

APPLICATION OF THE NMME IN THE DEVELOPMENT OF A NEW REGIONAL SEASONAL CLIMATE FORECAST TOOL

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With the use of the North American Multi-Model Ensemble, a web-based tool provides useful information to users who rely on seasonal climate forecasts for their operations and decision-making.

Recent regional climate extremes, including the ongoing drought in California (Seager et al. 2015) and extreme cold outbreaks across the northeastern United States (Clites et al. 2014), have directed national attention to the importance of

understanding and anticipating climate variability (Herring et al. 2014). Commercial, municipal, and recreational sectors are sensitive to impacts from climate variability and climate extremes. Decision-making processes adopted by the various sectors require reliable climate prediction resources to better anticipate, adapt to, and respond to these changes and extremes in climate (Kerr 2011). Of particular importance at the regional scale is the skill in seasonal forecasting (Yuan et al. 2015).

The National Oceanic Atmospheric Administration's (NOAA) Climate Prediction Center (CPC; part of the National Centers for Environmental Prediction) has been a leader in seasonal climate prediction with their production of long-range forecasts (LRFs; O'Lenic et al. 2008). Despite the success of these products, including their regional uses for decision-making (Croley 2000), several limitations should be acknowledged. For example, recent research underscores the challenges introduced by truncating (or restricting) climate information at geopolitical boundaries (Gronewold and Fortin 2012). This problem is prevalent in basins that intersect international borders but is not addressed by CPC's outlooks. One solution to this problem would be the utilization of

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global or regional climate models that are not defined or restricted by artificial boundaries. Additionally, use of the national product for regional decision-making can present challenges. We are not aware of a commonly adopted protocol for downscaling the LRFs, yet variability in these protocols can lead to significant differences between downscaled products that can be potentially confusing to users.

A recent multiagency effort to provide an operational ensemble of global climate model predictions, known as the North American Multi-Model Ensemble (NMME; Kirtman et al. 2014), has the potential to fill some of these gaps in regional climate forecasting. Launched in 2011, the NMME delivers global coverage forecasts from a number of U.S. and Canadian agencies. Most recent NMME forecasts include inputs from the Climate Forecast System, version 2 (CFSv2; Saha et al. 2014); the Geophysical Fluid Dynamics Laboratory (GFDL; Zhang et al. 2007) and GFDL Forecast-Oriented Low Ocean Resolution (FLOR; Jia et al. 2015) models; the National Center for Atmospheric Research (NCAR) Community Climate System Model, version 4 (CCSM4; Gent et al. 2011); the National Aeronautics and Space Administration (NASA) Goddard Earth Observing System, version 5 (GEOS-5), sea ice and ocean data assimilation systems model (Vernieres et al. 2012); and two models from the Canadian Meteorological Centre [Third Generation Canadian Coupled Global Climate Model (CanCM3) and Fourth Generation Canadian Coupled Global Climate Model (CanCM4); Merryfield et al. 2013]. The full list of models used is described in detail by Kirtman et al. (2014).

Research has been done to assess the overall skill of the NMME, including Wood et al. (2015), Becker et al. (2014), and Mo and Lettenmaier (2014). These studies have found that the NMME often meets or exceeds the forecast skill of individual models. Other research has focused on using NMME for region-specific forecasts and hindcasts. Ma et al. (2015) analyzed the skill of NMME as a drought predictor in China. Tian et al. (2014) researched statistical downscaling of the NMME's precipitation and temperature forecasts over Florida, Georgia, and Alabama, and Thiaw and Kumar (2015) documented work toward improved seasonal climate forecasts throughout Africa.

Although research on the NMME's skill and utilization at regional scales (noted above) is extensive, NMME is still very much in a research and testing phase. There are limited research-to-operations (R2O) examples showing use of NMME within regional applications. Yuan et al. (2015) showed that

the NMME can be used for real-time applications (predicting the 2012 drought over the central United States), a necessary step for moving toward an operational product. Another regional example (Barnston et al. 2015) detailed the efforts of improving seasonal predictions in the tropical Pacific [a region commonly assessed for El Niño–Southern Oscillation (ENSO) conditions], which have directly impacted operational forecasted ENSO plumes. However, there remains untapped potential for implementation of the NMME within regional, operational decision-making.

In this paper, we document the leveraging of the NMME to advance current regional climate forecasting methods through the development of a region-specific seasonal climate forecast tool. This tool serves as an example of a successful R2O within a water resource management framework and can be easily expanded and applied to other regions.

DEVELOPMENT AND APPLICATION OF A NEW NMME-BASED REGIONAL CLIMATE TOOL.

While the NMME analysis, tool development, and testing procedures we describe in the following sections are applicable to any region of North America, we demonstrate their utility specifically for the North American Great Lakes because it is a focal point for high-level water resource management planning agencies (e.g., the U.S. Army Corps of Engineers, Environment Canada, the New York Power Authority, and Ontario Power Generation). These and other regional agencies rely on basin-scale climate outlooks to develop water budget and water-level forecasts (Lee et al. 1997; Noorbakhsh and Wilshaw 1990) and guide decisions, such as (but not limited to) those pertaining to commercial navigation (Millerd 2011). We also focus on the Great Lakes because climate information for this region must explicitly account not only for climate impacts on broad-scale land–lake–atmosphere interactions (the Great Lakes basin is roughly one-third surface water and Lakes Superior and Michigan–Huron constitute the largest surface area of freshwater on Earth; Mortsch and Quinn 1996), but also for how those interactions feed back into regional climate dynamics (Lofgren et al. 2013; Notaro et al. 2013). While there is a clear and urgent need for Great Lakes region-specific climate information, we find there are few resources that seamlessly integrate existing national-scale information (including, e.g., CPC's LRFs) across the binational land and lake surfaces of the Great Lakes basin. Our new tool and analysis procedures directly address this gap in the nation's (and the continent's) climate portfolio.

Here, we present the development and application of a regional forecast tool specifically for the U.S. Army Corps of Engineers, Detroit District (USACE-Detroit), a regional agency responsible for the operational production and release of water budget and seasonal water-level projections. Current protocol includes use of a physically based hydrologic model (Gronewold et al. 2011) and empirical models (Noorbakhsh and Wilshaw 1990), which are partially driven by CPC's LRFs. Figure 1 represents the collection of possible probabilistic LRFs that are used for constructing the outlook maps (Fig. 2, left side). Outlook maps are constructed based on analysis of a suite of tools utilized by CPC forecasters, including dynamic models, statistical patterns, soil moisture information, and ENSO conditions. Within the Great Lakes hydrologic model framework, historical simulations are run, with greater weight given to climatic conditions in the historic record that are similar to the outlook maps for the region. For example, if a given season is forecasted by CPC to have a 40% chance of above-normal precipitation, historic simulations with precipitation values that match this adjusted distribution will be given greater weighting in the model (Croley 2000). For the empirical method, USACE-Detroit forecasters assign specific precipitation and temperature estimates based on a qualitative analysis of the probabilities on the LRF maps, as predictor variables forcing a regression model. Final forecast values of a lake's water supply are also influenced by the forecasters' qualitative assessment of the LRF maps. The resulting forecast represents the USACE-Detroit contribution to an internationally coordinated 6-month Great Lakes water-level forecast.

The left side of Fig. 2 signifies USACE-Detroit's old method, solely using the CPC outlook information for seasonal prediction. The left side tells a forecaster that there is an increased probability of above-normal temperatures for the Great Lakes region. With the available information, the forecaster will make assumptions

about conditions in the region that are not within U.S. borders. Also, it is difficult for the forecaster to determine the magnitude of above-normal conditions. The right side of Fig. 2 shows one example of how utilizing the NMME within a regional context provides more information to the forecaster. There is explicit information for the entirety of the Great Lakes basin. Also, the display of individual models of the NMME (far-right Fig. 2) for the 2015/16 winter communicates the variability and uncertainty in forecasts, despite a developing strong El Niño, which is correlated with warm winter conditions over the Great Lakes (Rodionov and Assel 2003; Assel 1998). The NMME not only provides magnitudes of anomalies, it still provides the forecaster with the information necessary to deduce the likelihood of above-normal conditions. The additional detail in the right side of Fig. 2 gives a more comprehensive "snapshot" that could be critical for decision-making and risk-based planning.

While the targeted regional maps in Fig. 2 offer a useful, qualitative perspective, the region-specific seasonal climate forecast tool produces a quantitative, ensemble forecast. Development and application of the tool are discussed in the following sections.

Overview of development strategy. The primary component of the Region-Specific Seasonal Climate Forecast (RSCF-NMME) tool is the processing of regularly

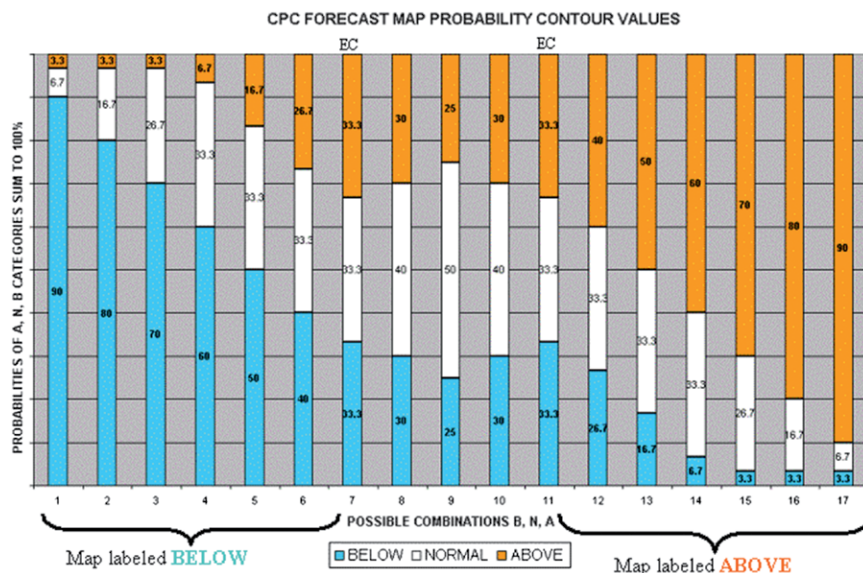


FIG. 1. Visualization of all possible forecast probabilities available for the CPC's LRF maps. An equal-chances forecast (EC) and with no shading on the LRF maps means there is an equal chance of below-normal, near-normal, and above-normal conditions. Areas marked above normal (A) and below normal (B) on the maps denote the use of categories 12–17 and 1–6, respectively. (Graphic taken from www.cpc.ncep.noaa.gov.)

updated forecasts from the NMME suite of global climate models (available at ftp://ftp.cpc.ncep.noaa.gov/NMME/realtime_anom/). These NMME anomaly forecasts, provided by CPC, include a systematic error correction for all the models using 29 years of hindcasts (Becker et al. 2013). Basin grid cells (at 1° resolution) are defined by watershed boundaries (Fig. 2, right) to generate the region-specific forecasts. Basin-averaged temperature and precipitation anomalies are approximated as follows:

$$\text{var} = \frac{\sum_{i=1}^n w_i^* p_i}{\sum_{i=1}^n w_i},$$

where the product of the grid cell value p_i and the fraction of the grid cell that resides within the basin w_i summed over all the grid cells n and divided by the sum of the grid cell fractions gives an area-weighted mean. The number of grid cells ranges from $n = 19$ grids in the Erie basin to $n = 56$ grids in the Michigan–Huron basin.

Another key component of the RSCF–NMME is the use of a regional climatology to translate

anomalies into absolute air temperature and precipitation forecasts. The regional climatology, developed from the NOAA/Great Lakes Environmental Research Laboratory (GLERL) Great Lakes hydrometeorological database (Hunter et al. 2015), is based on station measurements from both the United States and Canada. While other observational datasets are available to create the regional climatology, we felt that the NOAA/GLERL dataset would be most appropriate for the Great Lakes region because it employs comparable data and methodologies as USACE-Detroit’s dataset, which plays a critical role in Great Lakes operational water-level modeling.

Region-specific forecast anomalies from the NMME are converted to actual values using the historic observation data. Every run of every model is assigned a monthly forecast value for each basin (with a 6-month forecast horizon) and archived. By preserving the information of every member (currently over 100 members total) from the seven different models, the RSCF–NMME dataset now contains a range of values that can be used to construct a probabilistic forecast.

The data gathering and preparation portion of the RSCF–NMME is designed to be easily transferrable to

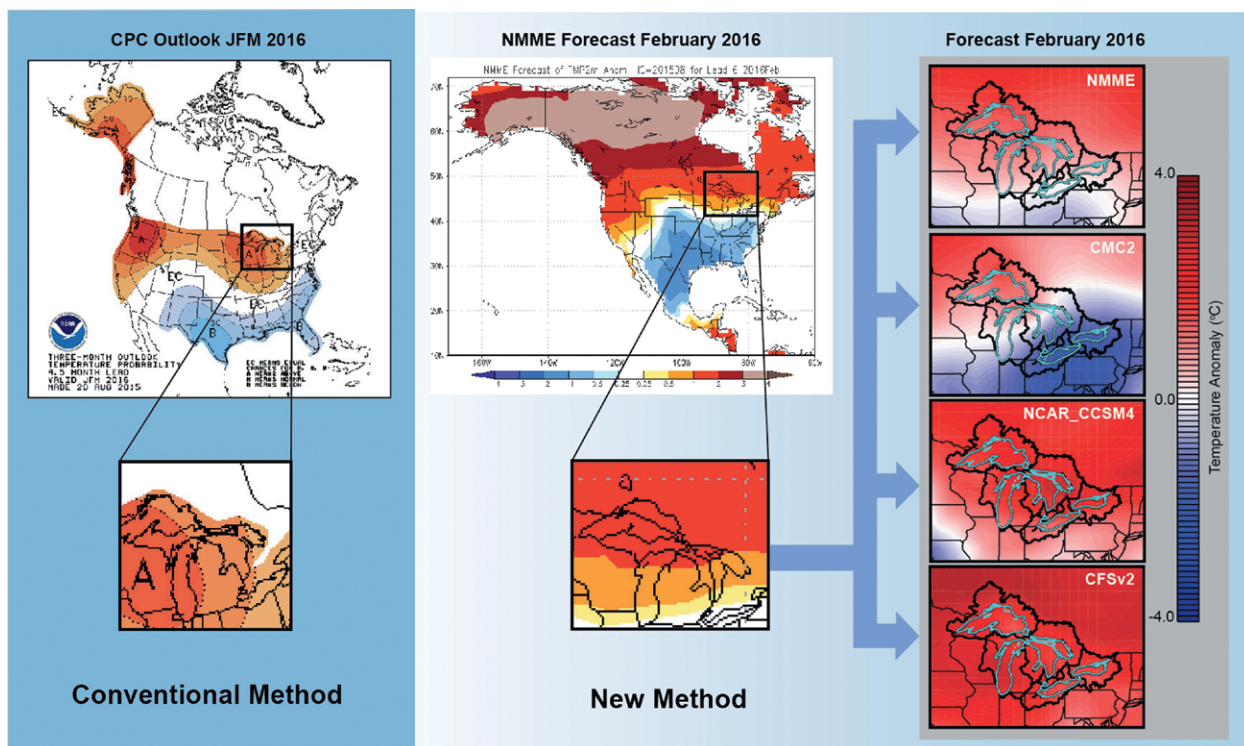


FIG. 2. Schematic depiction of the flow of information used by USACE-Detroit when making a monthly forecast. (left) Their conventional method relies on CPC’s LRFs, limited by international borders, with details regarding probability, climatology, and uncertainty all blended into one map. (right) The new method utilizes the NMME monthly forecasts, with coverage spanning international borders, and the flexibility to isolate details of a forecast, for example, specifically viewing deviations from climatology or uncertainty.

any region of interest. Code is written in an open-source programming language and is designed to automatically run (updating new files and archived files) each month. The second portion of the RSCF–NMME tool is the development of a web-based graphical interface.

This dynamic web tool allows users to visualize all the data available within the RSCF–NMME data files.

Application of RSCF–NMME. Figure 3 previews the graphical interface of the RSCF–NMME tool.

Great Lakes Seasonal Climate Forecast Tool (Version 2)

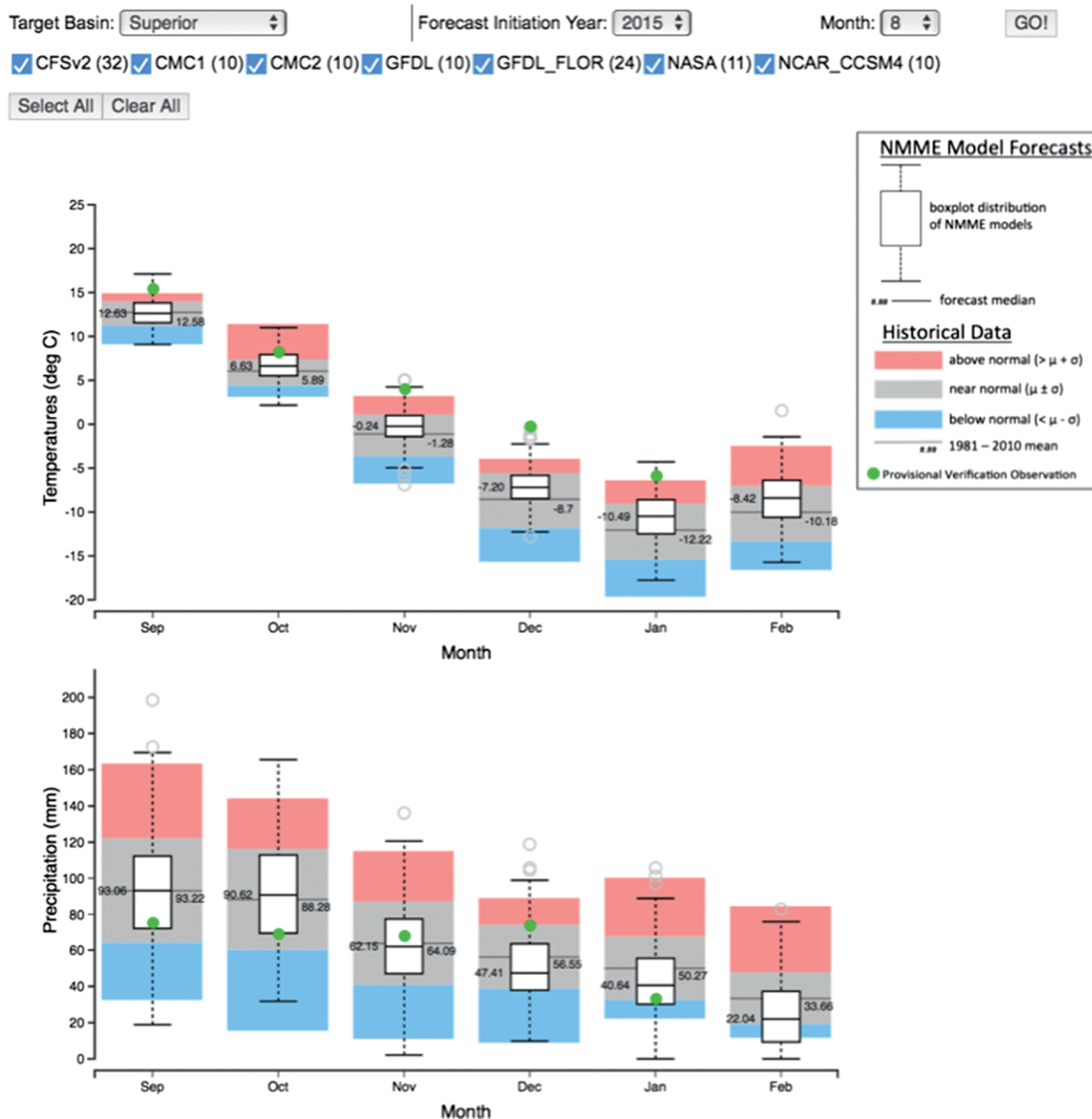


FIG. 3. Snapshot of the RSCF–NMME tool displaying monthly (top) temperature and (bottom) precipitation forecasts. Historical data from NOAA/GLERL Great Lakes hydrometeorological database (1948–2010 for temperature and 1900–2012 for precipitation) are shaded gray for values within one standard deviation of the 1981–2010 mean (referred to as the normal range), pink for values above the normal range, and blue for values below the normal range. Full distribution of NMME forecasts is depicted in the box-and-whisker plots, with the 25th–75th-percentile range of forecast values within the box; outliers are denoted with gray circles. Verification observations (green dots) are provided by NOAA/GLERL and are subject to change.

Boxplots representing the full range of NMME forecasts, or any combination of the individual models, are automatically generated by clicking on the boxes associated with each NMME model (Fig. 3, top). The distribution of forecast values emphasizes the full range (and uncertainty) within the NMME.

The tool automatically defaults to the most recent forecast period, but, as seen in Fig. 3, any forecast initiation date may be chosen. On 1 February 2016, the tool was accessed with a chosen initiation date of August 2015. The resulting display, seen in Fig. 3, shows the archived NMME forecasts for the following 6 months: September 2015–February 2016. In addition to the forecast information, for each month for which there is observation data, a verification point is added (green dot). Note that the verification observations are calculated using the same methods and stations as the regional climatology but are provisional and are subject to change. Since this example was accessed on 1 February 2016, there is no verification observation for the final month of the forecast sequence. The addition of the verification observations allows a user to easily assess how well the NMME (or one of its individual models) performed for the chosen forecast period.

Use of the RSCF–NMME has been effectively implemented into the forecasting operations at USACE–Detroit. The RSCF–NMME forecast median values are used as input into the previously mentioned empirical model, and forecasters regularly use the graphical interface to guide their water-level forecasting decisions.

RSCF–NMME FORECAST EVALUATION.

While the RSCF–NMME tool does not currently contain information from a full hindcast, the forecast archive (starting August 2011) can be used to evaluate the NMME forecasts for a displayed time period. Figure 4 shows the entire archive of the 3-month lead forecasts for the Lake Superior basin. For this example, the historical climatology shading now represents terciles to be more consistent with the CPC LRFs. However, instead of restricting the climatology to the 1981–2010 period, the full historical range is shown. The dashed lines within the shading show what the range would be limited to if the 1981–2010 period were chosen.

Figure 4 gives a direct comparison of the tool's forecasts versus the CPC's forecasts for a similar lead time. Even in the absence of an assessment of skill or performance, Fig. 4 highlights how much additional information is available to the user, beyond what can be gleaned from the LRFs.

The RSCF–NMME tool provides details about a region's climate that is not available when viewing the LRFs. The shaded background in the tool (Fig. 4, top panel) communicates what precipitation values are typical for the Superior basin and what magnitudes constitute an extreme event. While CPC's LRFs are based on the basin's climatology, a user would have to conduct an additional search to obtain specific details about that climatology. The added information that the tool provides in terms of climatology can be particularly useful for a decision-maker. For example, if a user needs to know in what month the average temperature for a basin typically rises above freezing (which relates to snowmelt and runoff), and if an above- or below-average forecast will significantly impact those conditions, the user can easily find that information with the RSCF–NMME tool.

With the RSCF–NMME tool, a user can access the full ensemble of forecasted values for a specific basin. These values are available to users in graphical form via the web interface but can also be retrieved in a data file. For example, USACE–Detroit accesses specific quantitative values to use as inputs into their empirical model. The USACE–Detroit forecasters have the option to use the forecasted median value from the entire ensemble, or they can choose the median from a specific model. For risk assessment and planning purposes, extreme values are also readily available for analysis. These are added benefits over the LRFs, which provide one probability distribution for a forecast period, and quantitative values are available only for individual stations (or climate divisions) that reside within the United States.

Users of the tool also have the benefit of being able to immediately see a verification observation (Fig. 4, green dots) and how that compared to the forecasts. While users of the LRFs have the ability to view archived outlook maps, observation maps for the same time periods are not included in that archive and may be difficult to find.

When evaluating the tool's entire archive of 3-month lead precipitation forecasts for the Superior basin (Fig. 4, top panel), we find that the range of the ensemble can change over time. Upper and lower bounds of the RSCF–NMME forecasts are flexible, meaning the forecasts are capable of forecasting extreme events. The CPC LRF probabilities are calculated based on the 1981–2010 climatology, so the upper and lower bounds will be restricted to within that observed range. While the RSCF–NMME tool can overcome these restrictions, it should also be noted that ensemble ranges can be fairly large, as seen in Fig. 4, where the full range is often larger

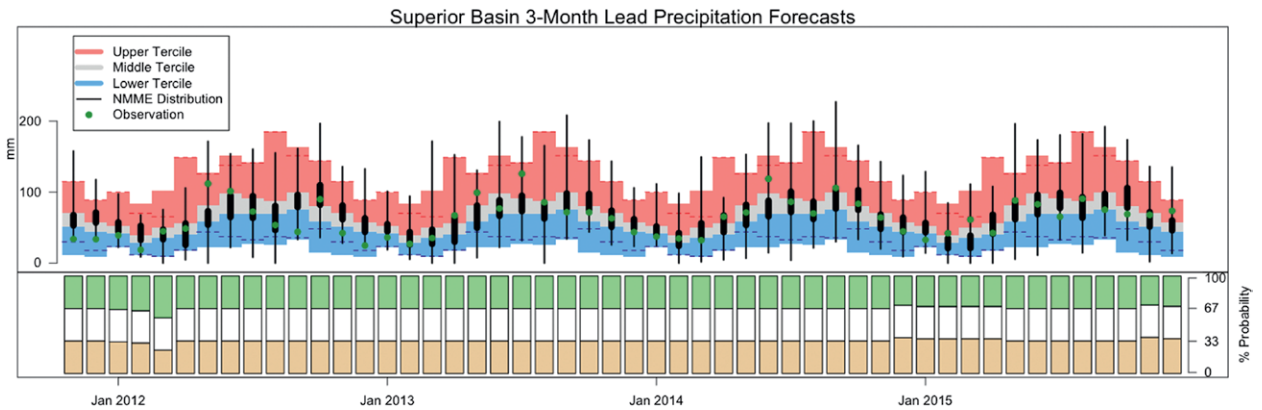


FIG. 4. Precipitation forecasts at a 3-month lead for the Superior basin. (top) Shading represents the historical range of observations, divided into the upper 33% of values in pink, the middle 33% of values in gray, and the lower 33% of values in blue. Full distribution of NMME is denoted in black, with thick black marking the middle 33% of forecasts. Green dots denote the verification observation for that month. (bottom) CPC's LRF for the same period, averaged over stations residing in the Superior basin. Probability of above-normal (below normal) precipitation is shaded in green (tan), and probability of near-normal precipitation is given in the white region. The top panel forecasts for a specific month (e.g., Jan 2012), and the bottom panel forecasts for a 3-month period (e.g., Jan–Mar 2012), both with a 3-month lead time (e.g., forecast initiated in Oct 2011).

than the entire historical range of observations. This introduces more uncertainty and can mean that certain model members are predicting extreme events too often.

The archive of precipitation forecasts also shows that the range of the middle-tercile forecasts (Fig. 4, thick black in top panel) can change in location (relative to the historical climatology) and width and can also deviate from the near-normal range (gray shading). The larger width of this middle tercile could suggest more uncertainty, but it can also give a clearer indication as to whether the ensemble forecast is leaning more toward above-normal or below-normal conditions. In the bottom panel of Fig. 4, we find that the probability of near-normal conditions remains the same throughout the entire time period (at 33%). Recall from Fig. 1 that it is possible for a forecast of above- or below-normal conditions to be so large that it reduces the probability of near-normal conditions, but that does not occur over the Superior basin in the 4 years analyzed. In fact, there were only 10 instances out of the 50 months in the analysis where equal chances were not forecasted. So, while there is a wide range of possible categories for the LRFs, the forecasts for the Superior basin (and the other Great Lakes basins) remain conservative. This is likely due to a lack of skill in the tools utilized by CPC forecasters over the region. While the RSCF–NMME tool does not give users an indication of the skill of the forecast they are viewing, it can give them more information than an equal-chances forecast on the LRF maps. For

example, forecasters at USACE-Detroit are limited to running their models assuming average conditions when relying on an equal-chances LRF. But when they have the extra information provided by the tool at their disposal, they can adjust their models to deviate from the average more often.

To demonstrate the effective delivery of the NMME forecasts to the USACE-Detroit forecasters, we detail their forecasting operations during the 2015/16 winter. Water-level forecasts are typically produced on the second day of the month. A forecaster begins the process before forecast day by writing a summary of the temperature and precipitation outlooks for the following 6 months. There is a direct relationship between water levels and precipitation, where a precipitation anomaly will result in a water supply anomaly of the same sign. The relationship between water levels and temperature is indirect and can vary throughout the year. Forecasters rely on the RSCF–NMME tool for temperature anomalies (paying close attention to the regional climatology) that could affect precipitation type (frozen precipitation will delay water supply increases), magnitude of evaporative loss from the lakes (based on air vs water temperatures), timing of lake freezing (affecting evaporative loss), and timing of snowmelt (which impacts timing of runoff into the lakes). It is evident, during this part of the forecast procedure, how the RSCF–NMME tool provides useful information, above and beyond the LRFs, that aids in the forecaster's decision-making process.

During the strong El Niño of 2015/16, both NMME and CPC LRFs predicted warm temperature anomalies throughout fall and winter and dry precipitation anomalies over the Great Lakes during the winter months. These predicted anomalies were taken into consideration by USACE-Detroit forecasters, and it was noted in their climate outlook summaries that although warm anomalies would decrease the likelihood of the lakes freezing over, the warm air temperatures would inhibit large evaporative losses off the lakes during November and December. Thus, they predicted higher water supplies increasing the water levels in the late fall and early winter due to warm temperature anomalies and lower water supplies decreasing the water levels in late winter due to the dry precipitation anomalies. The anomalously warm fall and winter verified (Fig. 3, green dots), and water supplies were anomalously high during the fall months. However, the winter was not uniformly dry across the basin for all winter months, as was anticipated (Superior was anomalously wet in December, for example, as seen in bottom of Fig. 3), and water supplies remained anomalously high into the spring.

This example highlights how USACE-Detroit forecasters were able to make more informed decisions during their forecasting procedure with the use of the RSCF–NMME tool, despite the fact that the forecasted anomalies from both sources (NMME and CPC LRFs) were similar. It is currently unclear whether their forecasts will demonstrate improved skill based on the inclusion of the RSCF–NMME into their operations. However, the possibility exists that Great Lakes water-level forecasts may improve with time, not only because of the addition of the regional climatology information provided by the tool, but also as the NMME climate models themselves are continually updated and improved.

SUMMARY AND FUTURE WORK. While the CPC LRFs remain a useful and informative operational product, we have introduced a web-based graphical tool that delivers added valuable information to end users who rely on seasonal climate forecasts for their decision-making. The tool has been successfully integrated into water-level forecasting operations at USACE-Detroit and has the potential to be modified and reproduced for other regions where there is demand.

The RSCF–NMME forecasts may present new challenges for water resources planning and management. A broad range of uncertainty among the models may prove less informative to decision-makers (Gronewold et al. 2011). However, with the flexibility of the tool,

the ability to choose specific models, and its display of regional climatology and verification observations, we believe the tool can better inform users who previously only had the LRFs at their disposal.

Future work is already under way to further improve the tool. Based on the request of forecasters at USACE-Detroit, regional maps of temperature and precipitation anomaly forecasts (as shown in Fig. 2, right) have been added to the web interface and can similarly be displayed for the entire ensemble or for individual models. To better align with CPC's LRFs, there is a plan to include a seasonal forecast option (i.e., 3-month averages instead of 1-month averages) and to utilize the NMME probabilistic forecasts that are also available. These additions will allow for better comparison of the performance of the tool to the performance of the LRFs and may be useful to potential future users.

A robust analysis on the performance of the NMME, and its individual models, for the Great Lakes region can better be determined by utilizing the full 29-yr hindcast datasets available for each model. A more comprehensive skill assessment is a necessary next step but is beyond the scope of this paper. Regardless, the application of the NMME within a seasonal climate forecast tool is a big step toward the advancement of the current state of operational climate forecasting and has proven useful in regional decision-making.

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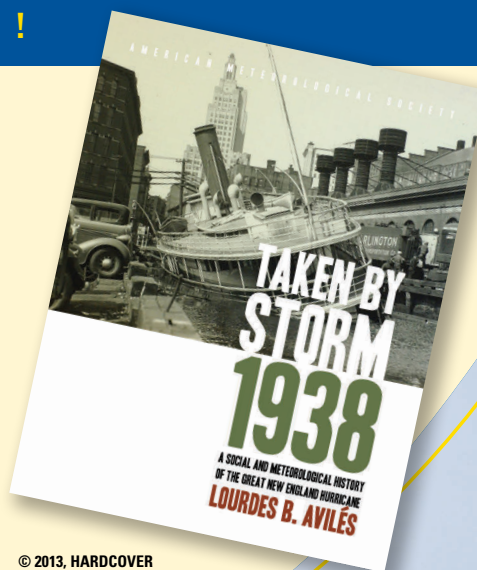
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