3.2

Improving Localized Aviation MOS Program (LAMP) Guidance by Utilizing Emerging Forecast and Observation Resources

Judy E. Ghirardelli*, Jerome P. Charba, Jung-Sun Im,
Frederick G. Samplatsky, Bob Glahn
Meteorological Development Laboratory
Office of Science and Technology
National Weather Service, NOAA
Silver Spring, Maryland

Runhua Yang
IM Systems Group
Rockville, Maryland

Andrew J. Kochenash
Wyle Science, Technology & Engineering Group
Silver Spring, MD

1. Introduction

The National Weather Service's (NWS) Meteorological Development Laboratory (MDL) has developed and implemented the Localized Aviation MOS Program (LAMP) to provide objective forecast guidance for the aviation forecasting community. Since 2006, the LAMP system has provided centrally-produced, statistically-based forecast guidance for sensible weather elements at METAR stations, as well as thunderstorm guidance produced (directly) on a 5-km grid. The LAMP guidance serves to update the Global Forecast System (GFS; Kalnay et al. 1990) MOS guidance (Dallavalle et al. 2004). The GFS MOS guidance is produced four times a day, while the LAMP guidance is produced every hour. LAMP incorporates the most recent GFS MOS data, the most recent observational data of various types, and output from simple advective-type models (Ghirardelli and Glahn 2010).

In 2010, MDL implemented Gridded LAMP into NWS operations. Gridded LAMP provides forecast guidance on the 2.5-km National Digital Forecast Database (NDFD; Glahn and Ruth 2003) grid for temperature, dewpoint, ceiling height, and visibility (Ghirardelli and Glahn 2011). Also provided are grids of observations of the same fields as well as temperature and dewpoint error estimation grids (Im and Glahn 2012; Glahn and Im 2013). In 2012, MDL replaced the gridded LAMP 5-km thunderstorm guidance with an upgraded "lightning" product and also added gridded convection guidance, with both elements valid on the 2.5-km NDFD grid (Charba et al. 2011).

NWS forecast offices are in great need of improved gridded guidance for the aviation forecast elements of lightning, convection, ceiling height, and visibility. LAMP guidance for these elements is discussed in more detail in the subsequent section. Present challenges and the need to further improve these products are discussed in section 3. In section 4, we describe recently available fine-scale observational and model data sets, which show strong promise toward improving each of the above-noted LAMP guidance products, while in section 5 we describe approaches to improving the various elements. The latter part of this paper deals with current research to improve ceiling and visibility, with the majority of the results to date pertaining to visibility. We present some background ceiling and visibility verification in section 6, new prototype visibility regression development is described in section 7, and visibility verification results are presented in section 8. Finally, this effort is summarized, and MDL's plans for future development and improvements based on this prototype are discussed in section 9.

**Corresponding author address*: Judy E. Ghirardelli, Meteorological Development Laboratory, Office of Science and Technology, 1325 East-West Highway, Silver Spring, MD 20910; email: Judy.Ghirardelli@noaa.gov

2. LAMP background

The development method of the gridded LAMP lightning and convection guidance fundamentally differs from that of the station-based

LAMP ceiling height and visibility guidance, and thus differences apply to upgrades of each of these products. The backgrounds of the different elements are presented here to give the reader an understanding of these inherent differences.

a. *Gridded LAMP lightning and convection*

The gridded LAMP lightning and convection guidance is produced from multiple linear regression equations and associated statistically-derived thresholds. The predictand for the lighting guidance is defined as an event of at least one cloud-to-ground (CG) lightning strike in a 20-km grid box in a 2-h period. The predictand of the convection guidance is defined as an event of at least one CG lightning strike and/or radar reflectivity of 40 DBz. The lightning data source is the National Lightning Detection Network (Cummins et al. 1998), while the radar data source is the Radar Coded Message (RCM; OFCM 1991; Kitzmiller et al. 2002).

LAMP lightning and convection guidance is derived from a variety of predictor sources (Charba et al. 2011), which include GFS MOS and North American Mesoscale model (NAM; Rodgers et al. 2005) MOS 2-h lightning and convection probabilities, the GFS and NAM direct model output, gridded observations of CG lightning and RCM radar together with advected representations of these grids, and fine-scale CG lightning and convection climatology.

The regression equations are derived via the Regression Estimation of Event Probabilities (REEP) method (Miller 1958; Wilks 2011). REEP is regression where the predictand is binary and takes on the value 1 when the event occurred and 0 otherwise. The REEP equation will produce an estimate of the probability of the predictand event conditional on the predictor values. Because the predictor and predictand data are available in gridded form, the regression equation development is performed on the grid, and the equations are evaluated on the grid to produce the gridded guidance.

The LAMP guidance is available on the 2.5-km NDFD grid and is produced hourly. The guidance is valid over 2-h periods that overlap in the short-term and over contiguous non-overlapping 2-h periods after that. The forecasts go out to 24 or 25 hours, depending on the LAMP cycle. Please refer to Charba et al. (2011) for more details.

b. *Station-based and gridded LAMP ceiling height and visibility*

In contrast to the LAMP lightning and convection guidance, the LAMP ceiling and visibility equations are developed at stations. This is because the predictor and predictand data are valid at stations. The predictands are METAR observations, while the predictors are GFS MOS and observations at the stations, and gridded simple model output interpolated to the stations. The LAMP ceiling and visibility regression equation development also follows the REEP methodology. Evaluating the equations yields forecast probabilities that along with statistically-derived thresholds result in categorical forecast guidance for ceiling and visibility. Please see Ghirardelli and Glahn (2010) for more details on the LAMP station-based development for these elements.

NWS currently provides LAMP ceiling and visibility guidance valid at 1678 stations. The guidance is produced every hour and covers the 1- to 25-h period in 1-h time steps. The guidance can be used by aviation forecasters to create Terminal Aerodrome Forecasts (TAF; NWS 2008) which are valid at airports (i.e., at stations).

The aviation community also has a need for good quality gridded guidance of ceiling and visibility for a variety of stakeholders. In 2012, MDL implemented Gridded LAMP for ceiling and visibility. To produce these grids, the LAMP station-based ceiling and visibility forecasts are analyzed to the NDFD grid via the Bergthorssen-Cressman-Doos-Glahn (BCDG) process described in Glahn et al. (2009) and Im and Glahn (2012).

3. Current challenges

The LAMP guidance is intended to meet the evolving needs of the aviation community. With respect to lightning and convection guidance, MDL understands that our stakeholders require products with increased spatial and temporal resolution, especially in the short-term period. An important weakness of the present LAMP lightning and convection guidance is that it does not incorporate predictors that depict convection initiation or dissipation on a fine scale or that are updated frequently; the only relevant predictor input is from NAM and GFS model output and MOS probabilities, each of which is for rather coarse space and time scales.

Providing digital aviation services, which include gridded ceiling and visibility forecasts, is part of the NWS' plan for Enhanced Digital Services (Uskievich and Pontius 2015). In addition, in 2012 the Federal Aviation Administration (FAA) made a number of ceiling and visibility research priority recommendations (FAA 2012), two of which were to improve ceiling and visibility forecast accuracy with TAFs at high-impact terminals as well as to improve gridded ceiling and visibility observations and forecasts across the National Airspace System. Gridded LAMP guidance for ceiling and visibility can be used to support the NWS digital aviation services as well as to provide TAF guidance and gridded observations and forecasts to meet the FAA needs.

Weaknesses of the Gridded LAMP ceiling and visibility guidance include the lack of station observations and LAMP forecasts of ceiling and visibility to adequately cover the 2.5-km NDFD grid. In 2015, MDL will add additional LAMP station input to the Gridded LAMP ceiling and visibility guidance, which will provide more data points for the analyses, but even with additional stations, the total number of stations is still inadequate to resolve the fields of ceiling height and visibility in the CONUS at 2.5-km resolution. In addition, LAMP guidance at points over water (ocean, Great Lakes, Great Salt Lake) was produced without observational input valid at those points, as the reporting platforms over the water do not in general report ceiling and visibility. Therefore the accuracy of these new LAMP forecasts is most likely less than that of the LAMP forecasts valid at land stations for which there are observations. In addition, both ceiling and visibility are very discontinuous fields, which makes producing good quality gridded products from an inadequate number of data points very challenging.

Given the above challenges and weaknesses, it became apparent that Gridded LAMP guidance for lightning, convection, ceiling, and visibility should be upgraded based on fine-scale data that have recently become available.

4. Newly available data

a. *Lightning data*

Lightning data is used both as a predictor and predictand for LAMP lightning guidance. Using improved lightning data would be one way to improve LAMP lightning guidance. Therefore, MDL is now investigating the use of Total Lightning (TL) data, which has recently become available.

Total lightning data consist of a mix of individual CG and in-cloud (IC) flashes, as measured by a ground-based, remotely-sensed network across the CONUS. For development of upgraded lightning and convection guidance, MDL has been utilizing a TL archive provided by Earth Networks, Inc. (ENI), but TL data have also recently become available from the National Lightning Detection Network operated by Vaisala, Inc. Operational implementation of TL data, as likely provided by one of these systems, is expected by mid-2015.

b. *Radar data*

Another type of CONUS ground-based remotely-sensed observational data used in LAMP is radar reflectivity. As with lightning data, radar reflectivity data are used both as a predictor and predictand in the LAMP convection guidance, only as a predictor in the corresponding lightning guidance, and to a slight degree as a predictor in LAMP station guidance. The current RCM radar data used in LAMP is rather coarse spatially, temporally, and quantitatively, and it lacks good quality control.

High resolution Multi-Radar/Multi-Sensor System (MRMS) has recently become available. These data consist of WSR-88D radar reflectivity-based products, which also incorporate other observational data types (mainly precipitation gage and satellite measurements) especially in the mountainous western US where radar coverage is poor. The native MRMS data have a spatial resolution of approximately 1-km and a temporal resolution of 2.5-min (Zhang et al. 2011; Zhang et al. 2014).

For development of upgraded LAMP lightning and convection guidance, MDL has acquired an archive of MRMS data from the National Severe Storms Laboratory (NSSL). Also, MRMS data became operationally available in September 2014. Incorporation of both the MRMS archive and real time data into upgraded LAMP lightning and convection products should provide a big step forward towards improved LAMP lightning and convection products.

c. *Mesoscale model output data*

A high-resolution mesoscale model with frequent updates should benefit LAMP, as the current model or MOS inputs to LAMP are only updated every 6 hours. The High Resolution Rapid Refresh (HRRR; Smith et al. 2008; Ikeda et al. 2013) model data are produced hourly at 1-h time steps, with some fields available in 15-min time steps. Many model output variables are available, whose focus is on aviation applications (e. g., simulated radar reflectivity, ceiling height, and visibility). [For the most up-to-date information on the HRRR configuration, readers should refer to the HRRR website: http://rapidrefresh.noaa.gov/hrrr].

For the purposes of research and development, MDL has acquired an archive of HRRR model output grids from the NOAA/Earth Systems Research Laboratory/Global Systems Division, which spans the period of April 2013 through September 2014. Such data are on a 3-km grid referenced to a Lambert map projection covering most of the NDFD CONUS grid.

The HRRR produces forecasts for projections 1 through 15 hours. The HRRR visibility forecasts are in units of meters, which we converted for convenience to miles, the units used by aviation interests in the United States and the units used by LAMP. We used the HRRR grid of "cloud base" as ceiling height, per the suggestion of the HRRR developers that the HRRR cloud base is a representation of ceiling height (S. Benjamin and C. Alexander 2014, personal communication). The HRRR model became operationally available in September 2014.

5. Upgrading LAMP with high-resolution datasets

a. *LAMP lightning and convection*

MDL expects to use the high-resolution datasets discussed above to improve the spatial and temporal resolution of the LAMP lightning and convection forecasts. Specifically, the mesh of the forecast grid will be reduced from 20-km used presently to 10-km, which will allow for increased spatial detail. Also, the forecast valid period will be reduced from the present 2 hours to 1 hour, at least for the forecasts in the first 6-8 hours, which provides enhanced temporal resolution.

Note that the predictand valid area will remain unchanged from the present 20-km square box to avoid excessive loss of sharpness in the forecast probabilities (Charba et al. 2011) that would likely occur with a reduction in both the grid box size and valid period. It is also worth noting that the TL data should enhance the specification of the convection predictand as well as predictors for both lightning and convection, since the frequency of IC flashes in ENI TL data is about six times the number CG flashes (Charba et al. 2015).

The high-resolution MRMS radar and TL observations together with the HRRR forecasts are expected to support the increased spatial and temporal detail in the convection predictands. Specifically, the MRMS data will be incorporated on a 5-km grid every 15 minutes, which provides a big improvement on the 10-km spatial and 30-minute temporal resolution of the RCM radar data ingest presently being used. Also, the HRRR model forecasts exhibit remarkable spatial and temporal detail, which should be reflected in the LAMP forecasts since HRRR predictors will be used.

It is noted that the TL and HRRR data are also used to improve the quality of the MRMS data prior to inclusion of the latter into LAMP. Specifically, an automated supplemental QC process for MRMS data is being developed, wherein the TL observations and HRRR forecasts are used to identify and remove false echoes in the MRMS data. MDL is currently preparing these datasets for use in redeveloping the LAMP lightning and convection guidance.

b. *LAMP ceiling height and visibility*

The goal for LAMP ceiling and visibility work is not just to improve LAMP at the LAMP stations, but also to improve Gridded LAMP for these elements in between the LAMP stations. To this end, MDL began investigating a second-order development where regression equations would be developed at LAMP stations using predictors made up of ceiling and visibility forecasts from both LAMP and HRRR. Such equations could then be applied at the Gridded LAMP gridpoints with Gridded LAMP and HRRR predictors to produce a grid which could be seen as a statistical blend of the Gridded LAMP and HRRR forecasts.

The rest of this paper deals with the results to date from MDL efforts to improve LAMP ceiling and visibility.

6. HRRR ceiling and visibility verification

Before any development began, MDL evaluated ceiling and visibility forecasts from the HRRR model compared to the Rapid Refresh (RAP; Benjamin et al. 2007) model and the LAMP forecasts. The intent was to determine which model might be the best input to a redeveloped LAMP system. The results are not shown here, but in general the HRRR was found to have better scores for more projections than the RAP, so the decision was made to use the HRRR in the LAMP development. Therefore this section will focus on the HRRR verification results.

For the verification, the HRRR model cloud base (hereafter referred to as ceiling) and visibility forecasts were interpolated to 1,562 LAMP stations in the CONUS. In addition, because the HRRR ceiling forecasts are relative to sea level, the values were adjusted by using the HRRR terrain to represent ceiling above ground level, which is consistent with LAMP ceiling forecasts and METAR observations. The verification metrics evaluated were bias, threat score (or Critical Success Index [CSI]) (Donaldson et al. 1975; Shaffer 1990), probability of detection, and false alarm ratio (Wilks 2011). The events (categories) of ceiling < 500 ft, <1000 ft, and ≤ 3000 feet, and visibility < 0.5 mile, < 1 mile, and < 3 miles were verified.

Data verified were for one warm season (April – September 2013) and one cool season (October 2013 – March 2014). This paper focuses on the cool season results. Two cycles were selected to verify: 0000 and 1200 UTC. Because the HRRR does not complete for approximately an hour after the LAMP forecasts are available and disseminated, in the verification we used HRRR forecasts produced for the run time 1 hour previous to LAMP so as to be comparing the products that would have been available at the time the LAMP guidance became available. Therefore, the 0000 and 1200 UTC LAMP guidance was compared with the corresponding 2300 and 1100 UTC HRRR model output. Persistence, which is the forecast that would result from persisting the observations into the forecast period, was also evaluated, as that is often very difficult to improve on in the very early projections. Because the HRRR model only goes out 15 hours in time, and the verification used a model run already 1 hour old, only 14 projections of matching LAMP, HRRR, and persistence forecasts could be verified.

The verification for visibility forecasts at 0000 UTC (2300 UTC HRRR) for the cool season showed that LAMP had much higher threat scores than HRRR for the first few hours at the LAMP stations, and the HRRR had comparable or slightly better threat scores after 3-6 hours, depending on the category. The crossover point where HRRR had higher threat scores than LAMP was later for ceiling. However, this result wasn't seen with the 1200 UTC (1100 UTC HRRR) verification, where LAMP typically had a higher or comparable threat score to the HRRR at all projections. It is possible that using the 1-h old HRRR is more detrimental at 1200 UTC when conditions may be changing more rapidly than they are at 0000 UTC.

While the HRRR threat scores were higher than LAMP's at most longer projections for visibility at 0000 UTC, the bias scores showed an overforecasting bias in the HRRR for the lower two cumulative categories. For ceiling, there was also an overforecasting bias for the HRRR, but it wasn't as high as that for visibility. This was true for the 0000 UTC as well as the 1200 UTC results.

As one goal of using the HRRR model data is to improve Gridded LAMP between the LAMP stations where there are no data points, additional verification was performed to evaluate the HRRR in between the LAMP stations. To do this, Gridded LAMP ceiling and visibility forecasts as well as HRRR forecasts were interpolated to 314 CONUS stations that had no LAMP forecasts, but that did have observations. Again, the HRRR ceiling forecasts were adjusted to be above ground level.

This verification showed that the Gridded LAMP forecasts interpolated to the non-LAMP stations (hereafter referred to as GLMP at non-LAMP stations) had lower threat scores in the first 3 hours compared to what was seen with the LAMP forecasts at LAMP stations, which was to be expected. For visibility, HRRR threat scores were higher than GLMP at non-LAMP stations for both cycles and all categories and projections except at 0000 UTC for the first projection for visibility < 3 miles, and at 1200 UTC for the 1-10 h projections for visibility < 3 miles and the first projection for visibility < 1 mile.

For ceiling, the HRRR results were not as good compared to GLMP at non-LAMP stations as what was seen with visibility. The HRRR threat scores were higher than the GLMP at non-LAMP stations at 0000 UTC after projection 4 for visibility < 1000 ft and after projection 6 for visibility < 500 ft. HRRR threat scores were not higher than LAMP at 1200 UTC for any ceiling category or projection. As at the LAMP stations, the HRRR biases tended to be high for the lower two cumulative categories for both ceiling and visibility.

These results indicate that the HRRR contains valuable information, especially for visibility and at the points between the LAMP stations.

7. Regression equation development for visibility

The verification results discussed in the previous section encouraged us to determine whether or not a combination of LAMP and HRRR could produce better forecasts than either alone. Our initial work was on cool season visibility; the technique for combining is explained in this section and the results are shown in the next section. Cool season is defined as October through March.

The developmental period was limited by the availability of HRRR forecasts. We used HRRR data which covered the cool season of October 1, 2013 through March 31, 2014. The data were prepared as discussed in Section 4c.

LAMP produces probability forecasts for each of the visibility categories shown in Table 1 for projections 1 through 25 hours. These probabilities are used to produce "best category" forecasts by thresholding the probability forecasts such that the biases are in an acceptable range near unity and the threat score is maximized. In the conversion, information is necessarily lost, and it was confirmed with initial tests that the categorical forecasts did not provide useful information over and above the probabilistic forecasts. For combining LAMP and HRRR, only the LAMP probabilistic forecasts were used.

Table 1. Category definitions of visibility in miles.

Category Number	Visibility (mi.)
1	< 0.5
2	≥ 0.5 and < 1.0
3	≥ 1.0 and < 2.0
4	≥ 2.0 and < 3.0
5	≥ 3.0 and ≤ 5.0
6	> 5.0 and ≤ 6.0
7	> 6.0

The LAMP equations that produce the experimental probability forecasts were developed by the REEP technique, as were the original LAMP probabilistic visibility equations. Usually for rare events such as low visibilities, many stations are pooled over areas where the predictand-predictor relationships are thought to be similar, and a sample of several years is used. We had only one season of data, so we used a generalized operator approach where all stations were pooled and only one equation was produced for each visibility category and each forecast projection. LAMP forecasts and matching observations were available for 1,562 CONUS stations, and we "interpolated" the HRRR forecasts to those points by using the closest HRRR gridpoint to the station location.

The predictors used in the equations are usually selected from a pool of potential predictors automatically according to their usefulness in reducing the predictand variance. MDL software uses the forward selection method, and when more than one projection is involved, screening is over all projections and predictands. That is, for the first selection, the predictor is chosen that reduces the variance the most for any predictand category and any projection. The second and following choices are made in the same way, given that the previous one(s) has (have) been selected.

Many times the predictors in a REEP equation are cumulative binary and one or more such binaries defined from a continuous variable produces much better results than the continuous variable itself. The cumulative from above binaries we defined from the HRRR visibility forecasts were for the same categories as the categories defined by the upper category values in Table 1, and in addition we included binaries for > 7, > 8, > 9, > 10, > 15, and > 20 mi to take into account the full range of the HRRR forecasts. The total number of potential HRRR predictors was 12.

We divided the 6 months of data into a developmental sample of 4 months (October, December, January, and March), and an independent sample of 2 months (November and February). As with the verification, we used the HRRR forecasts produced at the previous hour to the LAMP cycle for which we were developing since that is what would be available in real-time operations. That is, for a LAMP run time of 0000 UTC, we used the HRRR for the previous run time of 2300 UTC. Our total potential predictor set consisted of the six continuous LAMP probability forecasts and 12 HRRR binary predictors. The screening stopped when the next best predictor did not reduce the variance of any predictand by at least 0.5%.

The predictor set chosen by screening consisted of all six LAMP predictors and five HRRR predictors. To produce categorical forecasts, as the current LAMP system does, thresholds were calculated such that the threat score for each category was maximized within a bias range of 1.0-1.2. New categorical forecasts for 0000 UTC from this system, hereafter referred to as the LAMP+HRRR forecasts, were then created from the LAMP+HRRR probabilities and associated thresholds. For additional detail, see Glahn et al. (2014).

8. Results for redeveloped LAMP/HRRR visibility forecasts

As noted above, the months of November 2013 and February 2014 were withheld from the development sample and were used as independent data for verification of the new LAMP+HRRR categorical forecasts and comparison with LAMP, HRRR, and persistence at the same 1,562 stations used in the development. Figures 2, 3, and 4 show the threat scores for the cumulative categories of visibility < 0.5 miles, < 1 mile, and < 3 miles, respectively.

The figures all show the same overall result: the original LAMP forecasts are comparable to persistence in the first 2 or 3 hours, and increasingly more accurate than persistence thereafter. The original LAMP forecasts are also much more accurate than the HRRR forecasts in the early projections, but the HRRR forecasts are more accurate than the original LAMP forecasts after a certain “crossover” projection. This crossover projection varies based on the category; the HRRR forecasts become more accurate than the original LAMP forecasts after 11 hours for visibility < 0.5 miles, after 4 hours for visibility < 1 mile, and after only 3 hours for visibility < 3 miles. The new LAMP+HRRR forecasts are as accurate or more accurate than any of the other forecasts, with the improvement over the original LAMP forecasts being the greatest for visibility < 3 miles where LAMP+HRRR forecasts are more accurate than the original LAMP forecasts even as early as the 1-h projection

Figure 5 shows the percentage improvement of the threat scores of the new LAMP+HRRR forecasts over the threat scores of the original LAMP forecasts for visibility < 0.5 miles, < 1 mile, and < 3 miles. The improvement is small in the very first hours, but the improvement quickly increases with projection. The improvement was positive for all projections except for projection 2 for visibility < 0.5 miles, where it was only slightly negative (-1%), and the improvements generally were between 20% and 30%, with as much as a 42% improvement for visibility < 1 mile at 12 hours.

As we discovered in the earlier verification of the HRRR forecasts, there was an overforecasting bias for the lower categories. The biases for the forecasts of visibility < 0.5 miles are shown in Fig. 6. The HRRR forecasts have a high bias of 2.5 – 3.1, which is much higher than the original LAMP forecast biases, which range from 1.1 to 1.6. Persistence has an underforecasting bias (as low as 0.2) because 0000 UTC is at a time of fewer observations of low visibility, with more occurrences of low visibility thereafter. The LAMP+HRRR forecasts exhibit a bias near unity (the range being from 1.0 to 1.3), which is generally better than any of the other systems that we evaluated.

The bias results for the second LAMP category (visibility ≥ 0.5 miles and < 1.0 mile; not shown) indicate that the HRRR forecasts were underforecasted in this category as the biases were around 0.5 from 5 to 14 hours. The biases for the visibility < 3.0 miles (not shown) indicate the HRRR forecasts have a bias closer to unity when all three categories are considered, which indicates that the biggest issue of overforecasting for the HRRR bias originates with the visibility forecasts < 0.5 miles. The LAMP+HRRR statistical blend is able to successfully correct for this bias, as evidenced in the LAMP+HRRR biases being close to unity for all categories investigated.

The results presented above are at stations, but the objective is to produce gridded forecasts that can be put into the National Digital Gridded Database (NDGD), a companion to the NDFD, therefore implementation must be on a grid, and specifically the NDFD grid. The equations and thresholds, being generalized, can be applied to any point, including gridpoints. The HRRR forecasts can be interpolated to points on the NDFD grid. The LAMP probabilities at stations can be analyzed to the same grid with the BCDG method, and that analysis produces probabilities at the same gridpoints. These two sets of values, six from LAMP and five from HRRR, can be used with the generalized equations, one for each of the visibility predictand categories, to produce a probability grid for each category. Then the thresholds, developed for stations, can be applied at each gridpoint to yield a gridded categorical visibility forecast.

This process has been carried out for the 6-h projection for the 0000 UTC cycle of October 7,

2013. The 6-h projection was chosen because it is into the period where the quality of HRRR and LAMP forecasts are somewhat comparable. Figures 7-10 show, respectively, the LAMP forecast, the HRRR forecast, the combined LAMP+HRRR forecast, and the verifying grid. Figures 7 and 10 were made by analyzing the LAMP station forecasts and the observations with the BCDG method. Values of $\geq$ 10 miles are shown as off-white.

Figures 7 and 10, being analyses of rather sparse values, are somewhat "spotty." On the other hand, the HRRR forecast in Fig. 8 shows great detail, with "spottiness" of pixel size. The pattern of actual low visibilities is generally captured by both LAMP and HRRR, with some overcasting. The HRRR has large areas of > 5 and < 10 miles (green), that are neither observed nor forecast by LAMP. The visibilities depicted over ocean areas are in question on all maps.

Figure 9 shows that the combined LAMP+ HRRR forecast has the detail of the HRRR generally preserved, without the large HRRR overforecasting of > 5 and < 10 miles. The combined forecast also shows details of the LAMP forecast, and more visibilities < 10 miles are forecast than observed. The pixel-sized spottiness is somewhat troublesome, as a 6-h forecast cannot be expected to be correct in that detail. However, the general areas of low visibility are depicted rather well; the Ohio to eastern Tennessee band, the western Virginia through Alabama and into the Gulf of Mexico band, and the New England southward band are rather well placed.

9. Summary and Plans

These initial results of combining LAMP and HRRR for visibility are very encouraging, and this seems a viable path to improvement of operational ceiling and visibility products. We plan to continue with other cycles, and extend the method to ceiling. The upgraded redevelopment of gridded LAMP lightning and convection is not yet complete and therefore we do not have preliminary results, however it is expected that the inclusion of the new datasets will likewise greatly improve the LAMP guidance for these elements.

Two large concerns for these redevelopments are the considerable development time needed to extend to all cycles, and the possibility the HRRR will be modified in ways that will largely invalidate the regression relationships. The latter concern can be mitigated somewhat by the availability of an archive of data from an upgraded HRRR model that can be tested with and redeveloped on, if necessary, prior to any HRRR upgrade.

The real time production of such prototype LAMP+HRRR guidance for visibility, lightning, and convection forecasts is expected to begin during the summer of 2015. The production of the prototype LAMP+HRRR ceiling height guidance will begin in 2016.

10. Acknowledgements

The authors wish to thank Stan Benjamin, Curtis Alexander, and Geoff Manikin for their assistance with the HRRR archive and for answering many technical and scientific questions about the HRRR data. We also wish to thank the NSSL staff of Kenneth Howard for general help with use of MRMS data, Carrie Langston for assisting with acquisition of MRMS archive, and Jian Zhang for answering many questions about the MRMS data. In addition, we are grateful to Christopher Sloop of ENI, who assisted with acquisition of ENI TL archive and for thoroughly answering many MDL questions about ENI's TL data.

We also acknowledge the efforts of Tamarah Curtis for her assistance with the programs to gather and plot the verification data, to Chenjie Huang for assistance in data preparation, and Mike Allard for help with the HRRR visualization. David Rudack and Phil Shaffer also provided helpful advice and comments.

References

Benjamin, S.G., S.S. Weygandt, J.M. Brown, T.G. Smirnova, D. Devenyi, K. Brundage, G.A. Grell, S. Peckham, T. Schlatter, T.L. Smith, G. Manikin, 2007: From the Radar-Enhanced RUC to the WRF-Based Rapid Refresh. *22nd Conf. Wea. Analysis Forecasting/18th Conf. Num. Wea. Pred.*, Park City, UT, Amer. Meteor. Soc., J3.4.

Charba, J.P., F.G. Samplatsky, and P.E. Shafer, 2011: Experimental LAMP 2-h Convection Guidance on a 20-km grid. Preprints, *24th Conference on Weather Analysis and Forecasting/20th Conference on Numerical Weather Prediction*. Seattle, WA, Amer. Meteor. Soc., J19.3.

Charba, J. P., F. G. Samplatsky, J. E. Ghirardelli, A, J. Kochenash, and P. D. Bothwell, 2015: Statistical properties of ENI IC/CG flashes relative to NLDN CG flashes over the CONUS. *Seventh Conference on the Meteorological Applications of Lightning Data*. Phoenix, AZ, Amer. Meteor. Soc., 1.2.

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., 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.

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

FAA, 2012: Ceiling and Visibility Research Evolution Plan: An Aviation Weather Research Guide, Version 1.0, 2012. Available by request from: http://clientportal.avmet.com/clientportal/

Ghirardelli, J. E., and B. Glahn, 2010: The Meteorological Development Laboratory's Aviation Weather Prediction System. *Wea. Forecasting*, **25**, 1027-1051

_____, and _____, 2011: Gridded Localized Aviation MOS Porgram (LAMP) Guidance for Aviation Forecasting. Pre-prints, *15th Conference on Aviation, Range, and Aerospace Meteorology*. Los Angeles, CA, Amer. Meteor. Soc., 4.4

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

_____, and J.-S. Im, 2013: Error estimation of objective analysis of surface observations. *J. Operational Meteor*., **1** (11), 114-127.

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

_____, R. Yang, and J. Ghirardelli, 2014: Combining LAMP and HRRR visibility forecasts. MDL Office Note 14-2, 20 pp.

Ikeda, K., M. Steiner, J. Pinto, and C. Alexander, 2013: Evaluation of Cold-Season Precipitation Forecasts Generated by the Hourly Updating High-Resolution Rapid Refresh Model. *Wea. Forecasting*, **28**, 921–939.

Im, J.-S., and B. Glahn, 2012: Objective analysis of hourly 2-m temperature and dewpoint observations at the Meteorological Development Laboratory. *Nat. Wea. Dig.*,**36**, 103-114.

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.

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.

Miller, R. G., 1958: Regression estimation of event probabilities, U.S. Weather Bureau, Contract Cwb-10704, Tech. Rep. No. 1, The Travelers Research Center, Inc., Hartford, CN.

National Weather Service, 2008: Terminal Aerodrome Forecasts. National Weather Service Instruction 10-813, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 60 pp.

OFCM, 1991: Doppler radar meteorological observations: Part C, WSR-88D products and algorithms. Federal Meteorological Handbook 11, FMC-H11C-1991, Office of the Federal Coordinator for Meteorological Services and Supporting Research, Silver Spring, MD, 210 pp.

Rodgers, E., Y. Lin, K. Mitchell, W.-S. Wu, B. Ferrier, G. Gayno, M. Pondeca, M. Pyle, V. Wong, and M. Ek, 2005: The NCEP North American Mesoscale Modelling System: Final Eta model/analysis changes and preliminary experiments using the WRF-NMM. Preprints, *21st Conf. on Wea. Analysis and Forecasting*, Washington, D.C., Amer. Meteor. Soc., 4B.5.

Shaffer, J. T., 1990: The Critical Success Index as an indicator of warning skill. *Wea. Forecasting*, **5**, 570-575.

Smith, T. L., S. G. Benjamin, J. M. Brown, S. Weygandt, T. Smirnova, B. Schwartz, 2008: Convection Forecasts from the Hourly Updated, 3-km High Resolution Rapid Refresh (HRRR) Model. *24th Conf. on Severe Local Storms*, Savannah, GA, Amer. Meteor. Soc., 11.1.

Uskievich, C. S., and S. Pontius, 2015: Enhanced Digital Services for Aviation. *17th Conference on Aviation, Range, and Aerospace Meteorology*, Phoenix, AZ, Amer. Meteor. Soc., 2.1A.

Wilks, D. S., 2011: Statistical Methods in the Atmospheric Sciences. Academic Press, 676 pp.

Zhang, J., K Howard, C. Langston, et al., 2011: National mosaic and multi-sensor QPE (NMQ) system: Description, results and future plans: *Bull. Amer. Met. Soc.*, **92**, 1321-1338.

Zhang, J., K. Howard, S. Vasiloff, et al., 2014: Initial operating capabilities of quantitative precipitation estimation in the multi-radar multi-sensor system. Preprints, *28th Conference on Hydrology*, Atlanta, GA, Amer. Meteor. Soc., 5.3.

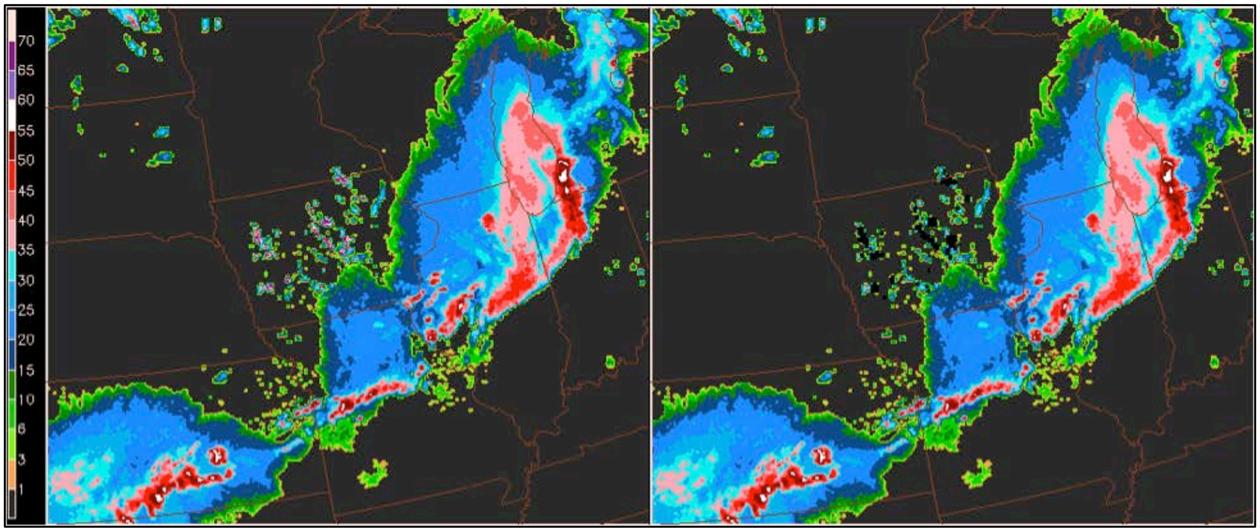

FIG. 1. MRMS composite reflectivity for 01 July 2014 at 0444 UTC before (left) and after (right) an automated supplemental quality control process (QC) was applied. Small scattered echoes in Iowa are due to anomalous radar beam propagation (AP), and those AP echoes 40 DBz and higher are removed (shown as black) by the QC.

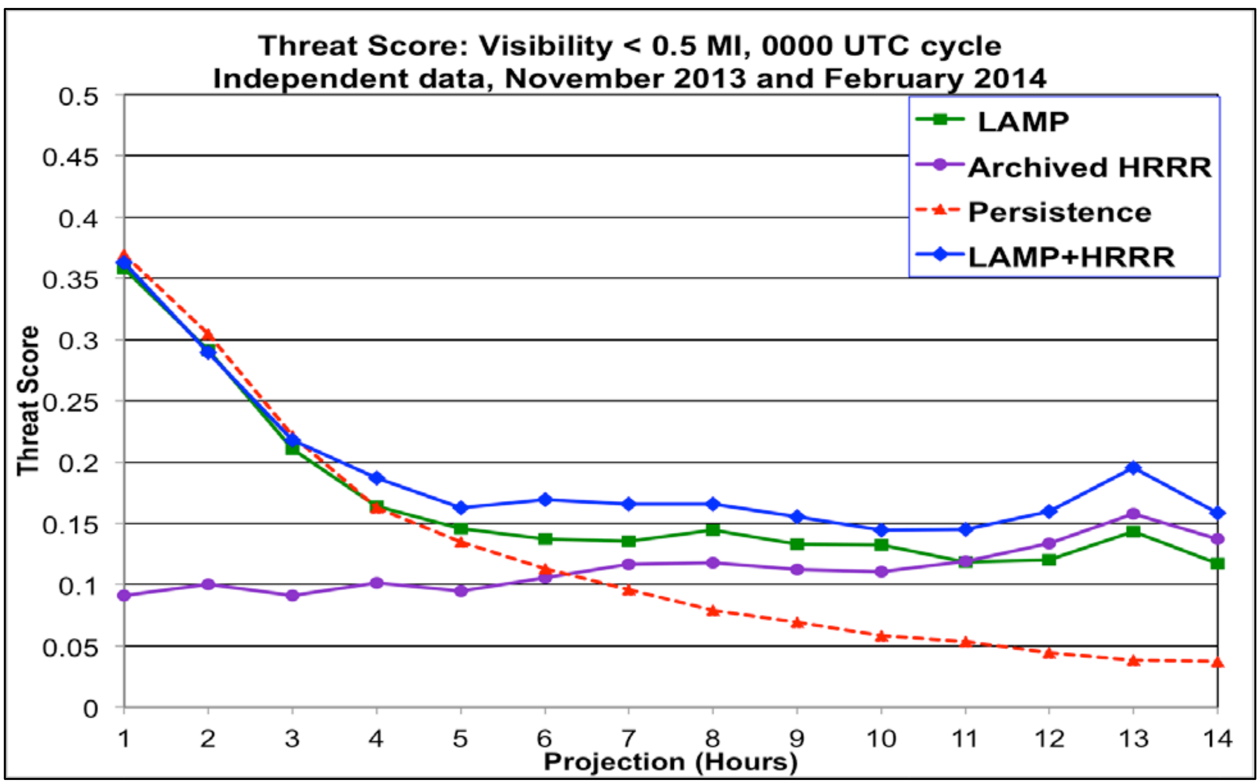

FIG. 2. Threat score for visibility < 0.5 miles for 0000 UTC LAMP (green squares), 2300 UTC Archived HRRR (purple circles), Persistence (red triangles), and the new LAMP+HRRR forecasts (blue diamonds).

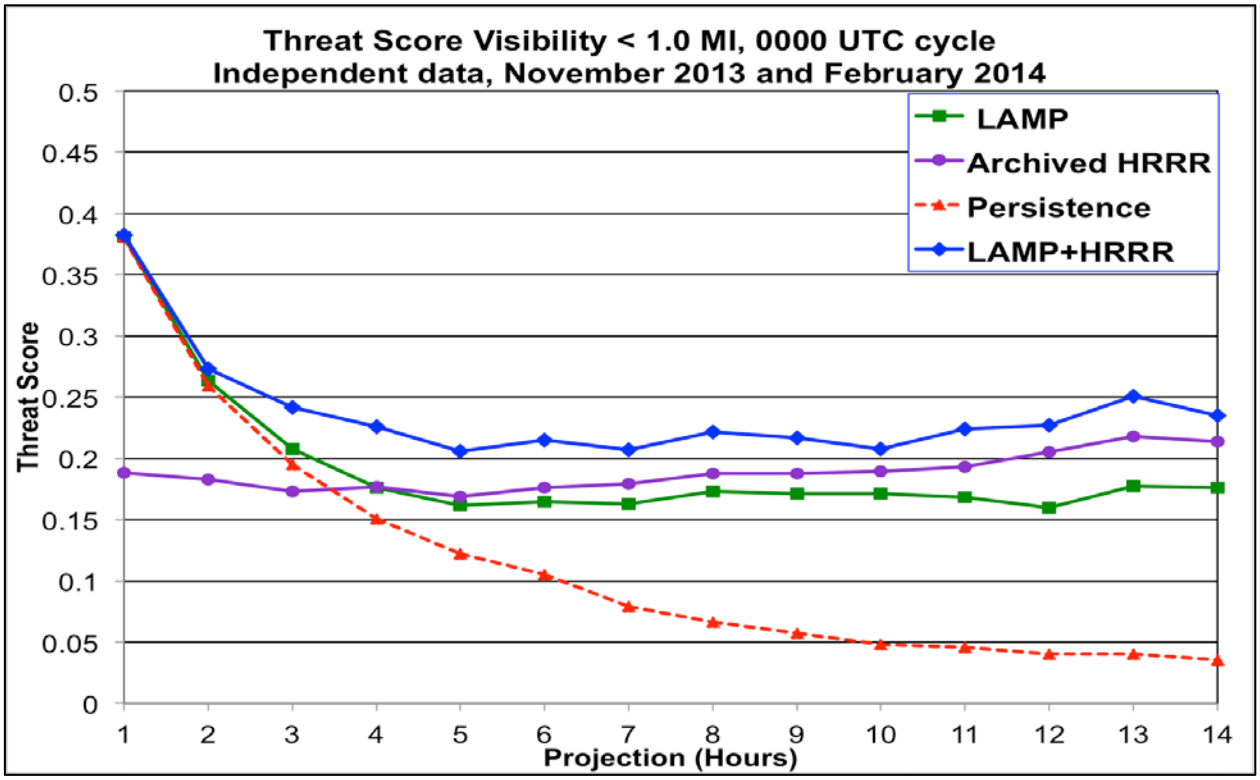

FIG. 3. Same as Fig. 1, but for visibility < 1.0 mile.

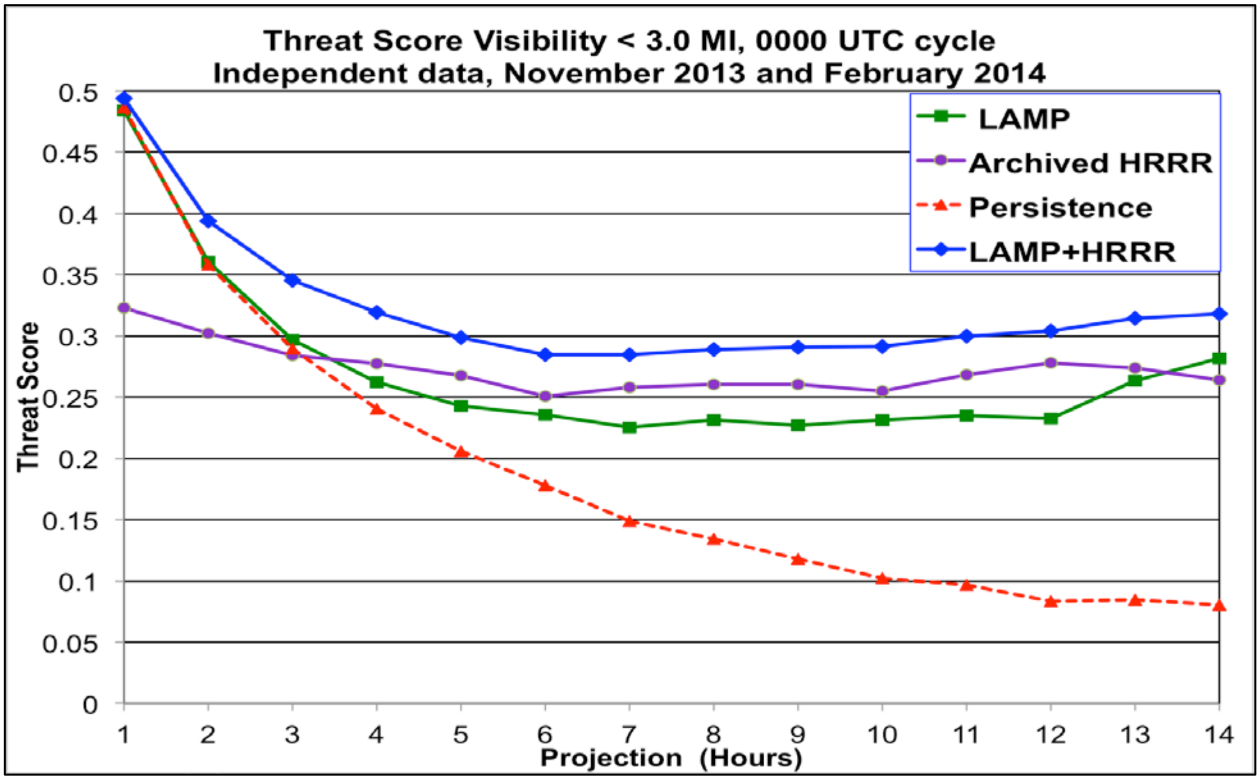

FIG. 4. Same as Fig 1, but for visibility < 3.0 miles.

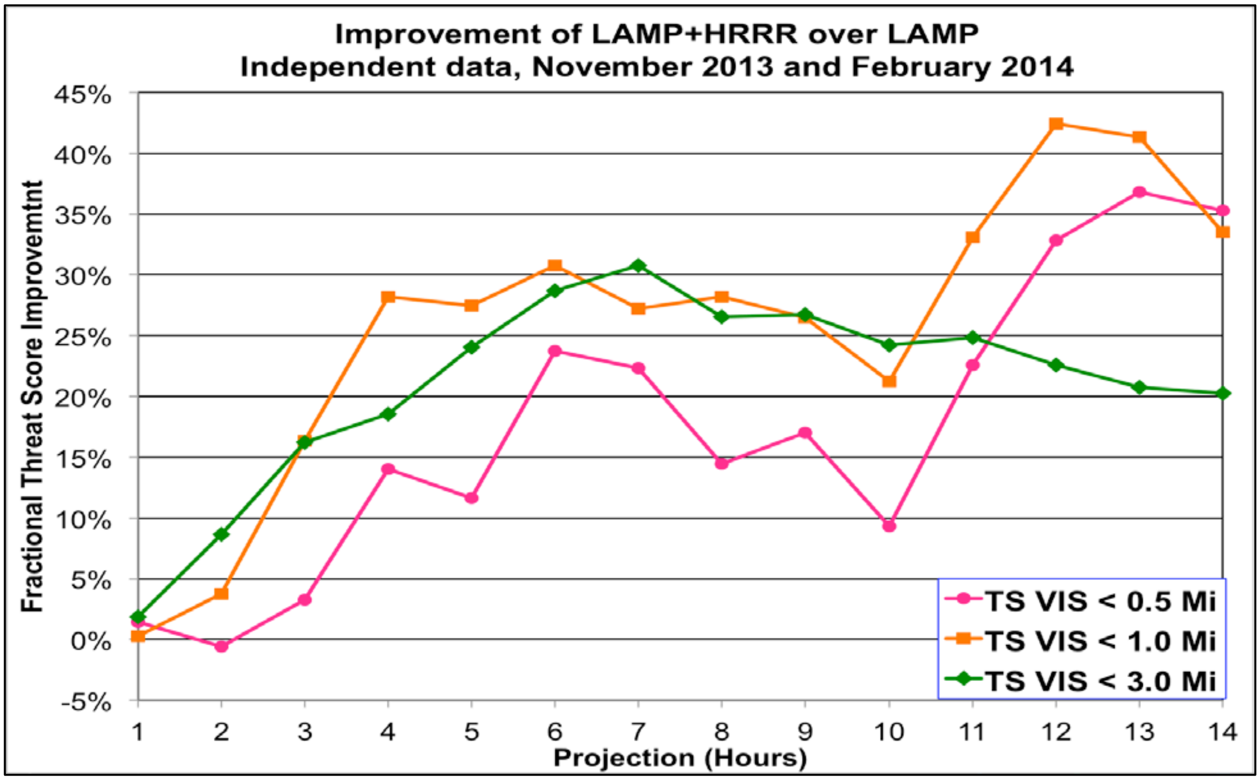

FIG. 5. Improvement in threat score of new 0000 UTC LAMP+HRRR forecasts over threat score of original 0000 UTC LAMP forecasts for visibility < 0.5 miles (pink circles), visibility < 1 mile (orange squares), and visibility < 3.0 miles (green diamonds).

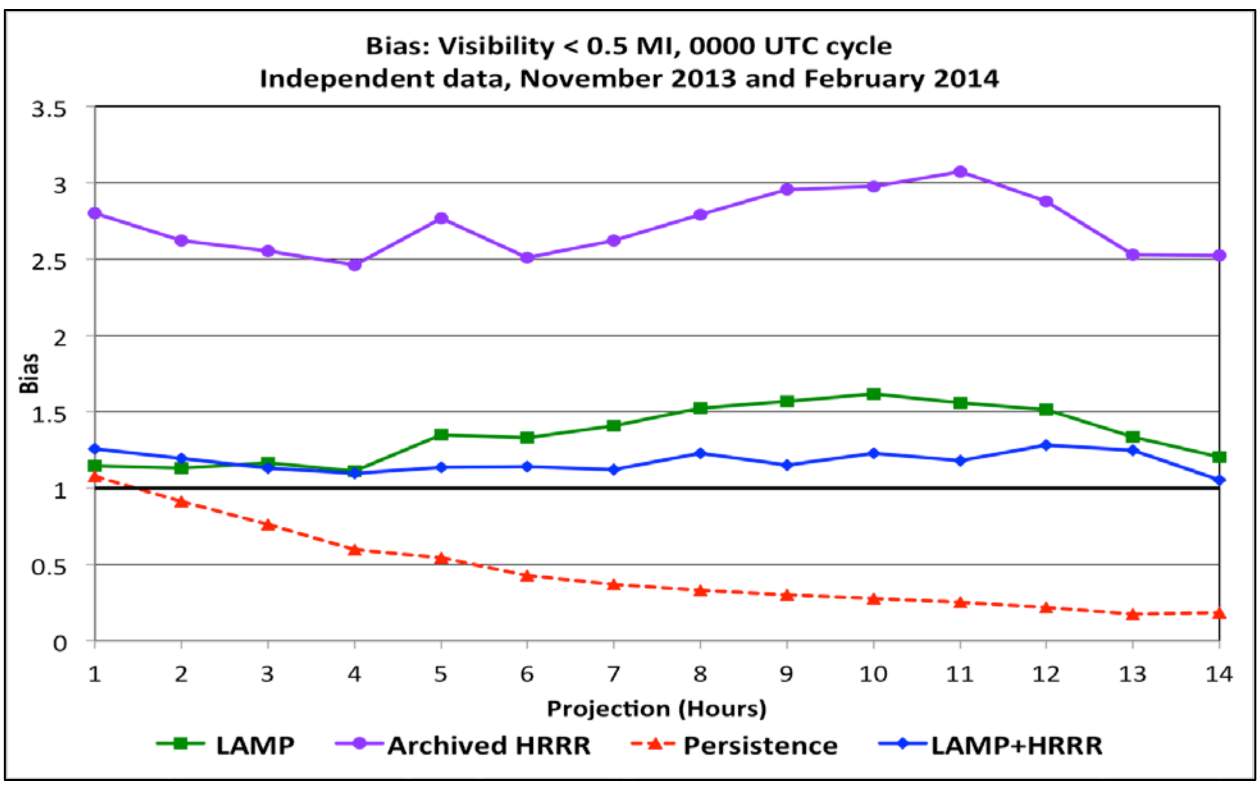

FIG. 6. Bias for visibility < 0.5 miles for the same series as in Fig. 1.

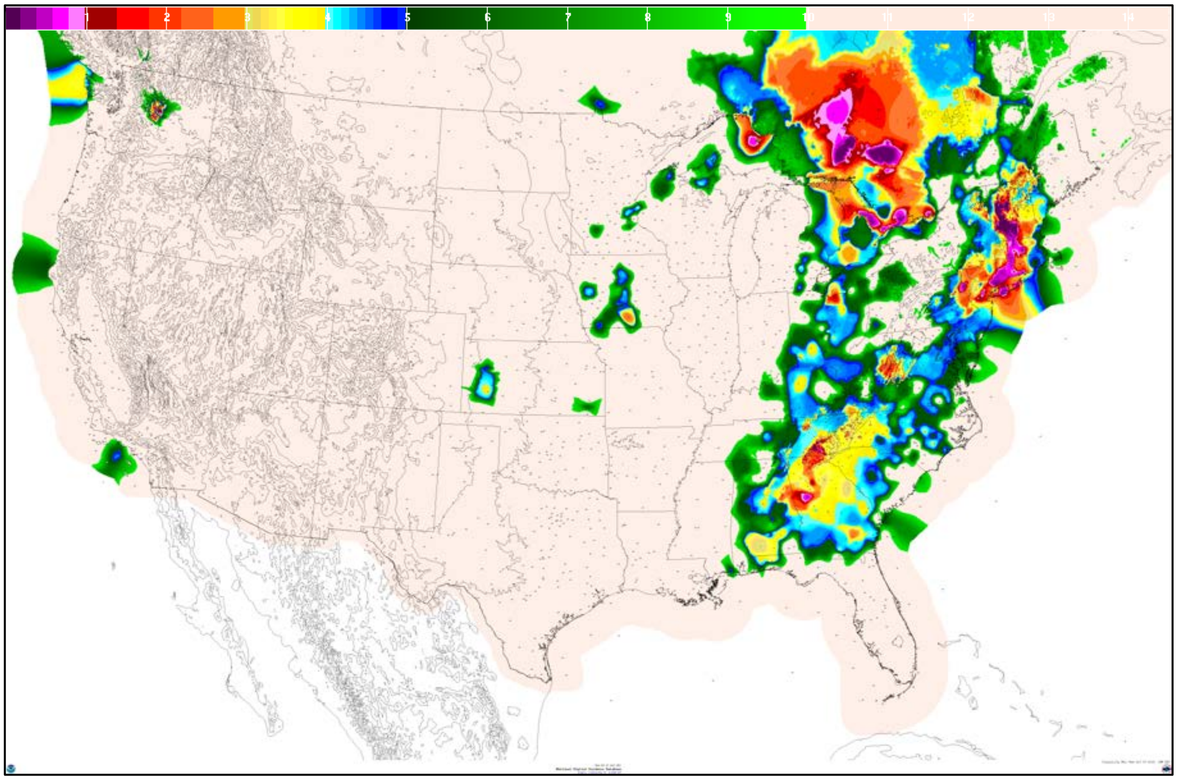

FIG. 7. 6-h visibility Gridded LAMP forecast in miles from October 7, 2013, 0000 UTC cycle, valid at 0600 UTC.

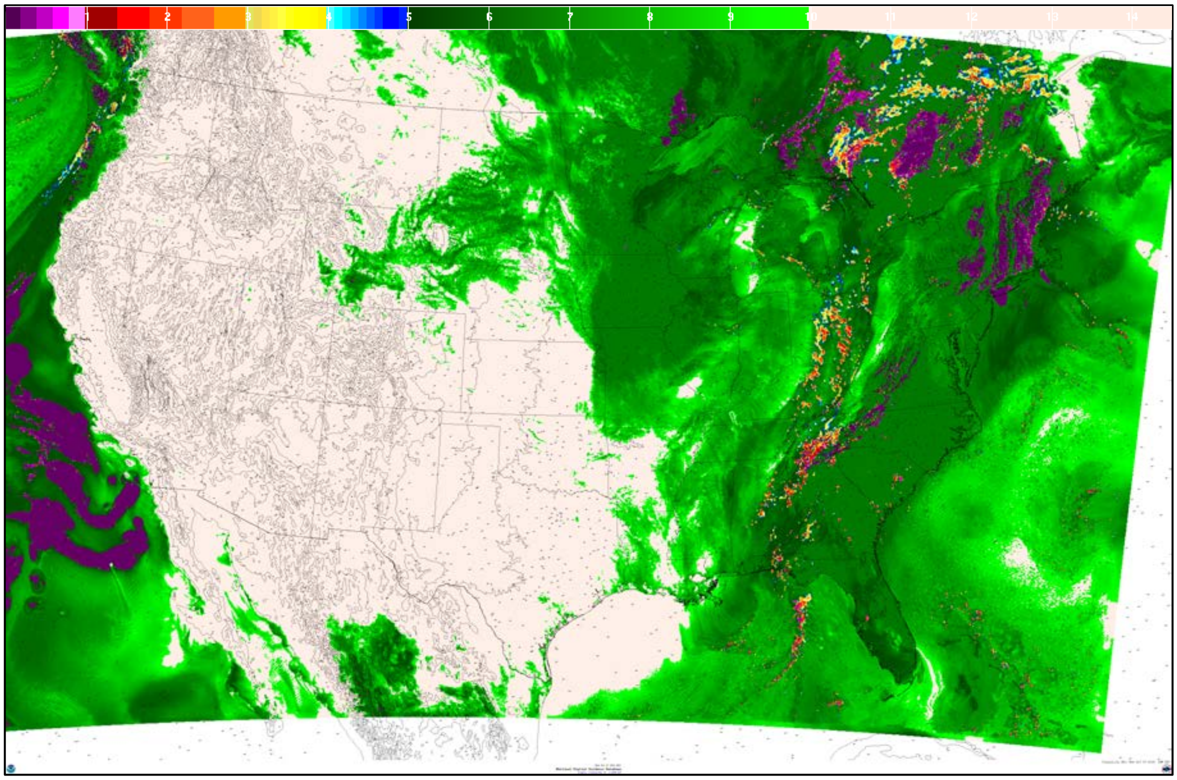

FIG. 8. The HRRR 7-h visibility forecast in miles from 2300 UTC October 6, 2013, valid at 0600 UTC.

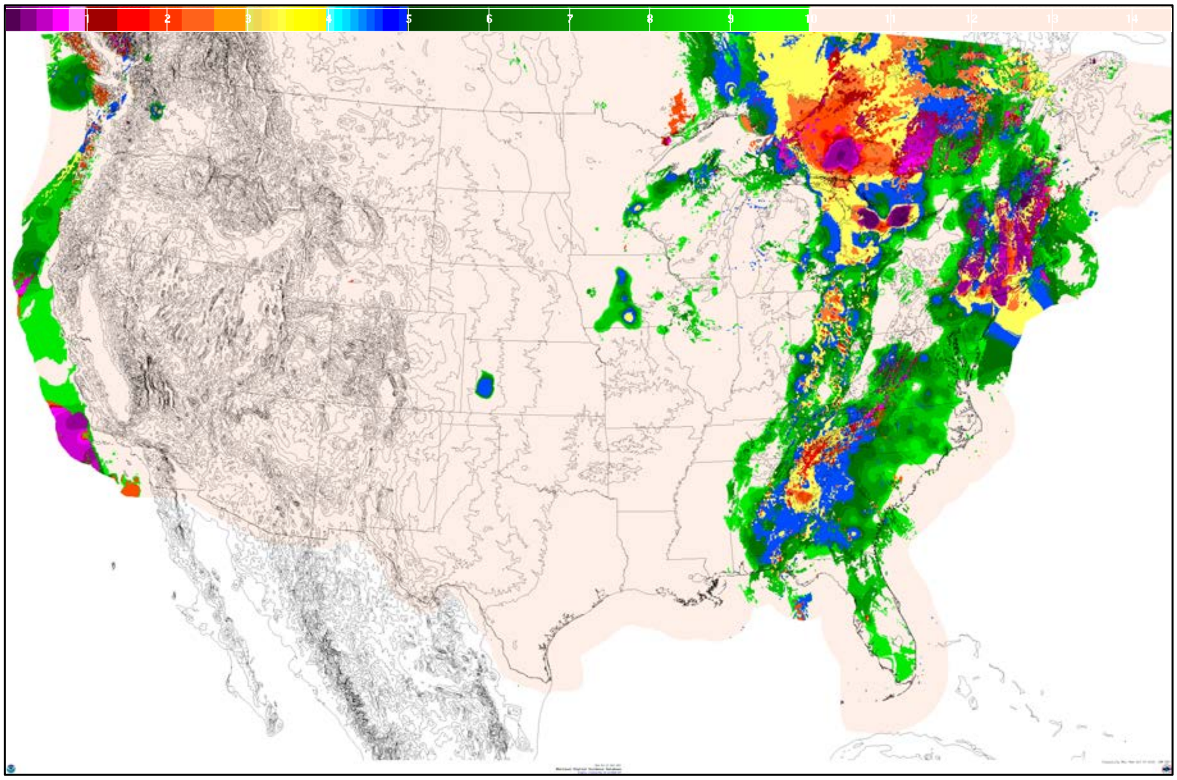

FIG. 9. Same as for Fig. 7, but for LAMP+HRRR.

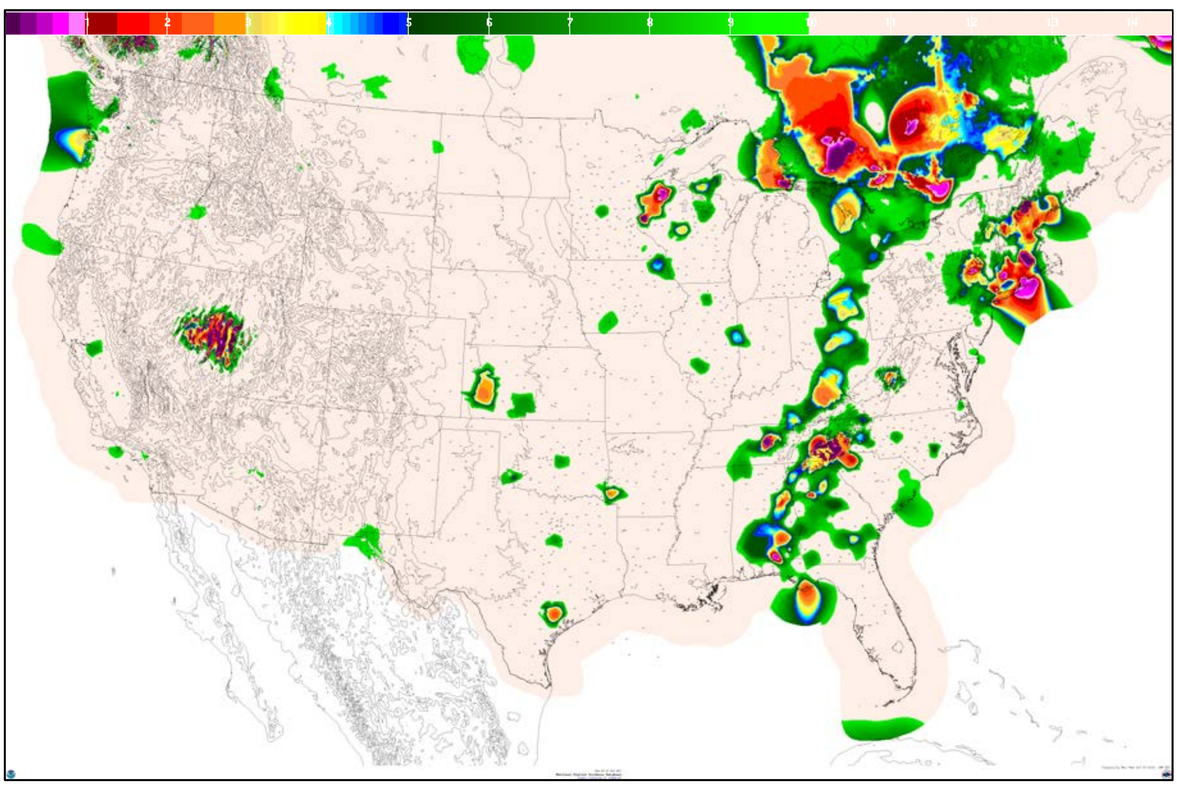

FIG. 10. Verifying Gridded Observations for visibility in miles from Gridded LAMP for 0600 UTC October 07, 2013.