Reprinted from AMS 21st Conference on Weather Analysis and Forecasting, August 1 - 5, 2005, Washington, D. C.

13B.2 TOWARD A GRIDDED MOS SYSTEM

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1. INTRODUCTION

With the recent introduction of the National Digital Forecast Database (NDFD, Glahn and Ruth 2003), the National Weather Service (NWS) has initiated a new era in which official NWS products are available in digital form on high-resolution grids covering the United States, Puerto Rico, and Guam. NWS forecasters generate these grids through use of the Interactive Forecast Preparation System (IFPS, Ruth 2002). Forecasters can edit and manipulate grids to generate the final product; however, such interactions require that an initial grid at the proper resolution be available. Optimally, the initial grid should have some of the features that the forecasters want to depict in the final digital representation. Candidate grids for initialization include output from a numerical weather prediction (NWP) model "downscaled" to the NDFD grid resolution (currently 5 km), a grid created during a previous forecast cycle and valid at the same time ("continuity"), or grids for the NDFD forecast elements created by the Hydrometeorological Prediction Center (HPC) of the National Centers for Environmental Prediction (NCEP). Yet another solution is to use a grid created by an application of the Model Output Statistics (MOS) approach (Glahn and Lowry 1972). For over three decades, the MOS technique has been used to relate observations at specific locations to NWP output, previous observations, and geoclimatic information. In this paper, we discuss how MOS is being adapted to meet the NWS requirement for high-resolution gridded guidance. As an example, we describe efforts to develop high-resolution prototype grids for the western United States. These grids are now available for maximum/minimum (max/min) temperature, 2-m temperature, and 2-m dewpoint.

2. APPROACH

In the traditional use of the MOS technique, observations at specific observing sites are related to NWP model variables, previous observations, and geoclimatic data, such as terrain elevation or the climatic average of the event of interest. The resulting forecast equations are used operationally to generate an objective interpretation of the underlying NWP model in terms of weather elements that forecasters include in many of their daily forecast products. This objective interpretation removes some of the systematic biases in the NWP model, provides probabilistic estimates for the occurrence of certain weather elements, enhances the NWP model forecast by including additional variables in a forecast equation, tends toward mean conditions as uncertainty in the model solution increases, and generates guidance specific to the observing characteristics of the site.

An historical sample of observations at specific observing sites is essential for this usage of MOS. The NWP model forecasts used in the equations are interpolated in space to the observation sites and are approximately coincident in time with the observations. For certain weather elements such as temperature, dewpoint, or wind speed, the historical sample of observations and model data is adequate to derive "single-station" equations for each station in the MOS system, each forecast cycle, and each projection. The single-station equations generate guidance that is highly tuned to the specific observing site. For other weather elements, such as the probability of precipitation or precipitation type, observations of the event of interest are often inadequate to develop stable forecast equations. Consequently, observational and forecast model data for stations in a relatively homogeneous area are combined to develop equations that can be applied to any of the stations in that area. Often, geoclimatic variables such as station elevation or the average value of the observation are used to provide additional station specificity. This "regionalized" equation approach is used in the MOS system to predict the probability of precipitation, conditional probability of precipitation type, sky cover, ceiling height, visibility, and so forth. In general, the regionalized equations do not produce guidance that is as tuned to individual sites as do the single-station equations. A "generalized-operator" equation is developed when all the data from a large, inhomogeneous area, such as the contiguous U.S. (CONUS), are combined in the developmental sample. As before, geoclimatic variables are used to compensate for the lack of tuning to individual locations.

One possible approach, then, to the problem of developing high-resolution MOS guidance is to derive regionalized or generalized-operator equations that can be applied to every "site" or grid point on the high-resolution grid. This approach requires that the equations be developed by using NWP model data and geoclimatic variables that provide good site specificity. Because guidance generated in this way is less accurate than guidance generated by single-station equations, a variant on this approach is to combine guidance produced by equations for individual sites with guidance made by generalized-operator equations. One way to

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combine the two sets of guidance is to analyze the single-station guidance with the generalized-operator guidance serving as a first-guess background field. Successful analysis requires that as many observing sites as possible be included in the MOS system and that the analysis scheme use high-resolution geoclimatic data to adjust for terrain, land use, or water influences.

A second approach to providing high-resolution MOS guidance is to obtain observational data at each grid point and use those data in equation development. With in situ observations, of course, this density of reporting sites is not possible. However, the use of remote-sensing data as a source of observations makes this approach feasible. Remote-sensing data, random in space and time, can be projected on a grid of regularly spaced points for a specific interval of time. By using this developmental method, MOS guidance is valid for a grid of some pre-specified resolution. Hughes (2001) describes GFS-based MOS thunderstorm guidance where this approach is applied; Charba and Liang (2005) describe similar work in which thunderstorm guidance is developed for the aviation community. For both systems, lightning strikes reported by the National Lightning Detection Network were assigned to specific locations on a predetermined grid.

3. GEOCLIMATIC DATASETS

As noted in the previous section, regionalized or generalized-operator forecast equations are enhanced by the use of appropriate geoclimatic variables. As part of the gridded MOS development, we've obtained a number of high-resolution datasets that may be helpful in improving the MOS equations or can be used in the analysis scheme mentioned earlier. These datasets include geophysical variables such as the terrain elevation, terrain slope and aspect, land/water coverage, and land characteristics. Climatic variables include high-resolution monthly max/min temperature normals and monthly average precipitation amounts. These variables were obtained from Oregon State University and were generated via the PRISM modeling system (Daly et al. 1997). These geoclimatic datasets come in a variety of formats and with different resolutions; a significant amount of processing is required to put the data into a form and on a map projection with the necessary spatial resolution. Sheets et al. (2005) and Trimarco et al. (2005) describe some of the processes that are required before the data can be used in the MOS system. We are currently using terrain elevation extensively in producing prototype gridded MOS products for the western CONUS. Figure 1 shows terrain elevation for this area. Use of other variables in the MOS system is awaiting further software development.

4. OBSERVATIONAL DATASETS

4.1 *Station Observations*

In the traditional MOS approach, most of the guidance is developed from hourly observations taken at standard observing sites, usually airports. For the rest of this document, we refer to these sites as METAR sites to distinguish them from other observing systems not normally used in MOS development. Dallavalle et al. (2004) describe the current MOS system developed from the operational Global Forecast System (GFS). Currently, GFS-based MOS guidance is available for approximately 1500 METAR sites in the CONUS.

While availability of MOS guidance at 1500 METAR sites is nearly double that of 10 years ago, the station density is still insufficient to support guidance on a 5-km grid. Furthermore, the location of these METAR sites may be optimal for airport operations, but may be inadequate to represent the weather conditions in an area. To support the requirement for a gridded MOS system, we began to obtain archives of surface observations from a diverse group of observing systems and to incorporate those observations into our MOS development system. Lacking observations over large water bodies such as the Great Lakes or the Chesapeake Bay and along the coastal waters of the CONUS, we first obtained a 4- to 5-year archive for 121 buoys and Coastal-Automated Marine Network (C-MAN) sites from the National Data Buoy Center (NDBC). These sites provided observations of air temperature, wind speed, and wind direction. Some of the sites also reported dewpoints. The quality of the data was good, and to incorporate these reports into the MOS system we did no further quality-control beyond what NDBC had already done. McAloon (2005) describes the development of the MOS system for marine sites and the specific marine guidance products that resulted as an added benefit from this effort. For these 121 sites, we developed MOS equations to predict max/min temperature, temperature, dewpoint, wind speed, and wind direction, provided, of course, that either the site reported those elements or we could infer the observation (for instance, max/min temperature) from the available reports.

The marine sites helped to provide additional guidance detail along the coasts. However, particularly in the western CONUS, the spatial density of stations over land was still quite low. Next, we obtained an archive of U.S. cooperative observer reports from the National Climatic Data Center. The cooperative observer sites provided a much greater density of reports for the western CONUS, although the reports were usually available only for daily max/min temperature, snowfall, and precipitation amount. Cosgrove and Sfanos (2004) discuss some of the challenges of working with the cooperative observer reports, including the format of the data, the inconsistency in reporting times among stations, the shift in location and reporting times of certain stations, and so forth. The max/min temperature observations were particularly difficult to prepare for developmental use (Carroll 2004, personal communication). In the GFS-based MOS system, the max temperature is valid for the 0700 a.m. Local Standard Time (LST) to 0700 p.m. LST period, while the min temperature is valid for the 0700 p.m. LST to 0800 a.m. LST period.

Because the hourly temperature and the temperature extremes are reported only once daily at the cooperative observer sites, the MOS developers must deal with a notable ambiguity in the reports, namely, the time of occurrence of the max and min temperature. If, for example, an observer reports at 7 a.m. LST, it is not clear whether the reported min occurred during the current overnight period or during the nighttime period ending the previous morning. Thus, we developed an algorithm that attempted to infer whether the max/min temperature observation was for the proper daytime/nighttime period and then eliminated questionable reports. Because this algorithm can not provide the correct answer in all cases, we expected to find some deterioration in accuracy between the METAR sites and the cooperative observer sites. During our developmental work, we also found certain stations where the root mean square errors of the forecast equations were inexplicably high. Whether the large errors were due to instrument siting (see, for example, Davey and Pielke 2005), station relocation, or some other reason was not determined. These stations were discarded from the system. Eventually, we added approximately 5500 cooperative observer sites to the MOS system, and about 1325 of these were in the western CONUS.

Sites in the cooperative observer network reported max/min temperature and snowfall amounts, but not hourly temperatures or winds. For a better sample of these elements in the western CONUS, we obtained a sample of archived reports from the MesoWest station network (Horel et al. 2002). According to Horel et al., the MesoWest network in 2001 included weather information at over 2800 sites in the western CONUS. While the average separation between METAR sites in the western CONUS was estimated to be 44 km, Horel et al. concluded that the increased spatial coverage from the MesoWest sites lowered the average station separation to approximately 15 km. For our purposes, we chose to use sites primarily from the Remote Automated Weather Stations (RAWS) and the Snowpack Telemetry (SNOTEL) networks. For the most part, we ignored observations from state department of transportation networks because of fears about siting and representativeness of the reports. As with sites from the cooperative observer network, we were concerned about the quality of the data, the reporting time, and the completeness of the reports. Most of the MesoWest sites reported hourly temperatures, from which we inferred the daytime max and nighttime min values. We used only observations near the top of the hour. Some of the sites also reported wind speed, wind direction, wind gusts, and relative humidity, the last of which we used with the temperature to estimate dewpoint, the element for which MOS equations are usually derived. Finally, we did some quality control of the data over and above what was done with the original MesoWest data, primarily to check for suspicious “runs” in the reports, that is, observations of the same temperature, wind, or dewpoint for many hours in a row.

Two remaining sources of data contributed to the expanded set of MOS sites in the western CONUS. Several years ago, the NWS Northwest, Missouri Basin, and Colorado Basin River Forecast Centers (RFCs) provided max/min temperature data for a number of sites that the RFCs asked to be added to the MOS system. In addition, in 2004, the California-Nevada RFC provided hourly temperature data for almost 200 sites in the Sierra-Nevada Mountains that seemed unavailable in the MesoWest network. After observations from the MesoWest network and the RFC sites were checked for quality, we incorporated appropriate sites into the MOS system and developed the relevant max/min temperature, temperature, dewpoint, and wind forecast equations. Of course, availability of observations determined which single-station equations could be developed.

When all stations were included, we had approximately 300 METAR/marine sites, 1325 cooperative observer sites, 1175 MesoWest sites, and 80 RFC sites in the western CONUS. Figure 1 shows the locations of these sites. These stations provide a separation of approximately 30 km, if we assume each station reports all elements and if stations are evenly distributed across the area. Both assumptions, of course, are incorrect. We should note, too, that Hart et al. (2004) successfully used MesoWest data to develop a MOS system based on a high-resolution mesoscale model for sites in northern Utah. We had no reason to think that our use of the MesoWest data would be any less successful in increasing the resolution of the MOS system in the western CONUS.

4.2 *Remote-Sensing Observations*

As discussed earlier, another approach to providing high-resolution MOS guidance is to use remote-sensing data from radar, satellite, or lightning detection networks as a source of observations for equation development. Currently, the thunderstorm guidance developed from lightning reports is the sole operational MOS product developed from remotely-sensed data and valid for a grid. Hughes and Trimarco (2004) describe the changes in the character of the thunderstorm guidance as the spatial resolution of the predictand grid is modified. Antolik (2004) discusses the use of radar- and satellite-based precipitation estimates to create a true gridded MOS product providing the probability of precipitation amount on a high-resolution grid over the CONUS. An archive of RFC estimates of precipitation has been obtained from NCEP’s National Precipitation Verification Unit; work is on-going to establish the proper quality-control of these data and to develop the necessary equations. Finally, in cooperation with NOAA’s National Environmental Satellite and Data Information Service (NESDIS), MDL has established an archive of satellite-based cloud cover estimates on a 10-km grid covering the CONUS. By 2007, MDL should have adequate data to attempt development of a true high-resolution MOS system to predict cloud cover.

5. PROTOTYPE GRIDS FOR THE WESTERN CONUS

After obtaining observational datasets for the western CONUS, incorporating new sites into the MOS system, and developing both single-station and generalized-operator equations for max/min temperature, 2-m temperature, and 2-m dewpoint, we created a process to generate prototype guidance grids for these elements. The guidance grids are for the same forecast projections and at the same spatial resolution as the NDFD, namely 5 km. These prototype grids are valid for the area shown in Fig. 1, and are produced twice daily for projections out to approximately 7 days in advance. We chose the western CONUS for the prototype grids because of the complex terrain and availability of assorted observational networks. The prototype was designed to demonstrate that a tailored analysis accounting for single-station MOS guidance and terrain elevation could provide good high-resolution guidance. Note that guidance produced by generalized-operator equations provided a first-guess background field for the analysis.

Many methods for interpolating from a quasi-random set of points to a regularly spaced grid have been used to provide initial fields for NWP models. As such, consistency constraints can be used in the vertical and horizontal to obtain analyses that are internally consistent and consistent with other related analyses. No such consistency relationships exist when surface weather variables like temperature or dewpoint are being analyzed on a high-resolution grid. MOS forecasts and observations do not, in general, exist at different vertical levels at the same point on the earth, and even without major differences in elevation, values can vary considerably over an area as small as the resolution of the grid. There *are* consistency relationships that the resulting analysis should obey--for instance, temperature $\geq$ dewpoint, but there is no practical limit to how much temperature can exceed dewpoint.

For the variables analyzed on our prototype grids, there is usually a vertical dependency, but one that has to be inferred from surface observations (or forecasts) taken at sites at different elevations. This vertical “lapse rate,” as we will call it, can vary not only with weather element, but also with spatial location, time of day, season of year, and synoptic situation. So we have chosen to let the data (i.e., the MOS forecasts) define this lapse rate for use in the analysis.

Bergthorssen and Doos (1955) described an analysis technique which Cressman (1959) implemented for purposes of large-scale numerical weather prediction. This is widely called the "Cressman Analysis," and many implementations of the basic technique described by Bergthorssen and Doos have been used. One such implementation was in the Local AFOS MOS Program (LAMP) (Glahn 1985), and there it was called "BCD" in honor of the three persons responsible for bringing the technique into mainstream meteorology--Bergthorssen, Cressman, and Doos. Here, a "G" has been appended because of its major extensions and to distinguish it from the other implementations.

The software that implements the BCDG technique has many options available (knobs to twist) to tune it to the situation to which it is applied. The two major differences between BCD and BCDG are that BCDG treats land and water gridpoints and stations differently from each other, and BCDG has the elevation dependency which is adjusted on the fly from the data.

One of the major challenges of many analysis schemes is how to deal with widely different data densities over the grid. The extreme of this is where land and water meet and there are no, or almost no, observations over water. That is the situation here; the data points over land are relatively dense but are extremely sparse over the Pacific Ocean. BCDG treats this situation by (1) using different analysis parameters over land and water, and by (2) letting land (water) data points affect only land (water) gridpoints. This has the effect of there being two analysis systems in one, but with a common analysis output.

BCDG, in a series of five passes through the data, adjusts each gridpoint based on the weighted average difference between the existing analysis (the previous pass or the first guess) and the data within a prescribed radius of influence, adjusted by the lapse rate in the vicinity of the station. The difference between the datum and the analysis is determined by interpolation into the grid to get a current value at the station. The radius of influence varies by pass and whether the point is water or land. The weight given by each datum is determined by the distance between the gridpoint being modified and the datum. This allows the terrain to highly influence the analysis, but only where a lapse rate is indicated by the data. In BCDG, the interpolation is bilinear, provided the four gridpoints surrounding the station are of the same type (land or water) as the station. Otherwise, the closest gridpoint of the station type is used.

To assess the usefulness of the BCDG method, we did a series of test analyses over the western CONUS for selected max/min temperature, temperature, and dewpoint guidance. The analyses were produced by using 0000 UTC MOS guidance from July 15, 2004. First, the analyses were done by using all available stations, both with and without the terrain correction. Next, a series of 48 runs was made with the same analysis parameters in which a different random set of 10 stations was withheld from each run. These analyses were also done both with and without the terrain correction. Over the analysis area, the number of stations with MOS guidance varied between 1023 and 2636, depending on the weather variable; also, a few stations outside the analysis area were allowed to influence the analysis. Table 1 shows the results. BCDG can be made to fit the analysis stations very closely, but perhaps unrealistically so. The results in Table 1 indicate that the lapse rate

Table 1. Mean absolute error (MAE) in degrees F, when the analysis is interpolated to all stations and when the analysis is interpolated to stations that had been withheld from the analysis. The column labeled "Terrain Correction" indicates whether the terrain correction was used or not. The column labeled "Number of Stations" denotes the number of sites in the analysis area for which MOS guidance values were available.

Variable	**Projection (h)**	**Terrain Correction**	**Number of Stations**	**MAE (all stations)**	**MAE (withheld stations)**
Dewpoint	27	Yes	1023	0.60	3.04
Dewpoint	27	No	1023	0.66	3.50
Temperature	27	Yes	1406	0.98	2.92
Temperature	27	No	1406	1.34	4.29
Max Temp.	Tomorrow	Yes	2621	1.11	3.00
Max Temp.	Tomorrow	No	2621	1.38	4.08
Min Temp.	Tonight	Yes	2636	1.31	3.42
Min Temp.	Tonight	No	2636	1.35	3.70

adjustment helps the fit for the withheld stations as well as for the stations used in the analysis, thereby improving the quality of the analysis.

Figures 2 and 3 show, respectively, an analysis of MOS 27-h temperature forecasts with and without the terrain correction. Note the detail in the Grand Canyon, Death Valley, in the mountains, and to the east of Kings Canyon National Park when the terrain correction is used. These details are largely absent without the correction. The lapse rate adjustment not only fits the data better, as indicated by the MAE at data points, but also gives the analysis a "meteorological" appearance.

Figures 4 and 5 show a prototype gridded MOS guidance product and the corresponding NDFD gridded forecast, respectively, for the southwestern U.S. for the day 1 max temperature. Note the similarity in both the plotted values and the grids for the guidance and the official forecast. In both cases, the plotted values were interpolated from the grids. A close inspection shows that the MOS guidance appears somewhat cooler in central Nevada where few observing sites are located.

6. CURRENT WORK AND FUTURE PLANS

The prototype grids valid for the western CONUS are available on the NWS ftp server. We are planning to transmit the gridded MOS guidance in GRIB2 format later in 2005 or early in 2006. Until now, we've only looked at grids for max/min temperature, 2-m temperature, and 2-m dewpoint. We don't know yet whether the quality of grids for other weather elements such as probability of precipitation, probability of thunderstorms, snowfall amount, sky cover, precipitation type, and so forth will be acceptable to the users. Certainly, the analysis of the wind direction and wind speed poses a challenge, particularly in areas of complex terrain. We also know from MOS verifications and from conversations with forecasters in the NWS Western Region that the MOS guidance does not accurately forecast low-level inversions in the winter. This problem may be even more obvious when high-resolution grids require that the MOS guidance predict the trapping of cold air in valleys in the winter. Thus, improvement in the MOS temperature guidance needs to be made, over and above the search for higher resolution. We have deficiencies in the generalized operator equations used to produce the first guess for the analysis. Much more work needs to be done to incorporate the high-resolution geoclimatic data as predictors in those equations.

Our immediate plans are to extend over the entire CONUS the prototype grids available for four weather elements. We'll also add grids for the probability of precipitation, probability of thunderstorms, wind speed and direction, and snowfall. Grids for sky cover, precipitation type, and wind gusts will follow later. We've started work to incorporate more stations into the MOS system to provide better coverage over the CONUS. As we've learned, obtaining data for more stations, doing quality-control of those data, adding stations to the MOS system, and then developing the MOS equations is extremely time-consuming. Obtaining data for one network at a time is not efficient. We are currently working with the Meteorological Assimilation Data Ingest System (MADIS, Miller et al. 2005) of NOAA's Forecast Systems Laboratory (FSL) to obtain archives of hourly observations for other observing networks in the U.S. We will need to determine which networks to incorporate into the MOS system and which to ignore because the stations are not sited properly or because they do not represent meteorological conditions well. Work is also ongoing to use remote-sensing estimates of precipitation in development of gridded MOS guidance for precipitation amount.

Evaluation of grid quality also needs to be done. We plan to interpolate the gridded MOS guidance back to observing sites, and then use those interpolated values in comparisons between the guidance and the NDFD products. These comparisons, of course, provide insufficient insight into the quality of the guidance for points between observing locations. Since an adequate high-resolution analysis does not exist yet for such a purpose, we'll use a verification system modeled after one currently used within MDL to verify the NDFD forecasts (Dagostaro et al. 2004). A subjective evaluation will also be done by asking NWS forecasters to provide us with feedback as to the quality of the gridded guidance

7. ACKNOWLEDGMENTS

Many people in MDL have contributed to the MOS guidance system. Some have been referenced in this paper. We thank all of the MOS developers for their work. We particularly want to thank John Horel and Mike Splitt from the University of Utah who provided us with the MesoWest data, Alan Haynes of the California-Nevada RFC who gave us observations for the CNRFC area, and the Northwest, Missouri Basin, and Colorado River RFC's who long ago gave us observations that were incorporated into the MOS system.

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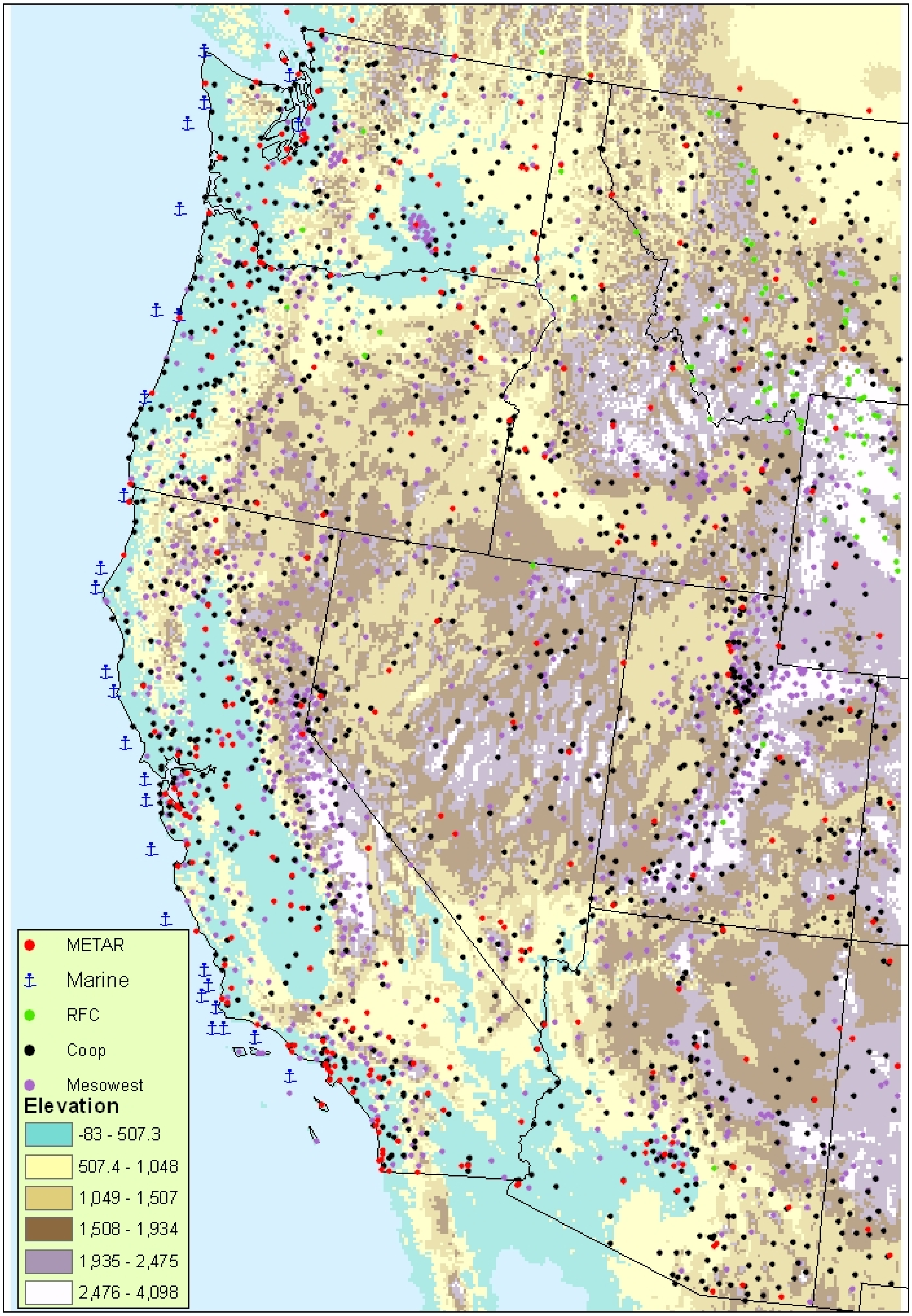

Figure 1. Terrain elevation (m) and MOS stations for the western CONUS. The origin of the data used for the various station sets is described in the text.

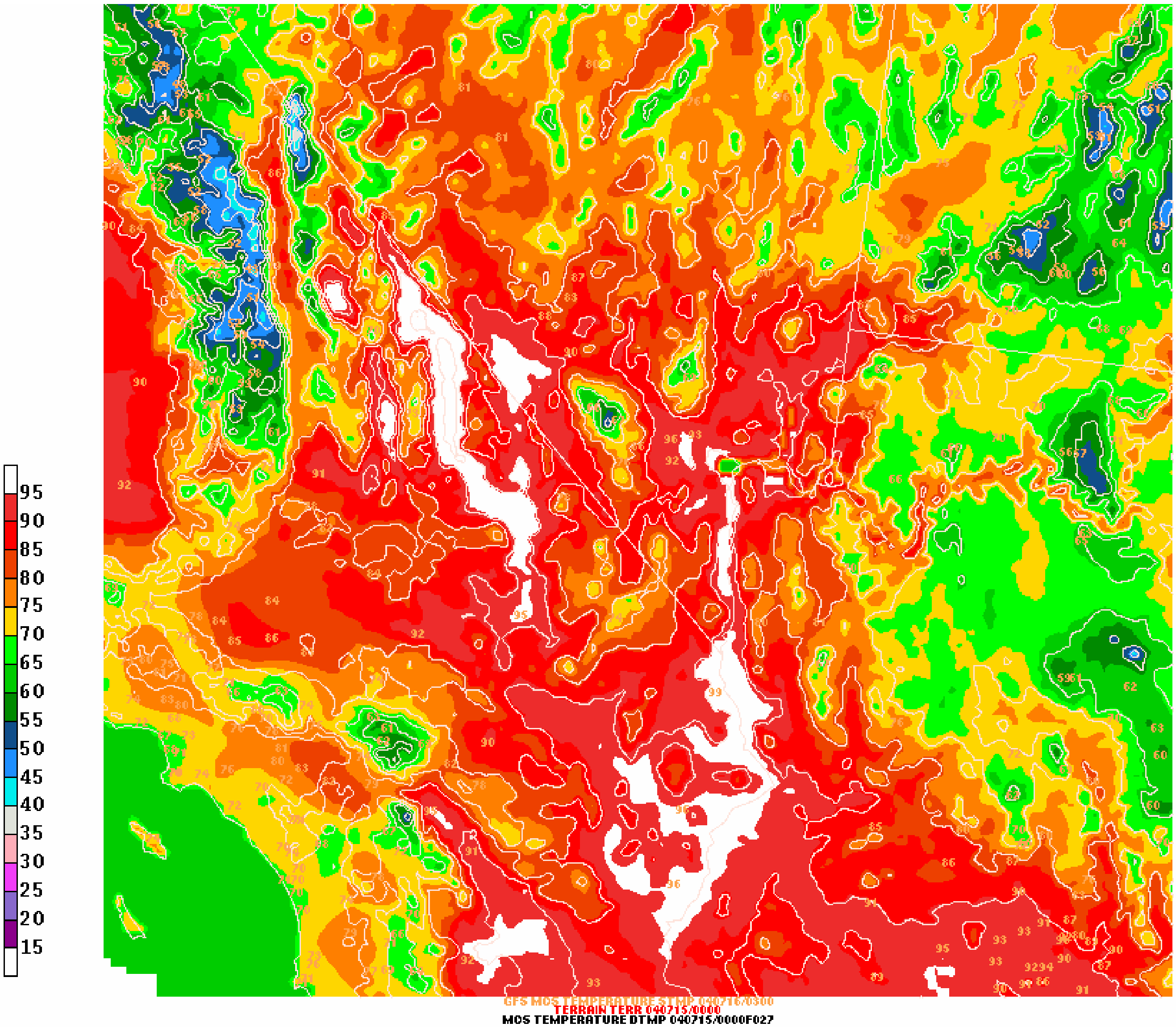

Figure 2. Analysis of MOS temperature guidance (° F), 27-h projection, 0000 UTC cycle, July 15, 2004. The analysis was generated by using the terrain correction described in the text. Contours shown are elevation isohyets. Plotted values denote MOS guidance at specific sites.

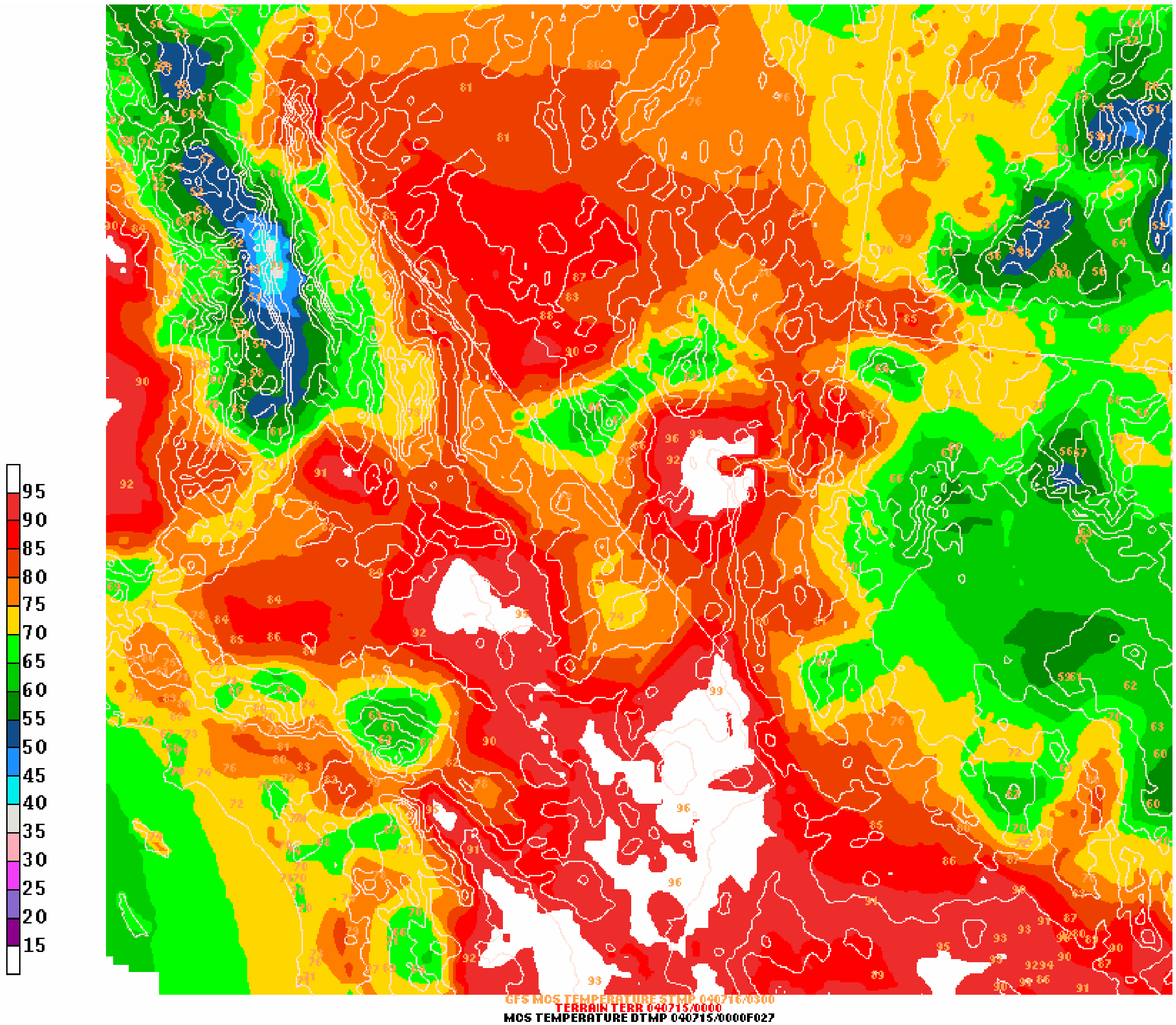

Figure 3. Same as Fig. 2, except no terrain correction was used in the analysis.

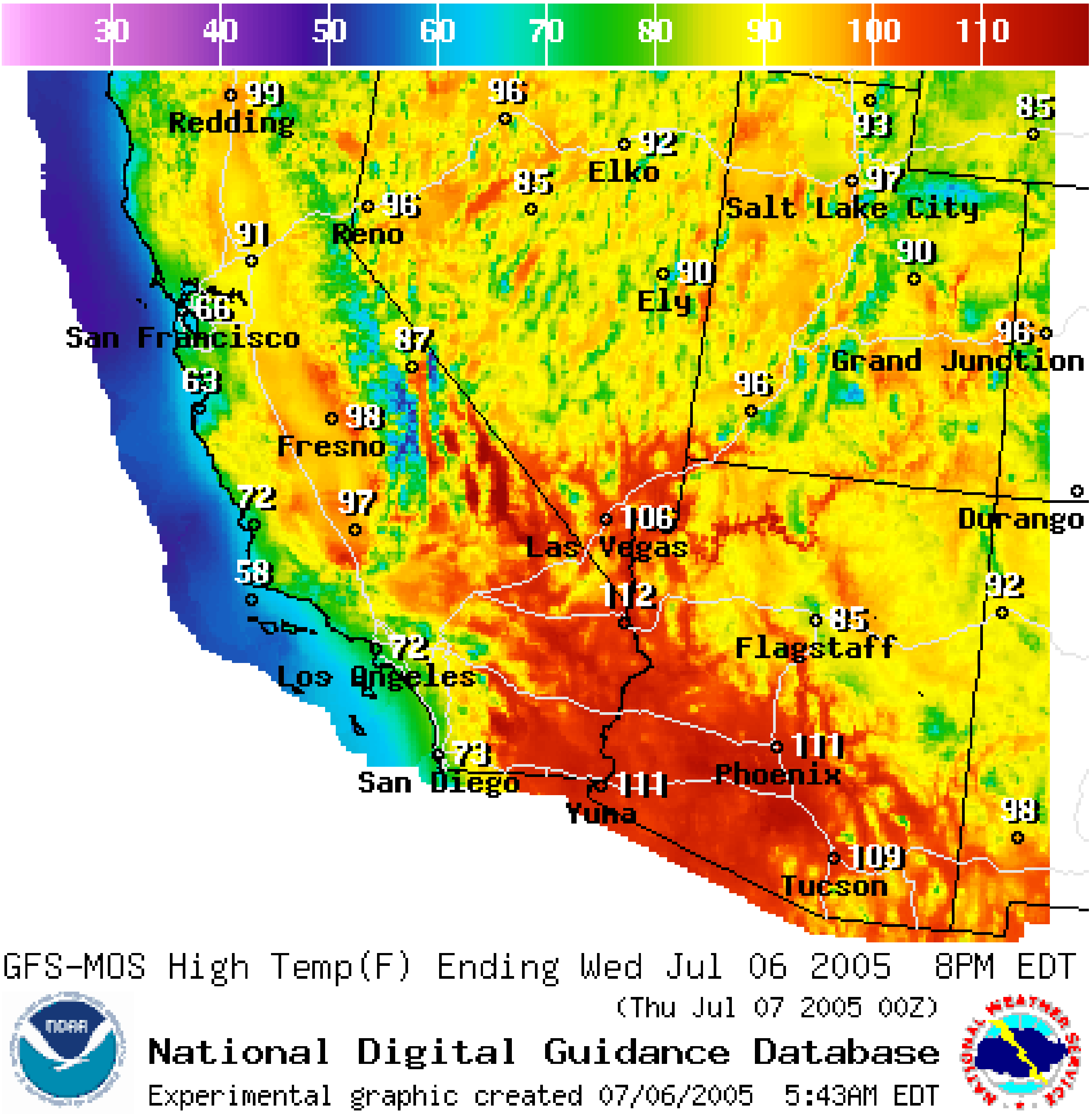

Figure 4. Gridded MOS guidance (° F) produced from the 0000 UTC cycle on July 6, 2005. The guidance is valid for "today's" max temperature.

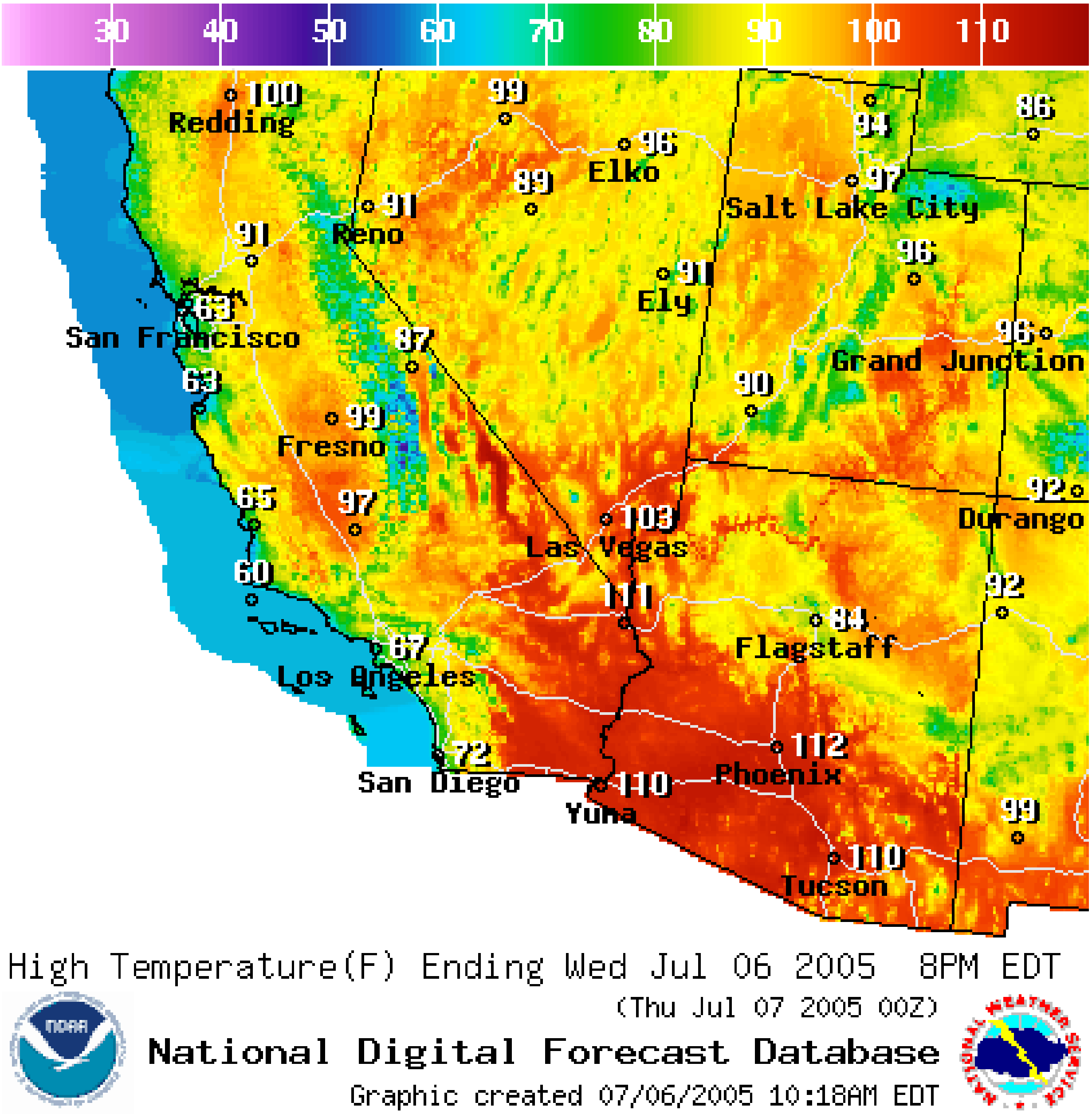

Figure 5. Official NDFD forecast valid at the same time as the gridded MOS guidance shown in Fig. 4. The official forecast graphic was created at 0618 UTC on July 6, 2005.