lake regulation [a monthly plan balancing Lakes Superior, Michigan, and Huron (International Lake Superior Board of Control, 1981, 1982) and a quarter-monthly plan balancing Lake Ontario and the St. Lawrence River (International St. Lawrence River Board of Control, 1963)], and diversions and consumption (International Great Lakes Diversions and Consumptive Uses Study Board, 1981). Croley et al. (1996) conveniently summarizes details of these models. The modeling system is modularly built, allowing model upgrades to be added as they develop.

The modeling system is coupled with near real-time data acquisition and reduction to enable representation of current system states; see Figure 1. Inputs are daily meteorology (air temperature, dew point temperature, precipitation, wind speed, and cloud cover) for all available stations. Optional inputs are snow water equivalent, soil moisture, lake water temperature, and lake levels. Thiessen weighting (Croley and Hartmann, 1985) is used to convert daily provisional point data to areal averages for each watershed and lake surface (see A in Figure 1) for GLERL's runoff and lake thermodynamics models to estimate basin moisture and lake heat as antecedent (initial) conditions to a forecast (B in Figure 1). A deterministic "forecast" of all hydrologic variables, including lake supply, may be made then by simulating the hydrology from the point of estimated initial conditions forward with a meteorological scenario (taken from the historical record, for example); see C in Figure 1. The resulting lake supply scenarios, one for each lake, then are used with connecting-channel routing and lake regulation models to determine a lake levels scenario (D in Figure 1). This is repeated for alternate meteorological scenarios (other segments of the historical record) in an operational hydrology approach [used also by the NWS in their Ensemble Streamflow Prediction (ESP) forecasts]; see E in Figure 1. The resulting set of scenarios serves as a statistical sample for inferring probabilities and other parameters associated with both meteorology and hydrology (F in Figure 1). Probabilistic hydrologic outlooks then can be made directly from this sample for each variable of interest (not shown in Figure 1). The resulting probabilistic hydrologic outlooks would properly consider antecedent hydrological conditions, but not other-agency meteorological predictions (G in Figure 1).

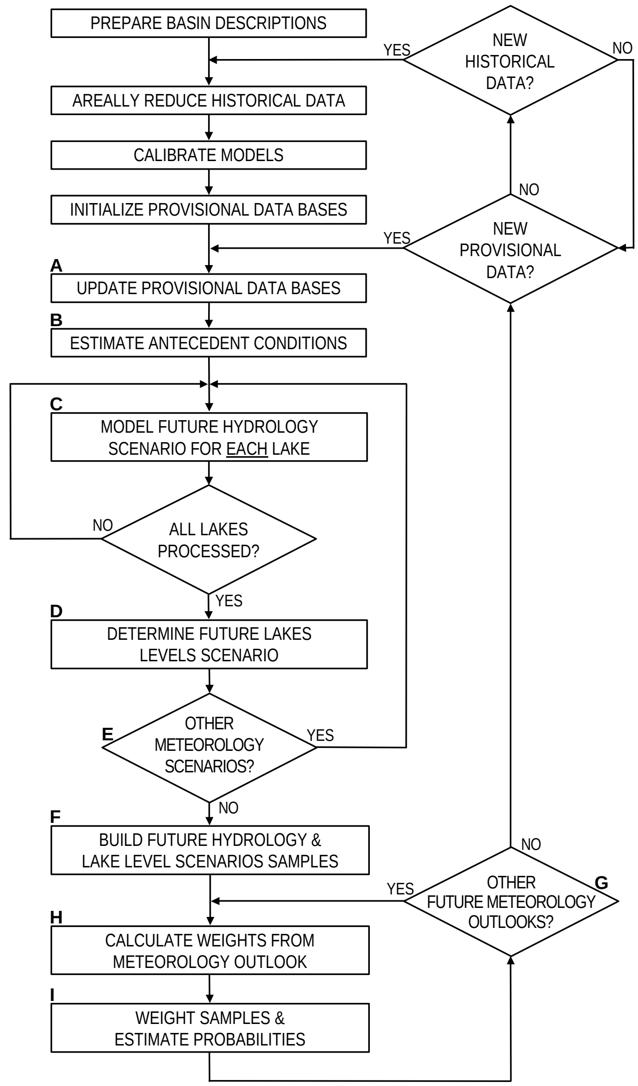

Figure 1. Overview of the Great Lakes Advanced Hydrologic Prediction System.

Multiple long-lead probabilistic meteorological outlooks of improving skill are now available to the water resource engineer or hydrologist (G in Figure 1). They are defined over different time periods at different time lags; they forecast either event probabilities or most-probable events. Each outlook yields probability equations or inequalities each month for every location in the Great Lakes. The probability equations are transformed into equations involving sample weights and are solved simultaneously for physically relevant values of the weights (Croley, 1996, 1997a,b, 2000a, 2001a); see H in Figure 1. The solution may involve an optimization, when there is more than one set of weights possible, and therefore may require an objective function to select between various solutions. Since all equations may not be satisfied simultaneously, they are ordered in priority and as many as possible are used (the lowest-priority equations are discarded). More weight is given to those sample scenarios whose corresponding historical meteorological record segments contain events appropriate to the meteorological forecasts. For example, more weight is given to those six-month lake level scenarios corresponding to monthly air temperatures in the upper third of their range when the meteorological outlook calls for above-normal monthly air temperatures; the value of the weight depends on the probabilities specified in the meteorological outlook. GLERL's AHPS weights the sample of six-month lake level scenarios each month to agree with these equations and then estimates outlook probabilities from the weighted sample (I in Figure 1) with the Weibull estimator (Croley, 2001a).

WEATHER FORECASTS

The following descriptions of available extended probabilistic weather forecasts are taken largely from Croley (2000a) and supplemented with other material. The focus is on extended meteorology probability forecasts over periods of several days to several months.

NOAA Climate Outlooks

Multiple probabilistic meteorology outlooks can consist of multiple forms of probability outlooks: event probabilities and most-probable events. There are now several kinds of event probability outlooks available to the water resource engineer or hydrologist for making derivative forecasts. One of the earliest still available is the NOAA CPC *Climate Outlook*, which is available over the World Wide Web via links from the NOAA home page to the CPC products page. The CPC provides this outlook each month at approximately mid-month; it consists of a 1-month outlook for the next (full) month and thirteen 3-month outlooks, going into the future in overlapping fashion in 1-month steps. Background and recent history on seasonal forecasting are provided in Barnston et al. (1994), van den Dool (1994), Livezey (1990), Wagner (1989), Epstein (1988), Ropelewski and Halpert (1986), and Gilman (1985). The forecasts in the *Climate Outlook* are formed by a combination of methods. For US air temperature and precipitation forecasts, these methods included, as of 1994, (1) canonical correlation analysis (Barnston and Ropelewski 1992) relating spatial anomalies of sea surface temperature in selected regions, Northern Hemisphere 700-mb height, and the US surface climate (referred to as “teleconnections”); and also (2) observed interannual persistence of anomalies (Huang et al. 1994), as well as (3) forecasts from two 6-month atmospheric general circulation models driven by sea surface temperatures. One is a set continued from one-half month earlier and the other is a set assembled from coupled ocean-atmosphere model runs (Ji et al. 1994). The general circulation model is a version of the NCEP Environmental Modeling Center’s (EMC’s) Medium-Range Forecast Model, which has a global domain, with special developmental emphasis on tropical processes.

Each outlook estimates probabilities of average air temperature and total precipitation falling within pre-selected value ranges. The value ranges (low, normal, and high) are defined as the lower, middle, and upper thirds of observations for each variable over the period 1961–90 (for forecasts made prior to 17 May 2001) or over the period 1971-2000 (for forecasts made on or after 17 May 2001). The climate outlooks presume that one of only four possibilities exists for the probability distribution type for each variable: (1) the probability of being in the high range exceeds one-third, and the probability of being in the low range is reduced accordingly (it remains at one-third for the normal range)—referred to as being “above normal”; (2) the probability of being in the normal range exceeds one-third, and the probabilities of being in the low and high ranges are reduced accordingly and are equal—referred to as being “normal”; (3) the probability of being in the low range exceeds one-third, and the probability of being in the high range is reduced accordingly (it remains at one-third for the normal range)—referred to as being “below normal”; or (4) skill is insufficient to make a forecast, and so probabilities of one-third in each range are used—referred to as “climatological.” This “four-distribution universe” is a built-in definition associated with using NOAA’s *Climate Outlook* and, while not always a realistic model of natural distributions, must be used in interpreting their outlooks.

An example outlook of precipitation probabilities is shown in Figure 2, representing the NOAA 1-month climatic outlook for September 1998, made on August 13, 1998. It is shown in an alternative form in Figure 3, which depicts only the continental United States and has less map detail, clarifying the presentation somewhat. The actual *Climate Outlook* is presented in color with all probabilities mapped together. They are separated here, because gray scales for probabilities "above" and "below" are confusing if plotted together. Forecast probabilities can be ascertained for any point on the outlook map. For example, in mid-Texas in Figure 2 or 3, the probability of September 1998 precipitation (Q_{Sep98}) in the lower third of historical observations is forecast to rise by about 0.02. According to NOAA's convention, the corresponding probability of September precipitation in the upper third of historical observations is forecast to drop by about 0.02, and the probability of September precipitation in the middle third of historical observations is forecast to remain unchanged at one-third:

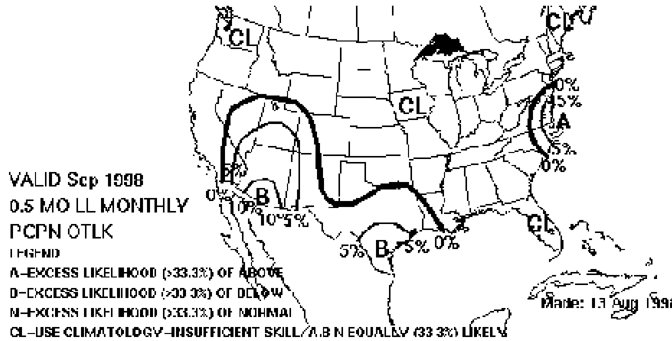

Figure 2. NOAA 1-month probabilistic precipitation outlook for September 1998.

$$
\begin{aligned}
\hat{P}\left[Q_{\text{Sep98}} \le \hat{q}_{\text{Sep},\,0.333}\right] &= 0.333 + 0.02 = 0.353 \\
\hat{P}\left[\hat{q}_{\text{Sep},\,0.333} < Q_{\text{Sep98}} \le \hat{q}_{\text{Sep},\,0.667}\right] &= 0.334 \\
\hat{P}\left[Q_{\text{Sep98}} > \hat{q}_{\text{Sep},\,0.667}\right] &= 0.333 - 0.02 = 0.313
\end{aligned} \tag{3}
$$

where $\hat{q}_{\text{Sep},\,g}$ denotes the reference September g-probability quantile estimate (calculated from the 1961–90 historical record for forecasts made prior to 17 May 2001, or from the 1971-2000 historical record for forecasts made on or after 17 May 2001).

Actually, there are multiple 1-month and 3-month outlooks every month from NOAA; Figure 3 is but one of 28 available each month, as shown in the full *Climate Outlook* in Figure 4.

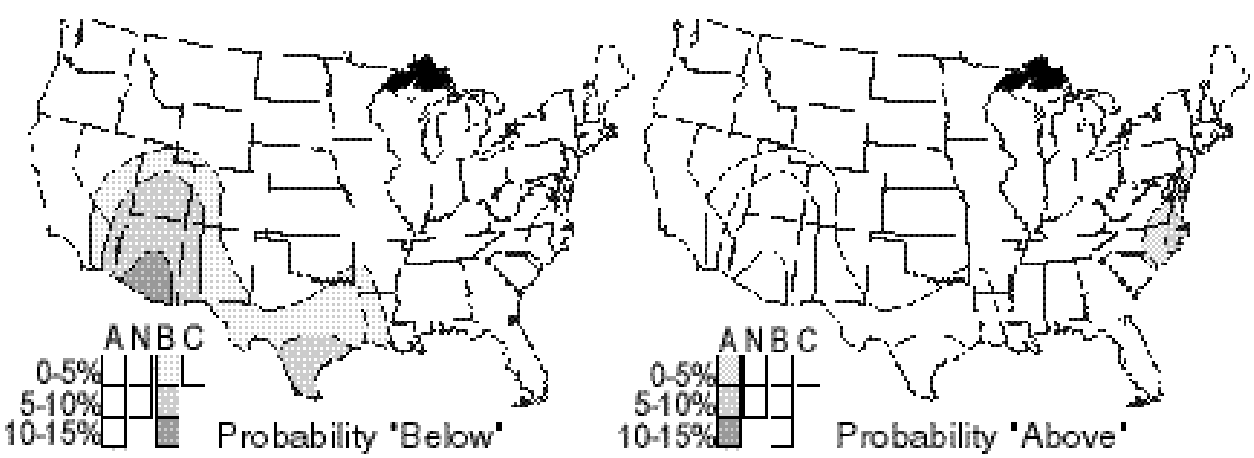

Figure 3. Alternative-form NOAA 1-month September 1998 probabilistic precipitation outlook.

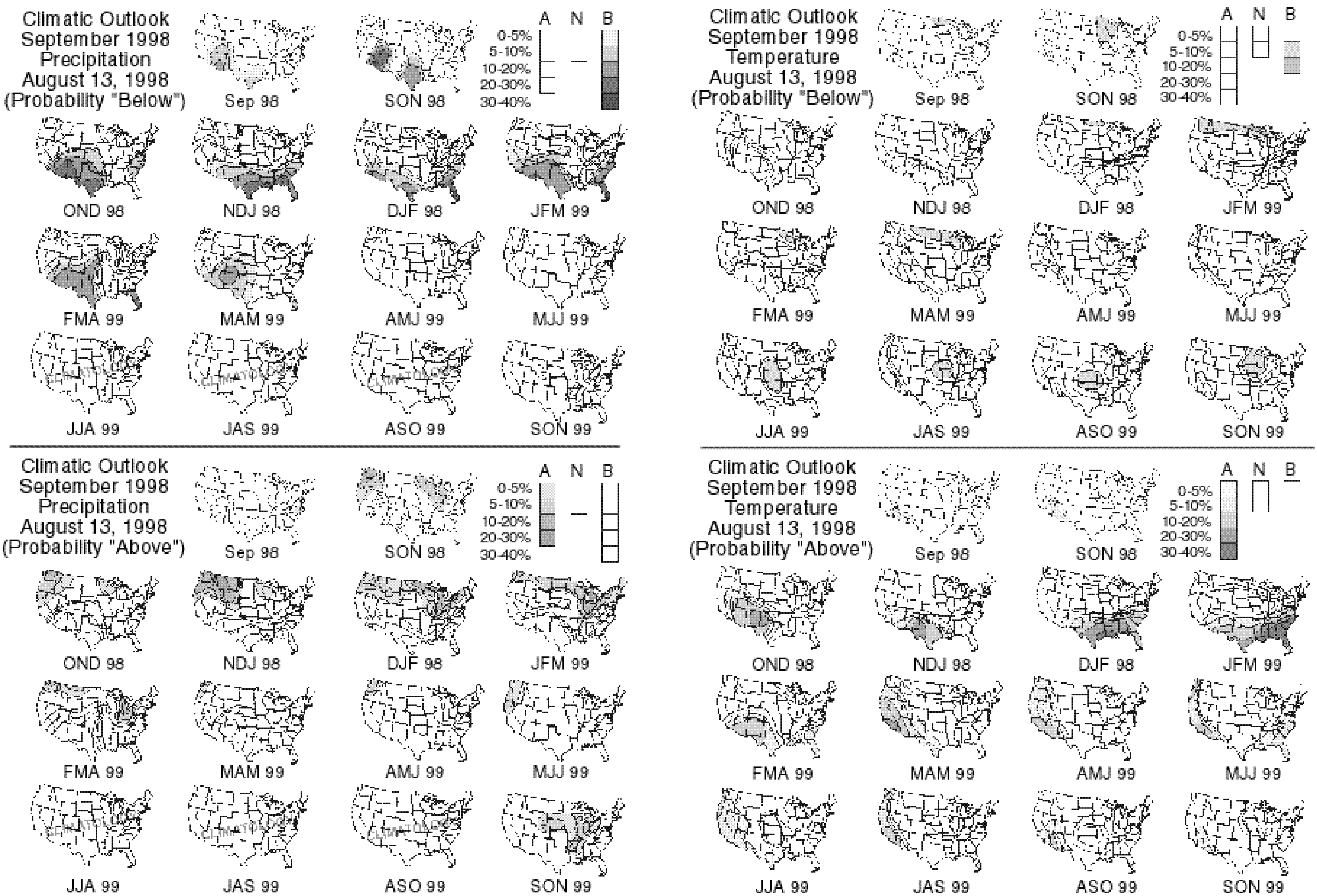

Figure 4. NOAA 1-month and extended 3-month probabilistic precipitation and temperature outlook for September 1998 and September-October-November 1998 through September-October-November 1999.

(Again, although the originals are presented in color; the probabilities for "above" and "below" are separated here, because gray scales for the two are confusing if plotted together.) These figures represent a large number of probability forecast statements. At any one particular site, the multiple outlooks consist of one 1-month and thirteen 3-month outlooks of both temperature and precipitation, each with three equations per outlook for each variable.

$$\left.\begin{aligned}\hat{P}\left[T_g \le \hat{t}_{g,0.333}\right] &= a_g \\ \hat{P}\left[T_g > \hat{t}_{g,0.667}\right] &= b_g \\ \hat{P}\left[\hat{t}_{g,0.333} < T_g \le \hat{t}_{g,0.667}\right] &= 1 - a_g - b_g \\ \hat{P}\left[Q_g \le \hat{q}_{g,0.333}\right] &= c_g \\ \hat{P}\left[Q_g > \hat{q}_{g,0.667}\right] &= d_g \\ \hat{P}\left[\hat{q}_{g,0.333} < Q_g \le \hat{q}_{g,0.667}\right] &= 1 - c_g - d_g\end{aligned}\right\} \quad g = 1, \ldots, 14 \qquad (4)$$

where T_g and Q_g are average air temperature and total precipitation at the site, respectively, over period g (g = 1 corresponds to a 1-month period, and g = 2, ... , 14 corresponds to 13 successive overlapping 3-month periods); $\hat{t}_{g,g}$ and $\hat{q}_{g,g}$ are, respectively, temperature and precipitation reference g-probability non-exceedance quantile estimates at the site for period g; and (a_g, b_g, c_g, and d_g, g = 1, ... , 14) are the outlook probability forecast estimates as calculated from the map readings at the site. Recall that the reference g-probability quantiles are estimated from the 1961–90 historical record at the site for each period g by definition. For the September 1998 *Climate Outlook* in Figure 4 at any site, there is a 1-month September outlook (g = 1 or "Sep") and thirteen 3-month outlooks successively lagged by 1 month each (g = 2 or "September-October-November" or "SON," and g = 3, 4, ... , 14 or "OND," "NDJ," ... , "SON," respectively).

The third and sixth lines in (4) are redundant in combination with the rest of (4) because probabilities (and probability estimates) sum to unity over the real line:

$$\begin{aligned}\hat{P}\left[T_g \le \hat{t}_{g,0.333}\right] + \hat{P}\left[\hat{t}_{g,0.333} < T_g \le \hat{t}_{g,0.667}\right] + \hat{P}\left[T_g > \hat{t}_{g,0.667}\right] &= 1 \\ \hat{P}\left[Q_g \le \hat{q}_{g,0.333}\right] + \hat{P}\left[\hat{q}_{g,0.333} < Q_g \le \hat{q}_{g,0.667}\right] + \hat{P}\left[Q_g > \hat{q}_{g,0.667}\right] &= 1\end{aligned} \qquad (5)$$

Therefore there are four independent settings in (4) at any site for each of the 14 climate outlooks, for a total of 56. Example numbers, taken from the September 1998 maps for the Lake Superior basin, appear in columns 2 and 7 in Table 1. (Note that, in Figures 2 and 3, Lake Superior has been blackened to highlight its location.) They are interpreted as increments or decrements to appropriate reference values to yield probability estimates in columns 3 through 5 and 8 through 10. Note that column 4 is redundant in combination with columns 3 and 5, as is column 9 with columns 8 and 10. The probability estimate equations represented by Figure 4 and Table 1 are listed in Figure 5.

Table 1. NOAA September 1998 Lake Superior basin outlook event probability estimates (%).

Period, g	$\hat{P}_T$ [a]	Temperature Probabilities[b]		
		$\left(-\infty, \hat{t}_{g,0.333}\right]$	$\left(\hat{\tau}_{g,0.333}, \hat{\tau}_{g,0.667}\right]$	$\left(\hat{\tau}_{g,0.667}, \infty\right)$
(1)	(2)	(3)	(4)	(5)
Sep 98	1 b	34.3	33.4	32.3
SON 98	5 b	38.3	33.4	28.3
OND 98	0 c	33.3	33.4	33.3
NDJ 98	0 c	33.3	33.4	33.3
DJF 98	0 c	33.3	33.4	33.3
JFM 99	11 b	44.3	33.4	22.3
FMA 99	6 b	39.3	33.4	27.3
MAM 99	7 b	40.3	33.4	26.3
AMJ 99	0 c	33.3	33.4	33.3
MJJ 99	0 c	33.3	33.4	33.3
JJA 99	0 c	33.3	33.4	33.3
JAS 99	0 c	33.3	33.4	33.3
ASO 99	0 c	33.3	33.4	33.3
SON 99	6 b	39.3	33.4	27.3

Period, g	$\hat{P}_Q$ [a]	Precipitation Probabilities[b]		
		$\left(-\infty, \hat{\theta}_{g,0.333}\right]$	$\left(\hat{\theta}_{g,0.333}, \hat{\theta}_{g,0.667}\right]$	$\left(\hat{\theta}_{g,0.667}, \infty\right)$
(6)	(7)	(8)	(9)	(10)
Sep 98	0 c	33.3	33.4	33.3
SON 98	5 a	28.3	33.4	38.3
OND 98	3 a	30.3	33.4	36.3
NDJ 98	3 a	30.3	33.4	36.3
DJF 98	11 a	22.3	33.4	44.3
JFM 99	10 a	23.3	33.4	43.3
FMA 99	1 a	32.3	33.4	34.3
MAM 99	0 c	33.3	33.4	33.3
AMJ 99	0 c	33.3	33.4	33.3
MJJ 99	0 c	33.3	33.4	33.3
JJA 99	0 c	33.3	33.4	33.3
JAS 99	0 c	33.3	33.4	33.3
ASO 99	0 c	33.3	33.4	33.3
SON 99	0 c	33.3	33.4	33.3

[a]Probability estimates ($\hat{P}_T$ and $\hat{P}_Q$ designate temperature and precipitation probability estimates, respectively) in excess of 33.3% in low interval (<u>b</u>elow normal), in mid interval (<u>n</u>ormal), or in high interval (<u>a</u>bove normal); "no forecast" is indicated by "0 c" (<u>c</u>limatological).

Lake Superior Basin Event Probability Estimates

September 1998 Air Temperature & Precipitation
SON 1998 through SON 1999 Air Temperature & Precipitation
Forecast August 13, 1998 by NOAA

$$\hat{P}\left[T_{\text{Sep98}} \le \hat{t}_{\text{Sep},\,0.333}\right] = 0.343$$
$$\hat{P}\left[T_{\text{Sep98}} > \hat{t}_{\text{Sep},\,0.667}\right] = 0.323$$
$$\hat{P}\left[Q_{\text{Sep98}} \le \hat{q}_{\text{Sep},\,0.333}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{Sep98}} > \hat{q}_{\text{Sep},\,0.667}\right] = 0.333$$
$$\hat{P}\left[T_{\text{SON98}} \le \hat{t}_{\text{SON},\,0.333}\right] = 0.383$$
$$\hat{P}\left[T_{\text{SON98}} > \hat{t}_{\text{SON},\,0.667}\right] = 0.283$$
$$\hat{P}\left[Q_{\text{SON98}} \le \hat{q}_{\text{SON},\,0.333}\right] = 0.283$$
$$\hat{P}\left[Q_{\text{SON98}} > \hat{q}_{\text{SON},\,0.667}\right] = 0.383$$
$$\hat{P}\left[T_{\text{OND98}} \le \hat{t}_{\text{OND},\,0.333}\right] = 0.333$$
$$\hat{P}\left[T_{\text{OND98}} > \hat{t}_{\text{OND},\,0.667}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{OND98}} \le \hat{q}_{\text{OND},\,0.333}\right] = 0.303$$
$$\hat{P}\left[Q_{\text{OND98}} > \hat{q}_{\text{OND},\,0.667}\right] = 0.363$$
$$\hat{P}\left[T_{\text{NDJ98}} \le \hat{t}_{\text{NDJ},\,0.333}\right] = 0.333$$
$$\hat{P}\left[T_{\text{NDJ98}} > \hat{t}_{\text{NDJ},\,0.667}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{NDJ98}} \le \hat{q}_{\text{NDJ},\,0.333}\right] = 0.303$$
$$\hat{P}\left[Q_{\text{NDJ98}} > \hat{q}_{\text{NDJ},\,0.667}\right] = 0.363$$
$$\hat{P}\left[T_{\text{DJF98}} \le \hat{t}_{\text{DJF},\,0.333}\right] = 0.333$$
$$\hat{P}\left[T_{\text{DJF98}} > \hat{t}_{\text{DJF},\,0.667}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{DJF98}} \le \hat{q}_{\text{DJF},\,0.333}\right] = 0.223$$
$$\hat{P}\left[Q_{\text{DJF98}} > \hat{q}_{\text{DJF},\,0.667}\right] = 0.443$$
$$\hat{P}\left[T_{\text{JFM99}} \le \hat{t}_{\text{JFM},\,0.333}\right] = 0.443$$
$$\hat{P}\left[T_{\text{JFM99}} > \hat{t}_{\text{JFM},\,0.667}\right] = 0.223$$
$$\hat{P}\left[Q_{\text{JFM99}} \le \hat{q}_{\text{JFM},\,0.333}\right] = 0.233$$
$$\hat{P}\left[Q_{\text{JFM99}} > \hat{q}_{\text{JFM},\,0.667}\right] = 0.433$$
$$\hat{P}\left[T_{\text{FMA99}} \le \hat{t}_{\text{FMA},\,0.333}\right] = 0.393$$
$$\hat{P}\left[T_{\text{FMA99}} > \hat{t}_{\text{FMA},\,0.667}\right] = 0.273$$
$$\hat{P}\left[Q_{\text{FMA99}} \le \hat{q}_{\text{FMA},\,0.333}\right] = 0.323$$
$$\hat{P}\left[Q_{\text{FMA99}} > \hat{q}_{\text{FMA},\,0.667}\right] = 0.343$$
$$\hat{P}\left[T_{\text{MAM99}} \le \hat{t}_{\text{MAM},\,0.333}\right] = 0.403$$
$$\hat{P}\left[T_{\text{MAM99}} > \hat{t}_{\text{MAM},\,0.667}\right] = 0.263$$
$$\hat{P}\left[Q_{\text{MAM99}} \le \hat{q}_{\text{MAM},\,0.333}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{MAM99}} > \hat{q}_{\text{MAM},\,0.667}\right] = 0.333$$
$$\hat{P}\left[T_{\text{AMJ99}} \le \hat{t}_{\text{AMJ},\,0.333}\right] = 0.333$$
$$\hat{P}\left[T_{\text{AMJ99}} > \hat{t}_{\text{AMJ},\,0.667}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{AMJ99}} \le \hat{q}_{\text{AMJ},\,0.333}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{AMJ99}} > \hat{q}_{\text{AMJ},\,0.667}\right] = 0.333$$
$$\hat{P}\left[T_{\text{MJJ99}} \le \hat{t}_{\text{MJJ},\,0.333}\right] = 0.333$$
$$\hat{P}\left[T_{\text{MJJ99}} > \hat{t}_{\text{MJJ},\,0.667}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{MJJ99}} \le \hat{q}_{\text{MJJ},\,0.333}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{MJJ99}} > \hat{q}_{\text{MJJ},\,0.667}\right] = 0.333$$
$$\hat{P}\left[T_{\text{JJA99}} \le \hat{t}_{\text{JJA},\,0.333}\right] = 0.333$$
$$\hat{P}\left[T_{\text{JJA99}} > \hat{t}_{\text{JJA},\,0.667}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{JJA99}} \le \hat{q}_{\text{JJA},\,0.333}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{JJA99}} > \hat{q}_{\text{JJA},\,0.667}\right] = 0.333$$
$$\hat{P}\left[T_{\text{JAS99}} \le \hat{t}_{\text{JAS},\,0.333}\right] = 0.333$$
$$\hat{P}\left[T_{\text{JAS99}} > \hat{t}_{\text{JAS},\,0.667}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{JAS99}} \le \hat{q}_{\text{JAS},\,0.333}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{JAS99}} > \hat{q}_{\text{JAS},\,0.667}\right] = 0.333$$
$$\hat{P}\left[T_{\text{ASO99}} \le \hat{t}_{\text{ASO},\,0.333}\right] = 0.333$$
$$\hat{P}\left[T_{\text{ASO99}} > \hat{t}_{\text{ASO},\,0.667}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{ASO99}} \le \hat{q}_{\text{ASO},\,0.333}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{ASO99}} > \hat{q}_{\text{ASO},\,0.667}\right] = 0.333$$
$$\hat{P}\left[T_{\text{SON99}} \le \hat{t}_{\text{SON},\,0.333}\right] = 0.393$$
$$\hat{P}\left[T_{\text{SON99}} > \hat{t}_{\text{SON},\,0.667}\right] = 0.273$$
$$\hat{P}\left[Q_{\text{SON99}} \le \hat{q}_{\text{SON},\,0.333}\right] = 0.333$$
$$\hat{P}\left[Q_{\text{SON99}} > \hat{q}_{\text{SON},\,0.667}\right] = 0.333$$

Figure 5. Event probability estimate equations for September 1998 Lake Superior basin climate outlook.

NOAA 8–14 Day Event Probability Outlooks

The NOAA CPC also makes an experimental "second-week" outlook at about 3:00 p.m. EST every day that gives probabilities for average air temperature and total precipitation events over a 7-day period beginning 7 days from the forecast date. Therefore, there are four independent settings in this outlook. NOAA calls this its *8–14 day outlook,* and it is based on teleconnections, persistence, and model simulations using the medium-range forecast model, similar to the generation of their *Climate Outlook*. Each 8–14 day outlook provides probability estimates of average air temperature and total precipitation falling within pre-selected value ranges of low, normal, and high, again defined as the lower, middle, and upper thirds of observations for each variable over the period 1961–90 (for forecasts prior to 17 May 2001) or the period 1971-2000 (for forecasts on or after 17 May 2001). The climate outlooks again presume the "four-distribution universe" that was defined before. Recall that only four possibilities are assumed to exist for the probability distributions for each variable: (1) "above normal" (probability of high exceeds one-third, with probability of low reduced accordingly), (2) "normal" (probability of middle range exceeds one-third, with probabilities of being low and high reduced accordingly and equally), (3) "below normal" (probability of low exceeds one-third, with probability of high range reduced accordingly), and (4) "climatological" (probabilities of one-third in each range are used).

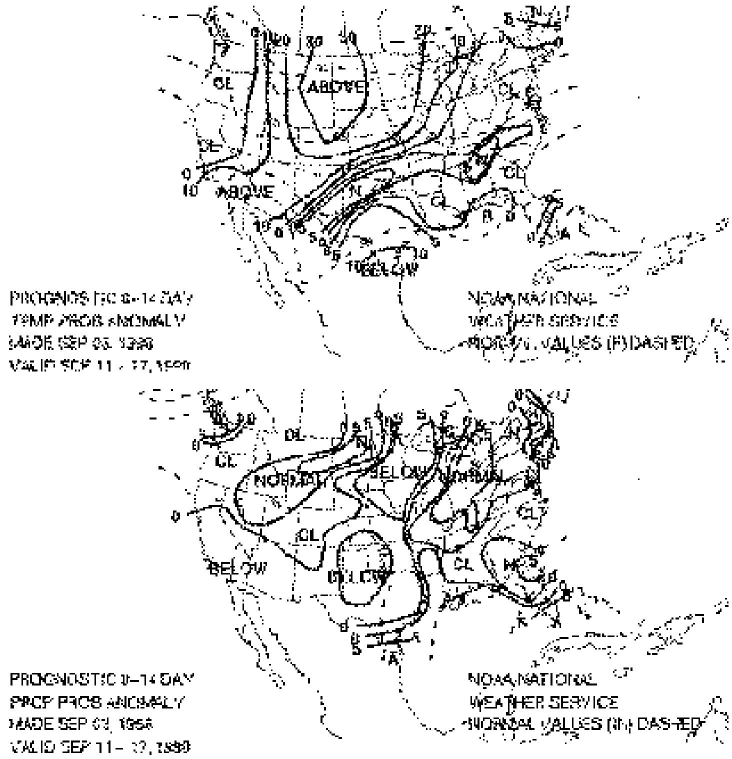

Figure 6. NOAA 8–14 day probabilistic outlook for September 11-17, 1998.

An example is pictured in Figure 6 for September 11–17, 1998; it was forecast on September 3, 1998, and downloaded from NOAA's CPC Web site. Example numbers are taken from these maps for the Lake Superior basin: 0.18 above for air temperature and 0.06 below for precipitation. They are interpreted as increments or decrements to the appropriate reference values to yield probability estimate equations, similar to reading and using NOAA's 1- and 3-month outlooks. The resulting probability estimate equations are

$$\begin{aligned}
\hat{P}\left[T_{11\text{–}17\text{Sep}98} \le \hat{t}_{11\text{–}17\text{Sep},\,0.333}\right] &= 0.333 - 0.18 = 0.153 \\
\hat{P}\left[T_{11\text{–}17\text{Sep}98} > \hat{t}_{11\text{–}17\text{Sep},\,0.667}\right] &= 0.333 + 0.18 = 0.513 \\
\hat{P}\left[Q_{11\text{–}17\text{Sep}98} \le \hat{q}_{11\text{–}17\text{Sep},\,0.333}\right] &= 0.333 + 0.06 = 0.393 \\
\hat{P}\left[Q_{11\text{–}17\text{Sep}98} > \hat{q}_{11\text{–}17\text{Sep},\,0.667}\right] &= 0.333 - 0.06 = 0.273
\end{aligned} \qquad (6)$$

NOAA 6–10 Day Event Probability Outlooks

The NOAA CPC also makes experimental 5-day outlooks at about 3:00 p.m. EST every day that give probabilities for average air temperature and total precipitation events over a 5-day period

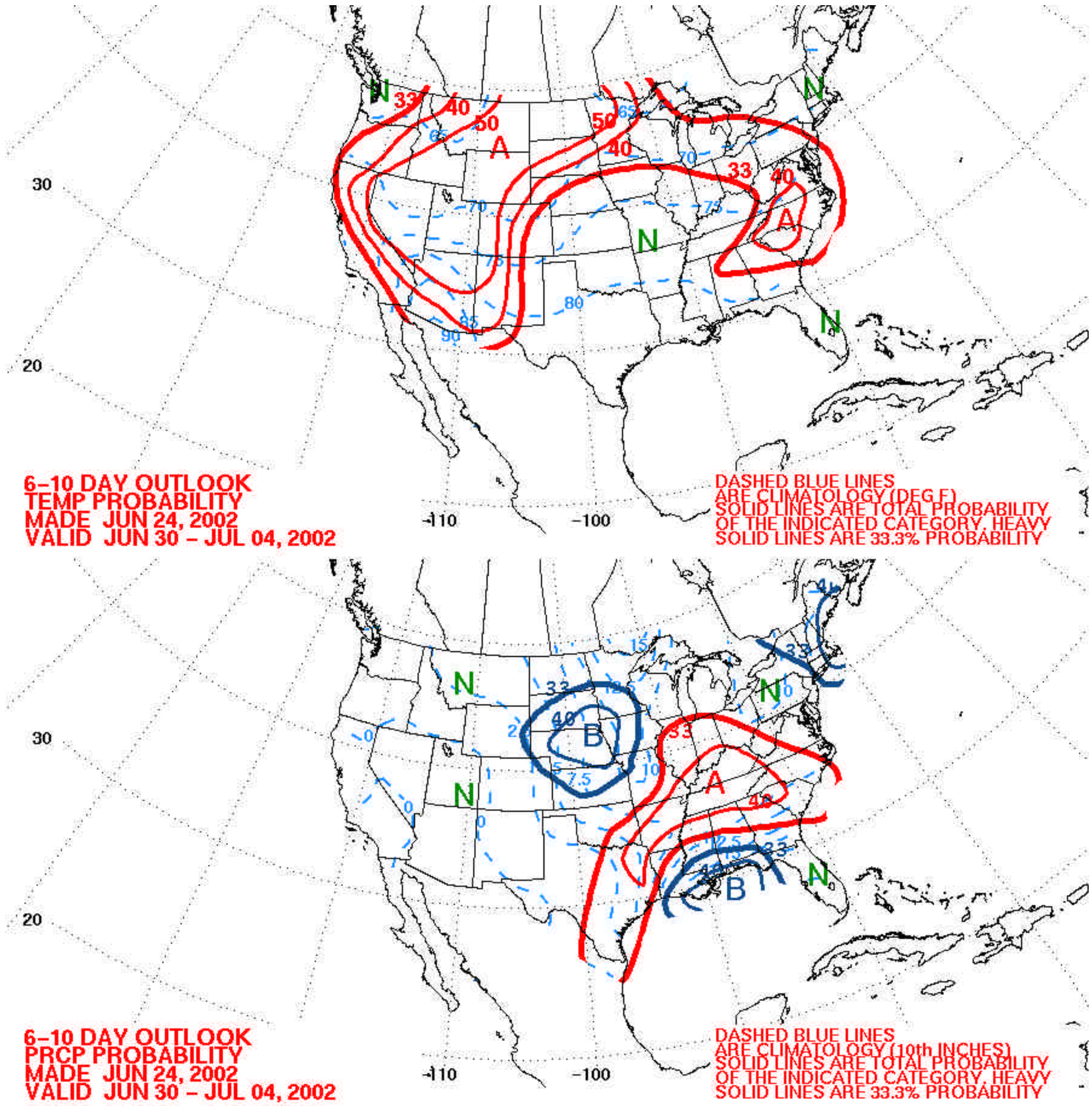

Figure 7. NOAA 6-10 day probabilistic outlook for June 30—July 04, 2002.

beginning 5-days from the forecast date. It is similar in origin and interpretation to NOAA's 8–14 day outlook, described above. An example is pictured in Figure 7 for June 30—July 4, 2002; it was forecast on June 24, and downloaded from NOAA's CPC Web site. Example numbers are taken from these maps for the Lake Superior basin: 0.35 that air temperature is in the upper third tercile and equal chance that precipitation is in any tercile. The resulting probability estimate equations are:

$$\begin{aligned}
\hat{P}\left[T_{\text{30Jun}-\text{4Jul02}} \le \hat{t}_{\text{30Jun}-\text{4Jul, 0.333}}\right] &= 0.310 \\
\hat{P}\left[T_{\text{30Jun}-\text{4Jul02}} > \hat{t}_{\text{30Jun}-\text{4Jul, 0.667}}\right] &= 0.350 \\
\hat{P}\left[Q_{\text{30Jun}-\text{4Jul02}} \le \hat{q}_{\text{30Jun}-\text{4Jul, 0.333}}\right] &= 0.333 \\
\hat{P}\left[Q_{\text{30Jun}-\text{4Jul02}} > \hat{q}_{\text{30Jun}-\text{4Jul, 0.667}}\right] &= 0.333
\end{aligned} \qquad (7)$$

NOAA Ensemble Event Probability Forecast Products

It is possible to obtain information on the inherent predictability of a deterministic forecast of the weather by running atmospheric models from a number of likely initial conditions, based on actual observations and their likely errors, called an "ensemble" of initial conditions. For a sufficiently large number of realizations (simulations) in the resulting model output ensemble, any forecast quantity can be expressed in terms of probability estimates, conveying information regarding future weather. At NCEP, the ensemble approach has been applied operationally, using the NCEP Environmental Modeling Center (EMC) medium-range forecast model for short-range forecasts as well as using the model in a non-ensemble mode for the extended-range *Climate Outlook* previously discussed. These short-range forecasts are created on an experimental basis. Each day, the EMC publishes on the Web nine successively lagged 1-day outlooks, a 1–5 day outlook, a 6–10 day outlook, and an 8–14 day outlook of precipitation event probabilities. An example is given for the first 24-hour outlook of January 16, 1998, in Figure 8. This was downloaded from the NCEP EMC Web site NCEP Ensemble Products of the Global Modeling Branch. The probabilities are given directly in terms of certain specified amounts and do not involve reference to historical quantiles as do NOAA's 1- and 3-month outlooks or their 6—10 or 8—14 day outlooks. Also, no assumptions are being made as to the form of the distributions (NOAA's "four-distribution universe," described previously). The original is in color. Numbers extracted from Figure 8 for the Lake Superior basin result in the following probability equations:

$$\begin{aligned}
P\left[P_{\text{12:16 Jan 98–12:17 Jan 98}} > 2.54\text{mm}\right] &\cong 0.35 \\
P\left[P_{\text{12:16 Jan 98–12:17 Jan 98}} > 6.35\text{mm}\right] &\cong 0.02 \\
P\left[P_{\text{12:16 Jan 98–12:17 Jan 98}} > 12.7\text{mm}\right] &\cong 0.0 \\
P\left[P_{\text{12:16 Jan 98–12:17 Jan 98}} > 25.4\text{mm}\right] &\cong 0.0
\end{aligned} \qquad (8)$$

NOAA 1-Day Precipitation Event Probability Anomaly Outlooks

Another NOAA NCEP office, the Hydrometeorology Prediction Center (HPC), makes daily 1-day outlooks for days 3, 4, 5, 6, and 7 into the future for departures from normal of the estimated probability of precipitation. HPC refers to the day-3, 4, and 5 outlooks as medium-range forecast products, which include maps of surface pressure patterns, circulation centers, fronts, daily maximum and minimum temperature anomalies, daily precipitation probability anomalies, and total 5-day precipitation for days 1 through 5. These products are also based on output from the medium-range forecast model and other medium range models and ensembles (simulation runs based on alternative initial conditions). An example for day 3, representing January 30, 1999, made January 27, is given on the left in Figure 9. To use it, one requires an estimate of the nor-

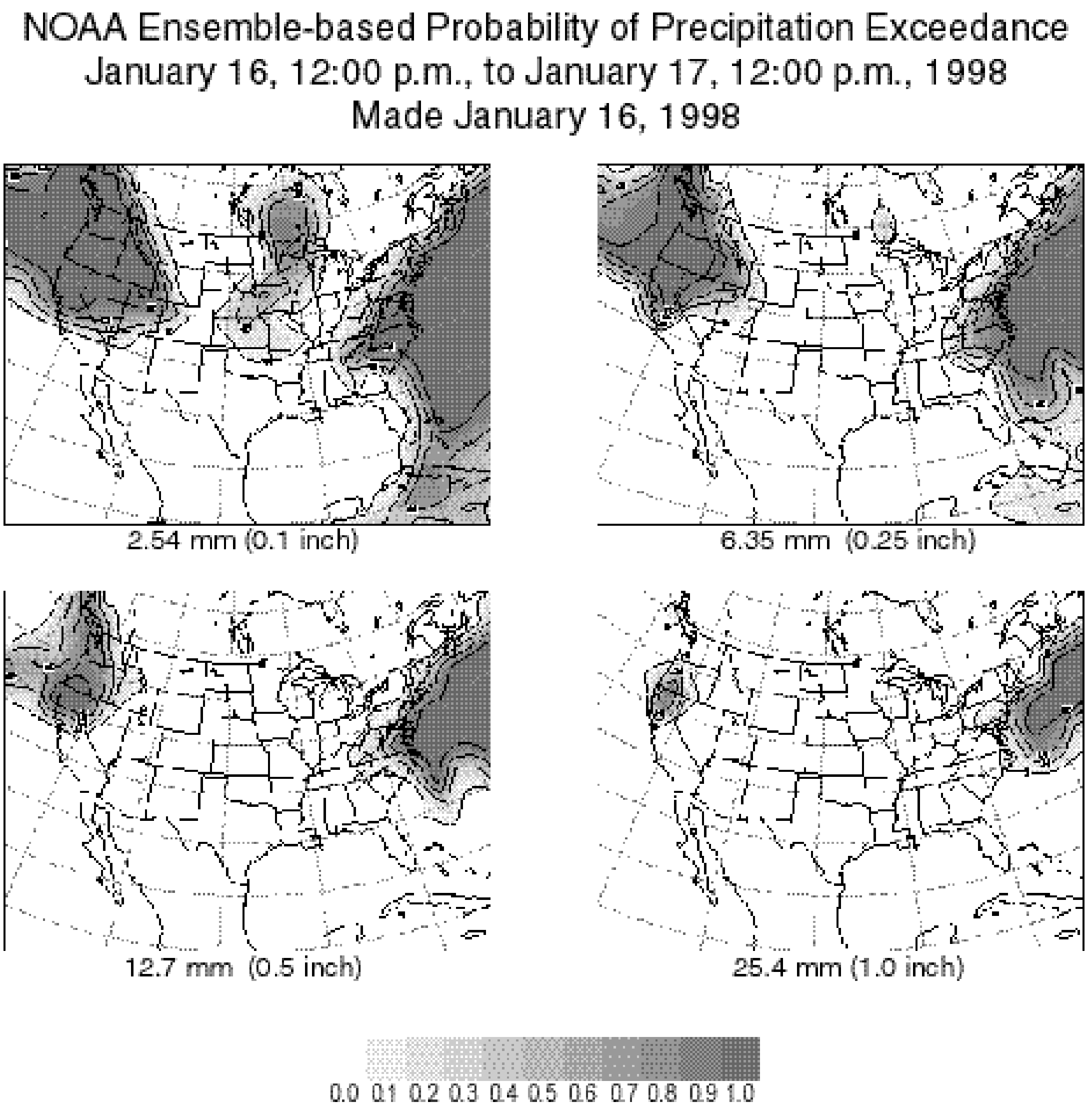

Figure 8. NOAA 24-hour ensemble forecast product for January 16, 1998.

mal probability of precipitation, which is given on the right in Figure 9. These products were downloaded from the HPC Web page Current Products and the CPC Web page on Experimental US Threats Assessment. Example numbers are taken from these maps for the Lake Superior basin; the normal probability of precipitation there on January 30 is about 50%, and the departure from normal is forecast at about –36%. Therefore the outlook for the Lake Superior basin is

$$\begin{aligned} \hat{P}[Q_{30\text{Jan}99} > 0] &= 0.50 - 0.36 = 0.14 \\ \hat{P}[Q_{30\text{Jan}99} = 0] &= 1 - \hat{P}[Q_{30\text{Jan}99} > 0] = 0.86 \end{aligned} \tag{9}$$

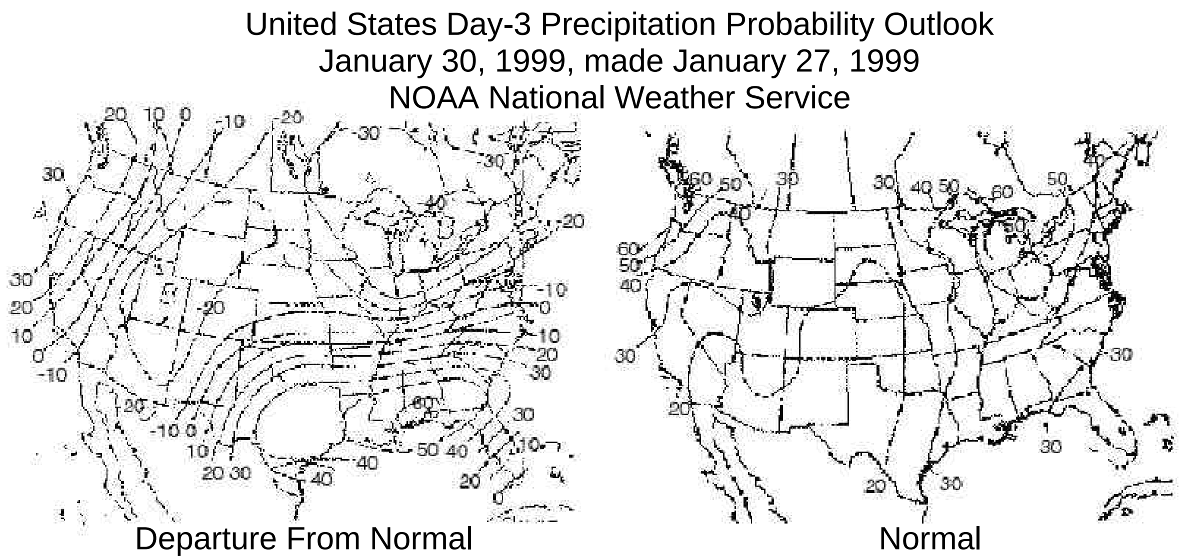

Figure 9. NOAA day-3 precipitation probability outlook for January 30, 1999.

El Niño- and La Niña-Based Event Probability Outlooks

Consider the following as simply a further example of potentially useful realistic event probability outlooks. The two phases of the El Niño–Southern Oscillation (ENSO) are the El Niño and La Niña events and refer to the oceanic and atmospheric circulation in and over the equatorial Pacific. It is recognized that weather in many parts of the world is related to the occurrence of El Niño and La Niña. In fact, it is one of the prime factors used in NOAA's *Climate Outlook* discussed previously. The study of historical El Niño and La Niña events can yield event probabilities useful in hydrology or other derivative outlooks. A simple technique may be applied to derive probabilistic meteorology outlooks that consider the influence of El Niño or La Niña. That is, probabilities of various meteorology events can be estimated from the historical meteorology record *conditioned* on the occurrence of El Niño or La Niña or the absence of both. Then, given that one of these three events is occurring at the time of a forecast, the appropriate set of conditional probabilities can be used as a probabilistic meteorology outlook.

Strong to moderate ENSO years are defined as those in which the 5-month running Southern Oscillation Index (mean difference in sea-level pressure between Tahiti and Darwin) remained in the lower 25% (El Niño) or upper 25% (La Niña) of the distribution for 5 months or longer. This definition is consistent with that used by Rasmusson (1984), Ropelewski and Jones (1987), and Halpert and Ropelewski (1992). Table 2 contains the years of onset of strong or moderate El Niño and La Niña events, as given originally by Shabbar and Khandekar (1996) and corrected and extended by Shabbar et al. (1997).

By inspecting the historical meteorology record of an application area for those years of El Niño or La Niña in Table 2, one can estimate the probability of any event with its relative frequency during those years. For example, in the Great Lakes, there is much interest in the effects of ENSO on winter precipitation and air temperatures. Table 3 presents the relative frequencies of precipitation over the Lake Superior basin in selected 3-month periods falling within lower and upper thirds of the historical range (observed in 1961–90) for all El Niño years. Table 4 does the same for air temperatures. *Given* that an El Niño is occurring, the numbers in Tables 3 and 4 can be interpreted as forecast probabilities *conditioned* on El Niño occurrence and used in making a derivative forecast. For example, in September 1997 it was recognized that a very strong El Niño was occurring. A forecast then for Lake Superior would have been, from Tables 3 and 4,

$$\begin{aligned} \hat{P}\left[Q_{\text{DJF97}} \leq \hat{q}_{\text{DJF, 0.333}}\right] &= 0.875 \\ \hat{P}\left[Q_{\text{DJF97}} > \hat{q}_{\text{DJF, 0.667}}\right] &= 0.042 \\ \hat{P}\left[T_{\text{DJF97}} \leq \hat{t}_{\text{DJF, 0.333}}\right] &= 0.167 \\ \hat{P}\left[T_{\text{DJF97}} > \hat{t}_{\text{DJF, 0.667}}\right] &= 0.542 \end{aligned} \tag{10}$$

Table 2. El Niño and La Niña event onset years[a].

Year (1)	Event (2)	Year (3)	Event (4)	Year (5)	Event (6)	Year (7)	Event (8)
1900		1924	La Niña	1948		1972	El Niño
1901		1925	El Niño	1949		1973	La Niña
1902	El Niño	1926	El Niño	1950	La Niña	1974	
1903		1927		1951	El Niño	1975	La Niña
1904	La Niña	1928	La Niña	1952		1976	El Niño
1905	El Niño	1929	El Niño	1953	El Niño	1977	
1906		1930	El Niño	1954		1978	
1907		1931		1955	La Niña	1979	
1908		1932		1956	La Niña	1980	
1909	La Niña	1933		1957	El Niño	1981	
1910	La Niña	1934		1958	El Niño	1982	El Niño
1911	El Niño	1935		1959		1983	
1912	El Niño	1936		1960		1984	
1913		1937		1961		1985	
1914	El Niño	1938	La Niña	1962		1986	El Niño
1915		1939	El Niño	1963		1987	
1916	La Niña	1940		1964	La Niña	1988	La Niña
1917	La Niña	1941	El Niño	1965	El Niño	1989	
1918	El Niño	1942		1966		1990	
1919	El Niño	1943		1967		1991	El Niño
1920		1944		1968		1992	
1921		1945		1969	El Niño	1993	
1922		1946		1970	La Niña	1994	
1923		1947		1971	La Niña		

[a]After Shabbar and Khandekar (1996) and Shabbar et al. (1997).

Table 3. Probability of Lake Superior basin precipitation within historical range[a] given El Niño occurrence.

Range[a] (1)	SON (2)	OND (3)	NDJ (4)	DJF (5)	JFM (6)	FMA (7)	MAM (8)
Lower	0.417	0.583	0.667	0.875	0.667	0.625	0.375
Upper	0.292	0.167	0.042	0.042	0.125	0.167	0.333

[a]Historical ranges are defined as the lowermost third and the uppermost third observed during the 1961–90 period.

Table 4. Probability of Lake Superior basin air temperature within historical range[a] given El Niño occurrence.

Range[a] (1)	SON (2)	OND (3)	NDJ (4)	DJF (5)	JFM (6)	FMA (7)	MAM (8)
Lower	0.458	0.375	0.333	0.167	0.208	0.167	0.375
Upper	0.208	0.375	0.500	0.542	0.542	0.417	0.375

[a]Historical ranges are defined as the lowermost third and the uppermost third observed during the 1961–90 period.

A warm winter is typical in the Great Lakes area for an El Niño year, and a dry winter is typical in the upper Great Lakes (Superior, Michigan, Huron, and Georgian Bay) for an El Niño year.

Likewise, Tables 5 and 6 present Lake Superior basin relative frequencies for La Niña years. Table 5 reveals patterns in La Niña winter precipitation (DJF, JFM, and FMA) less consistent than air temperature in Table 6. It is also less consistent than either El Niño precipitation or air temperature in Table 3 or 4, respectively. Therefore, there is little confidence in its use for forecasts. However, winter temperature trends in Table 6 are more significant. *Given* that a La Niña year is occurring, the numbers in Tables 5 and 6 can be interpreted as forecast probabilities *conditioned* on La Niña occurrence in the same manner just described for El Niño. For example, in September 1998, it was recognized that a La Niña was occurring; a forecast made then over successively overlapping 3-month periods would have been, from Table 6,

$$
\begin{aligned}
\hat{P}\left[T_{\mathrm{OND98}} \le \hat{t}_{\mathrm{OND},\,0.333}\right] &= 0.412 \\
\hat{P}\left[T_{\mathrm{OND98}} > \hat{t}_{\mathrm{OND},\,0.667}\right] &= 0.235 \\
\hat{P}\left[T_{\mathrm{NDJ98}} \le \hat{t}_{\mathrm{NDJ},\,0.333}\right] &= 0.588 \\
\hat{P}\left[T_{\mathrm{NDJ98}} > \hat{t}_{\mathrm{NDJ},\,0.667}\right] &= 0.176 \\
\hat{P}\left[T_{\mathrm{DJF98}} \le \hat{t}_{\mathrm{DJF},\,0.333}\right] &= 0.529 \\
\hat{P}\left[T_{\mathrm{DJF98}} > \hat{t}_{\mathrm{DJF},\,0.667}\right] &= 0.235 \\
\hat{P}\left[T_{\mathrm{JFM99}} \le \hat{t}_{\mathrm{JFM},\,0.333}\right] &= 0.529 \\
\hat{P}\left[T_{\mathrm{JFM99}} > \hat{t}_{\mathrm{JFM},\,0.667}\right] &= 0.176
\end{aligned}
\qquad (11)
$$

A cool winter is typical in the upper Great Lakes area for a La Niña year.

Table 5. Probability of Lake Superior basin precipitation within historical range[a] given La Niña occurrence.

Range[a] (1)	SON (2)	OND (3)	NDJ (4)	DJF (5)	JFM (6)	FMA (7)	MAM (8)
Lower	0.353	0.471	0.353	0.412	0.412	0.412	0.412
Upper	0.235	0.353	0.294	0.353	0.412	0.235	0.176

[a]Historical ranges are defined as the lowermost third and the uppermost third observed during the 1961–90 period.

Table 6. Probability of Lake Superior basin air temperature within historical range[a] given La Niña occurrence.

Range[a] (1)	SON (2)	OND (3)	NDJ (4)	DJF (5)	JFM (6)	FMA (7)	MAM (8)
Lower	0.118	0.412	0.588	0.529	0.529	0.412	0.529
Upper	0.294	0.235	0.176	0.235	0.176	0.176	0.118

[a]Historical ranges are defined as the lowermost third and the uppermost third observed during the 1961–90 period.

Old NOAA 6–10 Day Most-Probable Event Outlooks

There are several most probable event outlook types of interest here. Recall that a most probable event outlook can be interpreted to indicate that a forecast event has an associated higher than normal probability. Usually, the specification of a single interval (or event) as the most probable presumes that the actual probability density function will be unimodal; i.e., it will have only one peak. Also, most-probable event outlooks are usually interpreted to indicate that all intervals, defined by the issuing agency, other than the indicated most probable, have a smaller than normal probability associated with them.

NOAA's Climate Prediction Center also produced a 6–10 day outlook, covering the 5-day period beginning 6 days in the future. Figure 10 illustrates NOAA's 6–10 day outlook for September

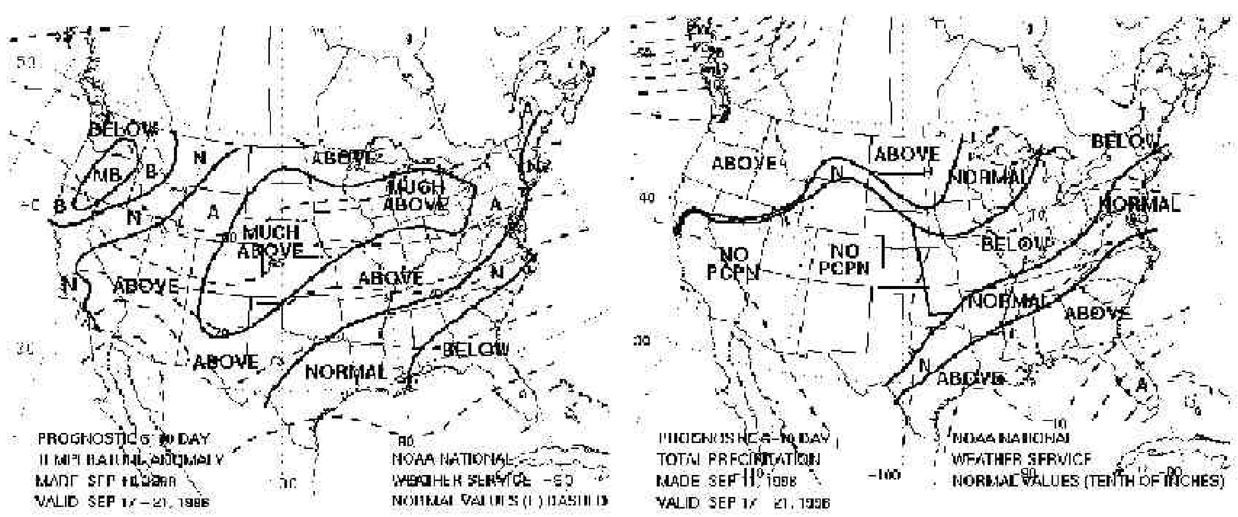

Figure 10. NOAA 6–10 day probabilistic outlook for September 17-21, 1998.

17–21, 1998, made September 11, 1998. It was issued every few days for both temperature and precipitation events. It predicts which of five intervals of 5-day average air temperature were expected: less than the 10% quantile (much below normal), between the 10% and 30% quantiles (below normal), between the 30% and 70% quantiles (normal), between the 70% and 90% quantiles (above normal), or greater than the 90% quantile (much above normal). The quantiles were defined from observations from 1961 to 1990 (J. D. Hoopingarner, personal communication, 1996). It also predicted which of three intervals (below normal, normal, or above normal) of total precipitation are expected (respectively, the lower, middle, or upper thirds of observations from 1961 to1990) or specifies that no precipitation is expected. This outlook results in up to eight inequalities. For example, the Lake Superior basin outlook is for above-normal air temperatures and normal precipitation, and can be interpreted in terms of probability statements as

$$\begin{aligned}
\hat{P}\left[T_{17-21\text{Sep}98} \le \hat{t}_{17-21\text{Sep},\,0.100}\right] &\le 0.100 \\
\hat{P}\left[\hat{t}_{17-21\text{Sep},\,0.100} < T_{17-21\text{Sep}98} \le \hat{t}_{17-21\text{Sep},\,0.300}\right] &\le 0.200 \\
\hat{P}\left[\hat{t}_{17-21\text{Sep},\,0.300} < T_{17-21\text{Sep}98} \le \hat{t}_{17-21\text{Sep},\,0.700}\right] &\le 0.400 \\
\hat{P}\left[\hat{t}_{17-21\text{Sep},\,0.700} < T_{17-21\text{Sep}98} \le \hat{t}_{17-21\text{Sep},\,0.900}\right] &> 0.200 \\
\hat{P}\left[T_{17-21\text{Sep}98} > \hat{t}_{17-21\text{Sep},\,0.900}\right] &\le 0.100 \qquad (12)
\end{aligned}$$

$$\begin{aligned}
\hat{P}\left[Q_{17-21\text{Sep}98} \le \hat{q}_{17-21\text{Sep},\,0.333}\right] &\le 0.333 \\
\hat{P}\left[\hat{q}_{17-21\text{Sep},\,0.333} < Q_{17-21\text{Sep}98} \le \hat{q}_{17-21\text{Sep},\,0.667}\right] &> 0.334 \\
\hat{P}\left[Q_{17-21\text{Sep}98} > \hat{q}_{17-21\text{Sep},\,0.667}\right] &\le 0.333
\end{aligned}$$

On the other hand, the outlook for the northernmost tip of Texas is for much above normal air temperatures and no precipitation, and can be interpreted in terms of probability statements as

$$\begin{aligned}
\hat{P}\left[T_{17-21\text{Sep}98} \le \hat{t}_{17\text{-}21\text{Sep},\,0.100}\right] &\le 0.100 \\
\hat{P}\left[\hat{t}_{17-21\text{Sep},\,0.100} < T_{17-21\text{Sep}98} \le \hat{t}_{17-21\text{Sep},\,0.300}\right] &\le 0.200 \\
\hat{P}\left[\hat{t}_{17-21\text{Sep},\,0.300} < T_{17-21\text{Sep}98} \le \hat{t}_{17\text{-}21\text{Sep},\,0.700}\right] &\le 0.400 \\
\hat{P}\left[\hat{t}_{17-21\text{Sep},\,0.700} < T_{17-21\text{Sep}98} \le \hat{t}_{17-21\text{Sep},\,0.900}\right] &\le 0.200 \qquad (13) \\
\hat{P}\left[T_{17-21\text{Sep}98} > \hat{t}_{17-21\text{Sep},\,0.900}\right] &> 0.100
\end{aligned}$$

$$\hat{P}\left[Q_{17-21\text{Sep}98} = 0\right] = 1.000$$

Environment Canada (EC) Monthly Most Probable Event Outlook

The Environment Canada (EC) Canadian Meteorology Centre (CMC) has been issuing a monthly climate outlook since June 1995, consisting of a most probable air temperature event.

This 1-month outlook is issued twice a month, near the 1st and 15th. It predicts which of three intervals (lower, middle, or upper thirds of observations from 1963 to 1993, respectively below normal, near normal, or above normal) of monthly average air temperature are expected over the Canadian part of North America.

The predictions are obtained directly from numerical model output, using the CMC's operational Global Spectral Model (Ritchie 1991; Ritchie et al. 1995). The CMC uses simple linear regressions between geopotential thickness (height difference between the 1000 hPa and 500 hPa pressure surfaces), produced by the model, and surface temperature anomalies for each season over the period 1963 to 1993. The CMC uses an ensemble approach to generate probability estimates from the regressions applied to their model, started from their atmospheric analyses taken from satellite and field observations. They also provide maps to help the user define the appropriate temperature values (quantile estimates) to use for definition of the lower, middle, and upper intervals. Figure 11 illustrates Environment Canada's monthly outlook for September 1998, made August 31, 1998. This outlook results in three inequalities. For example, the outlook on the Lake Superior basin is for below normal air temperatures, and is interpreted in terms of probability statements here as

$$\begin{aligned} \hat{P}\left[T_{\text{Sep98}} \le \hat{t}_{\text{Sep, 0.333}}\right] &> 0.333 \\ \hat{P}\left[\hat{t}_{\text{Sep, 0.333}} < T_{\text{Sep98}} \le \hat{t}_{\text{Sep, 0.667}}\right] &\le 0.334 \\ \hat{P}\left[T_{\text{Sep98}} > \hat{t}_{\text{Sep, 0.667}}\right] &\le 0.333 \end{aligned} \tag{14}$$

(Note again that Lake Superior has been blackened in Figure 11 to highlight its location.)

EC Seasonal Most Probable Event Outlook

The CMC also produces a 3-month seasonal outlook each quarter (in December, March, June, and September) of the most probable average 3-month air temperature and total precipitation. As with the CMC's monthly outlook, each seasonal outlook predicts which of three intervals of 3-month average air temperature or total precipitation are expected over Canada (lower, middle, or upper thirds of observations from 1963 to 1993 for surface temperature and from 1961 to 1990 for precipitation, respectively below normal, near normal, or above normal).

The technique used to produce the seasonal forecast is similar to the one used to produce the monthly forecast. The main difference is that the seasonal forecast is

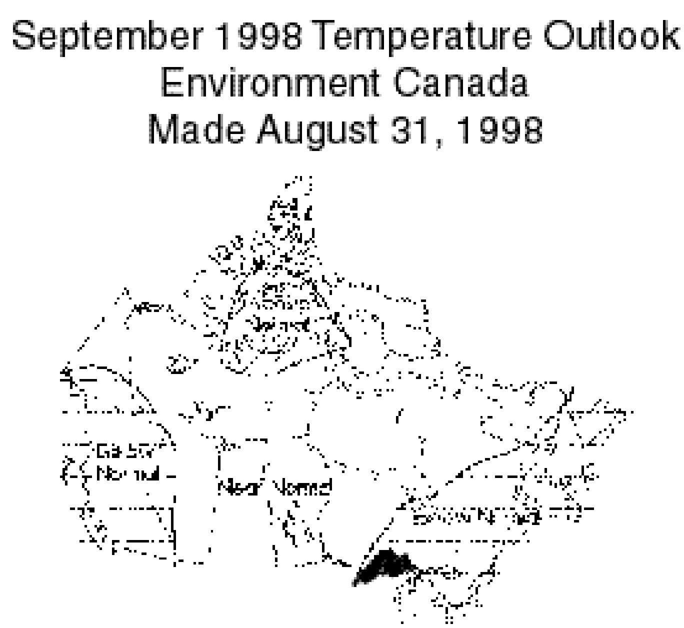

Figure 11. Environment Canada monthly probabilistic outlook for September 1998.

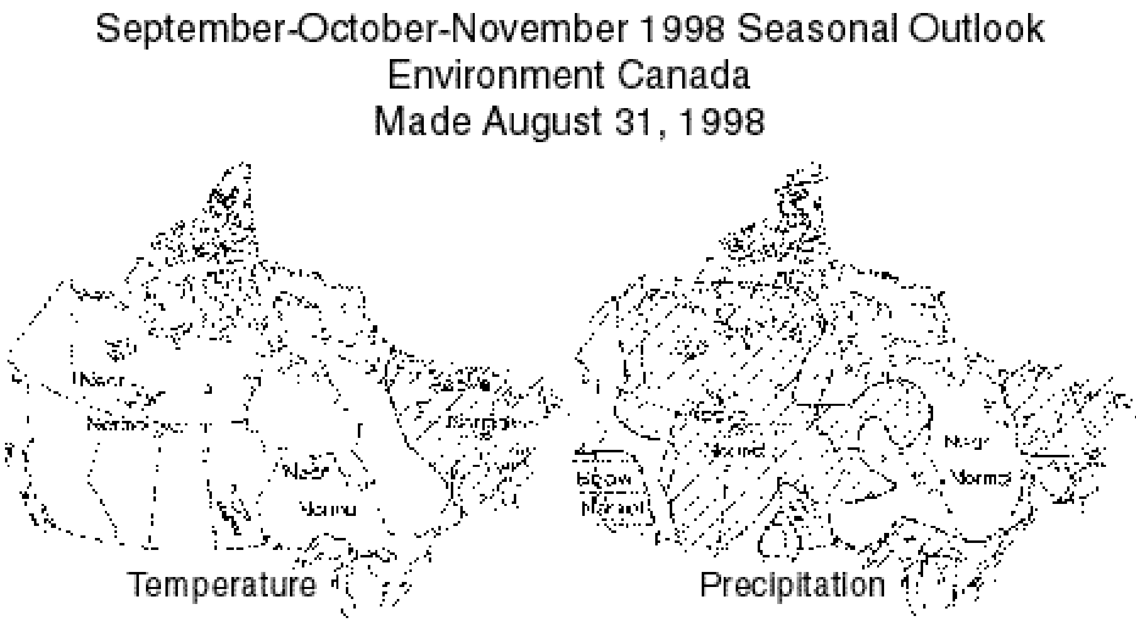

Figure 12. Environment Canada seasonal fall 1998 probabilistic outlook.

derived from an ensemble of 12 model runs, with 6 from the CMC global spectral model and 6 from a general circulation model (GCM) of the atmosphere. Both use the same CMC atmospheric analyses but differ in the way they use the analyzed surface fields. For the global spectral model, no interactive ocean is used, and so the sea surface temperatures and snow cover anomalies observed just prior to the beginning of the forecast are fixed throughout the forecast period and added to the evolving climatology. The ice cover anomalies are relaxed to climatology at the end of the first month of the forecast period. For the GCM, snow cover is a prognostic variable and no special treatment is required, but sea surface temperature and ice cover anomalies are handled as before.

Figure 12 illustrates Environment Canada's seasonal fall outlook for September-October-November 1998, made August 31, 1998. This outlook can result in six inequalities. For example, the outlook on the Lake Superior basin is for normal air temperatures and above normal precipitation, and can be interpreted in terms of probability statements as

$$
\begin{aligned}
\hat{P}\left[T_{\mathrm{SON98}} \le \hat{t}_{\mathrm{SON},\,0.333}\right] &\le 0.333 \\
\hat{P}\left[\hat{t}_{\mathrm{SON},\,0.333} < T_{\mathrm{SON98}} \le \hat{t}_{\mathrm{SON},\,0.667}\right] &> 0.334 \\
\hat{P}\left[T_{\mathrm{SON98}} > \hat{t}_{\mathrm{SON},\,0.667}\right] &\le 0.333 \\
\\
\hat{P}\left[Q_{\mathrm{SON98}} \le \hat{q}_{\mathrm{SON},\,0.333}\right] &\le 0.333 \\
\hat{P}\left[\hat{q}_{\mathrm{SON},\,0.333} < Q_{\mathrm{SON98}} \le \hat{q}_{\mathrm{SON},\,0.667}\right] &\le 0.334 \\
\hat{P}\left[Q_{\mathrm{SON98}} > \hat{q}_{\mathrm{SON},\,0.667}\right] &> 0.333
\end{aligned}
\qquad (15)
$$

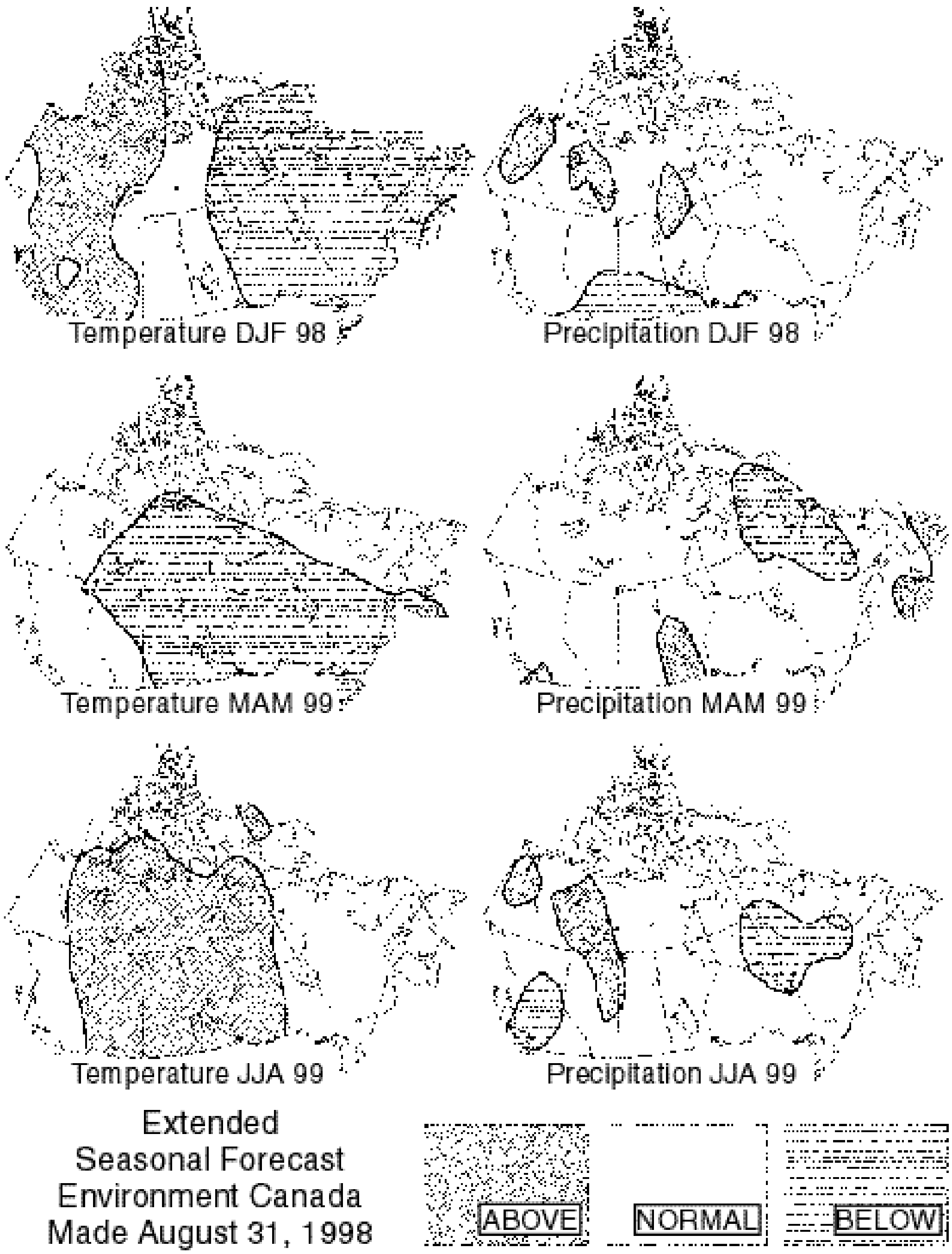

Figure 13. Environment Canada extended seasonal probabilistic outlooks.

EC Extended Seasonal Most-Probable Event Outlooks

The CMC also produces extended 3-month seasonal outlooks each quarter (in December, March, June, and September) of the most-probable average 3-month air temperature and total precipitation lagged 3 months, 6 months, and 9 months. As with the CMC's regular seasonal outlook, each predicts which of three intervals of 3-month average air temperature or total precipitation are expected over Canada in successive seasons (lower, middle, or upper thirds of observations from 1963 to 1993 for surface temperature and from 1961 to 1990 for precipitation, respectively below normal, near normal, or above normal). Figure 13 illustrates Environment Canada's extended seasonal outlooks for DJF 98, MAM 99, and JJA 99, all made August 31, 1998. These outlooks can result in 18 inequalities. For example, on the Lake Superior basin, the DJF 98 and MAM 99 outlooks are for below normal air temperature and normal precipitation; the JJA 99 outlook is for normal air temperature and precipitation. These outlooks can be interpreted in terms of probability statements as shown in Figure 14.

Lake Superior Basin Most-Probable Event Estimates
DJF 1998 through JJA 1999
Air Temperature & Precipitation
Forecast August 31, 1998 by Environment Canada

$$\hat{P}\left[T_{\text{DJF98}} \le \hat{t}_{\text{DJF, 0.333}}\right] > 0.333$$
$$\hat{P}\left[\hat{t}_{\text{DJF, 0.333}} < T_{\text{DJF98}} \le \hat{t}_{\text{DJF, 0.667}}\right] \le 0.334$$
$$\hat{P}\left[T_{\text{DJF98}} > \hat{t}_{\text{DJF, 0.667}}\right] \le 0.333$$
$$\hat{P}\left[Q_{\text{DJF98}} \le \hat{q}_{\text{DJF, 0.333}}\right] \le 0.333$$
$$\hat{P}\left[\hat{q}_{\text{DJF, 0.333}} < Q_{\text{DJF98}} \le \hat{q}_{\text{DJF, 0.667}}\right] > 0.334$$
$$\hat{P}\left[Q_{\text{DJF98}} > \hat{q}_{\text{DJF, 0.667}}\right] \le 0.333$$
$$\hat{P}\left[T_{\text{MAM99}} \le \hat{t}_{\text{MAM, 0.333}}\right] > 0.333$$
$$\hat{P}\left[\hat{t}_{\text{MAM, 0.333}} < T_{\text{MAM99}} \le \hat{t}_{\text{MAM, 0.667}}\right] \le 0.334$$
$$\hat{P}\left[T_{\text{MAM99}} > \hat{t}_{\text{MAM, 0.667}}\right] \le 0.333$$
$$\hat{P}\left[Q_{\text{MAM99}} \le \hat{q}_{\text{MAM, 0.333}}\right] \le 0.333$$
$$\hat{P}\left[\hat{q}_{\text{MAM, 0.333}} < Q_{\text{MAM99}} \le \hat{q}_{\text{MAM, 0.667}}\right] > 0.334$$
$$\hat{P}\left[Q_{\text{MAM99}} > \hat{q}_{\text{MAM, 0.667}}\right] \le 0.333$$
$$\hat{P}\left[T_{\text{JJA99}} \le \hat{t}_{\text{JJA, 0.333}}\right] \le 0.333$$
$$\hat{P}\left[\hat{t}_{\text{JJA, 0.333}} < T_{\text{JJA99}} \le \hat{t}_{\text{JJA, 0.667}}\right] > 0.334$$
$$\hat{P}\left[T_{\text{JJA99}} > \hat{t}_{\text{JJA, 0.667}}\right] \le 0.333$$
$$\hat{P}\left[Q_{\text{JJA99}} \le \hat{q}_{\text{JJA, 0.333}}\right] \le 0.333$$
$$\hat{P}\left[\hat{q}_{\text{JJA, 0.333}} < Q_{\text{JJA99}} \le \hat{q}_{\text{JJA, 0.667}}\right] > 0.334$$
$$\hat{P}\left[Q_{\text{JJA99}} > \hat{q}_{\text{JJA, 0.667}}\right] \le 0.333$$

Figure 14. Most-probable event estimate equations for extended seasonal Lake Superior basin climate outlook.

Other Most-Probable Event Outlooks

All of the outlooks, presented in this chapter, differ in several important respects. They are defined over different time periods (1 day, 5 days, 7 days, 1 month, 3 months). They are defined at different lag times (0, 1, 2, 3, 4, 5, 6, 7, and 8 days and ½, 1½, 2½, 3, 3½, 4½, 5½, 6, 6½, 7½, 8½, 9, 9½, 10½, 11½, and 12½ months from when they are issued; real lags depend on when they are actually used). And they specify either a probability of falling within an interval (event probability) or simply the most probable interval (most probable event). In the examples presented here (excluding the example El Niño and La Niña outlooks), it is possible on any given day to have as many as 145 equations representing probabilistic meteorology outlooks. More are on the way. Probabilistic meteorology outlooks exist for Africa and Great Britain. Besides those outlooks presented in this book, numerous outlooks provided by other agencies are available now or have been available recently but may be discontinued now. Certainly the available outlooks will constantly be changing with time. However, the examples listed in this section should provide guidance in interpreting other outlooks yet to come.

LAKE-LEVEL FORECAST COMPARISONS

The objective in evaluating and comparing Great Lakes extended water level forecasts is to quickly determine the value of considering antecedent conditions and (separately) the value of considering meteorological outlooks in making hydrological outlooks. Also considered is the suitability of GLERL's AHPS forecasts in making probabilistic outlooks of Great Lakes water levels relative to other existing methods.

Data Availability and Study design

1995—1997 Evaluation. GLERL began in September 1997 to evaluate their Great Lakes AHPS; the data at hand included an earlier 1982-1988 comparison of net basin supply (NBS) forecasts (Croley, 1993b; Croley and Lee, 1993). (Net basin supply consists of overlake precipitation and basin runoff less lake evaporation.) Environment Canada provided beginning-of-month lake levels of record, diversions of record, lake outflows of record, and "residual" NBS (computed as the monthly residual in a water balance on each Great Lake for 1900-1997). The Detroit Corps provided actual monthly and quarter-monthly average lake levels and the US, Canadian, and coordinated lake level forecasts for January 1990-August 1997. The latter forecasts represented lake levels in terms of the International Great Lakes Datum of 1955 (IGLD'55) through 1991 and in terms of the IGLD'85 subsequently. Furthermore, lake levels were given as end-of-month values through 1992 and as monthly averages subsequently. Prior to 1994, all forecasts were deterministic only. GLERL provided "component" NBS (computed as the monthly algebraic sum of overlake precipitation, estimated lake evaporation, and basin runoff to each lake for 1954-1997) and all of the NOAA and other agency meteorological outlooks for 1995-August 1997. GLERL also reduced all meteorological data to daily spatial averages over each of the 121 watersheds and seven water surfaces of the Great Lakes; for 1948-1995, data consist of final quality-controlled values (as reported by the collecting agencies) and for 1996-August 1997, data consist of provisional (as received in near-real time, unchecked for quality).

GLERL simulated probabilistic lake level outlooks for 1995-August 1997 with four "operational hydrology" methods. Firstly, GLERL assembled all six-month residual NBS time series from the historical record (1900-1997) that started the same month as each month of the period 1995-August 1997 into a sample for that month, from which to estimate a six-month forecast beginning that month. Only the period of record preceding each month of 1995-August 1997 was used to assemble the sample for that month, simulating operation in real time. For example, for the first month of the period, January 1995, GLERL used all six-month NBS time series beginning in January, prior to 1995, to build a sample; for the thirtieth month of the period, June 1997, GLERL used all six-month NBS time series beginning in June, prior to 1997, to build a sample. GLERL then converted each sample of six-month NBS time series into a sample of six-month lake level scenarios with appropriate routing and regulation models; they used the resulting samples to infer a six-month probabilistic outlook of lake levels beginning each month of the period with the Weibull estimator.

Secondly, they repeated this methodology with component NBS from the historical record (1954-1997) to again derive six-month lake level outlooks for each month of the period. Both of these operational hydrology methods represent forecasts without consideration of antecedent conditions and meteorological outlooks. Note the period used to assemble a sample for a monthly forecast differs between the residual- and the component-NBS-based forecasts (1900-

1997 versus 1954-1997). Thus, differences in the forecasts result not only from the type of net supply computations (residual versus component) but also from climatic or hydrologic differences between the two periods. Component NBS generally has lower monthly standard deviations than residual NBS on all lakes (as much as 30% lower on Superior and Michigan-Huron and within 5% on St. Clair and Erie). On Superior and Michigan-Huron, component NBS monthly means are lower than residual in winter-spring and higher in summer-fall (all within about 10% of each other except on Michigan-Huron in the late summer to early fall, when it is as much as about 20% different). On St. Clair and Erie, component NBS is more similar to residual (within about 5%). In general, seasonal residual NBS over the periods 1900-1953 and 1954-2000 are similar and differences with seasonal component NBS are the most pronounced on Michigan-Huron, particularly in late summer to early fall.

Thirdly, GLERL simulated six-month lake level scenarios (using component NBS) with their AHPS (which uses estimates of antecedent moisture and heat storage conditions with six-month pieces of the historical meteorological record). They did this for each month of the period 1995-August 1997 and assembled the six-month lake level scenarios into a sample for that month from which to estimate a six-month forecast beginning that month. Again, only historical meteorology preceding each forecast was used, simulating data availability in real time. Only provisional data were used, as they would have been available in near real time. Since no weightings were used, this represents forecasts, for each month of the period, that consider antecedent conditions but do not use meteorological outlooks.

Fourthly, GLERL simulated six-month lake level forecasts with their AHPS, using both antecedent conditions and NOAA's 1- and 3-month meteorological outlooks, for each month of the period. GLERL used ten methods for considering these meteorological outlooks in their hydrological outlooks. The first five methods used a mixture of simultaneous meteorological outlooks over seven lake basins, ordered as indicated in Table 7. They used different objective functions, however, to select among competing sets of weights: a) minimization of the sum of squared differences between each weight and unity while using the most meteorological outlooks (Croley, 1996, 1997a,b, 2000a), b) minimization of the sum of squared differences between each weight and unity while forcing all weights non-zero (use all hydrological scenarios), c) maximization of probability of mid-third (normal) values for the first six-month air temperature and precipitation over all basins (Croley, 2000a, 2001a), d) maximization of probability of first six-month air temperature and precipitation in one-third ranges as suggested by extended meteorological outlook over all basins, and e) no objective. The second five methods used meteorological outlooks over each basin individually, ordered as indicated in Table 8, and the same objective functions as above but defined only over each basin. (Of course, for lake level forecasting simultaneously on all lakes, only the simultaneous consideration of meteorological outlooks over all basins, as in the first five methods, is appropriate. However, consideration of meteorological outlooks over each basin independent of the other basins, in the second five methods, was attempted to discern possible improvements in single-lake forecasts of hydrological variables other than simultaneous lake levels on all lakes.) Inspection of results revealed the best method for forecasting lake levels to be one that used a mixture of simultaneous meteorological outlooks over the seven lake basins ordered as in Table 7 and using a minimization of the sum of squared differences between each weight and unity while using all non-zero weights. Actually, as will be revealed shortly, the meteorological outlooks added very little to the hydrological outlooks, and the manner in which the meteorological outlooks were used was not very significant. Thus the best method,

Table 7. Meteorological Outlook Definitions by Priority Order for the "All-Lakes" Outlooks.

Order	Basin[a]	Meteor-ology[b]	Range[c]	Order	Basin[a]	Meteor-ology[b]	Range[c]
1	SUP	1-mo T	Lower Third	29	HUR	3-mo T	Lower Third
2	SUP	1-mo T	Upper Third	30	HUR	3-mo T	Upper Third
3	MIC	1-mo T	Lower Third	31	GEO	3-mo T	Lower Third
4	MIC	1-mo T	Upper Third	32	GEO	3-mo T	Upper Third
5	HUR	1-mo T	Lower Third	33	ERI	3-mo T	Lower Third
6	HUR	1-mo T	Upper Third	34	ERI	3-mo T	Upper Third
7	GEO	1-mo T	Lower Third	35	ONT	3-mo T	Lower Third
8	GEO	1-mo T	Upper Third	36	ONT	3-mo T	Upper Third
9	ERI	1-mo T	Lower Third	37	SUP	3-mo P	Lower Third
10	ERI	1-mo T	Upper Third	38	SUP	3-mo P	Upper Third
11	ONT	1-mo T	Lower Third	39	MIC	3-mo P	Lower Third
12	ONT	1-mo T	Upper Third	40	MIC	3-mo P	Upper Third
13	SUP	1-mo P	Lower Third	41	HUR	3-mo P	Lower Third
14	SUP	1-mo P	Upper Third	42	HUR	3-mo P	Upper Third
15	MIC	1-mo P	Lower Third	43	GEO	3-mo P	Lower Third
16	MIC	1-mo P	Upper Third	44	GEO	3-mo P	Upper Third
17	HUR	1-mo P	Lower Third	45	ERI	3-mo P	Lower Third
18	HUR	1-mo P	Upper Third	46	ERI	3-mo P	Upper Third
19	GEO	1-mo P	Lower Third	47	ONT	3-mo P	Lower Third
20	GEO	1-mo P	Upper Third	48	ONT	3-mo P	Upper Third
21	ERI	1-mo P	Lower Third	49	STC	1-mo T	Lower Third
22	ERI	1-mo P	Upper Third	50	STC	1-mo T	Upper Third
23	ONT	1-mo P	Lower Third	51	STC	1-mo P	Lower Third
24	ONT	1-mo P	Upper Third	52	STC	1-mo P	Upper Third
25	SUP	3-mo T	Lower Third	53	STC	3-mo T	Lower Third
26	SUP	3-mo T	Upper Third	54	STC	3-mo T	Upper Third
27	MIC	3-mo T	Lower Third	55	STC	3-mo P	Upper Third
28	MIC	3-mo T	Upper Third	56	STC	3-mo P	Lower Third

[a]Great Lakes basin: SUP (Lake Superior), MIC (Lake Michigan), HUR (Lake Huron), GEO (Georgian Bay), STC (Lake St. Clair), ERI (Lake Erie), and ONT (Lake Ontario).
[b]Meteorological variable including first month or first three month forecast designation.
cRange of meteorological variable over which probability is forecast.

just identified, is only marginally better than most of the other methods investigated. Only results for it are presented here since they are representative of the other methods.

All four of these operational hydrology methods yielded a set of six-month probabilistic lake level outlooks, which were simplified to yield a set of six-month deterministic outlooks for comparison to actual conditions. The simplifications consisted of taking the mean, the median, the mid-range between the 5% and 95% quantiles, the mid-range between the 20% and 80% quantiles, and the mode (assuming a log-Pearson Type III distribution). There were little differences between uses of the various combinations, but the mean consistently gave the better results. Only results for it are presented here since it is representative of the other combination methods.

Table 8. Meteorological Outlook Definitions by Priority Order for each "Individual Lake" Outlook.

Order	Meteorology[a]	Range[b]	Order	Meteorology[a]	Range[b]
1	1st 1-mo T	Lower Third	29	7th 3-mo T	Lower Third
2	1st 1-mo T	Upper Third	30	7th 3-mo T	Upper Third
3	1st 1-mo P	Lower Third	31	7th 3-mo P	Lower Third
4	1st 1-mo P	Upper Third	32	7th 3-mo P	Upper Third
5	1st 3-mo T	Lower Third	33	8th 3-mo T	Lower Third
6	1st 3-mo T	Upper Third	34	8th 3-mo T	Upper Third
7	1st 3-mo P	Lower Third	35	8th 3-mo P	Lower Third
8	1st 3-mo P	Upper Third	36	8th 3-mo P	Upper Third
9	2nd 3-mo T	Lower Third	37	9th 3-mo T	Lower Third
10	2nd 3-mo T	Upper Third	38	9th 3-mo T	Upper Third
11	2nd 3-mo P	Lower Third	39	9th 3-mo P	Lower Third
12	2nd 3-mo P	Upper Third	40	9th 3-mo P	Upper Third
13	3rd 3-mo T	Lower Third	41	10th 3-mo T	Lower Third
14	3rd 3-mo T	Upper Third	42	10th 3-mo T	Upper Third
15	3rd 3-mo P	Lower Third	43	10th 3-mo P	Lower Third
16	3rd 3-mo P	Upper Third	44	10th 3-mo P	Upper Third
17	4th 3-mo T	Lower Third	45	11th 3-mo T	Lower Third
18	4th 3-mo T	Upper Third	46	11th 3-mo T	Upper Third
19	4th 3-mo P	Lower Third	47	11th 3-mo P	Lower Third
20	4th 3-mo P	Upper Third	48	11th 3-mo P	Upper Third
21	5th 3-mo T	Lower Third	49	12th 3-mo T	Lower Third
22	5th 3-mo T	Upper Third	50	12th 3-mo T	Upper Third
23	5th 3-mo P	Lower Third	51	12th 3-mo P	Lower Third
24	5th 3-mo P	Upper Third	52	12th 3-mo P	Upper Third
25	6th 3-mo T	Lower Third	53	13th 3-mo T	Lower Third
26	6th 3-mo T	Upper Third	54	13th 3-mo T	Upper Third
27	6th 3-mo P	Lower Third	55	13th 3-mo P	Upper Third
28	6th 3-mo P	Upper Third	56	13th 3-mo P	Lower Third

[a]Meteorological variable including period-of-forecast designation.
[b]Range of meteorological variable over which probability is forecast.

GLERL then compared each deterministic forecast with what actually occurred to find the effects of considering residual versus component NBS, considering antecedent moisture and heat storage conditions, and considering meteorological outlooks. GLERL also simulated AHPS lake level forecasts for 1993-1995 to compare with existing US, Canadian, and Coordinated lake level forecasts over this period as well as 1995-August 1997. For the 1993-1995 period, GLERL simulated provisional data with climatic data since actual provisional data were unavailable; hence the data for 1993-1995 were a little better than they would have been in real time.

Subsequent Evaluations. More recently, GLERL updated all data sets and repeated all of these calculations in a second evaluation to take advantage of the additional data available since August 1997 and to extend the observations made in the first evaluation. Environment Canada, the Detroit Corps, and GLERL extended their original data sets through 2000 and GLERL evaluated both the value of antecedent conditions and meteorological outlooks and the relative suitability of their AHPS forecasts for the period 1996-2000. While archived meteorological data were used in the simulated forecasts, all data from 1996 onward was actually provisional data received in near real time, as GLERL made their actual forecasts, amended with later corrections as they were received. Thus, the provisional data set archived at GLERL and used in the 1996-2000 evaluation contains some corrections not available at the time of the actual forecasts. Therefore, simulating forecasts with this data set is not exactly equivalent to forecasting in near real time; however, the evaluated goodness of the forecast can be regarded as the "potential" possible with the present near-real-time data delivery system if no errors (recognized after the fact) occur. Of course, forecasting potential with best available data could be evaluated by using final quality-controlled meteorological data, generally available 6 months to a year after the fact. That is not done here as it has little practical significance and results would not be comparable with other real-time forecasting methods.

Finally, GLERL looked briefly at comparisons in a probabilistic sense between forecast and actual values. There were too little data for evaluating the probabilistic outlooks with much confidence (sampling error was large); grouping all first-month forecasts, regardless of their time-of-year, allowed building of larger samples and some evaluation of forecasts probabilistically. This was repeated for second- through sixth-month forecasts too. Results are presented herein for the first time from the 1993-1995, 1995-August 1997, and 1996-2000 deterministic evaluations and some of the 1995-August 1997 and 1996-2000 probabilistic evaluations.

Deterministic Comparisons

Comparison Statistics. GLERL compared first-month forecast means and actual monthly average levels by using root mean square error (RMSE), bias, and sample correlation, $\hat{\rho}$.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(f_i - a_i\right)^2} \qquad (16)$$

$$Bias = -\frac{1}{n}\sum_{i=1}^{n}\left(f_i - a_i\right) \qquad (17)$$

$$\hat{\rho} = \frac{1}{n}\sum_{i=1}^{n}\left(f_i - \bar{f}\right)\left(a_i - \bar{a}\right) \Bigg/ \left(\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(f_i - \bar{f}\right)^2}\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(a_i - \bar{a}\right)^2}\right) \qquad (18)$$

where f_i = first-month forecast monthly mean value i of n first-month forecasts, a_i = corresponding first-month actual monthly average lake level i, and their respective sample means are:

$$\bar{f} = \frac{1}{n}\sum_{i=1}^{n} f_i \qquad (19)$$

$$\bar{a} = \frac{1}{n}\sum_{i=1}^{n} a_i \qquad (20)$$

Forecasts were also compared to climatology (monthly-means from the historical record), used as a reference forecast. The climatological outlooks serve as benchmarks against which more sophisticated forecast methods can be compared. A skill measure was developed that aids in determining which methods best forecast extreme events. Climatology is also used in this measure to weight differences between forecasts and actual values to emphasize extremes.

$$Skill = \frac{1}{n}\sum_{i=1}^{n}\left|f_i - a_i\right|\frac{\left|a_i - \hat{\mu}_j\right|}{\hat{\sigma}_j} \Bigg/ \frac{1}{n}\sum_{i=1}^{n}\left|\hat{\mu}_j - a_i\right|\frac{\left|a_i - \hat{\mu}_j\right|}{\hat{\sigma}_j} \qquad (21)$$

where j = month of the year (1-12) corresponding to observation i, $\hat{\mu}_j$ = reference historical mean (climatological) forecast value for month j, and $\hat{\sigma}_j$ = reference historical (climatological) standard deviation for month j. GLERL also calculated these statistics for months 2-6.

RMSE and skill are measures of the absolute differences between forecast and actual values; low values of each of these measures indicate better performance. Skill is weighted to reflect the differences at extreme values more than differences near normal values. Bias is a measure of the shift between the distributions of forecast and actual values. Correlation is a measure of how well the timing of variability is captured by the forecast method.

Component Error Evaluation. Comparisons of RMSE in the first row of Figure 15 show that, in the 1995-August 1997 evaluation, there is marginal improvement in considering component NBS over residual NBS when making straightforward operational hydrology forecasts based upon historical values. [This is where a sample of 6-month time series of NBS are taken from the historical record (with the same starting month as the forecast), transformed into lake level time series, and used to estimate the distribution of lake levels each month of the forecast.] This is true for all lakes except Michigan-Huron. The 1996-2000 evaluation in the second row of Figure 15 reverses the comparison; that is, there is marginal improvement in considering residual NBS over component NBS when making a straightforward operational hydrology forecast based upon historical values, although the difference is not pronounced for Lakes St. Clair and Erie. One important note about all results on Lake St. Clair in particular, and on Lake Erie to a lesser extent, is that ice formation drastically effects levels and is not accounted for in any of the forecast methods (neither operational hydrology methods considered here nor other forecast methods considered subsequently). Therefore, Lake St. Clair results, and Lake Erie to a lesser extent, should be viewed with caution when comparing forecast methods there.

There is significant improvement when forecasting NBS directly from current antecedent conditions each month instead of using historical NBS in the straightforward operational hydrology approach. Both evaluation periods for RMSE in the first two rows of Figure 15 reveal this. This is more apparent in the correlation plots in the last two rows of Figure 15. However, there is very little improvement in the forecasts by considering available meteorological outlooks as far as RMSE and correlation are concerned. There is very little difference in forecasting (with antecedent conditions) either with or without meteorological outlooks. In fact, there are times when the use of meteorological outlooks slightly degrades RMSE and correlation.

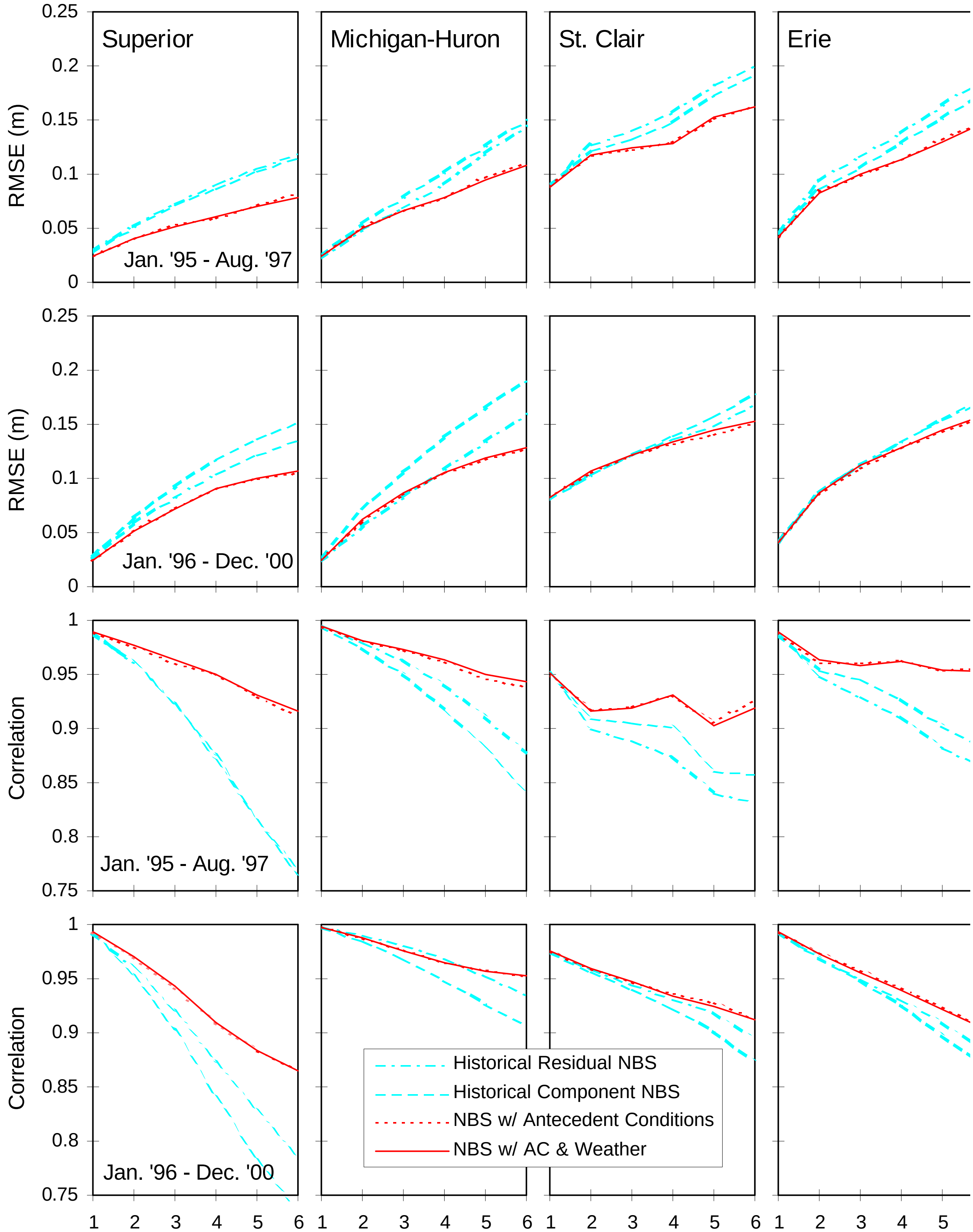

Figure 15. Incremental AHPS Lake Level Forecasts RMSE and Correlation vs. Forecast Month.

However, skill (which measures the ability to forecast non-central levels) does show more improvement (lower values) when meteorological outlooks are used in the forecast, as shown for the 1995-August 1997 evaluation in the first row of Figure 16. The 1996-2000 evaluation does not show this improvement in skill. Figures 15 and 16 demonstrate that the improvements in forecasting resulting from considering antecedent conditions are much greater than those associated with replacing residual with component NBS or with using meteorological outlooks.

In terms of bias, the differences are not large and, on Lakes St. Clair and Erie, considering antecedent conditions actually increases bias; see the last two rows in Figure 16. This suggests a problem in the computation of component NBS from antecedent conditions on these lakes, undoubtedly related both to ice formation and to ignored water balance groundwater terms, as well as more poorly estimated evaporation (particularly on Lake St. Clair). Also, the positive bias in the third row of Figure 16 indicates that forecasts under-predict at all lags on all lakes in the 1995-August 1996 evaluation; since the bias is almost linear with lag for the 1995-August 1997 evaluation, a near-constant bias exists in forecasting NBS for all forecast months. For the 1996-2000 evaluation in the fourth row of Figure 16, bias is much closer to zero on all lakes than in the earlier evaluation, with the same problem as already noted on Lakes St. Clair and Erie.

Alternate Method Evaluation. In light of the small differences between AHPS with meteorological outlooks and without, only results for the latter are shown henceforth. Figure 17 first and second row show AHPS (which uses antecedent conditions, simply referred to henceforth as "AHPS forecast") has about the same (less than 1 cm difference) or smaller RMSE as other forecasts on Lakes Superior and Michigan-Huron for all lags, although it appears slightly better in the earlier evaluation. The US Most-Probable forecast is next best on these lakes. In the earlier evaluation for Lake St. Clair, the two are about the same, and for Lake Erie the US Most-Probable has smaller RMSE. In the later evaluation, AHPS is close to or better than other methods on Lakes St. Clair and Erie and better than other methods on Lakes Superior and Michigan-Huron at higher lags only. The Canadian 50% forecast has the largest RMSE in general and the Coordinated 50% forecast RMSE lies between the Canadian 50% and the US Most-Probable.

For the period 1993-1995 (not shown), the AHPS forecast has about the same or smaller RMSE as the other forecasts on Lakes Superior, Michigan-Huron, and St. Clair. On Lake Erie, it is second best only at two lags, but this time the Canadian 50% forecast is better. The US Most-Probable forecast exhibits greater RMSE on Lakes Michigan-Huron, St. Clair, and Erie. Again the Coordinated 50% forecast RMSE lies between the Canadian 50% and the US Most-Probable. Thus, the AHPS has consistently lower RMSE over different time periods than other forecasts.

The correlation associated with the AHPS forecast, in the 1995-August 1997 evaluation in the third row of Figure 17, is uniformly and significantly higher for all lakes and all lags than the other forecasts. This suggests that the AHPS forecast best captures the timing of variations in lake levels. In the 1996-2000 evaluation in the fourth row of Figure 17, all forecasts are worse on Superior than in the earlier evaluation and the AHPS forecast is now close to the US most-probable at some lags and better at higher lags. On Lake Michigan-Huron and Lake St. Clair, all methods are better in the later evaluation than in the earlier evaluation with the AHPS forecast better than the others at higher lags. On Lake Erie, the AHPS forecast has lower correlation in the later evaluation than in the earlier evaluation and the other methods are better in the later than in the earlier evaluations. However, the AHPS forecast still has the highest correlation in both.

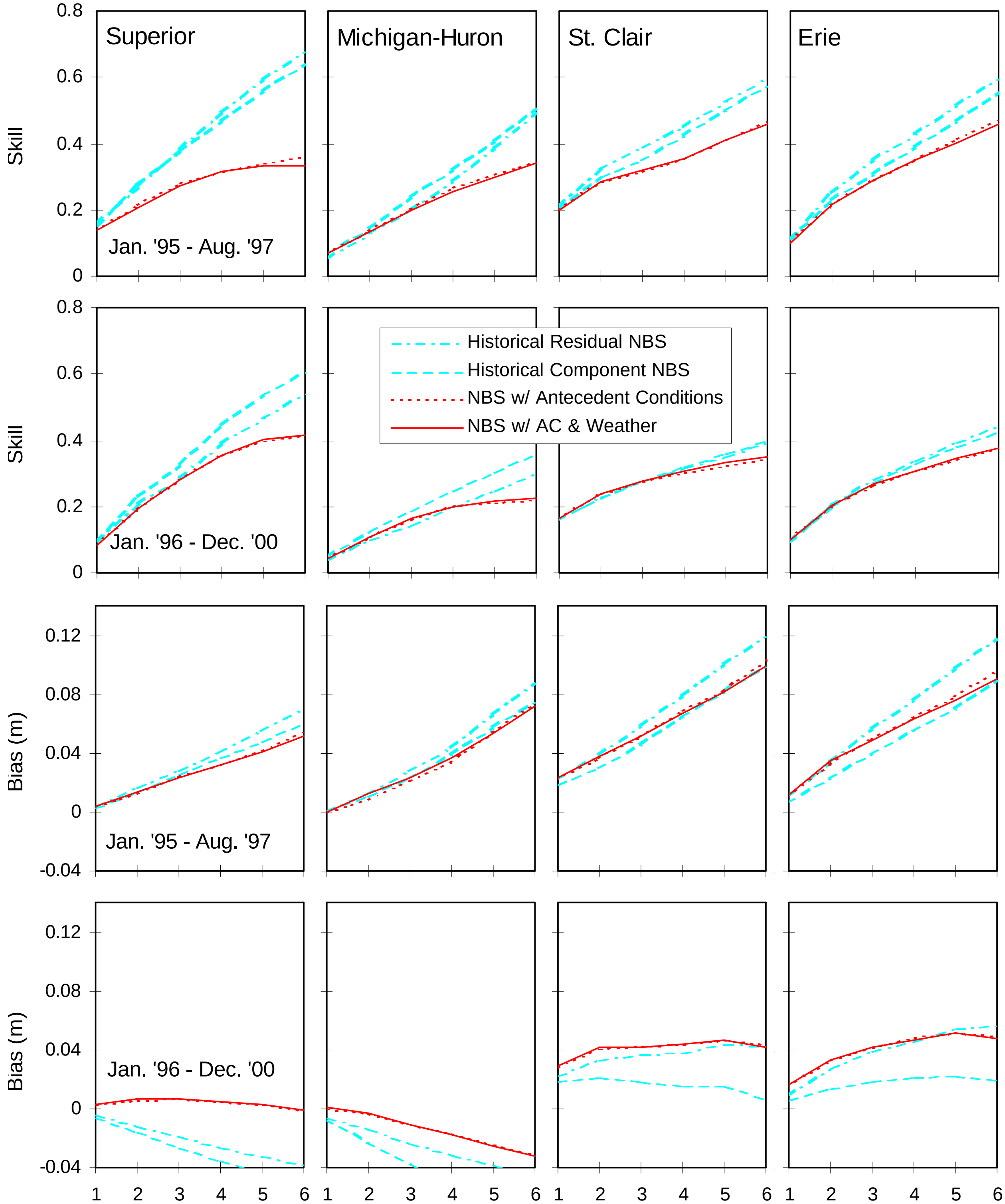

Figure 16. Incremental AHPS Lake Level Forecasts Skill and Bias vs. Forecast Month.

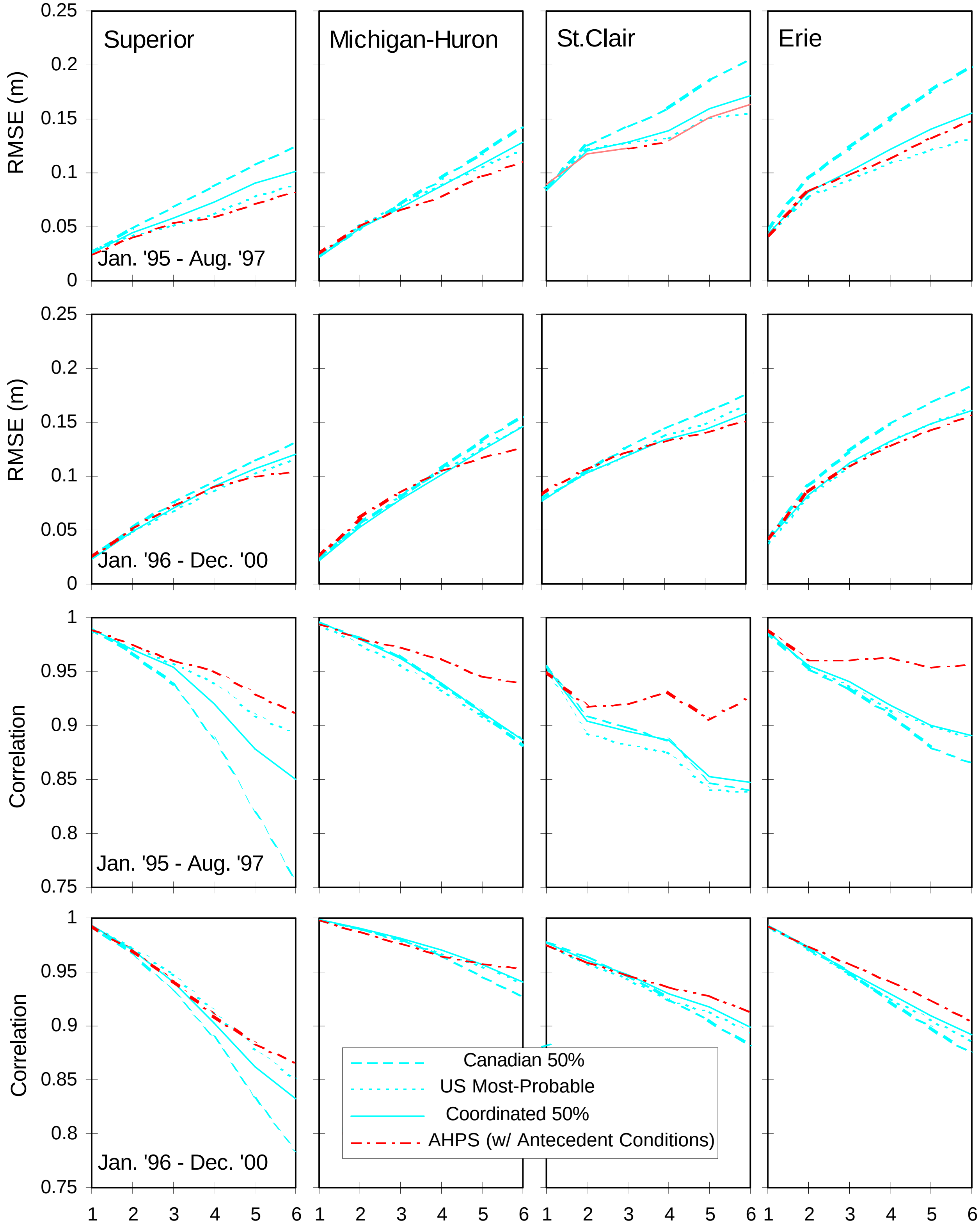

Figure 17. AHPS and Other Lake Level Forecasts RMSE and Correlation vs. Forecast Month.

Skill scores in the first row of Figure 18 for the 1995-August 1997 period are generally the best for either the AHPS forecast or the US Most-Probable forecast. Skill scores are much closer for the 1996-2000 evaluation, in row two of Figure 18, among all methods. However, for the 1993-1995 period (not shown), skill scores are generally the best for either the AHPS forecast or the Canadian 50% forecast. Surprisingly, the Coordinated 50% forecast skill on Lakes St. Clair and Erie does not lie between the US and Canadian skills but was lower still for some lags. So, while the AHPS forecast is not uniformly better during the 1993-1995 period, the 1995-August 1997 period, or the 1996-2000 period, it is more consistent than other forecasts over all periods.

Bias in the third row of Figure 18 for the 1995-August 1997 period is closest to zero for the US Most-Probable forecast and largest for the Canadian 50% forecast. Both the Coordinated 50% and the AHPS forecast biases are between them. For the 1996-2000 period, in row four of Figure 18, bias on Lakes Superior and Michigan-Huron are closest to zero for the AHPS forecast, although improved for all methods over the earlier evaluation. For the 1993-1995 period (not shown), the AHPS forecast bias is also closest to zero on Lakes Superior and Erie. The Canadian 50% dominates on Lake Michigan-Huron and the Coordinated 50% dominates on Lake St. Clair. The US Most-Probable generally has the highest bias. So, while the AHPS forecast is not better on all lakes during all periods, it is more consistent than the other forecasts over the three periods. For any period, where the AHPS forecast bias is not close to zero, the forecast is positively biased (forecasts under predict), except for Michigan-Huron in 1996-2000. For the 1995-August 1997 period, the bias has an almost-linear trend with lag on all lakes, suggesting a near-constant bias exists in forecast AHPS for all forecast months of that period.

Probabilistic comparisons

Although the period of comparison is very short for comparison of probabilistic forecasts (only two or three forecasts for each month of the year in the 1995-August 1997 period and only five forecasts for each month of the year in the 1996-2000 period), GLERL did compare the various forecasts probabilistically. By combining all first-month forecasts, regardless of month of the year, there are 32 values in the 1995-August 1997 period and 60 in the 1996-2000 period. Likewise there are 31 and 59 second-month forecasts respectively, 30 and 58 third-month forecasts respectively, and so on. Shown in Figure 19 on the abscissa are non-exceedance probabilities generated in the forecasts. The forecast lake level associated with each probability was compared to the actual lake level for each forecast; the fraction of actual levels at or below the forecast level are estimated from the sample and plotted on the ordinate for each forecast month. The dashed line represents a perfect probabilistic forecast. Also shown are the Coordinated 5% & 95% non-exceedance levels.

On Superior, the AHPS forecast does better probabilistically than the Coordinated during the 1995-August 1997 evaluation, shown in the first row of Figure 19, for lags 1, 3, 4, 5, and 6 (lags 5 and 6 are not shown in Figure 19). Remember though that this is a small sample for comparison. Note, furthermore, that both methods consistently under-predict levels at longer lags, reflecting the increasing bias already observed (e.g., for the fourth month, the median forecast is not exceeded only about 30% of the time, or exceeded about 70% of the time). On Michigan (not shown), the AHPS forecast does better for the longer lags, 4 through 6. On Lake St. Clair (not shown), the Coordinated 5% and 95% forecasts do better for all lags, but all are horrible! On Lake Erie (not shown), the Coordinated 5% and 95% forecasts do better for all lags except 6.

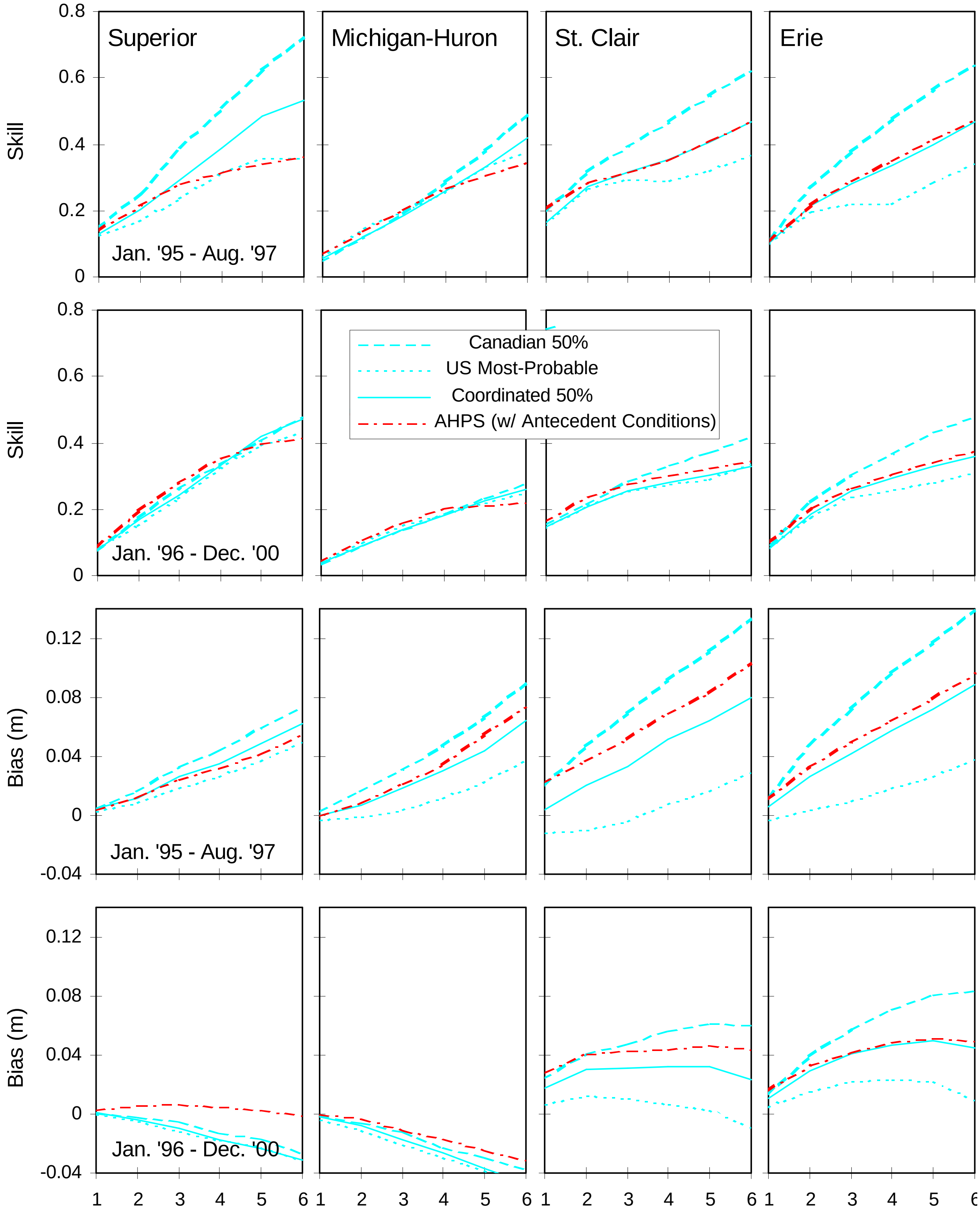

Figure 18. AHPS and National Lake Level Forecasts Skill and Bias vs. Forecast Month.

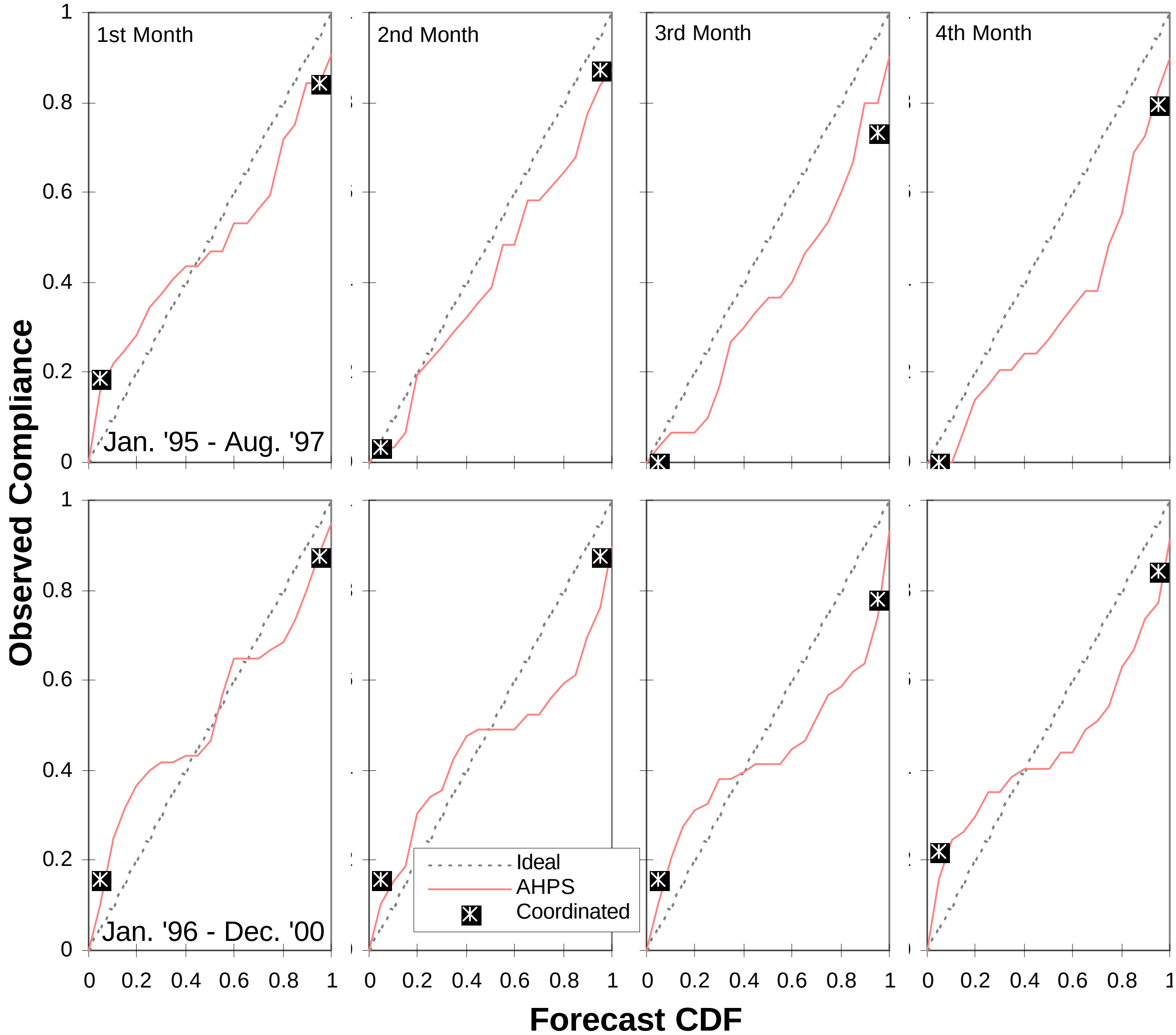

Figure 19. Lake Superior Probabilistic Comparisons.

For the 1996-2000 evaluation, the AHPS forecast looks better than in the earlier evaluation in that it does not consistently under-predict levels at lags greater than one month. Thus, the graphs in the second row of Figure 19 show some parts above and left of the ideal line as well as some parts below and to the right of the ideal line. The earlier evaluation showed this behavior only for the first-month forecast. This is not only true for Lake Superior as shown in Figure 19, but also for Lake Michigan-Huron (not shown). For Lakes St. Clair and Erie, the probabilistic comparisons are quite similar for both evaluation periods. The Coordinated forecast compares better to the AHPS forecast in the 1996-2000 period than it did in the 1995-August 1997 period but still the AHPS forecast comes closer to the ideal line more often. Figure 20 summarizes the first-month forecast probabilistic comparisons for each of the lakes for the 1996-2000 evaluation period. There one can see that under-prediction is more of a problem on Lakes St. Clair and Erie, as suggested by the bias plots in the deterministic comparisons in the fourth row of Figure 18.

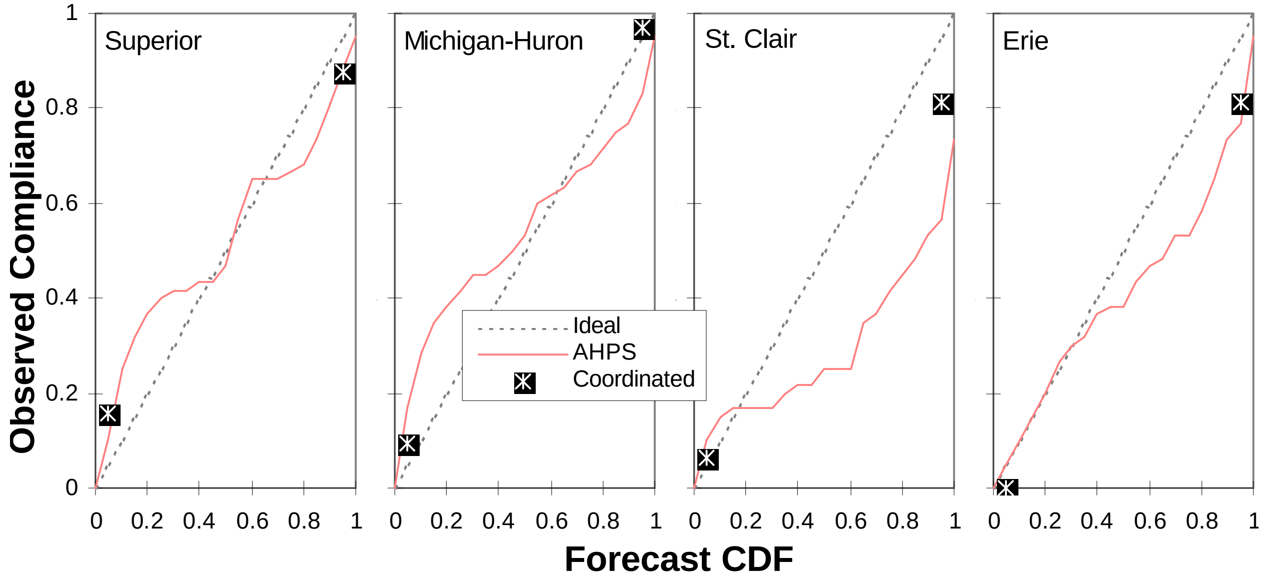

Figure 20. First Month 1996-2000 Probabilistic Comparisons.

Lake Level Forecasting Evaluation Summary

Overall, there is little difference much of the time between using residual or component historical NBS in making a probabilistic forecast of lake levels; when there is a difference, component NBS seem to do a better job. This is consistent with other studies of estimation errors associated with both ways of calculating NBS (Croley and Lee, 1993). Component NBS allow consideration of antecedent conditions, which greatly improves a forecast except in a few cases. Considering available meteorological outlooks generally improves estimation of extremes somewhat but has little effect overall; it may have more impact on a case-by-case basis.

The AHPS forecast using antecedent conditions and meteorological outlooks generally has lower RMSE, higher correlation, better skill, and lower maximum error (not shown) than the US Most-Probable, the Canadian 50%, and the Coordinated 50% forecasts of lake levels. This suggests that the AHPS forecast has generally the smallest differences with actual levels, best captures the timing of variations of lake levels, and is most-consistently best at the extremes over different periods. However, the AHPS forecast is often more biased than at least one of the other three during the early evaluation periods. This suggests that it is generally under-predicting slightly during those times of high levels (both 1993-1995 and 1995-August 1997), but the other forecasts are less consistent from period to period.

Although there are only six years of meteorological probability forecasts to assess, by combining all first-month forecasts into one sample, all second-month forecasts into another sample, and so on, it is possible to make some probabilistic comparisons. On Superior, the AHPS forecast more often is better than the Coordinated in both evaluation periods, especially in the 1995-August 1997 evaluation. Both the AHPS and the Coordinated forecasts appear to under predict at high levels for all forecast lags in both evaluation periods. Both over predict first-month low levels and under predict low levels at higher lags in the 1995-August 1997 evaluation. Probabilistic forecasting, in general, is better on Superior and Michigan-Huron than on St. Clair and Erie.

There are outside considerations affecting the evaluation. Both the Corps and EC use engineering judgment to adjust their actual forecasts, including alternate forecasts of NBS, their own use of GLERL's AHPS, experience with Superior regulation and mid-lakes routing, and precise knowledge of operating conditions (e.g., power plant capacities under existing head conditions at the time of a forecast and hence river flows at certain points). No doubt they can do better jobs of using GLERL's AHPS in actual practice than GLERL can. The 1993-1997 period represents above-normal lake levels and the 1996-2000 period represents below-normal lake levels, particularly in the latter part of the period. The improved performance of the US and Canadian forecasts, in the 1996-2000 evaluation relative to the 1995-August 1997 evaluation, may be due in part to the use of GLERL AHPS forecasts by the US and Canadian authorities (particularly the Detroit Corps) in making their outlooks during the 1996-2000 period. Furthermore, there are many details in the use of the Superior regulation plan and in the mid lakes routing that are glossed over with simple or antiquated assumptions in AHPS. These include rating equations, weed retardation coefficients, and ice retardation coefficients that are used in AHPS. Errors in routing make for differences with current practice. It should be possible to do a better job of simulating actual regulation and routing than AHPS does. This improvement awaits the final version of a Coordinated Great Lakes Routing and Regulation model (to determine Superior regulation and mid-lakes routing), currently being prepared by the Coordinating Committee on Great Lakes Basic Hydraulics and Hydrology Data.

GLERL's probabilistic hydrologic outlooks are state-of-the-art. They a) fully and correctly utilize NOAA and others' probabilistic long range meteorological outlooks for multiple areas simultaneously, b) explicitly account for basin soil moisture and snow pack and lake heat storage and ice cover initial conditions, c) allow daily extended outlook generation, taking advantage of near-real-time data availability to offer continuously updated probabilistic outlooks, d) utilize hydrology models in a modularly-built package that allows upgrades to be "dropped in" as developed and tested, e) provide probabilistic outlooks for each lake and river watershed, capitalizing on improving weather prediction skill and hydrometeorological observations, f) properly consider the wide range of possibilities that always exist, g) incorporate some of the uncertainty inherent in forecast estimates, and h) allow consideration of risk by decision makers.

NET BASIN SUPPLY FORECAST COMPARISONS

The poor performance of considering probabilistic meteorology outlooks in making probabilistic hydrology outlooks is undoubtedly due in part to the very large scale of the application. The evaluations of the preceding section used simultaneous probabilistic meteorology outlooks over multiple areas (each of the Great Lake basis); this can make it difficult to satisfy very many of them at the same time. If we look at a smaller scale, say a single Great Lake basin, we may be able to find more utility for probabilistic meteorology outlooks in making derivative hydrological outlooks. Since the forecast of lake levels involves the entire Great Lakes, it is not possible to estimate lake levels on a single lake without considering all lakes. Therefore, we look at forecasting net basin supplies to a lake (which is possible without considering other lakes).

Forecasts of net basin supply (rather than lake levels) were evaluated, in the manner described in the last section, for Lake Superior and compared with derived NBS, based on observed data. GLERL simulated probabilistic hydrological forecasts for 1996—2000 with three "operational hydrology" methods (Croley 2001c). Firstly, GLERL assembled all six-month NBS time series from the historical record (1948—1995) that started the same month as each month of the period 1996—2000 into a sample for that month, from which to estimate a six-month forecast beginning that month. GLERL then used the resulting samples to infer a six-month probabilistic NBS outlook beginning each month of the period with the Weibull estimator, representing forecasts without consideration of antecedent conditions or meteorological outlooks.

Secondly, GLERL simulated six-month NBS scenarios with AHPS, which uses estimates of antecedent moisture and heat storage conditions with six-month pieces of the 1948—1995 historical meteorological record. They did this for each month of 1996—2000 and assembled the six-month NBS scenarios into a sample for that month from which to estimate a six-month forecast beginning that month. Only provisional data were used to estimate antecedent conditions, as they would have been available in near real time. Since no sample weightings were used, this represents forecasts, for each month of the period, that consider antecedent conditions but do not use meteorological outlooks.

Thirdly, GLERL simulated six-month NBS forecasts with their AHPS, using both antecedent conditions and NOAA's 1- and 3-month meteorological outlooks, for each month of the period. GLERL used the last five methods of the preceding section for considering the forecast 56 meteorology probabilities in their hydrological outlooks. They used meteorological outlooks over Lake Superior, ordered as indicated in Table 8, and different objective functions: a) minimization of the sum of squared differences between each weight and unity while using the most meteorological outlooks (Croley, 1996, 1997a,b, 2000a), b) minimization of the sum of squared differences between each weight and unity while forcing all weights non-zero (use all hydrological scenarios), c) maximization of probability of mid-third (normal) values for the first six-month air temperature and precipitation over the Lake Superior basin (Croley, 2000a, 2001a), d) maximization of probability of first six-month air temperature and precipitation in one-third ranges as suggested by the extended meteorological outlook over the Lake Superior basin, and e) no objective. Inspection revealed that the best forecasting method used the normal weather objective.

All three of these operational hydrology methods yielded six-month probabilistic NBS outlooks, which were simplified to deterministic outlooks for comparison to actual conditions. The simplifications consisted of taking the mean, the median, the mid-range between the 5% and 95% quantiles, the mid-range between the 15% and 85% quantiles, and the mode (assuming a normal distribution). There were little differences between uses of the various combinations, but the mean consistently gave the better results. GLERL then compared each deterministic forecast with what actually occurred to find the effects of considering antecedent moisture and heat storage conditions and considering meteorological outlooks. Figure 21 presents several statistics for the three methods using both mean and mid-range (5%—95 %) forecasts. Figure 21 reveals that the most improvement to the forecast occurs when antecedent conditions are considered. Root mean square error (RMSE) drops, correlation increases, maximum error drops, and skill improves. [Skill measures the difference between forecast and actual NBS, weighted more for the extremes, normalized by reference to climatic outlooks. Lower skill scores indicate better performance and skill = 1 indicates a climatic outlook (average from the historical record)]. Bias appears to worsen. With the addition of weather information, the forecast improves slightly more with regard to RMSE and correlation. The mid-range forecast also shows better bias and skill considering weather and antecedent conditions, as opposed to just antecedent conditions alone.

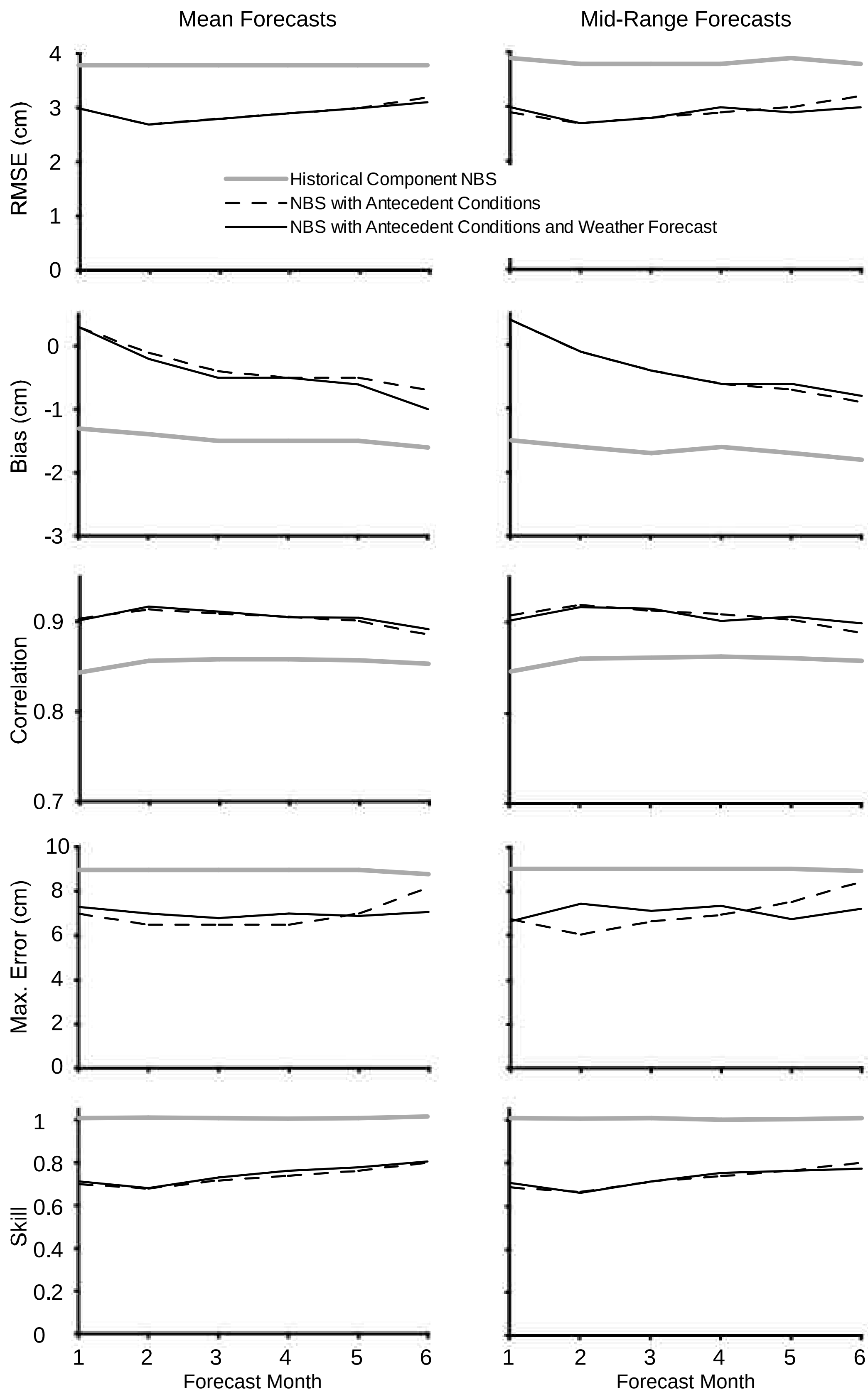

Figure 21. NBS Forecast Statistics

RISK ASSESSMENT DEMONSTRATION

The Buffalo District of the US Army Corps of Engineers provides advice and makes decisions on Lake Ontario regulation. They consider the balance between interests on Lake Ontario and downstream on the St. Lawrence River. In particular, they make probabilistic outlooks of water levels on Lake Ontario and the St. Lawrence River, in cooperation with Canadian agencies. They provide direction in the administration of Plan 1958-D and advise on suspending the plan under extraordinary circumstances. Presently, they rely on comparison of supply indices, based on the present upper Great Lakes levels, with supply indices of the past. They recognize that uncertainties in their current procedure must be quantified and are exploring a risk-based decision model approach for their regulation decisions. This will allow them to incorporate some of the uncertainty inherent in forecasts, to properly consider the wide range of possibilities always present, and *to consider the risk associated with their decisions*, not possible with the current procedure. This is in keeping with the recommendation of the IJC to improve forecasts of the frequency of extreme water levels, which came from the IJC Great Lakes Levels Reference Study.

Several "forecasts" of Great Lakes supplies are used operationally in Lake Ontario regulation, each based on different assumptions and overlapping historical record segments. Plan 1958-D defines and uses the ***Regulation plan supply indicator***. The ***Criterion (k) indicator*** is a proxy for the total supplies to Lake Ontario expected from "now" through the end of the following June. It indicates supplies expected in excess of supplies of the past. Similar indicators through end-of-March and mid-December indicate supplies expected below supplies of the past. The ***monthly Lake Ontario total basin supply forecast*** over next 12 months is called "Probabilistic" but actually is the median inflow plus historical variations. It sets "probabilistic" lake levels in the Regulation Representatives letter. Finally, there are ***monthly probabilistic lake level outlooks*** in the various agency forecast bulletins, as described earlier. (Recall the US extrapolates trends in NBS and Canada uses statistical analysis of historical supplies.) We need a unified approach—all outlooks should use the underlying theory and represent the same underlying processes. All should recognize boundary conditions and weather outlooks and be generated as relevant samples from the underlying population.

The Buffalo Corps of Engineers, in advising the invocation or revocation of Plan 1958D in the regulation of Lake Ontario, considers the ***Criterion (k) indicator***, which is used to estimate when supplies will exceed supplies-of-the-past-as-adjusted; see Figure 22. They also consider the probability of exceeding the Criterion (h) flood level before the seasonal high occurs, snow on the basin (a subjective assessment), and whether the lake is rising or falling.

The past definition of Criterion (k) employs exponential decay relationships (derived under linear-reservoir assumptions for all lakes) to relate observed levels on Lakes Michigan-Huron and Erie to future supplies to Ontario. Lake Superior levels and net basin supplies to all lakes are ignored (as well as other initial conditions and weather outlooks). This supply index is compared to reference values, derived likewise from historical data for 1900-1954, to indicate when supplies will exceed supplies of the past.

With the a system such as GLERL's AHPS, we can base Criterion (k) and the other three factors on the same (consistent) underlying physical concepts and introduce risk evaluation into all factors. As a demonstration, Criterion (k) was replaced here with a consistently derived probabilistic outlook of total basin supplies; reference values were recalculated from the same reference

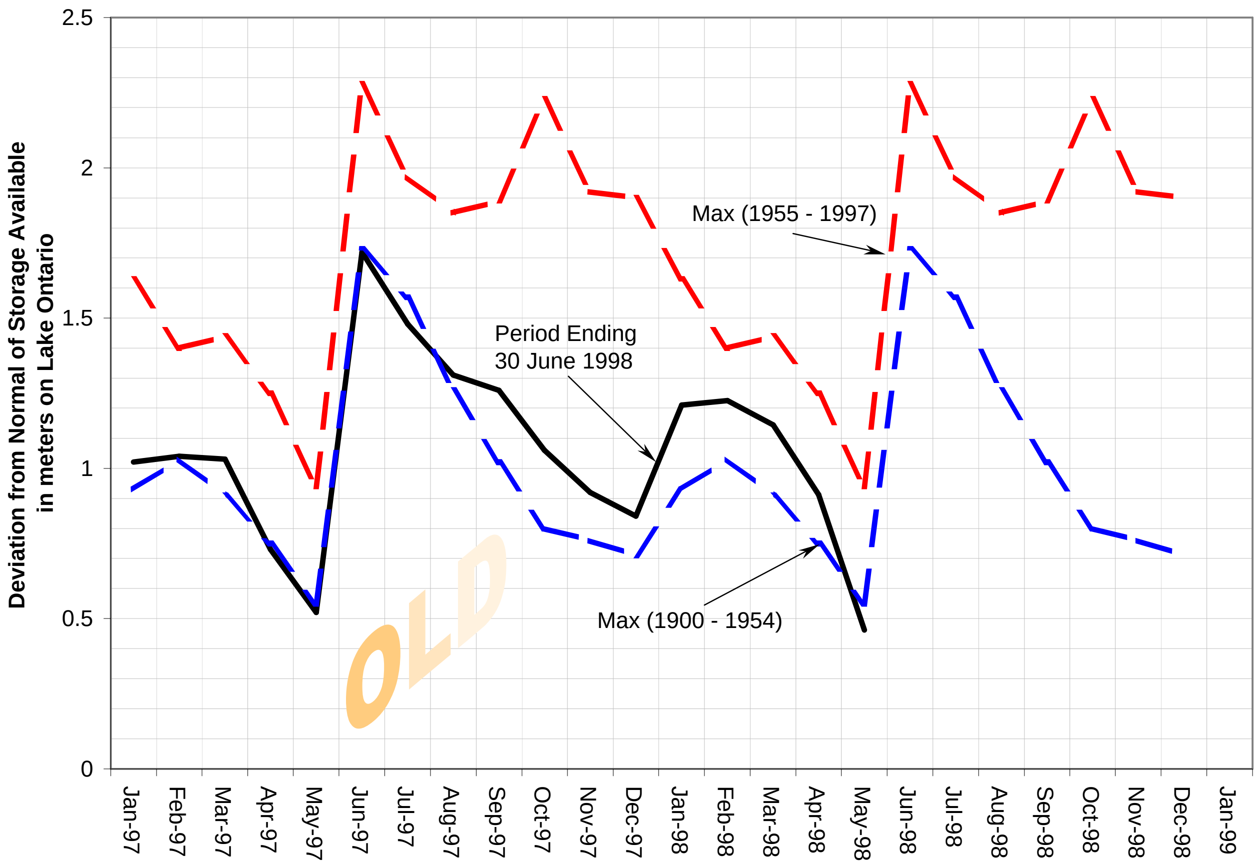

Figure 22. Lake Ontario Definition of Supplies in Excess of Supplies of the Past as Adjusted for the Period Ending 30 June.

period as the old values. While the definition of Criterion (k) is new, it is consistent with the old, but allows acceptable risk determination; see Figure 23. Similar indicators through the end of the following March and mid-December are also defined to indicate when supplies are expected below "supplies-of-the-past-as-adjusted."

The Buffalo District Army Corps of Engineers could supplant their outlooks of total basin supply, lake outflow, lake level, and river levels, with probabilistic outlooks in the same way as above for Criterion K, for use in their monthly letter to the Regulation Representatives. They would all be generated with the Advanced Hydrologic Prediction System in the same manner as the many other hydrologic variables. The generation of lake outflows and levels, and levels downstream would be made by using the Corps existing software for regulation plan 1958D with no diversions, for regulation plan 1958D with prespecified diversions, and for regulation plan 1998. Instead of using their software to process three quantile times series (5%, 50%, and 95%, typically) of total basin supplies to generate the corresponding three (so-called) quantiles of lake levels and outflows, as done now, the procedure would change. The new procedure would use their software with all the scenarios (typically 50), generated in the Advanced Hydrologic Prediction System, to generate corresponding scenarios of lake levels, outflows, and downstream parameters. These form samples from which probabilistic outlook estimates would be made for

Figure 23. Lake Ontario Forecast Supplies and Supplies-of-the-Past-As-Adjusted for Period Ending 30 June (10 Oct 1997 Forecast; relative to 1900-1954 average; "Normal" distribution fit).

these parameters. The entire procedure would be automated so that it is similar to the use of the present procedures.

ADDITIONAL RISK ASSESSMENT CASE STUDIES

In addition to the risk assessment demonstration, GLERL explored three retrospective case studies to demonstrate the utility of using probabilistic Great Lakes water level forecasts to assess risk in operational decision-making (Lee, Clites, and Keillor, 1997). The first case study examines the 1985 International Joint Commission decision to store water on Lake Superior to reduce high levels on the downstream lakes. This case study also demonstrates the translation of hydrologic risks to interest satisfaction. The second case study evaluates the risk of lake flooding at Milwaukee, Wisconsin and the decision whether to make municipal investments in flood control projects. The third case study quantifies the risks of impaired municipal water works operation during a period of extreme low water levels on Lakes Huron, St. Clair, Erie, and Ontario. The case studies, summarized below, illustrate the additional information a risk-based approach can contribute to decision-making. GLERL also performed a case study that investigates the technical and institutional issues surrounding risk-based water resources management (Lee, 1999). These issues are presented following the case studies.

Lake Superior Regulation

In December, 1984, Lakes Michigan-Huron, St. Clair and Erie (middle lakes)were approaching the record high levels of 1973-74. Lake Superior was 14 cm above its average. In early 1985, precipitation over the middle lakes caused them to further rise. In response to public concern, the IJC took steps to mitigate the high water conditions of the middle lakes. The IJC instructed the Lake Superior Board of Control to reduce Lake Superior outflows by about 1/3 of those prescribed by the regulation plan while not exceeding the upper regulation limit, thus increasing storage on Lake Superior and reducing levels of the middle lakes. The reduction of flows began in May and was discontinued in early September when heavy precipitation over the Lake Superior basin resulted in Lake Superior levels approaching the upper regulation limit. Despite increased outflows greater than those specified by the plan, the lake rose above the upper regulation limit in October and November. While this action temporarily reduced the middle lakes' levels, they continued to rise and set record levels in 1986.

Two probabilistic outlooks (Figure 24) were generated using an Extended Streamflow Prediction approach (Day, 1985) using recorded net basin supplies from 1940-1984 (a wet period), the initial conditions for May 1985, and the Great Lakes regulation and routing model with no reduced outflows and with reduced outflows. As shown in Figure 24, there was a significant upward shift (increased risk of exceeding the upper regulation limit) in the Lake Superior probabilistic outlook with the reduction in outflows, and a corresponding downward shift (reduced risk of exceeding the previous record high) in the Lakes Michigan-Huron outlook.

Table 9 summarizes the probabilities of Lake Superior exceeding its upper regulation limit and the probabilities of Lakes Michigan-Huron exceeding its 1973-74 record high levels, without the reduction in flows and with the reduction in flows. With the risks quantified, the decision to take action becomes a policy decision.

Value functions, developed for the previous International Joint Commission Levels Reference Study, relate the value of specific water levels to an interest group. Shown in Figure 25 are the riparian inundation value functions that relate inundation damage to Lake Superior and Lake Michigan-Huron lake levels. The values range from 0, the most desired condition, to 1, the least desired condition. By convoluting (weighting) the probabilistic outlooks with the value functions, an index is created that represents normalized probable levels of interest satisfaction ranging from 0 (satisfied) to 1 (least satisfied). Shown in Figure 26 are the value function tradeoff curves for Lakes Superior and Michigan-Huron without reduced Superior outflows and with reduced Superior outflows. These curves help to illustrate the potential tradeoffs in making the decision to reduce Lake Superior outflows.

Flood Protection

In October 1986, Lakes Michigan-Huron set record high levels 0.4 m below a critical level at Milwaukee, Wisconsin at which a hazard area of 85 ha containing 168 structures would be flooded. Other potential impacts at the critical level included water overflowing diversion gates into intercepting sewers; basement flooding via sewer surcharging; impaired storm sewer, industrial and other clear water discharge pipe flows; high groundwater flooding of utility tunnels and basements; and flooded transportation facilities and the Jones Island sewage treatment plant.

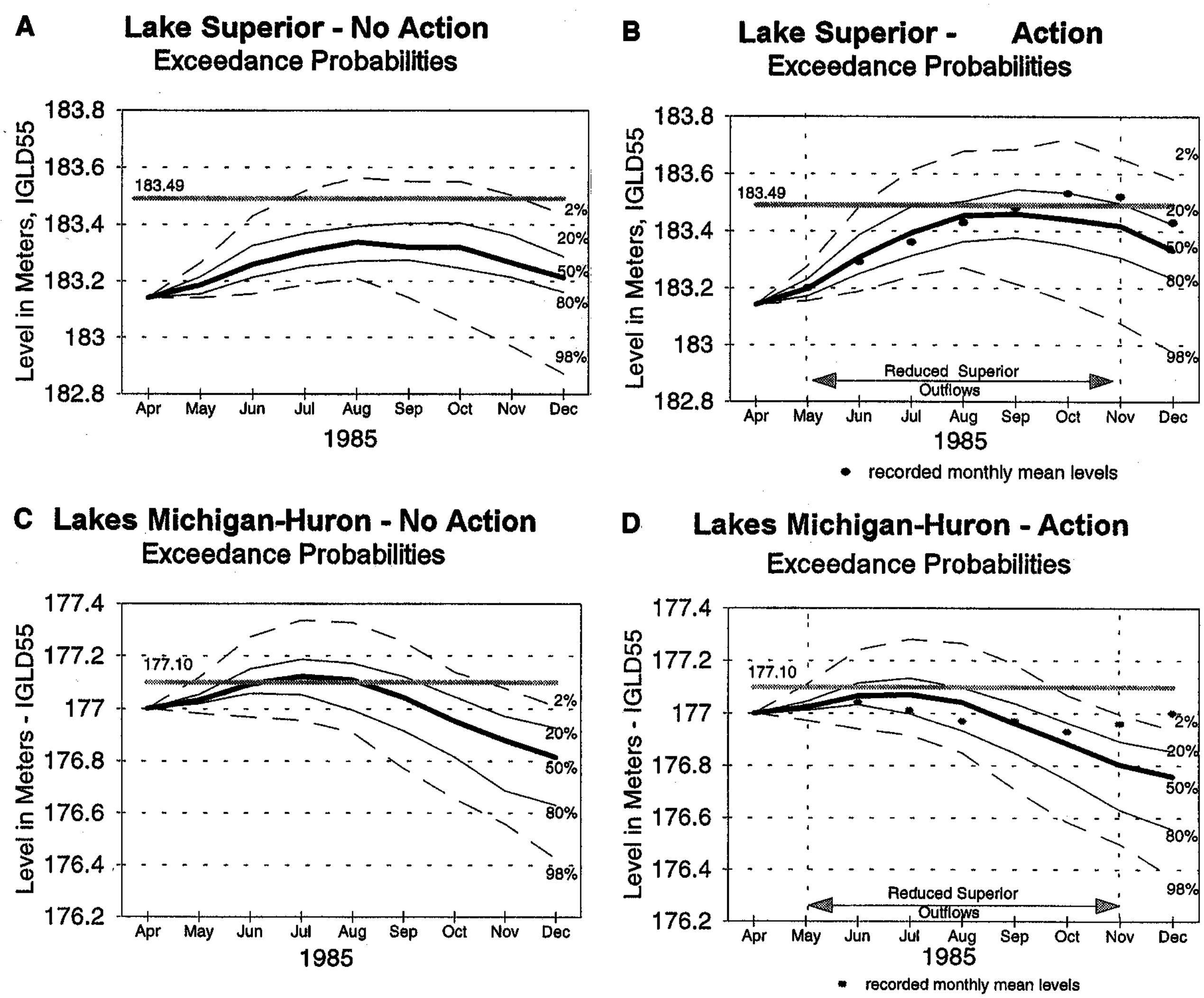

Figure 24. Probabilistic forecasts of Lake Superior and Lakes Michigan-Huron water levels for April to December 1985, with (action) and without (no action) reduced Lake Superior outflows.

Table 9. Probabilities of exceeding Lake Superior's upper regulation limit and Lake Michigan-Huron's 1973 record high level for May-December 1985.

Month	Lake Superior, probability of exceeding 183.49 m (%)			Lakes Michigan–Huron, probability of exceeding 177.10 m (%)		
	No action	Action	Increase in risk	No action	Action	Decrease in risk
May	<2	<2	0	3	3	0
June	<2	<2	0	42	27	15
July	3	14	11	59	34	25
August	5	30	25	52	18	34
September	6	40	34	24	8	16
October	5	37	32	12	<2	10 > *P* < 12
November	4	24	20	<2	<2	0
December	<2	9	7 > *P* < 9	<2	<2	0

[a]Action—with the IJC's decision to store water on Lake Superior; no action—with no storage on Lake Superior.

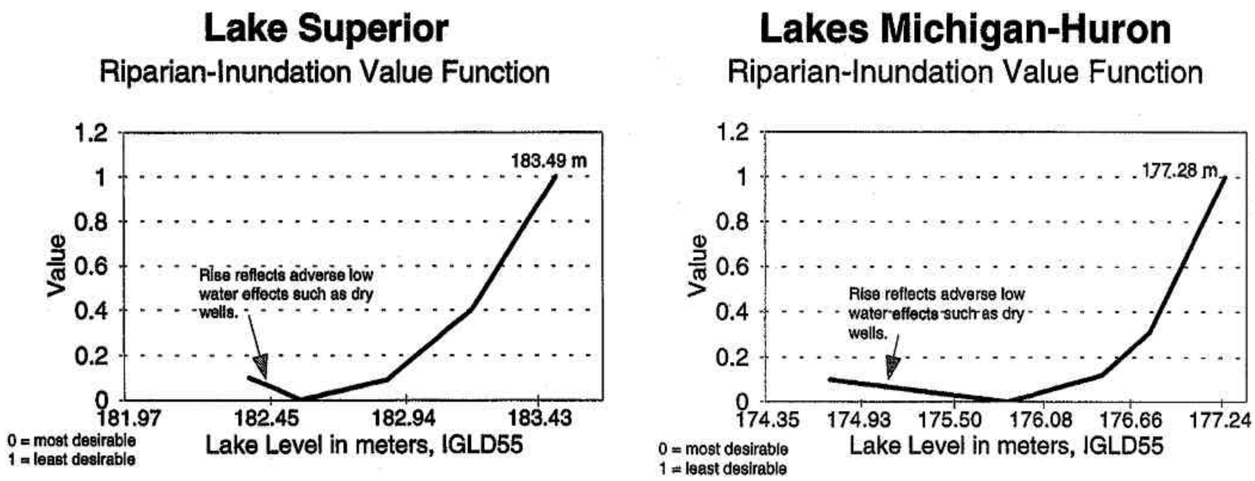

Figure 25. Riparian-inundation value functions relating inundation damage to monthly mean lake levels on Lake Superior and Lakes Michigan-Huron.

Concerned that the trend of rising lake levels would continue, the Milwaukee County Board of Supervisors requested the Southeastern Wisconsin Regional Planning Commission to prepare a prospectus of high lake level impacts on the city of Milwaukee, Wisconsin. The prospectus recommended that a contingency plan for flooding be prepared and estimated the cost at $253,200.00. The Board of Supervisors was faced with the decision as to whether the money should be spent to prepare the plan. Knowledge of the probability of the lake exceeding the critical level in the 12-24 months following October 1986 could have been useful in assessing the imminent risk of flooding and in making the Board's decision.

A retrospective probabilistic forecast was prepared using the adapted ESP approach described in the preceding case study. The forecast, shown in Figure 27, indicated that the probabilities of exceeding the October 1986 record level in the coming June through August period were be-

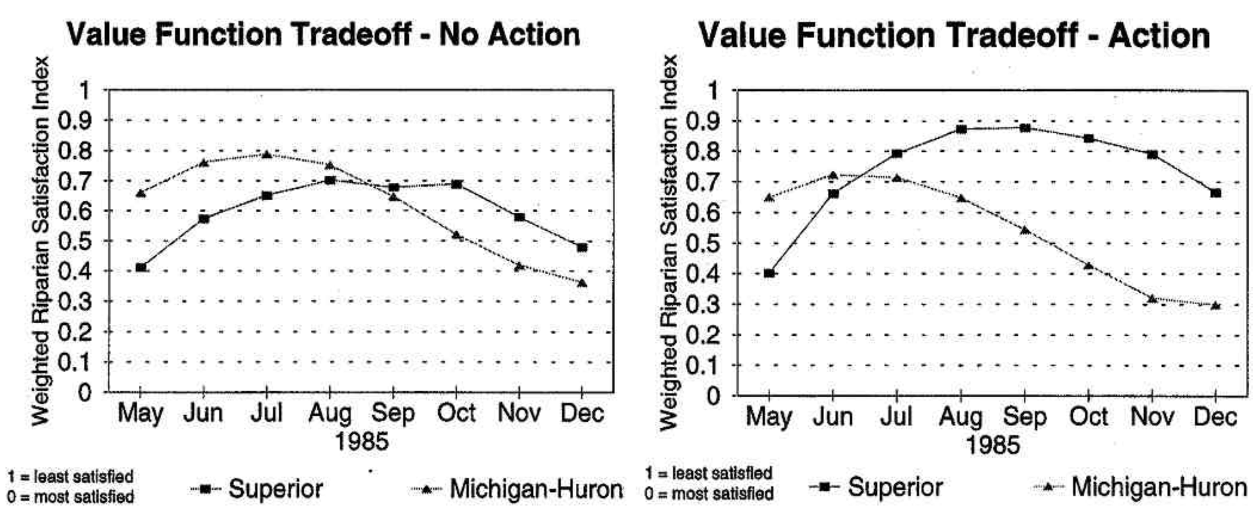

Figure 26. Weighted riparian satisfaction index relating riparian satisfaction with probable lake levels for May to December 1985 for Lake Superior and Lakes Michigan-Huron: (A) without, and (B) with reduced Lake Superior outflows.

tween 19% and 22%. The 2% probability of exceedance line peaked in July 1987, 26 cm below the critical flood level. With this information, the Milwaukee Board of Supervisors could have made the decision that funds need not be spent on the contingency flood plan. In fact, the actual lake levels began a rapid decline in response to below average precipitation in the winter and spring of 1987, as shown in Figure 27.

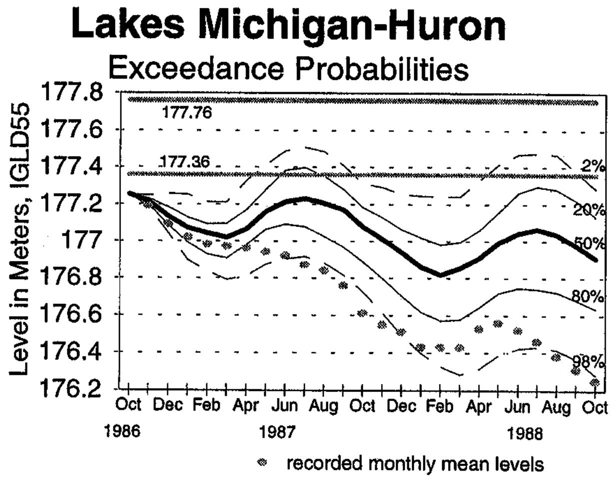

Figure 27. Probabilistic forecast of Lake Michigan water levels for October 1986 to October 1988.

Municipal Waterworks Operation

In early 1964, Lakes Michigan-Huron began setting record low levels, and Lakes Erie, St. Clair, and Ontario were approaching their record low levels established in the mid-1930s. Critically low levels were experienced during the winter months at the end of 1964 and early 1965. Late in 1964, the International St. Lawrence River Board of Control requested the Ontario Water Resources Commission to conduct a survey of the impacts of low water levels on the operation of major Canadian water intakes and wastewater outfalls. The survey resulted in information for 75 municipal water works, 24 of which were experiencing problems due to low lake levels. Three types of problems were reported: 1) reduced intake capacities due to loss of available head, accompanied by increased pumping costs and cavitation, 2) deterioration in water quality near shallow intakes, and 3) increased frazil ice development on intakes. More than 500,000 people were affected. Table 10 summarizes the information from the 24 water works experiencing problems.

Reduced intake capacity, resulting in water shortages and failure to meet maximum demand, was the most prevalent problem. Many of the facilities installed inline intake pumps, installed new or temporary intakes, or modified existing intakes. A probabilistic water level forecast made at the beginning of the seasonal decline (about the end of July) may have helped the operators to assess their risks due to low levels and to prepare during the fall months.

Retrospective probabilistic water level forecasts were prepared for August 1964 through July 1965, with due consideration of the initial conditions and the hydraulic regime of that time. Because the decision-makers would be risk averse to falling lake levels, water supplies from 1900-1939 (a dry climate regime) were used in the ESP approach. The resulting forecasts are shown for Lakes Michigan-Huron, Lake St. Clair, Lake Erie, and Lake Ontario in Figure 28. Table 11 summarizes non-exceedance probabilities for maximum demand levels for select municipalities.

From Figure 28 and Table 11, the municipalities of Parry Sound and Little Current on Georgian Bay (Lakes Michigan-Huron) could have expected to be unable to meet their maximum demand from August 1964 to April 1965 because there was a greater than 50% chance that their maximum demand water level would not be exceeded. Similarly, the municipality of Wiarton could have also expected to be unable to meet its maximum demand from October 1964 to April 1965.

Table 10. Water intake problems at 24 Canadian municipal water works.

Municipality	Population	Maximum demand		Problem experienced
		Flow (liters/sec)	Water elev. required (m, IGLD 55)	
Lake Ontario and St. Lawrence River				
Deseronto	1,800	NR[b]	NR	water quality problem
Belleville	32,100	358	73.69	reduced intake capacity
Picton	7,000	126	73.27	reduced intake capacity
Port Hope	8,200	79	73.73	reduced intake capacity
Metro Toronto/New Toronto Station	1,700,000[c]	631	74.98	reduced intake capacity
Port Credit	7,100	79	73.76	water quality problem
Hamilton	300,000	4,473	73.76	reduced intake capacity
Vineland	750	47	74.37	reduced intake capacity
Town of Niagara	3,500	NR	NR	reduced intake capacity
Lake Erie				
Fort Erie	9,200	263	172.82	reduced intake capacity
Crystal Beach	15,000	90	173.25	reduced intake capacity
Port Colborne	17,400	237	173.74	reduced intake capacity
Dunnville Area	8,000 + industry	1,316	171.90	frazil ice problem
Port Rowan	834	34	173.74	reduced intake capacity
Lake St. Clair				
Belle River	1,920	158	173.19	reduced intake capacity
Stoney Point	2,000	NR	NR	reduced intake capacity
Tilbury	2,000	NR	NR	reduced intake capacity
Lake Huron–Georgian Bay				
Kincardine	2,850	116	NR	reduced intake capacity
Port Elgin	7,000	50	173.27	frazil ice problem
Wiarton	2,030	55	175.50	reduced intake capacity
Waubaushene	1,200	NR	NR	reduced intake capacity
Parry Sound	6,100	105	175.56	reduced intake capacity
Little Current	1,600	38	175.56	reduced intake capacity

[a]Problems due to low lake levels and supporting data reported to the Ontario Water Resources Commission (1965).

[b]NR, not reported.

[c]The New Toronto Station was one of five stations serving this population. The population served by each station was not given.

The probabilistic forecast for Lake Ontario shows that the New Toronto Station serving Metropolitan Toronto would continue to experience significant reduction in intake capacity. For the forecast period, a probability near or greater than 97% existed that its maximum demand water level would not be exceeded. In contrast, the municipalities of Hamilton, Port Credit, Port Hope, and Belleville had very small forecast probabilities of not exceeding their required maximum demand levels. Their largest risk occurred in February and was less than 17%. However, in December and January, Lake Ontario levels did fall below their maximum demand levels, and these municipalities experienced reduced intake capacities. The recorded levels were very near the forecasted 3% non-exceedance levels. In this circumstance, the municipalities may have postponed their decision to take action because of their low forecasted risk. They could have waited to make their decision until new forecasts were made in September or October, reflecting the continued trend in decreasing lake levels. The updated forecasts would have shown substantially increased risk with sufficient time remaining in the fall season to take action.

Similar examples for the other municipalities listed in Table 10 are illustrated in Lee, et al. (1997). All of the municipalities that reported problems due to low water levels could have benefited from the risk information contained in the probabilistic forecasts. Whether used to as-

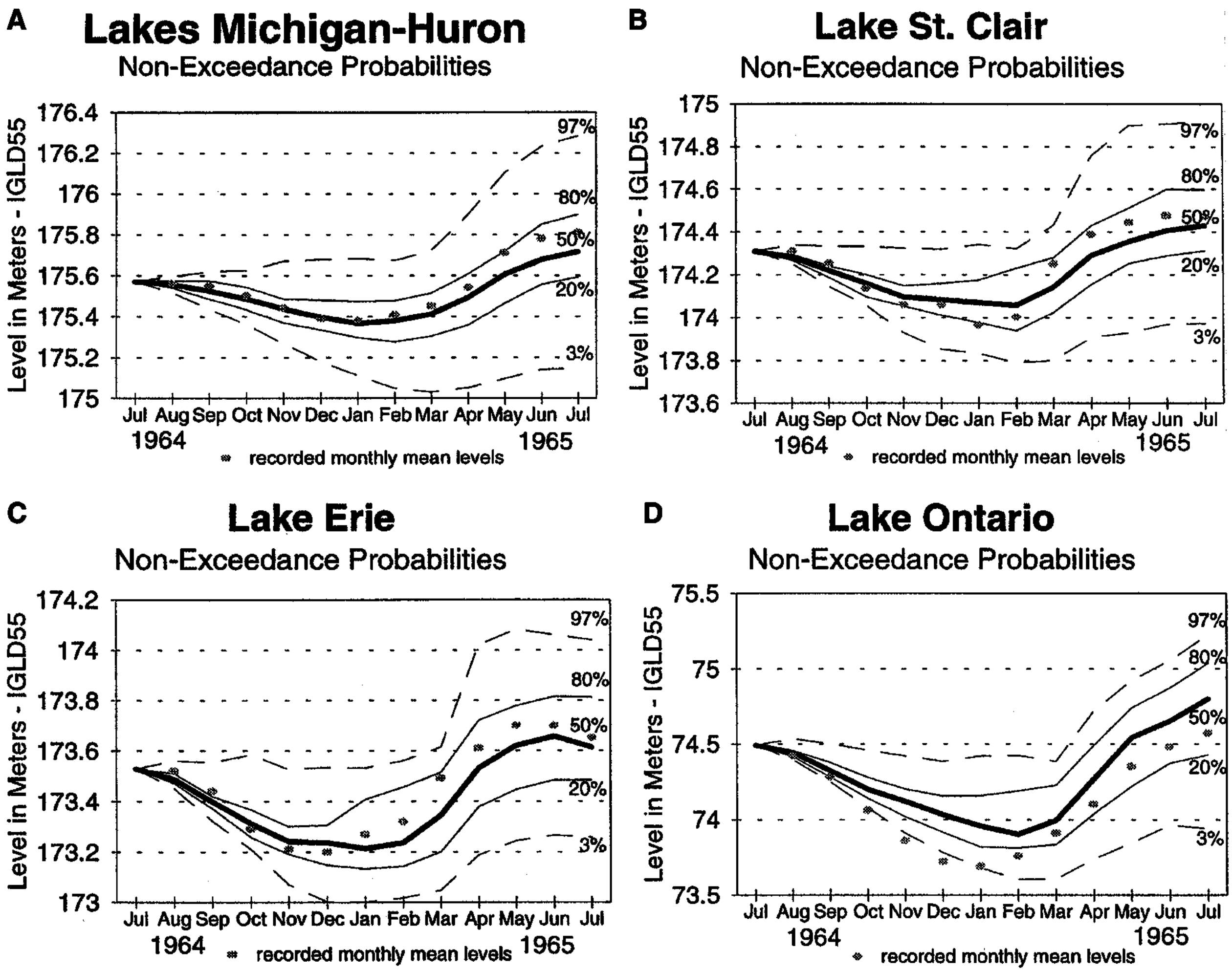

Figure 28. Probabilistic forecasts of water levels for August 1964 to July 1965.

sess the need for additional intake capacity, prepare emergency contingency plans, or estimate potential water quality, the forecasts could have been very valuable to local decision makers.

Other Applications

In addition to making the types of decisions illustrated here by the three case studies, there are many other potential applications. Hydroelectric power utilities could use probabilistic forecasts of levels and flows in anticipating power production for devising preliminary load schedules and, in the case of low flows, for sending notifications of possible reductions in power delivery. The forecasts could also be used for short-term revenue forecasts. Commercial navigation could use such outlooks for anticipating loading capacities and transportation costs and in making routing decisions. The Federal Emergency Management Agency and commercial insurers could anticipate flood and erosion damage claims. Other possible applications are correct timing of beach nourishment or wetland restoration efforts and advance application for dredging permits by marina operators.

The benefits of using probabilistic outlooks for risk-based decision making are that they 1) incorporate the inherent uncertainty, 2) consider the wide-range of possibilities, 3) quantify the associated risk and risk-sensitivity, 4) provide a unified approach (all tools/indicators/outlooks use same underlying theory and process), and 5) incorporate the underlying meteorological outlook skill.

Table 11. Probabilities of not exceeding maximum demand levels for selected municipal water intakes.

	Nonexceedance probability (%)					
	Lakes Michigan–Huron		Lake Erie		Lake Ontario	
Month	175.56 m	175.50 m	173.74 m	173.25 m	74.37 m	73.76 m
August 1964	56	<3	>97	<3	<3	<3
September	73	27	>97	<3	79	<3
October	88	63	>97	17	94	<3
November	91	82	>97	57	96	<3
December	93	88	>97	61	97	<3
January 1965	95	90	>97	57	95	10
February	95	90	>97	55	95	17
March	90	73	>97	29	96	10
April	63	51	85	5	63	3
May	40	31	78	3	28	<3
June	22	14	72	<3	20	<3
July	15	10	71	<3	14	<3

Technical and Institutional Issues

Technical Issues. Technical issues that must be addressed are 1) users' lack of experience and frame of reference, 2) translation of risk to interest benefits and disbenefits, 3) assessment of probabilistic forecast skill, 4) low underlying meteorological forecast skill, and 5) uncaptured uncertainty. In regards to the users' lack of experience, case studies such as those related above are very valuable in demonstrating the use of probabilistic outlooks. The retrospective case studies can also be used to define an interest's risk threshold to begin building the interest's frame of reference. The first case study illustrated one technique for translating hydrologic risk to interest benefits/disbenefits. Other techniques should be identified, and ways of evaluating the interest tradeoffs should be explored. Some assessment of probabilistic forecast skill has been undertaken and is described earlier in this report. At present, the hydrologic forecast skill is primarily limited by the underlying meteorological forecast skill, especially for long-range forecasts. Utilizing the higher skilled shorter- and mid-range meteorological forecasts and blending with the less skilled long-range meteorological forecasts may benefit the hydrological forecasts. The uncaptured uncertainty in the probabilistic outlooks (for example, ice jam effects) must also be recognized and the potential sensitivity of the forecast quantified. Also, the appropriate types of decisions need to be paired with the appropriate forecast horizon and level of uncertainty.

Institutional Issues. Institutional as well as technical issues must be addressed for implementation of probabilistic hydrological forecasts and risk-based decision making. The institutional issues are 1) reluctance of operational agencies to adopt the methodology, 2) complex institutional process of changing lake level management procedures, 3) lack of a public or governmental call for risk-based lake level management, and 4) difficulty of communicating technical changes and allaying misperceptions. The operational agencies have primarily been reluctant to adopt the methodology because of the technical reasons cited above. Additionally, they want more experience with the methodology from an operational viewpoint prior to making significant changes to the current standard operating procedures. Recent downsizing of staff and budget reductions in both Canadian and US agencies presents additional challenges to implementing the new technology. The complex institutional process of changing lake level management procedures is also a very serious issue. International Joint Commission reference studies are generally organized and conducted to address procedural changes. These studies are long processes (5 to 10 years historically) and generally result in incremental changes versus new management paradigms. And lastly, the call for risk-based water resources management is from the science community who is familiar with probabilistic approaches. The public is not clamoring for such an approach and may actually have misperceptions on the intent behind such an approach.

RECOMMENDATIONS

Forecast Improvements

Forecast agencies are already beginning to incorporate current hydrologic conditions and, in some cases, probabilistic meteorological outlooks into their Great Lakes water levels forecasts. They are using combinations of regression, other statistical relationships, and engineering judgment to consider current conditions antecedent to a hydrological forecast. However, much potential exists for forecast improvement if initial conditions could be estimated continuously and then directly used in forecasts through the use of hydrologic process models. Of course, the use of process models requires that adequate meteorological data be available in near-real-time and that a near-real-time data reduction package exist to support them.

- Consider the use of process models for rainfall-runoff, lake evaporation, and precipitation in forecasts.

- Improve near real time data acquisition and reduction for support of hydrological forecast models.

Forecast agencies in the Great Lakes are beginning to notice extended probabilistic meteorology forecasts, appropriate to long-term lake level forecasting, that are available from several agencies over multiple locations, time periods, time lags, and meteorological variables. While the utility of extended probabilistic meteorology outlooks is limited at present, the potential is growing and their use should be planned in future hydrologic forecasting developments.

- Incorporate extended probabilistic meteorology outlooks quantitatively into Great Lakes hydrology and water level forecasts.

Evaluations of existing and candidate methodologies for making extended Great Lakes water level forecasts show that varying relative performance exists among them. Furthermore, these methodologies will continue to evolve. It is important for Great Lakes forecasting agencies to begin or to continue ongoing evaluations of candidate forecast methodologies so that strengths and weaknesses of each may be determined and appropriate modifications made as they are needed.

- Evaluate, in an ongoing manner, alternative methodologies for making extended Great Lakes hydrologic and water level forecasts.

Finally, the use of operational hydrology approaches to making extended Great Lakes forecasts, while allowing the use of initial hydrologic conditions and probabilistic meteorological outlooks, also permits the generation of probabilistic hydrological forecasts. This is important since they offer the proper manner in which to consider the wide range of possibilities that always exist, incorporate some of the uncertainty inherent in forecast estimates, and allow consideration of risk by decision makers.

- Build operational hydrology forecast systems, that estimate and use initial hydrological conditions and use probabilistic meteorology outlooks, to generate extended Great Lakes probabilistic hydrology and lake level outlooks for use by decision makers to evaluate risk associated with their regulation decisions.

- Incorporate probabilistic hydrologic forecasts into regulation so that consideration of risk becomes part of the decision process.

Risk Management

Recommendations for future work in applying risk-based management to Lake Ontario regulation for the present IJC Lake Ontario-St. Lawrence River Study are:

- Identify and develop technical applications and tools for risk-based decision making with focus on:

    - linkages between hydrologic variables and decision-making parameters, and

    - reformulation of current tools (Criterion k, lake level forecasts, risk-optimized regulation plan, etc.),

- Apply the tools to retrospective case studies to assess their utility and identify interests' acceptable levels of risk,

- Develop an effective means of communicating risk-based information to policy-makers, agency operators, and the public, and

- Implement the tools and objectively measure their performance.

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