The Meteorological Development Laboratory's Aviation Weather Prediction System

JUDY E. GHIRARDELLI AND BOB GLAHN

NOAA/NWS/Meteorological Development Laboratory/Office of Science and Technology, Silver Spring, Maryland

(Manuscript received 8 June 2009, in final form 15 January 2010)

ABSTRACT

The Meteorological Development Laboratory (MDL) has developed and implemented an aviation weather prediction system that runs each hour and produces forecast guidance for each hour into the future out to 25 h covering the major forecast period of the National Weather Service (NWS) Terminal Aerodrome Forecast. The Localized Aviation Model Output Statistics (MOS) Program (LAMP) consists of analyses of observations, simple advective models, and a statistical component that updates the longer-range MOS forecasts from the Global Forecast System (GFS) model. LAMP, being an update to GFS MOS, is shown to be an improvement over it, as well as improving over persistence. LAMP produces probabilistic forecasts for the aviation weather elements of ceiling height, sky cover, visibility, obstruction to vision, precipitation occurrence and type, and thunderstorms. Best-category forecasts are derived from these probabilities and their associated thresholds. The LAMP guidance of sensible weather is available for 1591 stations in the contiguous United States, Alaska, Hawaii, Puerto Rico, and the Virgin Islands. Probabilistic guidance of thunderstorms is also available on a grid. The LAMP guidance is available to the entire weather enterprise via NWS communication networks and the World Wide Web. In the future, all station guidance will be gridded and be made available in a form compatible with the NWS's National Digital Forecast Database.

1. Introduction

Airport terminal weather forecasts are produced in the United States by civilian and military forecasters. These forecasts, called Terminal Aerodrome Forecasts (TAFs), are critical to decision making regarding aircraft movement within the National Airspace System. National Weather Service (NWS) forecasters routinely produce TAFs 4 times per day for projections up to 24 h from issuance time, with selected airports out to 30 h as of November 2008 (NWS 2008). In addition, updates are made when weather conditions have changed or are expected to change and those changes are operationally significant to airports or aircraft. Special attention is given to forecasts that have operational significance during the critical TAF period, which is defined as "0–6 hours from the current valid time within the TAF" (NWS 2008). TAFs, in a coded format, contain forecasts of clouds, visibility, wind, weather, obstructions to vision, and low-level wind shear. Prevailing conditions are forecast; temporary conditions can also be included, as well as probabilities of thunderstorms and precipitation.

The TAFs contain some of the most challenging weather elements to forecast skillfully, even for the relatively short period of the TAF. Forecasts of only a few hours are often compared to persistence, that is, a forecast of exactly what the most recent observation is. At longer projections, largely because of diurnal changes, some form of conditional climatology is used to deduce skill. The conditional climatology could be nothing more than the mean conditions stratified by time of day and month of year at the airport for which the forecasts are made, or can be more sophisticated with stratification by categories of existing conditions. The old RUSSWO[1] tables developed and used by the U.S. Air Force years ago are early examples of what can be done with stratified climatology. Such tables were not intended to be a final forecast but, rather, were to provide guidance to forecasters concerning what weather conditions were likely or not likely given the existing conditions.

Corresponding author address: Judy E. Ghirardelli, National Weather Service/Meteorological Development Laboratory, 1325 East–West Hwy., Silver Spring, MD 20910.
E-mail: judy.ghirardelli@noaa.gov

[1] RUSSWO stands for Revised Uniform Summary of Surface Weather Observations. The original tabulations are archived on microfiche at the National Climatic Data Center.

DOI: 10.1175/2010WAF2222312.1

Because good quality forecasts are of critical importance to the aviation community, there have been many attempts to provide meaningful numerical models and statistical guidance for aviation forecasting. The earliest attempts were purely statistical and had their heyday in the late 1950s and 1960s at the Travelers Research Center (e.g., Enger et al. 1962). Other early attempts were made at the U.S. Air Force's Cambridge Research Laboratory (e.g., Lund 1955). Somewhat later, work was carried out at the NWS's Techniques (now Meteorological) Development Laboratory (TDL/MDL, hereafter referred to as MDL; see Glahn 1964; Miller 1981).

While numerical weather prediction (NWP) models have improved significantly over the past 50 yr (Kalnay et al. 1998), the NWS TAFs [formerly known as terminal forecasts (FTs)] have not realized comparable improvements. Even though an early study (Zurndorfer et al. 1979) showed a general improvement in local NWS aviation forecasts, a later study (Dallavalle and Dagostaro 1995) showed no improvement. In addition, while the NWP models have improved, they have not yet developed to the point that the forecasts cannot be improved with postprocessing. Dallavalle et al. (2004) compared model output statistics (MOS) guidance from the Global Forecast System (GFS; Kalnay et al. 1990) and the Nested Grid Model (NGM; Hoke et al. 1989) with the direct model output from the GFS model. They found that the GFS MOS performed better than the NGM MOS, and both MOS systems performed better than the direct model output from the GFS.

Recently, short-range and mesoscale NWP models have begun to offer forecasts of nontraditional model elements, such as ceiling height and visibility, to assist with aviation forecasting. However, these model forecast elements are relatively new and have not yet proven to be of sufficient quality to be widely accepted, for many reasons. First, because of the time required for the collection of the data needed for the data assimilation, model initialization, and model execution, the forecasts may not be produced and distributed quickly enough to compete with persistence in the very short term. Second, the procedures to produce the weather elements needed for TAFs, such as ceiling height and visibility, are rather rudimentary and generally are an add-on to forecasting the state variables of temperature, pressure, moisture, and wind above the earth's surface. The models also do not generally contain all the physics necessary to simulate the processes involved in, for instance, visibility, and in addition, the observational data are generally not sufficient to adequately initialize such a model.

Given the need for aviation guidance, and considering the above difficulties and challenges, MDL began a project to provide objective statistical guidance for aviation weather forecasting. This paper provides an overview and the history of MDL's progress in providing such guidance. The concept of MDL's aviation guidance system is presented in section 2, and section 3 presents the history of the earlier, as well as the current, guidance systems developed by MDL to support aviation weather forecasting at NWS Weather Forecast Offices (WFOs). Section 4 discusses the development details of the current system. The current status of the system, available products, and current uses of LAMP are presented in section 5. Verification of the current guidance is presented in section 6. Future plans are presented in section 7, and a summary and conclusions are discussed in section 8.

2. The system concept

In an effort to provide good quality aviation guidance for TAFs, MDL began development of a system to blend persistence with what could be deduced from existing numerical models run at the National Centers for Environmental Prediction (NCEP), and to include an upstream component furnished by simple advective models. Such work started as early as 1980 (Glahn 1980); the project was called the Local Automation of Field Operations and Services (AFOS) MOS Program (LAMP; Glahn and Unger 1982). The LAMP concept was to develop a locally run MOS-like system to provide short-term guidance of sensible weather for public and aviation forecasting. There were to be three basic kinds of inputs to the system: 1) hourly observations of sensible weather at the surface, 2) output from simple, locally run models, and 3) MOS forecasts. The intent was that such a system would be able to be run by a forecaster on a local computer, at any time of the day. The system would be MOS-like in that multiple regression would be used to combine the various inputs, a technique that had been proven to be very successful for MOS (Glahn and Lowry 1972).

Consistent with the LAMP concept, NCEP numerical model output would not directly be used as predictor input. Instead, MOS guidance was intended to represent the pertinent model information. This was done for three reasons. First, regression equation development requires an adequate sample of data from a stable model, but numerical models do undergo change. Partly for that reason, the MOS guidance is rather regularly updated to keep pace with the models. It was believed that the updated MOS forecasts would still be rather stable, and their updating would not require updating LAMP, provided that LAMP continued to improve on the MOS guidance. While updating LAMP equations for new MOS guidance might be ideal, there would always be the question of resources and if any additional benefit would be worth the cost of redeveloping (D. A. Unger 2009, personal communication). Second, we wanted the LAMP forecasts to blend well, even approximate, the MOS

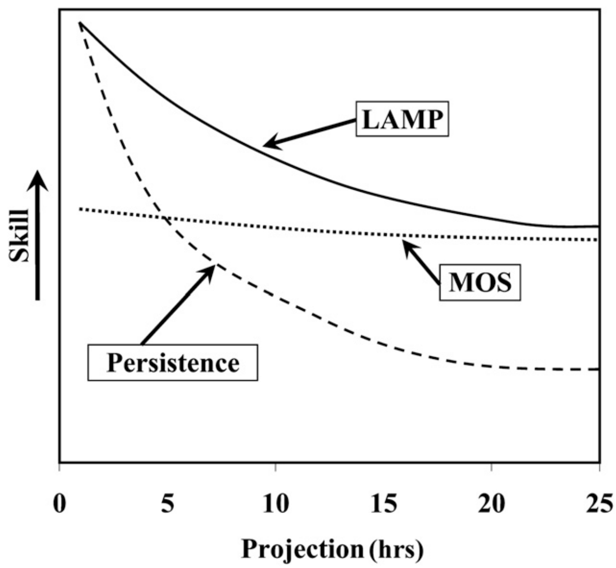

FIG. 1. Conceptual illustration of the LAMP paradigm. Persistence is indicated by the dashed line, MOS by the dotted line, and LAMP by the solid line.

forecasts at the end of the LAMP forecast range; using the MOS forecasts as input would not guarantee that, but the blending of LAMP into MOS would be much better than if raw model variables were used as input. Finally, the use of MOS simplified development in some respects, because the number of MOS predictors was not as large as the potential number of model predictors. Therefore, NCEP model data were not offered directly as predictors in the LAMP regression [however, this policy was relaxed in some cases; an exception is described in section 4b(5)]. By using MOS guidance as predictors, and recognizing that MOS is skillful at predicting sensible weather, one could consider MOS to be a very good first guess to the LAMP system. This use of MOS guidance as predictor information is a critical aspect of the LAMP concept.

While MOS produced guidance for comparable, and many of the same, weather elements for which LAMP would produce guidance, LAMP would differ from MOS in that it would be designed to run much more frequently than MOS to take advantage of the most recent observations. In this way, LAMP would act as an update to the MOS guidance. The use of the most recent observations as predictor information is another critical aspect of the LAMP concept.

A very similar approach to LAMP, which assigns great weight to the observations, has been reported by Jacobs and Maat (2005). They conclude that, ''Although advancements in NWP modeling have been substantial over the last decade, these models have not reached a state where clouds and precipitation can be resolved at the spatial and temporal resolutions needed for airport weather forecasts.... In particular, the quality of short-term forecasts, up to 6 h, depends mainly on the availability of local and upstream observations.'' Leyton and Fritsch (2003) also found that the most recent observations of ceiling height and visibility were very valuable predictors in the 1–3-h forecast time frame, as were the observations from neighboring sites. MDL's blended method of providing guidance in the very short range corresponds to the description of effectiveness of approaches to short-range forecasting described by Doswell (1985). His diagram shows linear extrapolation is best up to an hour or two, climatology has the edge for the next few hours, and mesoscale or large-scale models eventually become useful. The techniques employed in LAMP and by Jacobs and Maat (2005) blend these sources to approach what Doswell shows as ''knowledge of meteorology.'' This insightful diagram is repeated by Brooks et al. (1992).[2] Figure 1 illustrates the simple but powerful concept of LAMP; the persistence of the observation is a good competitor in the early projections, and the observations contribute strongly to LAMP in this time frame, while MOS is more accurate than persistence in the later periods. The simple models are intended to help blend these two important types of predictors. The result is a smart interpolation between the observations and the MOS guidance.

3. History of the LAMP systems

As discussed in the previous section, the original LAMP system was started in the early 1980s (Glahn and Unger 1982) and followed the concept described previously. The MOS used to develop this early LAMP approach was based on the Limited-Area Fine Mesh (LFM) model (Gerrity 1977; Newell and Deaven 1981). Studies were done to assess the performance of the LFM LAMP in the 1980s, and while the studies were limited to select stations or cycles, and were not performed on operational guidance, the studies showed that LAMP improved on MOS in the early to middle part of the forecast period, and for some elements throughout the entire period (Glahn and Unger 1982; Glahn 1984; Glahn and Unger 1986; Cammarata 1987; Unger 1987; Unger et al. 1989).

The LFM LAMP was not implemented in AFOS, although it was tested locally at the NWS forecast office in Topeka, Kansas, in 1989 (Unger et al. 1989). At this point, the NWS was in the process of making a number of changes that would impact LAMP. First, the NWS

[2] While the exact relative contributions of the sources can be debated, the concept is sound.

was planning to modernize its operations with the development of the Advanced Weather Interactive Processing System (AWIPS; Friday 1994). Second, the new MOS was developed based on the NGM (Carter et al. 1989). Finally, the NWS was planning to discontinue the LFM model, and therefore the LFM MOS would likewise be discontinued. Given these plans, it was determined that LAMP would update the new NGM MOS and run locally in AWIPS. Because redeveloping the LAMP system to use NGM MOS as predictor inputs would have been costly and time consuming, the equations developed from the LFM MOS were retained, but implemented such that the LFM MOS predictors were replaced in operations with comparable NGM MOS predictors.

The LAMP system was renamed the Local AWIPS MOS Program to indicate its place within AWIPS. The system was implemented in the late 1990s in AWIPS at local NWS WFOs in the contiguous United States (CONUS), and it produced local guidance 8 times per day at WFOs (Kelly and Ghirardelli 1998), but changing hardware, software, etc. made it very difficult to support. This local implementation exemplified the difficulty of integrating a guidance system into a hardware–software platform not designed for such applications.

Other deficiencies became apparent with the NGM LAMP system. The NGM LAMP provided guidance for less than 1000 stations in the CONUS only. Newer MOS guidance suites, such as that from the GFS, were available that were based on updated NWP models and provided guidance for upward of 1500 stations in the CONUS, as well as in Alaska, Puerto Rico, the Virgin Islands, Hawaii, and Guam. Finally, the NGM was "frozen," which meant that it was not realizing any NCEP improvements other than to the analysis and initialization procedures. Given these changes, it was clear that LAMP's development and its implementation could be improved.

The LAMP system was therefore redeveloped in order to provide more accurate guidance for more stations than the NGM LAMP system. In addition, the new LAMP would update the more timely and accurate GFS MOS guidance and run hourly out to 25 h, covering the standard 24-h TAF period.[3] The GFS MOS was chosen because it was the MOS package that offered the most complete set of guidance for aviation forecasting [see Dallavalle and Cosgrove (2005) for details of the GFS MOS guidance]. Recognizing that the main purpose of LAMP was to furnish guidance for aviation forecasts, we renamed the model the Localized Aviation MOS Program—the LAMP acronym remained (Glahn and Ghirardelli 2004; Ghirardelli 2005). Also, in an effort to ensure maintainability, the GFS LAMP (hereafter referred to simply as LAMP) was designed to run centrally on the National Oceanic and Atmospheric Administration (NOAA) Central Computing System at NCEP, and the official products would be disseminated centrally from NCEP. This is the LAMP system running in NWS operations today, and the remainder of the discussion deals with this current system.

[3] The recent extension to 30 h at some airports is not covered, but MOS guidance is available.

4. The current LAMP: Development details

The MOS approach (Glahn and Lowry 1972) was followed for the redevelopment of LAMP. Multiple regression equations were developed to provide guidance for sensible weather elements. Thresholds were developed to facilitate a best-category forecast selection based on the probabilities of multiple categories. Details of this development follow.

a. Predictand definitions

Predictands were defined for the elements shown in Table 1. For continuous forecasts, predictands were defined as the actual continuous observations. For probabilistic forecasts, the continuous observations were transformed prior to the regression process by defining the predictands as binary values of 1 or 0, which indicated whether the events were observed or not, respectively. For example, the predictand values for the probability of visibility <½ mile were determined from the visibility observations. The predictand was assigned a value of 1 if the observed visibility was <½ mile, and a value of 0 if it was not. The predictand data were taken from the hourly aviation routine weather report (METAR; OFCM 1995) observations for all elements except thunderstorms, for which the predictand data came from lightning strikes on a grid.

b. LAMP predictors

LAMP has five primary sources of input: 1) METAR observations at stations; 2) observation data (lightning and radar) on a grid; 3) GFS MOS forecasts; 4) output from advective and other simple models, which in turn require the aforementioned observations and upper-air data from the GFS; and 5) other miscellaneous predictors. In general, of all the predictors, the observations and the GFS MOS guidance explain the most predictand variance, and are considered the most important. These inputs are briefly described here.

1) Observations or analyses of observations

Persistence is a very competitive system in the very short term, especially in forecasting ceiling height and

TABLE 1. LAMP guidance elements.

Element description	Unit–best-category definition
Temp	°F
Dewpoint temp	°F
10-m wind direction	10s of °
10-m wind speed	kt
10-m wind gust speed	kt
Precipitation occurring on the hour	Probabilities (%) Best category (yes–no)
Measurable precipitation in a 6-h period	Probabilities (%)
Measurable precipitation in a 12-h period	Probabilities (%)
Thunderstorms in a 20-km grid box in a 2-h period	Probabilities (%) Best category (yes–no)
Precipitation type, conditional on precipitation	Probabilities (%) Best category (liquid, frozen, freezing)
Precipitation characteristics, conditional on precipitation	Probabilities (%) Best category (drizzle, continuous, showers)
Total sky cover	Probabilities (%) Best category (clear, scattered, few, broken, overcast)
Ceiling height	Probabilities (%) Best category (<200, 200–400, 500–900, 1000–1900, 2000–3000, 3100–6500, 6600–12 000, and >12 000 ft or unlimited ceiling)
Ceiling height, conditional on precipitation	Probabilities (%) Best category, same as ceiling height
Visibility	Probabilities (%) Best category (<½, ½ < 1, 1 < 2, 2 < 3, 3–5, 6, and >6 miles)
Visibility, conditional on precipitation	Probabilities (%) Best category, same as visibility
Obstruction to vision	Probabilities (%) Best category (none; haze, smoke, or dust; mist; fog; blowing dust, sand, or snow)

visibility (Dallavalle and Dagostaro 1995). Because of this, the most recent observations were provided as predictors in LAMP. For instance, for ceiling height equations, the observed ceiling height was used as a predictor. To compensate for times when the observation is missing, the other available observations were analyzed onto a grid. The elements analyzed were surface (2 m) temperature and dewpoint, ceiling height, sky cover, visibility, obstruction to vision, precipitation occurrence, precipitation type, and a moisture variable called the saturation deficit. For the variables with a continuous range of values (temperature, dewpoint, winds, saturation deficit), the analyses were made by a highly tuned successive correction method. The specific method was derived from the original formulation by Bergthorsson and Doos (1955) and implemented by Cressman (1959). The smoother used was a generalization of that used by Cressman and defined by Thomasell and Welsh (1962). For the variables with spatially discontinuous fields (ceiling height, sky cover, visibility, obstruction to vision, precipitation occurrence, and precipitation type), a nearest-neighbor approach was used; that is, a gridpoint value was given the value observed at the closest station. Each of these analysis approaches was tuned to the variable being analyzed in terms of search radius, degree of smoothing, quality control thresholds, etc. Also, if an observation was missing for the current analysis hour, the observation from an hour earlier was used under specified conditions. [Details of the analysis technique can be found in Glahn et al. (1985).] Each analysis was available hourly.

Once the analysis was performed, a simple interpolation was used to furnish an estimated observation at the station. This analyzed value was then used in a backup capability, and acted as a surrogate for the unavailable observation. While the analyzed value is a less desirable predictor than the true observation, it nonetheless still has predictive value and might yet be the most important predictor available for very short projections at times when a station's observation is unavailable.

2) GRIDDED OBSERVATION DATA

Gridded observation data consisting of radar reflectivity and cloud-to-ground lightning were offered as predictors in the new LAMP system. The two sources of radar data used in the development were 16-level, 2-km Weather Science Incorporated (WSI) radar reflectivity data available from National Aeronautics and Space

Administration's (NASA) Global Hydrology Resource Center (GHRC), and the 7-level, 10-km Radar Coded Messages (RCM) radar mosaic available from the NWS (Kitzmiller et al. 2002). The WSI radar data from 1 April 1997 to 31 March 2002 and the RCM data from 1 April 2002 onward were used in the equation development (Charba and Liang 2005). The WSI radar data were available every quarter hour, and the RCM radar data were available every half hour. If the most recent radar data were unavailable, the next most recent radar data were used (if available) for backup purposes. Since only the RCM data are available in real time, the RCM data are the radar data used as predictors in real time. As in development, the RCM data are available every half hour in real time, and the next most recent RCM data serve as backup if the most recent RCM data are unavailable.

The second type of gridded observational data was specified from observed cloud-to-ground lightning data from the National Lightning Detection Network (NLDN; Cummins et al. 1998). These data in their native format are not gridded, but are stored as strikes by latitude and longitude. The strike data were put on a 10-km polar stereographic grid that covers the CONUS and the adjacent offshore waters (Charba and Liang 2005). In real-time LAMP operations, the observed NLDN data are gridded and used as observational predictors.

3) GFS MOS FORECASTS

The third type of LAMP predictor was the GFS MOS guidance valid at the desired projection. Typically, the GFS MOS forecast for the same elements as the LAMP predictand was offered as a predictor. For example, the GFS MOS temperature forecast, valid at the hour corresponding to the LAMP forecast valid time, was offered as a predictor in the LAMP temperature development. GFS MOS forecasts for elements other than the LAMP predictand were also offered where appropriate. For example, GFS MOS wind forecasts in addition to the GFS MOS visibility forecasts were offered as predictors in developing equations for the LAMP visibility predictands. GFS MOS output was available with projections typically at 3-h time steps. To make forecasts at 1-h intervals for LAMP, it was necessary to temporally interpolate the GFS MOS forecasts valid at 3-h intervals to the desired 1-h projections.

GFS MOS guidance is produced every 6 h in NWS operations, and the GFS MOS forecasts from the MOS cycle that would be available to LAMP in real time were provided as predictors. While the nominal cycles of the GFS MOS are 0000, 0600, 1200, and 1800 UTC, the guidance is not available at those times but roughly 4 h later (e.g., 0000 GFS MOS is available around 0400 UTC, 0600 UTC MOS at 1000 UTC). Therefore, LAMP was developed using input from the GFS MOS cycle that would be available at the time when LAMP would run in operations. Figure 2 shows a timeline that illustrates the temporal relationship between the GFS MOS and LAMP guidance.

MOS, like LAMP, was developed with observations as predictors, and the observations input into GFS MOS in real time are from the hour before the issuance time (e.g., the 0000 UTC GFS MOS is issued at approximately 0400 UTC, and uses the 0300 UTC observations as predictor input). Therefore, when MOS is made available (e.g., at 0400 UTC), the observational input is already 1 h old, and gets older with every hour until the next GFS MOS guidance is produced (e.g., at 1000 UTC). This affords LAMP the opportunity to use the more recent observations (i.e., observations after 0300 UTC) to update the most recent GFS MOS. The timeline shown in Fig. 2 illustrates the relationship between the observations and the guidance systems.

4) LAMP MODELS

Output from three simple models was offered as predictors in LAMP. The first model is an advective model that was used to "look upstream" (Unger 1982; Unger 1985), a technique every forecaster practices. Schmeits et al. (2008) also found advected fields, specifically an ensemble of advected radar and lightning, useful in their MOS-like technique for forecasting thunderstorms. They state that while advecting cells out beyond a couple of hours may not be predictive for deterministic forecasts, such advection may provide predictive information for probabilistic forecasts even beyond 6 h because the conditions responsible for the observed cells have been advected to a new area.

The advective model used in LAMP is the cloud advection model (CLAM; Grayson and Bermowitz 1974). Its implementation in LAMP is detailed in Glahn and Unger (1986). One modification to previous uses of the CLAM model in LAMP is that in the current system, the winds that drive the advection come from highly smoothed winds from the GFS model, and a blend of different level winds can be used for different advected fields. In development, the model provided advective forecasts of temperature, dewpoint, ceiling height, sky cover, visibility, obstruction to vision, precipitation occurrence, precipitation type, radar, and lightning, and these forecasts were provided as predictors to indicate upstream conditions that would be affecting the station in the short range.

The second of the LAMP models is the sea level pressure model, and the third LAMP model is a moisture model, which provided forecasts of the saturation deficit (initially defined by Younkin et al. 1965). The implementations of the sea level pressure and moisture models

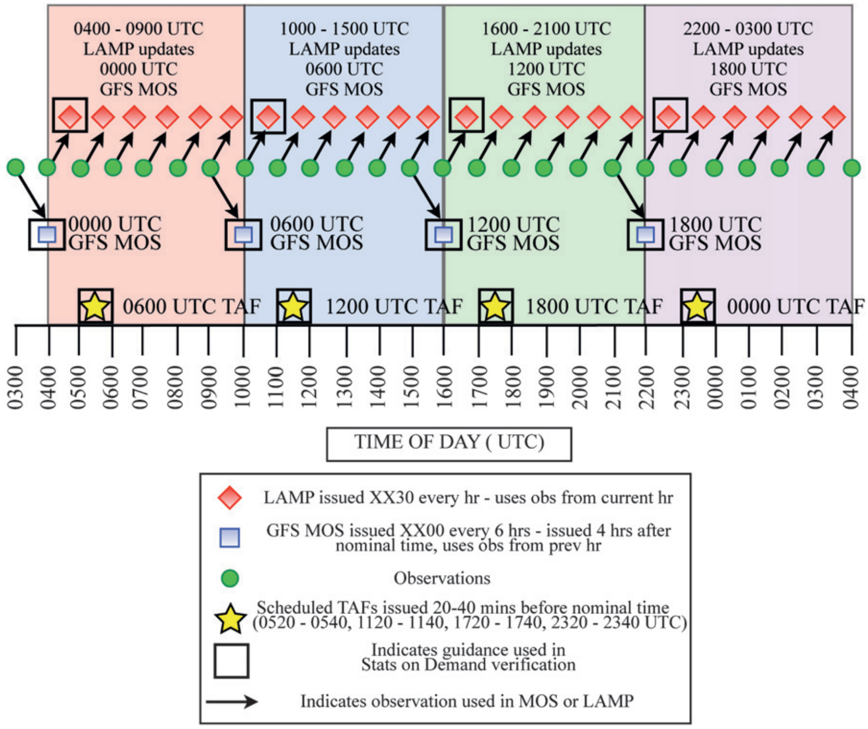

FIG. 2. Timeline showing temporal relationship between observations and the nominal and issuance times of the GFS MOS, LAMP, and scheduled TAFs. MOS is issued 4 h after the nominal time around XX00 UTC. LAMP is issued the same hour as the nominal time, at XX30 UTC. The scheduled TAF is issued 20–40 min before the nominal time, between (XX − 1)20 and (XX − 1)40 UTC. The observation input into GFS MOS is from the hour previous to the MOS issuance. The observation input into LAMP is from the same hour as the LAMP issuance. The systems used for Stats on Demand verification of scheduled TAFs (see section 6b) are indicated by a black outline around the system–issuance used. Forecasts from the GFS MOS cycles with nominal times of 0000, 0600, 1200, and 1800 UTC, and from the LAMP cycles with nominal times of 0400, 1000, 1600, and 2200 UTC, are verified in Stats on Demand for comparison with forecasts from the scheduled TAFs with nominal times of 0000, 0600, 1200, and 1800 UTC.

in LAMP are explained in Glahn and Unger (1986). Saturation deficit represents the difference between the 1000–500-mb thickness and the thickness that would be expected for precipitation to begin (Unger 1985). The specification of the saturation deficit uses the surface observations and GFS model precipitable water forecasts to help define a moisture layer and has been of some use in LAMP.

5) OTHER MISCELLANEOUS PREDICTORS

As stated previously, in some instances GFS direct model output was also offered as predictors in developing LAMP. These predictors were included in the development if the model information was not already contained in the GFS MOS guidance, and if it was believed that they would be useful in LAMP. Therefore, only GFS model predictors not already used in MOS, and considered stable, were permitted in the LAMP development. In addition, some interactive predictors were computed from GFS output and included in the development. For example, LAMP thunderstorm equation development included the product of a modified K index and the thunderstorm relative frequency as a predictor (here, the modification involved taking an average of the LAMP surface temperature and the GFS 850-mb temperature and likewise for dewpoint) (J. Charba 2009, personal communication). In addition to the other predictors mentioned, development also included climatological (e.g., the relative frequency of an event) and geoclimatic predictors (e.g., cosine of the day of the year).

c. Regression equation development

Multiple linear regression was used to develop the LAMP equations, and the predictors were selected with a forward-screening process (Glahn and Lowry 1972).

While the regression was linear, nonlinearity could be represented by transformations of the input variables. Examples of such transformations included predictors that were calculated as the cube root of a variable or the product of two variables. Equations were developed to produce continuous forecasts (such as temperature) as well as probabilistic forecasts (such as the probability of visibility $<$3 miles).

While the observations are excellent predictors, a station's observation may be unavailable at times, and a robust system must plan for such situations. Use of the observation as a predictor is the basic paradigm of LAMP, and we intended for all equations to have observations as predictors. However, a missing observation would therefore result in a missing forecast, which is not acceptable from an operational product. To avoid this, secondary, or backup, equations were developed that did not use the observations as predictors. The value interpolated from the observational analysis was used as a predictor in the development of backup equations to represent an estimate of the missing observation, as was discussed in section 4b(1). The forecast from a backup equation is used only if the equation developed with observations as predictors, called the primary equation, cannot be evaluated. Forecasts from backup equations are slightly inferior to forecasts generated from primary equations, especially in the very short term when the observations contribute the most to the forecast. Both primary and backup equations were developed for all elements.

Regression equations for 24 cycles (one set of equations per hourly cycle) were developed from data in various periods from 1997 through 2008. The developmental periods differ by cycle depending on when the equations were developed and what data were available at the time of development. Equations were developed for various seasons. Thunderstorm equations were developed for dates in three seasons: cool (16 October–15 March), early warm (16 March–30 June), and late warm (1 July–15 October). Precipitation type equations were developed for two seasons: cool (1 September–31 May) and warm (1 June–31 August). Precipitation-type forecasts for the warm season are only available for Alaska because the data were insufficient for development in the remainder of the country (i.e., there were too few cases of freezing or frozen precipitation). The remaining elements were developed with data from two seasons: cool (1 October–31 March) and warm (1 April–30 September). In general, data from 15 days on either side of these seasons were also included in the developmental sample to better handle the transition from one season to the next.

The equations for wind (Wiedenfeld 2005), temperature, and dewpoint were developed with a single-station approach. In the single-station approach, an equation is developed for a station from data specific to that station. However, some elements may not have a sufficient number of cases for all categories (e.g., the relatively rare category of visibility $<$½ mile) at individual stations, and for these elements the equations were developed from data pooled from multiple stations in a region. Equations for thunderstorms (Charba and Liang 2005; Charba and Samplatsky 2009), visibility and obstruction to vision (Rudack 2005), ceiling height and sky cover (Weiss and Ghirardelli 2005), wind gusts, probabilities of precipitation, and precipitation type and characteristics were developed with the regional approach.

To combat inter-element inconsistency, the equations for elements that one would expect to be related and whose definitions rely on each other, such as ceiling height and sky cover, were developed simultaneously. The equations for some other elements, such as temperature and dewpoint, were developed simultaneously and their forecasts were postprocessed to guarantee they were meteorologically consistent. Simultaneous development means selecting predictors based on their importance for all predictands being developed. That is, the elements developed simultaneously share common predictors; this helps to minimize inter-element inconsistencies. In addition, simultaneous development means that the equation development is based on the same sample for all the predictands for which the simultaneous development is being done. For example, when developing temperature and dewpoint equations simultaneously, if the temperature observation was available for a given date, but the dewpoint observation was missing, that case was not included in the data sample. By doing this, the equations for related predictands were developed on a matched sample of data.

MDL has written special regression software for use in LAMP development to minimize or eliminate small-scale temporal fluctuations in hourly forecasts. Glahn and Wiedenfeld (2006) describe the specialized MDL software, which is summarized here. This software selects predictors based on the highest reduction of variance contribution to any predictand at any projection in the forecast period. Once selected, this predictor is then included in the equations for all predictands at all projections. Of course, this chosen predictor may not always be useful for a given predictand or a given projection (i.e., when its additional reduction of variance is low for that predictand or projection). In such cases, the predictor is still present in the equation, but with a coefficient of zero. Finally, if a predictor is assigned a coefficient of zero for a reason mentioned above, then coefficients of zero are also assigned to it for subsequent projections if the predictor was an observation (this assumes that once the observation lost its predictive value, it did not later gain predictive value). Conversely, if the predictor assigned a coefficient of zero is an MOS predictor, coefficients of zero are also assigned to it for all preceding projections (this assumes that the contributing value of the MOS predictor should increase with projection). This set of rules implemented within the regression software aims 1) to ensure that a common set of predictors is chosen for all the projections in the forecast period, which should minimize temporal fluctuations since only the predictor values and coefficients change by projection, not the actual predictors themselves, and 2) to place the highest weight on observations early in the forecast period and MOS predictors later in the forecast period.

d. Threshold development and application

In addition to continuous and probabilistic guidance, LAMP also produces guidance that is categorical (e.g., ceiling height of 200–400 ft, visibility <½ mile, and sky cover of broken; see Table 1). The categorical forecasts are not produced from regression equations, but instead by a postprocessing step that compares the probability forecasts to corresponding thresholds to determine a best-category forecast given the probabilities of the various categories.

To develop the thresholds, the regression equations for probabilistic elements were evaluated to create probabilistic forecasts for the developmental sample. The probabilities were postprocessed to guarantee that their values were between zero and one. The thresholds were then derived from this developmental sample by using an iterative process to determine thresholds that, when used with the corresponding probabilities, yielded best-category forecasts that either achieved unit bias (meaning that the event was forecasted as often as it occurred), or which maximized the threat score, which is also called the critical success index (CSI; Donaldson et al. 1975; Wilks 2006), within a certain bias range. The goal of maximizing the threat score is usually preferable for rare, high-impact events (e.g., low ceilings). In LAMP, ceiling height thresholds, for example, were derived by selecting thresholds that maximized the threat score, while sky cover thresholds were derived by selecting thresholds that achieved unit bias (Weiss and Ghirardelli 2005).

In real time, the LAMP thresholds are used to facilitate the best-category decision in the following manner. As an example, the probability of the lowest ceiling height (ceiling height <200 ft) is compared to the threshold for the lowest ceiling. If the probability equals or exceeds the threshold, that category is chosen as the best-category forecast. If not, the probability for the next category (ceiling height <500 ft) is compared to its corresponding threshold. Again, if the probability equals or exceeds the threshold, that category is chosen. This continues until a probability equals or exceeds a threshold, and a selection is made. If the highest category that has a probability (in this case, ceiling height ≤12 000 ft) is reached without a probability equaling or exceeding its threshold, the default category (in this case, ceiling height >12 000 ft or unlimited) is selected (Weiss and Ghirardelli 2005).

e. Postprocessing for forecast consistency

Producing guidance at hourly intervals provides challenges for ensuring both meteorological and temporal consistency. When developing a forecast system such as LAMP, one must achieve an acceptable balance between forecast skill and both kinds of consistency. For example, if the system forecasted a high visibility, and then a lower visibility, in a short period of time, with no corresponding forecast of obstruction to vision or precipitation to account for the lowered visibility, the educated user would recognize this as a meteorological inconsistency. If the user changed the forecast so that the visibility was higher when LAMP indicated it should be lower, the result could be a more consistent but less accurate forecast (perhaps the original visibility forecast verified, and it was the obstruction to vision forecast that was erroneous).

Two kinds of temporal consistency issues exist. The first is that when making forecasts every hour, a user might want consistency from one issuance to the next. While this is generally desirable, one must remember that the purpose of LAMP is to provide updated guidance based on the most recent conditions. If the conditions are changing in a way not previously indicated in the LAMP or MOS guidance, one would *want* the new LAMP guidance to reflect that change and therefore be different from previous issuances. This is an acceptable temporal change between issuances. A change from the previous hour can also happen due to the MOS guidance changing. New MOS guidance is used in the LAMP cycles starting at 0400, 1000, 1600, and 2200 UTC. LAMP guidance can change at these times purely due to the change in the GFS MOS guidance used in LAMP, and not due to the recent observations. If this reflects an improvement in MOS, that is a desirable effect in LAMP.

A second kind of temporal in consistency can occur within the LAMP forecast period. For instance, one would not usually want to forecast only 1 h of overcast sky cover in the middle of a 25-h period when all of the other sky cover forecasts were clear. Even though skillfully forecasting a temporal fluctuation like this would be highly useful, any such LAMP forecast variations would probably not be skillful.

Therefore, some attention must be given to both meteorological and temporal consistency within the forecast period. One would not want to produce a dewpoint that was higher than the corresponding temperature, or have a reduced visibility with no precipitation or associated obstruction to vision. Simultaneous development of equations, discussed in section 4c, was one technique employed in the LAMP development and implementation to minimize meteorological inconsistencies. [Recent informal testing (not shown) of the development of ceiling height and sky cover forecasts supports this belief that simultaneous development of equations yields fewer inconsistencies between the forecasts than does separate developments.] In addition, simple postprocessing procedures were implemented to ensure meteorological consistency. One such example is to assure that the forecasted dewpoint does not exceed the forecasted temperature. If the dewpoint does exceed the temperature, the forecasts are changed to be the average of the temperature and the dewpoint. In addition, the specialized regression software discussed in section 4c is a technique designed to minimize temporal fluctuations and inconsistencies.

Consistency remains a highly desirable feature of any forecast system. While techniques have been implemented to reduce inconsistencies, current studies are in progress at MDL to develop additional postprocessing algorithms to further minimize or eliminate inconsistencies.

5. Current status, products, and usage

The current LAMP began running four cycles operationally at NCEP on 25 July 2006. Additional cycles were added to operations as they were developed. The last cycles of LAMP guidance were implemented into NWS operations at NCEP in November 2008, marking a milestone in that the NWS began providing objective statistical guidance for aviation forecasting every hour of the day.

LAMP provides guidance for continuous elements (e.g., temperature), probabilistic elements (e.g., probability of ceiling height), and categorical elements (e.g., best category of ceiling height; see Table 1). Most elements are valid at hourly time steps from 1 to 25 h. Exceptions to this are the probabilities of precipitation in 6- and 12-h periods and probabilities and occurrence of thunderstorms. Thunderstorm forecasts are valid over a 2-h period. The valid periods overlap in the early part of the forecast period, when they are valid for the 1–3-, 2–4-, . . . , and 5–7-h (6–8 h) projections for odd (even) LAMP cycle hours. Thereafter, the valid periods end every 2 h (7–9-, 9–11-, . . . , 23–25-h projections for odd LAMP cycle hours and 8–10-, 10–12-, . . . , 22–24-h projections for even LAMP cycle hours). The thunderstorm probabilities contain added temporal detail in the earlier projections to provide enhanced guidance to the aviation forecaster interested in the critical TAF period. In addition to the traditional MOS elements, LAMP provides guidance for conditional ceiling height and conditional visibility. These elements are intended to provide guidance for times when precipitation occurs, and were developed specifically for aviation forecasting. Rudack (2009) describes the conditional LAMP elements of ceiling height and visibility as well as their patterns of behavior with precipitation onset compared to observations.

Most of the weather elements are forecast at individual stations where observations are available. LAMP provides station guidance for all elements for 1591 stations in the CONUS, Alaska, Hawaii, Puerto Rico, and the Virgin Islands. However, thunderstorms are forecast on a 20-km Lambert conformal grid with an occurrence defined as one or more cloud-to-ground lightning strikes in a 2-h period in the grid box (Charba and Liang 2005; Charba and Samplatsky 2009). The thunderstorm guidance covers the CONUS and adjacent waters, and is interpolated to the LAMP stations within this domain. Thunderstorm guidance was not developed for areas outside the CONUS because an archive of lightning data was not available over these areas.

The official NWS LAMP products offer guidance in text bulletin (ASCII), binary universal form for the representation of meteorological data (BUFR), and gridded binary (GRIB2) formats. The official guidance is available to the user in a variety of ways. The products are transmitted over NOAAPORT, also known as the Satellite Broadcast Network (SBN; Friday 1994; information available online at http://www.weather.gov/noaaport/html/noaaport.shtml), as well as being available on the NWS file transfer protocol (FTP) server (tgftp.nws.noaa.gov). The gridded data are available in the National Digital Guidance Database (NDGD)—a guidance database interoperable with the National Digital Forecast Database (Glahn and Ruth 2003). NWS forecasters can view the text guidance and visual depictions of the guidance via AWIPS.

The public, as well as private and NWS forecasters, can also access the guidance online from the LAMP Web site (http://www.weather.gov/mdl/lamp). Images depicting the observational analyses that serve as predictors for LAMP elements (e.g., analyses of temperature, saturation deficit, etc.) are available on the Web site. The LAMP guidance is available in text format as well as via graphical displays. Figure 3 shows an example of the graphical depictions of the gridded thunderstorm probabilities and best-category (yes–no) forecasts of thunderstorms. Figure 4 is an example of a station plot map showing LAMP flight category guidance, which is derived via postprocessing of LAMP's ceiling and visibility guidance.

The user can also view forecast meteograms, which show the guidance for all elements contained in the text bulletin. Guidance from previous LAMP cycles, along with the corresponding GFS MOS guidance and the

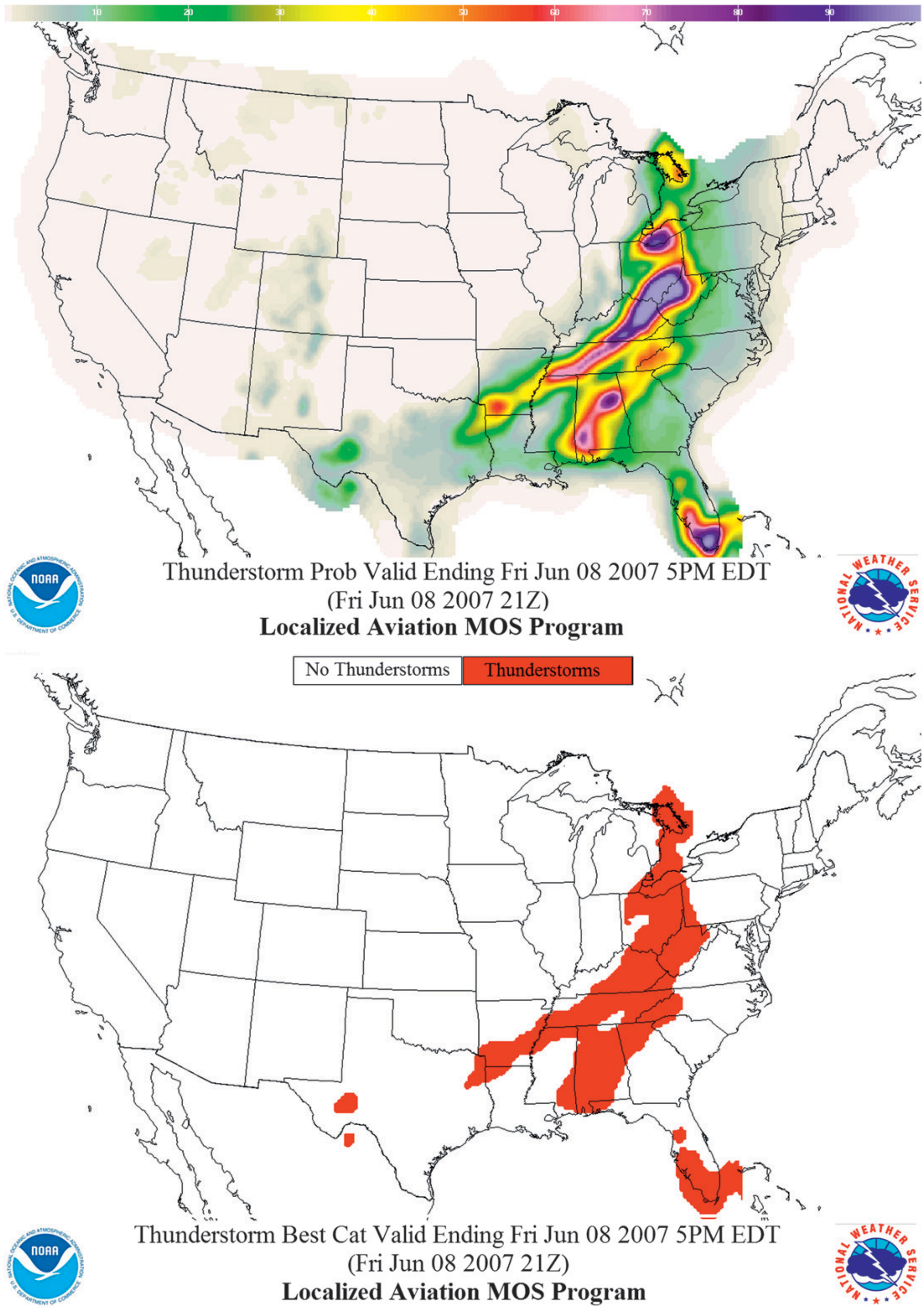

FIG. 3. LAMP Web graphics depicting LAMP thunderstorm guidance. (top) The probability of a thunderstorm in a 20-km gridbox in a 2-h period. (bottom) The corresponding best-category forecast (yes–no) of a thunderstorm occurring.

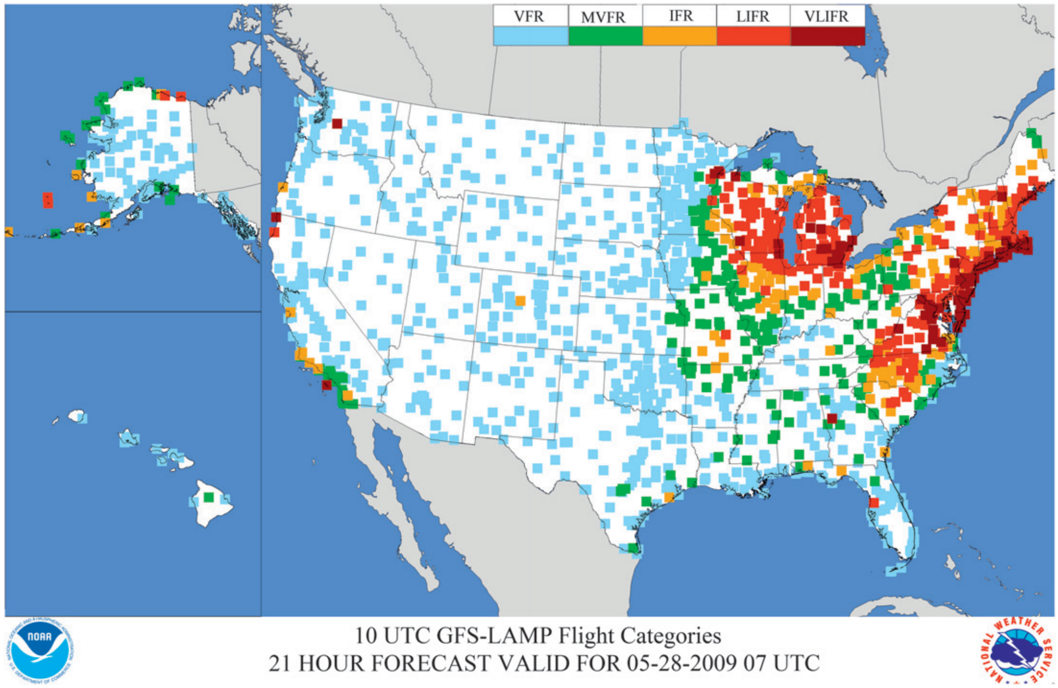

FIG. 4. LAMP Web graphic depicting Aviation Flight Category forecasts at LAMP stations. The flight categories are derived from the combination of the ceiling height and visibility best-category forecasts from LAMP. Similar graphical products are available for other weather elements forecasted by LAMP.

verifying observations, are also available to allow the user to determine the recent performance of LAMP. Figure 5a is an example of a meteogram depicting a previous LAMP cycle's forecast for ceiling height and visibility, and also the verifying observations for the period up until the current time.

MDL is also producing depictions of the probabilities of ceiling height, conditional ceiling height, visibility, conditional visibility, the probability of precipitation occurring on the hour, and precipitation type, as well as the corresponding thresholds that are used in the determination of the LAMP best-category forecast. Figure 5b shows a depiction of the LAMP probabilities (colored bars) and corresponding thresholds (horizontal lines) for ceiling height <1000 ft, by forecast projection. This display can give the user information about how likely the category is, based on the category's probability and the proximity of the probability to the corresponding threshold. By depicting this information on the Web site, the probabilistic information contained in LAMP for the aviation elements is readily accessible.

LAMP guidance is being utilized in various ways to support operational and user decisions. In the NWS, LAMP guidance is available as input to the Aviation Forecast Preparation System (AvnFPS). AvnFPS is an NWS computer application that runs locally at NWS WFOs and Center Weather Service Units to help forecasters prepare and monitor TAFs (Peroutka et al. 2004). AvnFPS can access the full set of LAMP weather elements, allowing for display and manipulation in various ways.

In addition, the forecaster can use AvnFPS to generate a TAF created directly from the LAMP guidance. Oberfield et al. (2008) describe how AvnFPS can compare data from the official TAF with probabilistic guidance from LAMP to generate an updated version of the official TAF. This technique results in automated TAFs that have characteristics similar to human-generated TAFs but that incorporate LAMP guidance.

LAMP forecasts are also used in the National Ceiling and Visibility (NCV) forecast system (Black et al. 2008). The NCV forecast system uses four input components, one of which is the LAMP forecasts of ceiling height and visibility, to produce forecasts of ceiling height and visibility. The system evaluates the recent performance of each component and selects the forecast from the system that is performing the best. Black et al. (2008) show that LAMP performs very well and at times is one of the best performers for the stations evaluated.

6. Verification

Typical verification results show LAMP is as skillful as persistence at the first hour and improves on persistence as the forecast projection increases. Conversely, the

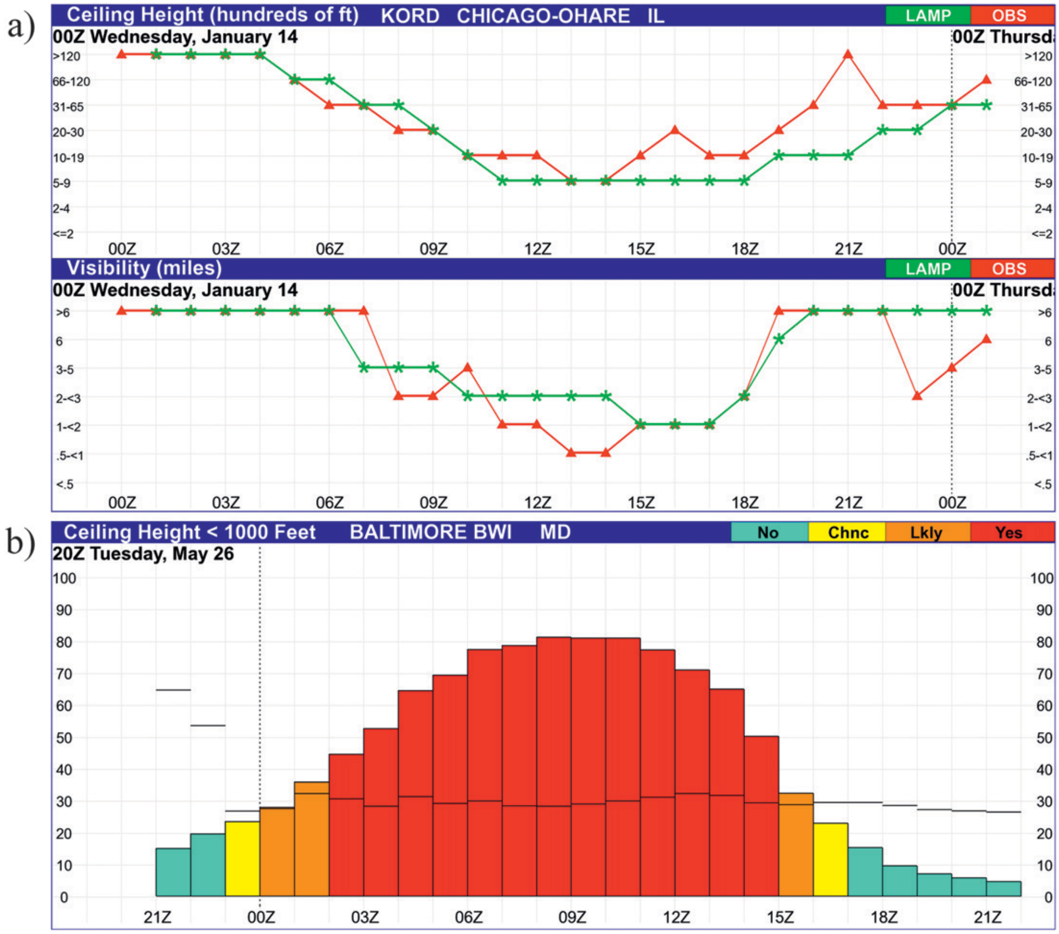

FIG. 5. LAMP Web site graphics. (a) A past LAMP cycle's guidance (in green) and the verifying observations (red) for ceiling height (upper time series) and visibility (lower time series). The user can select other LAMP elements to display, as well as previous LAMP cycles. (b) LAMP probability guidance for ceiling height <1000 ft. The colored bars represent the LAMP probability of the event, while the horizontal lines represent the threshold corresponding to the probability that is required for this event to be categorically forecast. This plot color codes the bars based on the probability's proximity to the threshold, as well as its exceedance or non-exceedance.

verification typically shows LAMP to have the most improvement over MOS at the first hour, with the improvement over MOS decreasing as the forecast projection increases. Different elements show different degrees of this pattern. These results are consistent with the paradigm of LAMP as depicted in Fig. 1, although the actual verification shows LAMP's level of skill approaching the skill of MOS quicker than what is depicted in Fig. 1.

a. Comparison of LAMP with GFS MOS and persistence

Verification was performed on the operational LAMP and GFS MOS forecasts of wind speed and direction, ceiling height, and visibility. The data verified were from the warm season of April–September 2007 and the cool season of October 2007–March 2008. The LAMP, GFS MOS, and persistence forecasts were verified for 1522 stations in the CONUS, Alaska, Hawaii, and Puerto Rico for every day of the verification periods. Thunderstorm forecasts were verified for the three developmental seasons, defined as ''early warm'' (16 March–30 June 2007), ''late warm'' (1 July–15 October 2007), and ''cool'' (16 October 2007–15 March 2008), at grid points in the CONUS domain. Note that the data were matched samples in that only cases for which forecasts from all systems were present were included in the verification. This verification was done on independent data, meaning that the data were not used in the development of the equations and thresholds.

Note that in operations, the 0900 UTC LAMP cycle uses 0000 UTC GFS MOS forecasts as predictor input. When the 0900 UTC LAMP is available at 0930 UTC, the other possible guidance that is available is the 0000 UTC GFS MOS (the 0600 UTC GFS MOS is not

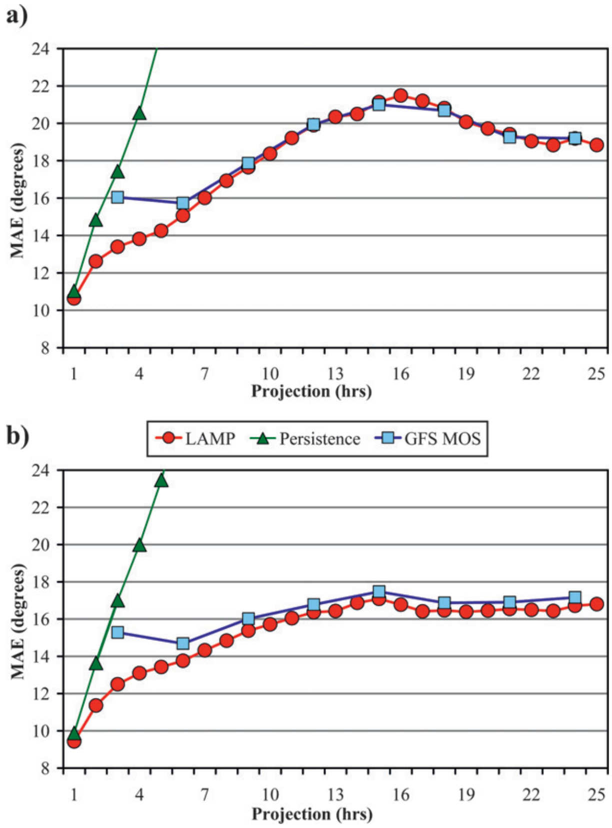

FIG. 6. Wind direction verification. Mean absolute errors (°) are shown for 0900 UTC LAMP (red circles), 0000 UTC GFS MOS (blue squares), and persistence of the 0900 UTC observation (green triangles) for (a) the warm season and (b) the cool season. The warm season data spanned the period of April–September 2007, and the cool season data spanned the period of October 2007–March 2008. Projection hour is relative to the 0900 UTC LAMP cycle.

yet available) and the 0900 UTC METAR observation (see Fig. 2 for timeline details). In an effort to compare guidance from products available at the LAMP issuance, the verification compared the 0900 UTC LAMP forecasts to the 0000 UTC GFS MOS forecasts and persistence from the 0900 UTC observation. Therefore, a 3-h projection for 0900 UTC LAMP guidance is valid at 1200 UTC, which corresponds to a 12-h projection from the 0000 UTC GFS MOS.

1) WIND VERIFICATION

Figure 6 shows the results of the verification of LAMP wind direction forecasts for the warm and cool seasons compared to the GFS MOS and persistence forecasts. The score used is the mean absolute error of the wind direction in degrees. Only cases that had verifying wind speed observations of 10 kt or more were considered in the wind direction verification. LAMP shows accuracy comparable to persistence at the first hour, but the accuracy of persistence quickly deteriorates after that hour. LAMP is more accurate than the GFS MOS for roughly the first 6 h and is comparable to GFS MOS after the sixth hour.

Figures 7a and 7b show the verification results for wind speed forecasts from LAMP, GFS MOS, and persistence. The score shown is the mean absolute error in knots. LAMP is as accurate as persistence at the first hour, but persistence quickly loses accuracy and LAMP becomes more accurate than persistence thereafter. LAMP is only slightly more accurate than GFS MOS at the 3-h projection in the cool season (Fig. 7b), and comparable to GFS MOS thereafter. This improvement on GFS MOS is less in the warm season (Fig. 7a) at the 3-h projection. Figures 7c and 7d show the wind speed bias (forecast − observation) in knots for LAMP and GFS MOS for the warm and cool seasons, respectively. A bias of zero indicates no bias. These results show that both systems forecast winds that were slightly too high by an average of 0.5 kt on these independent samples.

2) CATEGORICAL VERIFICATION

Figures 8 and 9 show the verification results for categorical forecasts of ceiling height <1000 ft and visibility <3 miles. The ceiling height and visibility forecasts were combined into flight categories (NWS 2008), and the event of instrument flight rules (IFR) or lower was also verified (Fig. 10). IFR or lower conditions occur when the ceiling height is <1000 ft and/or the visibility is <3 miles. The threat scores and forecast biases are shown. The threat score is the conditional relative frequency of a correctly forecast event when the event is either forecast or observed. A higher threat score indicates more accurate forecasts. The bias score for categorical forecasts is the ratio of the number of forecasts of an event divided by the number of observations of the event (Wilks 2006). A bias of one represents the unit bias, which indicates that the event was forecast as often as it occurred.

The results shown in panels a and b in Figs. 8–10 are similar to the results of the previously discussed wind elements in these regards: 1) LAMP is as accurate as persistence in the early period, with LAMP showing more accuracy than persistence after the first few hours; 2) LAMP is more accurate than the GFS MOS in the early to middle part of the 25-h forecast period; and 3) LAMP is comparable to the GFS MOS in the middle to later part of the 25-h forecast period. Aspects of the verification that are notable are 1) the accuracy of persistence deteriorates at a much slower rate than for the previously discussed elements and 2) LAMP does not improve much over persistence until about the third to fifth hour (depending on the season and element), while the previous verifications show LAMP's improvement over persistence is noticeable beginning at the second hour.

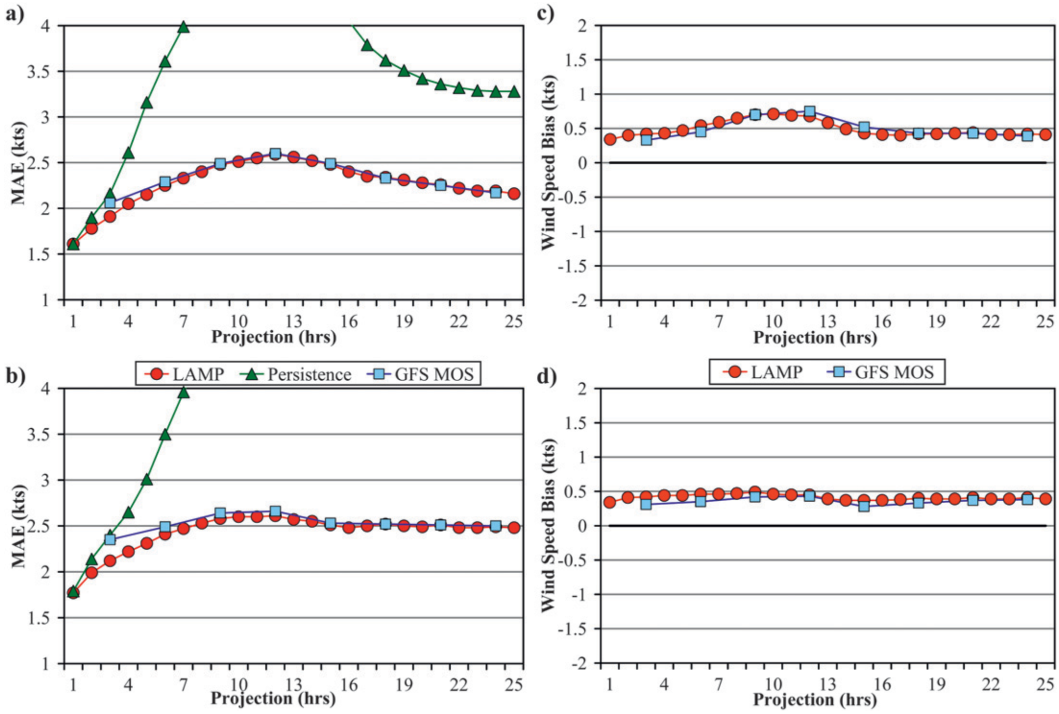

FIG. 7. Wind speed verification. Mean absolute errors (kt) are shown for 0900 UTC LAMP (red circles), 0000 UTC GFS MOS (blue squares), and persistence of the 0900 UTC observation (green triangles) for (a) the warm season and (b) the cool season. Bias scores are shown for 0900 UTC LAMP and 0000 UTC GFS MOS for (c) the warm season and (d) the cool season. ''No bias'' is indicated by a bias of 0. Projection hour is relative to the 0900 UTC LAMP cycle.

Ceiling height and visibility have historically been two of the most challenging forecast elements to forecast accurately. Persistence is considered a benchmark for comparisons for ceiling height and visibility in the very short term, and a difficult competitor to improve on in that time frame. The ceiling height, visibility, and IFR or lower verifications (Figs. 8–10) show that the LAMP threat scores decrease quickly. Because LAMP is a blend of the observations and GFS MOS, this decrease in threat score is attributed to the decreasing persistence scores and the lower GFS MOS scores. Threat scores for visibility <3 miles are in general lower than the ceiling height scores for all systems, indicating that visibility is the more difficult of the two elements to forecast accurately.

Figure 11 shows the percent improvements of the LAMP threat scores over the GFS MOS threat scores for these ceiling height and visibility events. LAMP's improvement over GFS MOS is higher for visibility <3 miles than for ceiling height <1000 ft at the earliest projection, while the opposite pattern of behavior is seen at subsequent projections. The improvements for both events and both seasons shown range from 46% to 61% at the 3-h projection, from 22% to 26% at the 6-h projection, and decrease to 14% to 16% by the 9-h projection. While the improvements decrease thereafter and may not represent significant differences, LAMP shows improvement on GFS MOS at the early projections, and is no worse than GFS MOS throughout the entire forecast period.

Figures 8–10 show the bias scores for LAMP and GFS MOS for the warm (panel c) and cool (panel d) seasons for ceiling height <1000 ft, visibility <3 miles, and IFR or lower conditions, respectively. LAMP shows less bias than GFS MOS in general for all categories shown with some notable exceptions. Results for bias of ceiling height <1000 ft in the cool season (Fig. 8d) show LAMP has less bias than GFS MOS at the 3-h projection, but has more bias thereafter and shows that LAMP overforecasted this event in this verification period, while GFS MOS shows little or no bias after the 3-h projection. For IFR or lower conditions in the warm season (Fig. 10c), LAMP underforecasted the event in the middle part of the forecast period, but the GFS MOS underforecasted the event to a greater extent. Other than the results for ceiling <1000 ft in the cool season, in general LAMP shows less bias than GFS MOS in the early and middle parts of the forecast period; however, GFS MOS tends to have biases closer to one than what is shown in the LAMP results at the 21- and 24-h projections.

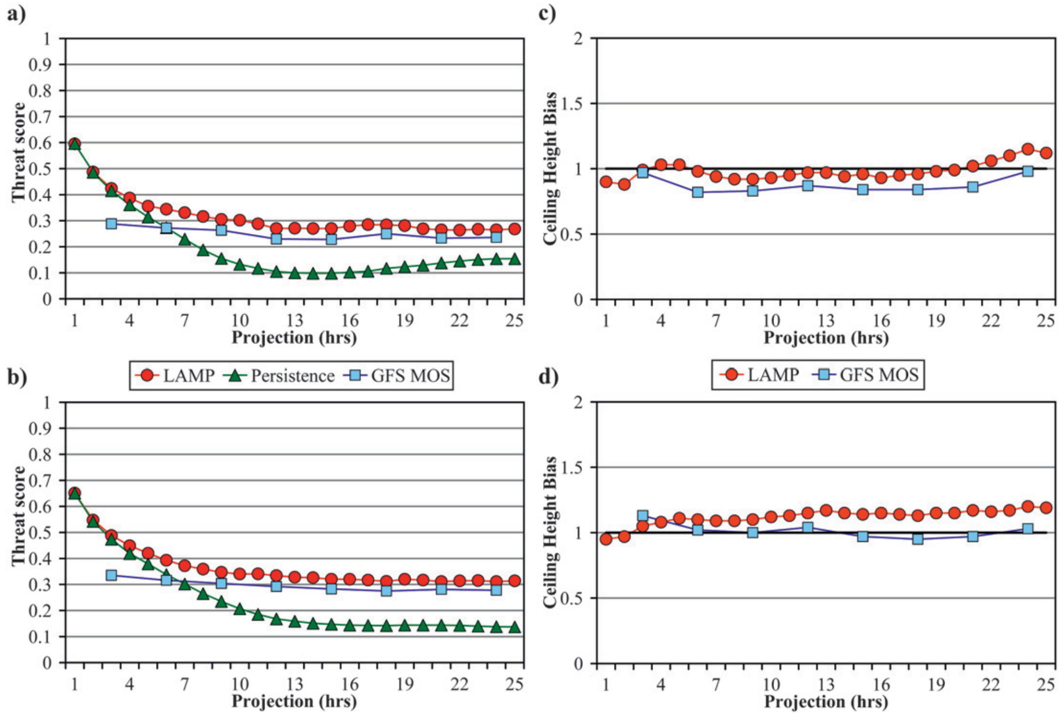

FIG. 8. Verification for ceiling height <1000 ft. Threat scores are shown for 0900 UTC LAMP (red circles), 0000 UTC GFS MOS (blue squares), and persistence of the 0900 UTC observation (green triangles) for (a) the warm season and (b) the cool season. Bias scores are shown for 0900 UTC LAMP and 0000 UTC GFS MOS for the same cycles for (c) the warm season and (d) the cool season. "Unit bias" is indicated by a bias of 1. Projection hour is relative to the 0900 UTC LAMP cycle.

3) PROBABILISTIC VERIFICATION

In addition to the categorical verification, the probabilistic forecasts of ceiling height and visibility were verified for the cool season of October 2007–March 2008 (the operational probabilistic forecasts for LAMP were not available for the warm season). Figures 12 and 13 show the reliability scores for LAMP and GFS MOS for probabilistic forecasts of ceiling height <1000 ft and visibility <3 miles, respectively. Reliability scores show the relationships between the forecasts and the observations that correspond to those specific forecasts (Wilks 2006). Perfect reliability is indicated by the 45° diagonal, and scores that fall on this line indicate that the event was observed with the same frequency as the forecast probability.

Figures 12 and 13 show very similar characteristics in the verification results in that LAMP forecasts are shown to have excellent reliability at the 3-h projection for both events, and for the lower forecast probability bins at the 6- and 9-h projections, although LAMP is less reliable for other bins at these projections. Results for LAMP probabilistic forecasts of ceiling height <1000 ft show slightly better reliability than for LAMP probabilistic forecasts of visibility <3 miles at the 6- and 9-h projections. LAMP is shown to be as reliable as GFS MOS in the lower bins for both events and all projections, but LAMP has better or comparable reliability in the middle bins. Both systems suffer from low numbers of forecasts in the higher bins, with the numbers of cases in the higher bins decreasing for both systems with projection. This is typically seen with forecasts of rarely occurring events such as low ceiling heights and visibilities because high forecast probabilities of rare events are more difficult to produce further out in the forecast period. Overall, these results show excellent reliability for LAMP at the 3-h projection and for the lower bins at the 6- and 9-h projections, and good but slightly lower reliability in the middle bins at the longer projections.

Brier scores (Brier 1950) were also calculated for LAMP and GFS MOS probability forecasts of ceiling <1000 ft and visibility <3 miles for the cool season (not shown). The improvements in the LAMP Brier scores over the GFS MOS Brier scores are shown in Fig. 14. In general, LAMP demonstrates more improvement over GFS MOS for probabilities of ceiling height <1000 ft than for probabilities of visibility <3 miles. The improvement is highest at the 3-h projection (21.3%–25.0%) and decreases thereafter.

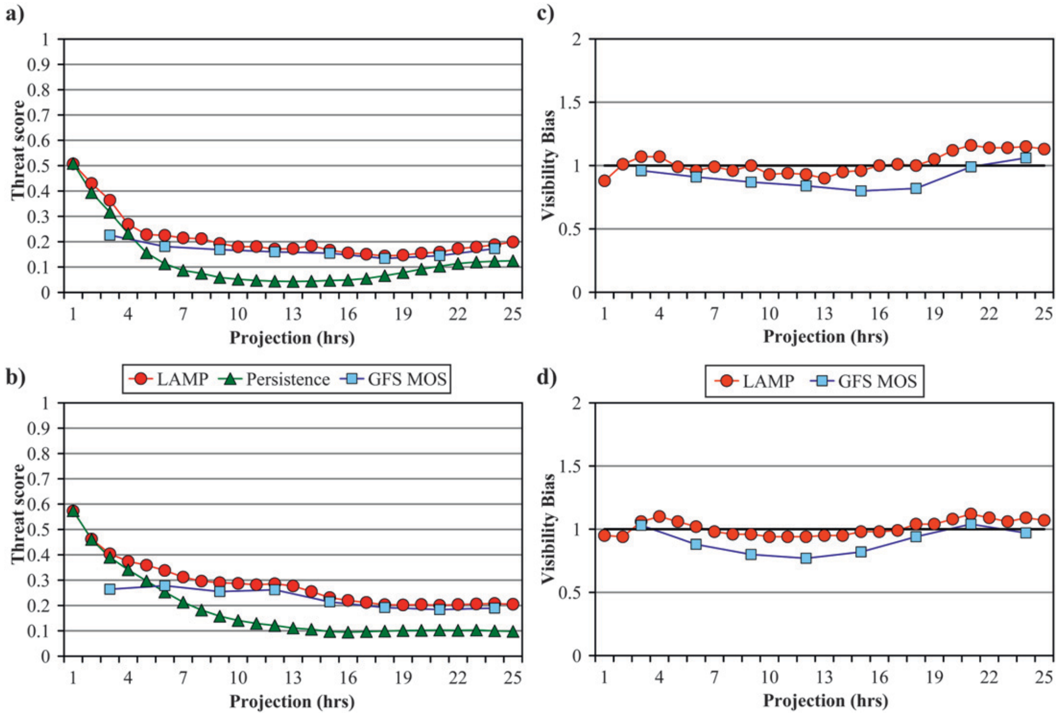

FIG. 9. As in Fig. 8, but for visibility <3 miles.

For the verification of LAMP's probabilistic thunderstorm guidance, no comparable GFS MOS guidance exists. While both the GFS MOS and LAMP thunderstorm forecasts apply to identical 20-km grid boxes, the former is valid for a 3-h period whereas the latter applies to a 2-h period. Brier scores were calculated for both the LAMP thunderstorm probabilities and the climatology of a thunderstorm in a 2-h period. The climatology was derived from a 14-yr historical sample (April 1994–March 2008) and represents a monthly relative frequency that is smoothed and interpolated to the day of the month. Charba and Liang (2005) describe the creation of a similar climatology based on a 10-yr sample.

Brier skill scores (BSSs), defined as the improvement over climatology, were calculated for the LAMP thunderstorm probabilities (Fig. 15) for each of the three thunderstorm seasons. The greatest forecast skill occurs at the earliest projections for all seasons, which is due to the contributions from the lightning strike and radar reflectivity predictors during this time. The improvement rapidly declines from the 1–3-h projection to the 7–9-h projection, but increases again after that, resulting in two distinct maxima, with the highest increases occurring in the cool season. This is partly attributed to the higher relative frequencies of thunderstorms at these times of day (after 1800 UTC) in all seasons.

Another interesting result is that the BSS is noticeably higher in the cool season than in the other seasons. This result is likely due to the predominantly synoptic-scale forcing of thunderstorms during the cool season compared to the predominantly mesoscale forcing, which results in small space–time scales of thunderstorms, during the warm seasons, the latter being less predictable. This is consistent with the results that show better scores for the LAMP thunderstorm guidance at night; we attribute the better scores to the larger scale of nighttime convective systems compared to daytime airmass thunderstorms. Similarly, seasonal differences in accuracy in quantitative precipitation forecasts (QPFs) have likewise been attributed to the scale of the forcing. Olson et al. (1995) attributed the lower verification scores for QPF in the warm season to small-scale convective processes driving warm season precipitation, while they considered the higher cool season scores to be a result of synoptic-scale systems driving cool season precipitation.

Also of interest is that the skill of the late warm season forecasts are rather low after the first few hours. Since the LAMP thunderstorm predictors at the longer projections contain mostly synoptic-scale information, the LAMP skill at the longer time ranges is less, especially in the late warm season, when synoptic systems are weaker. This could perhaps be improved by including mesoscale model output as predictors.

Reliability scores were calculated for the thunderstorm probabilities from the 0900 UTC LAMP cycle for the three thunderstorm seasons. The results for the 1–3-h

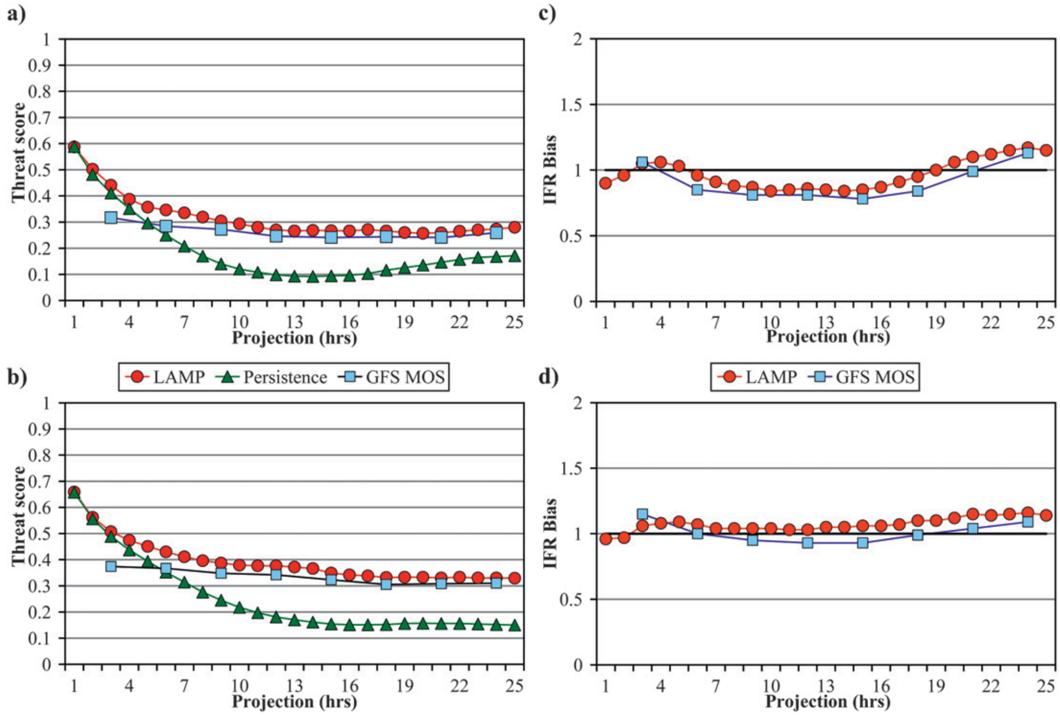

FIG. 10. As in Fig. 9, but for IFR conditions or lower.

projection (Fig. 16a) show good reliability for all seasons through the 50% probability bin, although the results show LAMP has a slight tendency to underforecast thunderstorms in these bins in the cool season. The results from the two warm seasons show LAMP has an overforecasting bias in the bins >50%, while the results from the cool season indicate a tendency for LAMP to overforecast in the bins >70%. The results show that LAMP overcasts the higher probabilities to a greater extent in the two warm seasons than in the cool season. The results for the 4–6-h projection (Fig. 16b) demonstrate good reliability in the lowest forecast bins. However, the forecasts suffer from very few cases in the middle probability bins, making the results difficult to interpret, and the probability bins above 50% had no forecasts. We hope to improve on this deficiency in the future, but the temporal and spatial resolutions of the product, as well as the rareness of the event, make this challenging.

b. *Comparison of LAMP forecasts of IFR conditions with NWS TAFs*

Official NWS TAFs can be compared with various forecast systems, including GFS MOS and LAMP, for any TAF site in the United States via the NWS's official verification program called Stats on Demand (NWS 2009). The Stats on Demand system verifies the scheduled TAF issuances at 0000, 0600, 1200, and 1800 UTC and compares them to the verification of another system. Forecasts are evaluated every 5 min using the most recent METAR or Aviation Selected Special Weather Report (SPECI) data. If the hourly METAR from just before the hour is missing, then the TAF is not evaluated until a new METAR/SPECI is received.

The LAMP forecasts are available for comparison in the Stats on Demand system beginning with data starting on 1 July 2008. For this paper, the Stats on Demand

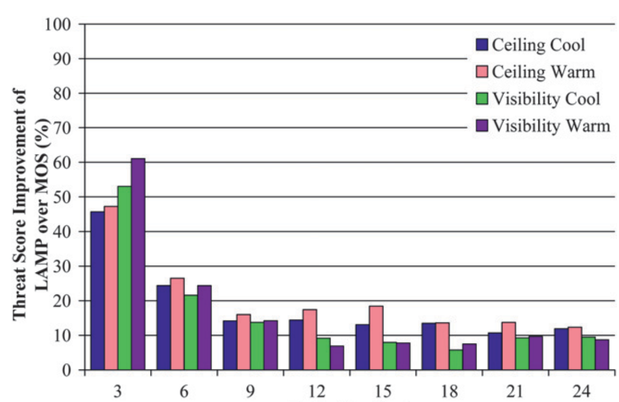

FIG. 11. Percent improvement in threat scores of categorical forecasts from 0900 UTC LAMP over threat scores of categorical forecasts from the 0000 UTC GFS MOS for ceiling height <1000 ft for the cool (blue) and warm (red) seasons and for visibility <3 miles for the cool (green) and warm (purple) seasons. Projection hour is relative to the 0900 UTC LAMP cycle.

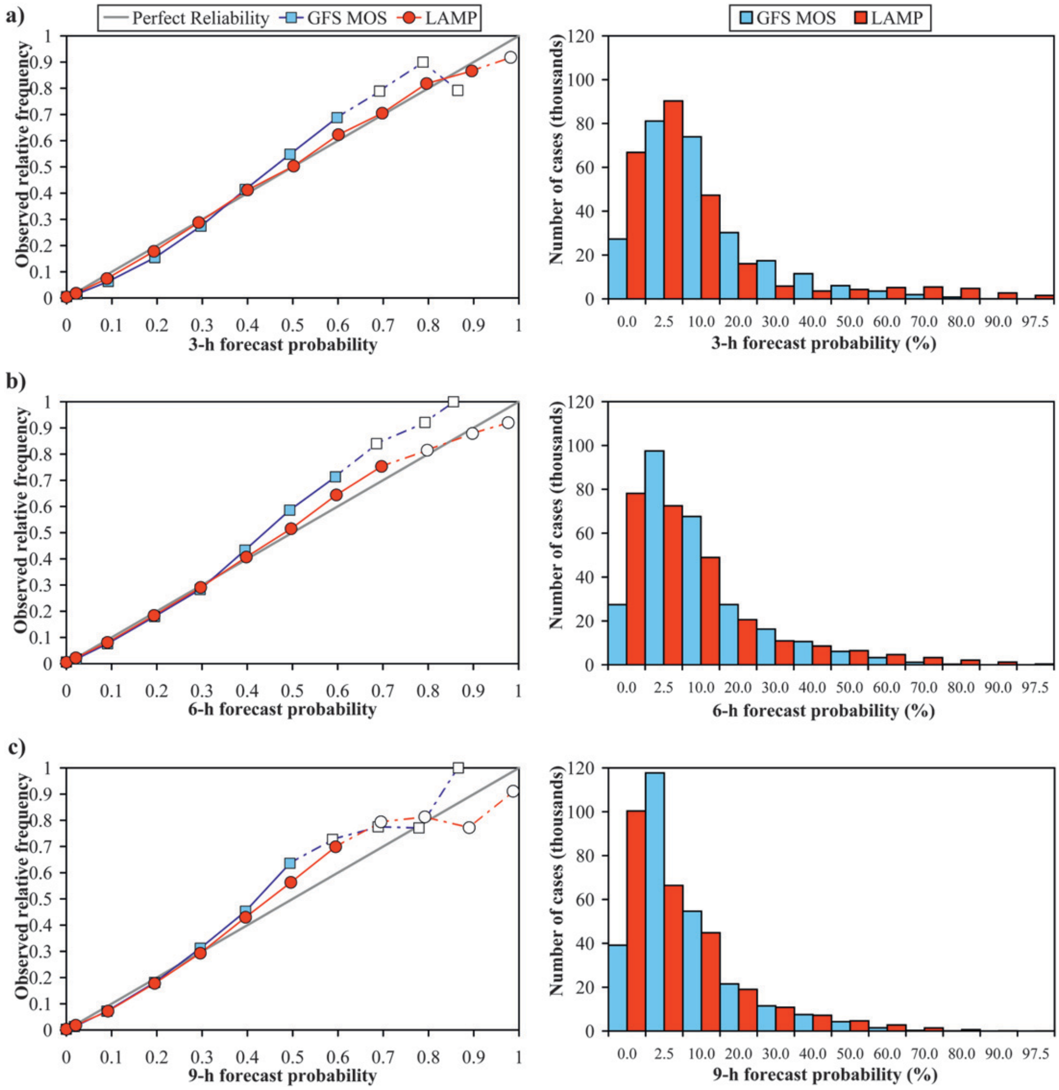

FIG. 12. Verification for the (a) 3-, (b) 6-, and (c) 9-h probabilities of ceiling height <1000 ft. (left) Reliability scores and (right) histograms are shown for 0000 UTC GFS MOS (blue squares–bars), 0900 UTC LAMP (red circles–bars), and perfect reliability (gray diagonal line) for the cool season of October 2007–March 2008. Reliability scores for bins in which there were <1% of cases forecasted are indicated by hollow symbols. Projection hour is relative to the 0900 UTC LAMP cycle.

system was used to compare LAMP and GFS MOS guidance (separately) against the prevailing forecasts from the scheduled NWS TAFs for all TAF stations in the national area. Forecasts from 1 July 2008 to 30 June 2009 were verified. This verification compared the accuracy of forecasts of IFR or lower conditions. Note that Stats on Demand can only compare two systems at a time, and matched samples are used for the two systems being compared. Since it was not possible to use Stats on Demand to compare three systems at once, the comparisons were done for TAF–LAMP and TAF–GFS MOS separately. Note that LAMP and GFS MOS do not provide guidance for all TAF sites in the United States; so in effect, the TAF stations that had LAMP (GFS MOS) guidance were verified in the comparison with LAMP (GFS MOS).

To best interpret the results, the reader should understand how the verification is done in the Stats on Demand system. Table 2 shows the nominal and issuance times of the scheduled TAFs and the systems compared by Stats on Demand, and Fig. 2 shows via a timeline the four GFS MOS cycles and four LAMP cycles used to compare with the four scheduled TAFs. From this, it can be seen that verification of guidance from the LAMP (GFS MOS) cycles available approximately 1 (1.5) h before the TAF issuances is compared with verification of TAFs from the

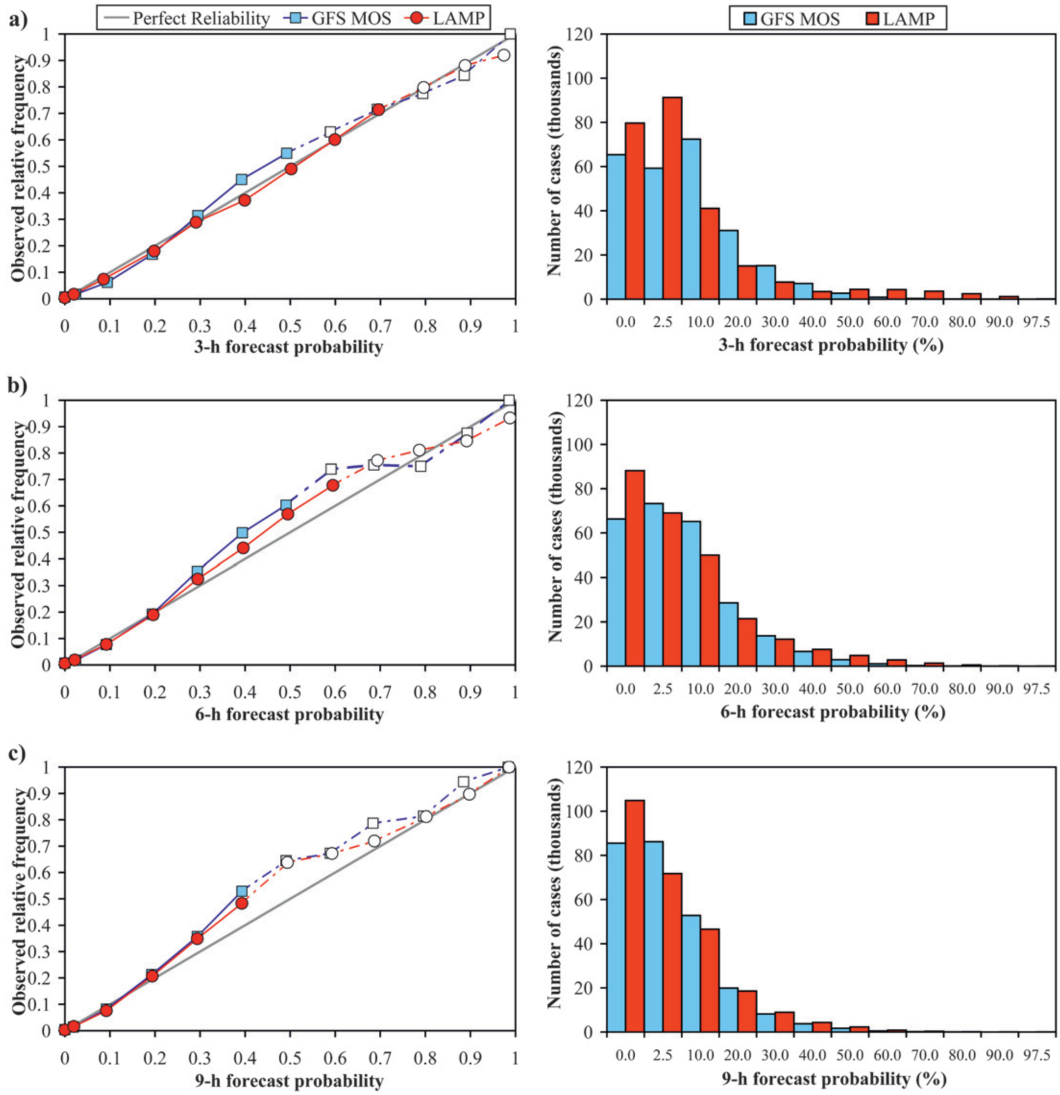

FIG. 13. As in Fig. 12, but for the probability of visibility <3 miles.

scheduled issuances. Since the LAMP verification uses the LAMP guidance available 1 h prior to the TAF issuance, instead of the LAMP guidance that might have been available at the time of the TAF issuance, this verification method provides a measure of the usefulness of the guidance in the forecast process, and not a measure of the LAMP guidance as a competitor to the TAF forecast. To determine the value to the forecaster, one must examine the accuracy of the guidance available well before the issuance time, which provides ample time for human interpretation.

Figure 17 shows the verification of the IFR or lower conditions in the first 0–6 h after the issuance of the scheduled NWS TAF for the period of 1 July 2008–30 June 2009 for national TAF locations. The TAF–LAMP comparison (left side of chart in Fig. 17) shows that while LAMP has a higher probability of detection (POD) than the TAFs (0.576 for LAMP; 0.510 for TAFs), it also has a higher false alarm rate (FAR; 0.451 for LAMP; 0.320 for TAFs). The threat score, which considers both detection and false alarms, is slightly higher (0.411) for the TAF than for LAMP (0.391). The TAF–GFS MOS comparison (right side of chart in Fig. 17) shows similar results as the TAF–LAMP comparison. GFS MOS has a slightly higher POD than the TAF (0.532 for GFS MOS; 0.511 for TAFs), but also a higher FAR (0.487 for GFS MOS; 0.319 for TAFs), and a lower threat score (0.353 for GFS MOS; 0.412 for TAFs).

7. Future plans

Now that the LAMP station-based guidance is available hourly in NWS operations, the development

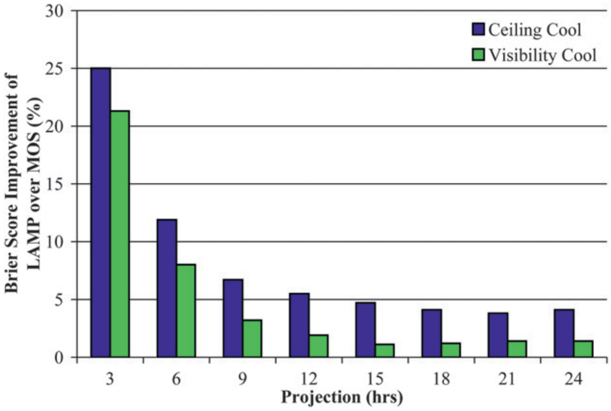

FIG. 14. Brier score improvement in forecasts from 0900 UTC LAMP over forecasts from 0000 UTC GFS MOS for probabilities of ceiling height <1000 ft (blue) and for probabilities of visibility <3 miles (green) in the cool season only (Brier scores were unavailable for the warm season). Projection hour is relative to the 0900 UTC LAMP cycle.

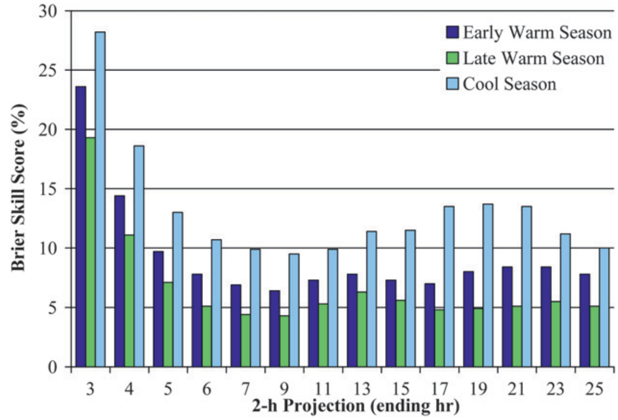

FIG. 15. BSSs for LAMP thunderstorm probabilities for 0900 UTC LAMP the early warm season of 16 Mar–30 Jun 2007 (dark blue), the late warm season of 1 Jul–15 Oct 2007 (green), and the cool season of 16 Oct 2007–15 Mar 2008 (light blue).

emphasis will shift to gridded LAMP guidance. Gridded LAMP will be produced in a manner similar to Gridded MOS (Glahn et al. 2009) and will be put into the NDGD each hour. While temperature and dewpoint grids will be developed, the novel work will involve developing gridded forecasts of the aviation elements, such as winds, ceiling height, visibility, sky cover, and obstruction to vision. Both forecast probabilities and categorical guidance for the aviation elements will be produced.

Probabilistic forecast guidance will be available in the Next Generation Air Transportation System (NextGen) via the Four-Dimensional Weather Data Cube (4-D Wx Data Cube), also known as the Weather Information Database (WIDB). This guidance will allow users to make knowledgeable decisions regarding critical planning for aviation given the likelihood of the event and the risk associated with the event (Souders et al. 2009; Abelman et al. 2009). Such guidance will also be vital in the development of new Air Traffic Management Decision Support Tools to improve efficiency in the NextGen era. MDL will provide gridded LAMP guidance of aviation elements required for NextGen, including grids of ceiling height, sky cover, visibility, obstruction to vision, and wind, along with the existing LAMP grids of thunderstorm guidance.

Plans beyond the immediate gridded work include maintenance updates to add (remove) stations to the LAMP guidance as stations are added (removed) from the GFS MOS guidance. We also plan to investigate running LAMP more frequently than hourly in response to SPECI observations that are received between the hours if the intermediate observations indicate an operationally significant change to the current conditions. MDL is also investigating the development of new gridded LAMP guidance for convective cloud tops, which NextGen requires for aviation forecasting (Joint Planning and Development Office 2008).

Long-term plans include an eventual update of the LAMP system. The original LAMP concept called for input from models that were self-contained and manageable enough to run locally at WFOs. LAMP no longer runs locally; however, the system still requires a stable model for input and a long historical archive of predictor data for development. While output from a mesoscale model would likely be a useful input source to LAMP, the requirements for stability and an adequate archive are difficult to meet with current NWP models. We believe future implementations of LAMP will meet this challenge when a stable mesoscale model with an adequate historical archive of data replaces the current LAMP models. In addition, we anticipate that the next iteration of LAMP will include additional observational predictors to indicate future development of events that are not indicated by MOS. Such an example of a development predictor is a convective initiation predictor derived from the current conditions at LAMP run time.

8. Summary and conclusions

MDL's aviation weather prediction system runs each hour and produces hourly guidance out to 25 h, covering the major forecast period of the TAF. This system is implemented at NCEP and the guidance is furnished via NOAAPORT/SBN, the NWS FTP server, and on an MDL Web site; gridded thunderstorm guidance also is available in the NDGD.

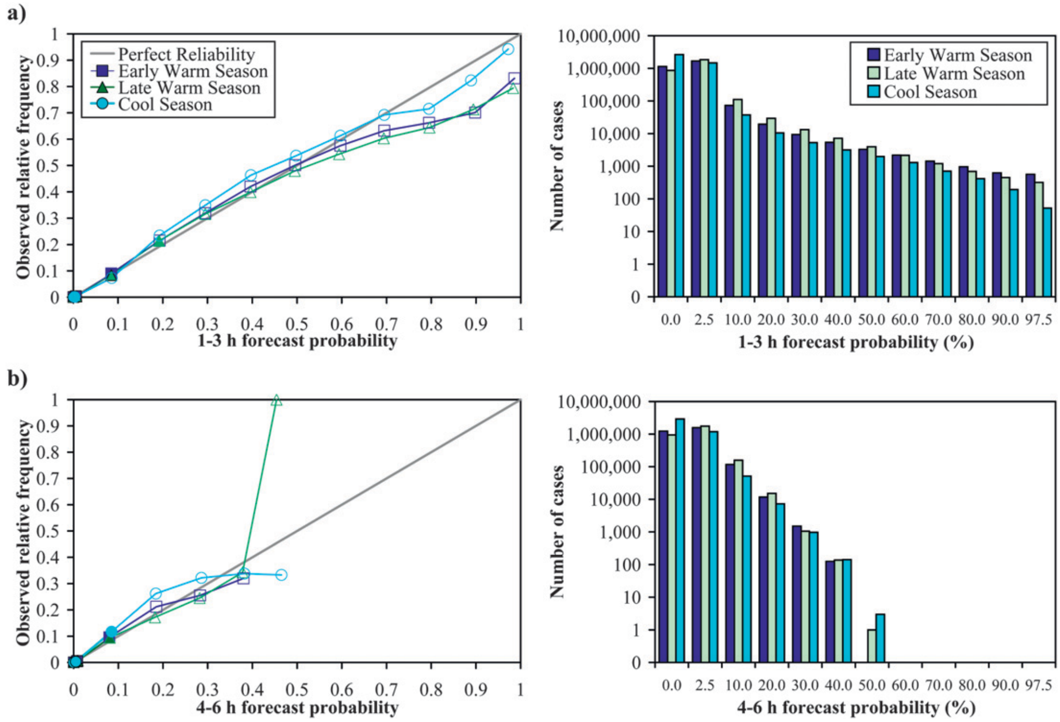

FIG. 16. Verification for the (a) 1–3- and (b) 4–6-h probabilities of thunderstorms. (left) Reliability scores and (right) histograms are shown for 0900 UTC LAMP, and perfect reliability (gray diagonal line) for the seasons of the early warm season (dark blue squares–bars), the late warm season (green triangles–bars), and the cool season (light blue circles–bars). Reliability scores for bins in which there were <1% of cases forecasted are indicated by hollow markers. Histograms display the numbers of cases on a logarithmic scale to better show the low numbers of cases in the middle and higher forecast probability bins.

LAMP forecasts have been shown to be equal to or better than persistence forecasts in the short term, better than GFS MOS forecasts through roughly the 10-h projection, and generally comparable to the GFS MOS in the later periods. LAMP offers added utility over GFS MOS by providing quality guidance at hourly projections out to 25 h, which fills in the gaps of the 3-h projections available from the GFS MOS, and in doing so provides guidance throughout the 24-h TAF period at the required temporal resolution. In addition, LAMP provides guidance for some elements not available from the GFS MOS, such as conditional ceiling height, conditional visibility, and hourly probability of precipitation occurrence. Verification of 12 months of recent data by the NWS Stats on Demand system shows that LAMP forecasts issued about an hour prior to the TAF issuance had a higher POD than the NWS TAFs, but LAMP also has a higher FAR and slightly lower threat score.

With the exception of the thunderstorm guidance, LAMP guidance is currently valid only at METAR stations. However, NWS forecasters require gridded guidance for routine forecast preparation. In addition, NextGen requires aviation guidance on a grid for aviation planning (Joint Planning and Development Office 2008). As a result, MDL plans to produce the gridded guidance for various elements of interest to the aviation community. The grids will contain continuous, probabilistic, and categorical guidance, and will be available to NWS forecasters and the aviation community.

In summary, LAMP provides much desired, hourly updated guidance for aviation use, and should be of benefit to forecasters interested in incorporating information from the most recent observations into their forecasts at stations. The planned, hourly updated, gridded LAMP guidance will be available for use in the WIDB to support NextGen.

TABLE 2. Nominal/issuance times of systems verified in Stats on Demand. All times are UTC.

Scheduled TAF		LAMP		GFS MOS	
Nominal	Issuance	Nominal	Issuance	Nominal	Issuance
0000	2320–2340	2200	2230	1800	2200
0600	0520–0540	0400	0430	0000	0400
1200	1120–1140	1000	1030	0600	1000
1800	1720–1740	1600	1630	1200	1600

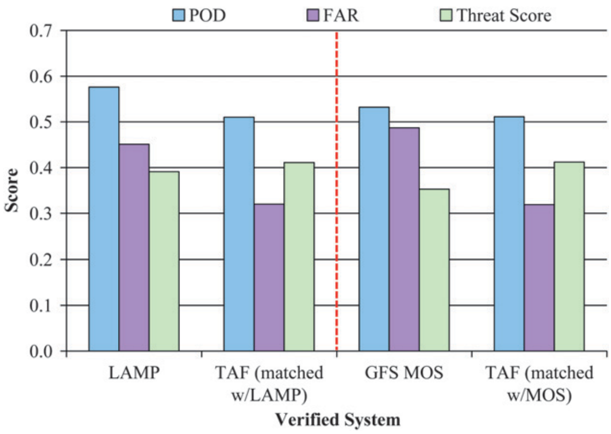

FIG. 17. Verification from the NWS Stats on Demand program. Scores for the POD (blue), FAR (purple), and the threat score (green) are shown. The threat event is of IFR or lower conditions in the 0–6-h period after the official NWS TAF scheduled issuance. Scores are shown for (left) the LAMP verification matched with verification of prevailing forecasts from the official NWS TAFs and (right) GFS MOS verification matched with verification of the TAFs. The period of time verified is 1 Jul 2008–30 Jun 2009, and national sites are verified.

Acknowledgments. The LAMP system is dependent on the dedicated efforts of the people in MDL's Statistical Modeling Branch. The authors thank them for their hard work and commitment to producing the excellent forecasts that serve as input to LAMP. We also wish to thank the LAMP developers, past and present, who have been dedicated to producing and maintaining the LAMP guidance, and for producing much of the verification shown here. We also want to thank MDL's AvnFPS developers who provided constructive feedback on the LAMP guidance, and Arthur Taylor and Marc Saccucci who supplied invaluable technical expertise that helped with the Web site graphics. We are grateful to Kelly Malone and James Cipriani for gathering much of the data for many of the figures included in this paper, to Scott Scallion for assisting with the figures, and to Mitch Weiss for providing the information from Stats on Demand. We would also like to thank David Rudack, Jess Charba, Dave Ruth, and Matthew Peroutka for providing helpful reviews of the drafts. We are grateful to the three anonymous reviewers who provided many helpful suggestions that contributed to the improvement of the manuscript.

The radar data used in the LAMP development were provided by the GHRC of the Global Hydrology and Climate Center (GHCC) in Huntsville, Alabama. The lightning strike data from 1994 through 2005 were provided by the GHRC through a license agreement with Global Atmospherics, Inc. (GAI). The lightning data from 2006 and on, as well as the real-time lightning data, were provided by Väisälä Inc. through NWS contract.

This paper is the responsibility of the authors and does not necessarily represent the views of the NWS or any other government agency.

REFERENCES

Abelman, S., C. Miner, and C. Neidhard, 2009: The NOAA aviation forecast process in the NextGen era. Preprints, *25th Conf. on International Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology,* Phoenix, AZ, Amer. Meteor. Soc., 4A.2. [Available online at http://ams.confex.com/ams/pdfpapers/150618.pdf.]

Bergthorsson, P., and B. R. Doos, 1955: Numerical weather map analysis. *Tellus,* **7,** 329–340.

Black, J. L., R. E. Bateman, P. H. Herzegh, G. Wiener, J. Cowie, and C. J. Kessinger, 2008: An automated national-scale ceiling and visibility forecast system: Development progress. Preprints, *13th Conf. on Aviation, Range, and Aerospace Meteorology,* New Orleans, LA, Amer. Meteor. Soc., 7.2. [Available online at http://ams.confex.com/ams/pdfpapers/133936.pdf.]

Brier, G. W., 1950: Verification of forecasts expressed in terms of probabilities. *Mon. Wea. Rev.,* **78,** 1–3.

Brooks, H. E., C. A. Doswell III, and R. A. Maddox, 1992: On the use of mesoscale and cloud-scale models in operational forecasting. *Wea. Forecasting,* **7,** 120–132.

Cammarata, M. W., 1987: Forecasting temperature, dew point, and maximum temperature, using the Local AFOS MOS Program (LAMP). TDL Office Note 87-3, NOAA/NWS, 27 pp.

Carter, G. M., J. P. Dallavalle, and H. R. Glahn, 1989: Statistical forecasts based on the National Meteorological Center's numerical weather prediction system. *Wea. Forecasting,* **4,** 401–412.

Charba, J. P., and F. Liang, 2005: Automated two-hour thunderstorm guidance forecasts. Preprints, *Conf. on Meteorological Applications of Lightning Data,* San Diego, CA, Amer. Meteor. Soc., 3.4. [Available online at http://ams.confex.com/ams/pdfpapers/84746.pdf.]

——, and F. G. Samplatsky, 2009: Operational 2-h thunderstorm guidance forecasts to 24 hours on a 20-km grid. Preprints, *23rd Conf. on Weather Analysis and Forecasting/19th Conf. on Numerical Weather Prediction,* Omaha, NE, Amer. Meteor. Soc., 17B.2. [Available online at http://ams.confex.com/ams/pdfpapers/154173.pdf.]

Cressman, G. P., 1959: An operational objective analysis system. *Mon. Wea. Rev.,* **87,** 367–374.

Cummins, K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer, 1998: A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network. *J. Geophys. Res.,* **103,** 9035–9044.

Dallavalle, J. P., and V. J. Dagostaro, 1995: The accuracy of ceiling and visibility forecasts produced by the National Weather Service. Preprints, *Sixth Conf. on Aviation Weather Systems,* Dallas, TX, Amer. Meteor. Soc., 213–218.

——, and R. L. Cosgrove, 2005: GFS-based MOS guidance—The short-range alphanumeric messages from the 0000/1200 UTC forecast cycles. MDL Tech. Procedures Bull. 05-03, NOAA/NWS, 13 pp. [Available online at http://www.nws.noaa.gov/mdl/pubs/Documents/TechProcBulls/mdltpb05-03.pdf.]

——, M. C. Erickson, and J. C. Maloney III, 2004: Model output statistics (MOS) guidance for short-range projections. Preprints, *20th Conf. on Weather Analysis and Forecasting/16th Conf. on Numerical Weather Prediction,* Seattle, WA, Amer. Meteor. Soc., 6.1. [Available online at http://ams.confex.com/ams/pdfpapers/73764.pdf.]

Donaldson, R. J., R. M. Dyer, and M. J. Kraus, 1975: An objective evaluator of techniques for predicting severe weather events. Preprints, *Ninth Conf. on Severe Local Storms,* Norman, OK, Amer. Meteor. Soc., 321–326.

Doswell, C. A., III, 1985: The operational meteorology of convective weather. Vol. II: Storm scale analysis. NOAA Tech. Memo. ERL ESG-15, 240 pp.

Enger, I., L. J. Reed, and J. E. MacMonegle, 1962: An evaluation of 2–7-hr aviation terminal forecasting techniques. Tech. Pub. 20, Contract FAA/BRD-363, Travelers Research Center, Inc., Hartford, CT, 36 pp.

Friday, E. W., Jr., 1994: The modernization and associated restructuring of the National Weather Service: An overview. *Bull. Amer. Meteor. Soc.,* **75,** 43–52.

Gerrity, J. F., Jr., 1977: The LFM-model—1976: A documentation. NOAA Tech. Memo. NWS NMC-60, 68 pp.

Ghirardelli, J. E., 2005: An overview of the redeveloped Localized Aviation MOS Program (LAMP) for short-range forecasting. Preprints, *21st Conf. on Weather Analysis and Forecasting/17th Conf. on Numerical Weather Prediction,* Washington, DC, Amer. Meteor. Soc., 13B5. [Available online at http://ams.confex.com/ams/pdfpapers/95038.pdf.]

Glahn, B., and J. Wiedenfeld, 2006: Insuring temporal consistency in short range statistical weather forecasts. Preprints, *18th Conf. on Probability and Statistics in the Atmospheric Sciences,* Atlanta, GA, Amer. Meteor. Soc., 6.3. [Available online at http://ams.confex.com/ams/pdfpapers/103378.pdf.]

——, K. Gilbert, R. Cosgrove, D. P. Ruth, and K. Sheets, 2009: The gridding of MOS. *Wea. Forecasting,* **24,** 520–529.

Glahn, H. R., 1964: The use of decision theory in meteorology with an application to aviation weather. *Mon. Wea. Rev.,* **92,** 383–388.

——, 1980: Plans for the development of a Local AFOS MOS Program (LAMP). Preprints, *Eighth Conf. on Weather Forecasting and Analysis,* Denver, CO, Amer. Meteor. Soc., 302–305.

——, 1984: Surface wind forecasts from the Local AFOS Program (LAMP). Preprints, *18th Conf. on Weather Forecasting and Analysis,* Clearwater Beach, FL, Amer. Meteor. Soc., 78–86.

——, and D. A. Lowry, 1972: The use of model output statistics (MOS) in objective weather forecasting. *J. Appl. Meteor.,* **11,** 1203–1211.

——, and D. A. Unger, 1982: Some results from the Local AFOS MOS Program (LAMP). Preprints, *Ninth Conf. on Weather Forecasting and Analysis,* Seattle, WA, Amer. Meteor. Soc., 364–371.

——, and ——, 1986: A Local AFOS MOS Program (LAMP) and its application to wind prediction. *Mon. Wea. Rev.,* **114,** 1313–1329.

——, and D. P. Ruth, 2003: The new digital forecast database of the National Weather Service. *Bull. Amer. Meteor. Soc.,* **84,** 195–201.

——, and J. E. Ghirardelli, 2004: The new and improved Localized Aviation MOS Program (LAMP) Analysis and Prediction System. Preprints, *17th Conf. on Probabilty and Statistics in the Atmospheric Sciences/20th Conf. on Weather Analysis and Forecasting/16th Conf. on Numerical Weather Prediction,* Seattle, WA, Amer. Meteor. Soc., J12.3. [Available online at http://ams.confex.com/ams/pdfpapers/72289.pdf.]

——, T. L. Chambers, W. S. Richardson, and H. P. Perrotti, 1985: Objective map analysis for the Local AFOS MOS Program. NOAA Tech. Memo. NWS TDL 75, 34 pp. [Available online at http://www.nws.noaa.gov/mdl/pubs/Documents/TechMemo/TechMemo75.pdf.]

Grayson, T. H., and R. J. Bermowitz, 1974: A subsynoptic update model and forecast system with application to aviation weather: Final Report, Phase II. FAA-RD-74-l00, 46 pp.

Hoke, J. E., N. A. Phillips, G. J. DiMego, J. J. Tuccillo, and J. G. Sela, 1989: The Regional Analysis and Forecast System of the National Meteorological Center. *Wea. Forecasting,* **4,** 323–334.

Jacobs, A. J. M., and N. Maat, 2005: Numerical guidance methods for decision support in aviation meteorological forecasting. *Wea. Forecasting,* **20,** 82–100.

Joint Planning and Development Office, 2008: Four dimensional weather functional requirements for NextGen air traffic management. JPDO Rep. 08-005, 180 pp. [Available online at http://www.jpdo.gov/library/4D_Weather_Funt_Reqs_V6_CSv2-2.pdf.]

Kalnay, E., M. Kanamitsu, and W. E. Baker, 1990: Global numerical weather prediction at the National Meteorological Center. *Bull. Amer. Meteor. Soc.,* **71,** 1410–1428.

——, S. J. Lord, and R. McPherson, 1998: Maturity of operational numerical weather prediction: Medium range. *Bull. Amer. Meteor. Soc.,* **79,** 2753–2769.

Kelly, D. S., and J. E. Ghirardelli, 1998: A general overview of methodology and applications of the Local AWIPS MOS Program (LAMP), a short-range forecast guidance product. Preprints, *16th Conf. on Weather Analysis and Forecasting,* Phoenix, AZ, Amer. Meteor. Soc., 437–439.

Kitzmiller, D. H., F. G. Samplatsky, and D. L. Keller, 2002: Production of a national radar reflectivity mosaic and automated radar observations from WSR-88D radar coded messages. NOAA Tech. Memo. NWS MDL 83, 23 pp.

Leyton, S. M., and J. M. Fritsch, 2003: Short-term forecasts of ceiling and visibility utilizing high-density surface weather observations. *Wea. Forecasting,* **18,** 891–902.

Lund, I. A., 1955: Estimating the probability of a future event from dichotomously classified predictors. *Bull. Amer. Meteor. Soc.,* **36,** 325–328.

Miller, R. G., 1981: GEM: A statistical weather forecasting procedure. NOAA Tech Rep. NWS 28, 89 pp.

National Weather Service, 2008: Terminal aerodrome forecasts. NWS Instruction 10-813, 60 pp.

——, 2009: Verification procedures. NWS Instruction 10-1601, 83 pp.

Newell, J. E., and D. G. Deaven, 1981: The LFM-II model—1980. NOAA Tech. Memo. NWS NMC-66, 20 pp.

Oberfield, M. G., M. R. Peroutka, and C. Abelman, 2008: Using probabilistic forecast guidance and an update technique to generate terminal aerodrome forecasts. Preprints, *13th Conf. on Aviation, Range, and Aerospace Meteorology,* New Orleans, LA, Amer. Meteor. Soc., 5.4. [Available online at http://ams.confex.com/ams/pdfpapers/128927.pdf.]

OFCM, 1995: Surface weather observations and reports. Federal Meteorological Handbook 1, NOAA/Office of the Federal Coordinator for Meteorological Services and Supporting Research, 104 pp.

Olson, D. A., N. W. Junker, and B. Korty, 1995: Evaluation of 33 years of quantitative precipitation forecasting at the NMC. *Wea. Forecasting,* **10,** 498–511.

Peroutka, M. R., M. Graf, M. G. Oberfield, G. Trojan, and B. Li, 2004: The Aviation Forecast Preparation System of the National Weather Service. Preprints, *11th Conf. on Aviation,* *Range, and Aerospace Meteorology,* Hyannis, MA, Amer. Meteor. Soc., P3.2. [Available online at http://ams.confex.com/ams/pdfpapers/81312.pdf.]

Rudack, D. E., 2005: Improvements in the Localized Aviation MOS Program (LAMP) categorical visibility and obstruction to vision statistical guidance. Preprints, *21st Conf. on Weather Analysis and Forecasting/17th Conf. on Numerical Weather Prediction,* Washington, DC, Amer. Meteor. Soc., P1.52. [Available online at http://ams.confex.com/ams/pdfpapers/95050.pdf.]

——, 2009: Aviation weather observations vs. LAMP forecasts with the onset of precipitation. *Bull. Amer. Meteor. Soc.,* **90,** 929–938.

Schmeits, M. J., K. J. Kok, D. H. P. Vogelezang, and R. M. van Westrhenen, 2008: Probabilistic forecasts of (severe) thunderstorms for the purpose of issuing a weather alarm in the Netherlands. *Wea. Forecasting,* **23,** 1253–1267.

Souders, C. G., S. Abelman, C. Miner, R. C. Showalter, J. Tauss, E. R. Dash, and J. May, 2009: NextGen weather requirements. Preprints, *Aviation, Range, and Aerospace Meteorology Special Symp. on Weather–Air Traffic Management Integration,* Phoenix, AZ, Amer. Meteor. Soc., 3.1. [Available online at http://ams.confex.com/ams/pdfpapers/149141.pdf.]

Thomasell, A., Jr., and J. G. Welsh, 1962: Objective analysis of sea level pressure and surface temperature, dewpoint and wind. Tech. Publ. 19, Contract FAA/BRD-363, The Travelers Research Center, Inc., Hartford, CT, 87 pp.

Unger, D. A., 1982: The sea level pressure prediction model of the Local AFOS MOS Program. NOAA Tech. Memo. NWS TDL 70, 33 pp. [Available online at http://www.nws.noaa.gov/mdl/pubs/Documents/TechMemo/TechMemo70.pdf.]

——, 1985: The moisture model for the Local AFOS MOS Program. NOAA Tech. Memo. NWS TDL 77, 41 pp. [Available online at http://www.nws.noaa.gov/mdl/pubs/Documents/TechMemo/TechMemo77.pdf.]

——, 1987: Updated MOS ceiling height and visibility forecasts from the Local AFOS MOS Program (LAMP). Preprints, *10th Conf. on Probability and Statistics in Atmospheric Sciences,* Edmonton, AB, Canada, Amer. Meteor. Soc., 18–25.

——, W. L. Wolf, T. L. Chambers, and M. W. Cammarata, 1989: The Local AFOS MOS Program: Current status and plans. Preprints, *11th Conf. on Probability and Statistics in Atmospheric Sciences,* Monterey, CA, Amer. Meteor. Soc., 114–119.

Weiss, M., and J. E. Ghirardelli, 2005: A summary of ceiling height and total sky cover short-term statistical forecasts in the Localized Aviation MOS Program (LAMP). Preprints, *21st Conf. on Weather Analysis and Forecasting/17th Conf. on Numerical Weather Prediction,* Washington, DC, Amer. Meteor. Soc., 13B.6. [Available online at http://ams.confex.com/ams/pdfpapers/95121.pdf.]

Wiedenfeld, J. R., 2005: Localized Aviation MOS Program (LAMP): Statistical guidance of wind speed, direction, and gusts for aviation weather. Preprints, *21st Conf. on Weather Analysis and Forecasting/17th Conf. on Numerical Weather Prediction,* Washington, DC, Amer. Meteor. Soc., P1.48. [Available online at http://ams.confex.com/ams/pdfpapers/95030.pdf.]

Wilks, D. S., 2006: *Statistical Methods in the Atmospheric Sciences*. 2nd ed. Academic Press, 627 pp.

Younkin, R. J., J. A. LaRue, and F. Sanders, 1965: The objective prediction of clouds and precipitation using vertically integrated moisture and adiabatic vertical motions. *J. Appl. Meteor.,* **4,** 3–17.

Zurndorfer, E. A., J. R. Bocchieri, G. M. Carter, J. P. Dallavalle, D. B. Gilhousen, K. F. Hebenstreit, and D. J. Vercelli, 1979: Trends in comparative verification scores for guidance and local aviation/public weather forecasts. *Mon. Wea. Rev.,* **107,** 799–811.