2.1 GRIDDED MOS--TECHNIQUES, STATUS, AND PLANS

Bob Glahn[1] and J. Paul Dallavalle
Meteorological Development Laboratory
Office of Science and Technology
National Weather Service, NOAA
Silver Spring, Maryland

1. INTRODUCTION

The Interactive Forecast Preparation System (IFPS; Ruth 2002) and the resulting National Digital Forecast Database (NDFD; Glahn and Ruth 2003) have ushered in a new era in the way forecasts are produced and disseminated by the National Weather Service (NWS). Instead of forecasters typing textual products which are then read or voiced over the air, grids of weather variables are prepared, and most routine products are produced automatically from them. While this new paradigm has expanded, and is continuing to expand, the NWS service to partners and customers, the process has created challenges for forecasters in preparing the grids. When one considers the enormous variability that can exist in a 7-day forecast from the number of weather variables and the number of projections at hourly intervals for each of those variables, even over an area as small as a Weather Forecast Office's (WFO) area of responsibility, preparing high resolution grids and keeping them current is a challenge.

Currently, the WFOs produce grids on 5-km or finer resolution grid, and many products are produced from them. They are sent to a central location where the grids are mosaicked--one for the CONUS (Conterminous United States) and one for Alaska; grids are also available for Hawaii and Puerto Rico. This mosaicking of grids produces one of the greater challenges for the forecaster--collaborating with neighboring WFOs and producing the grids so that they merge nicely at WFO borders. While individuality in the way forecasts are produced has always been a potential problem across WFO area borders, inconsistencies were not so readily noticed as they are now.

Optimizing the overall production of the grids is a challenge for the NWS and is being addressed. It is clear that the forecaster does not start from a blank slate and create the full suite of grids from scratch, but rather starts from a set of grids that bears considerable resemblance to what the new set will be. These "first guess" grids could be those prepared at the WFO at some time previously, output from a numerical model, or post-processed model output. To start from the previous forecast is likely, most times, the least work; presumably, there will not be wholesale changes from a forecast made a few hours ago. However, this "nudging" may not realize the full potential of new model guidance.

2. GRIDDED MOS

The Meteorological Development Laboratory (MDL) has been producing post-processed numerical model guidance since the late 1960's--usually by the Model Output Statistics (MOS) approach. MOS requires a sample of data--observations matched with output from a numerical model. The observations have usually been, and to a large extent continue to be, at specific, somewhat random locations (observing sites). This has almost dictated the production of MOS guidance for those same locations, and not for gridpoints. There are some data sources that lend themselves to a gridded approach, such as lightning reports, satellite cloud cover, and radar reflectivity, but even here there needs to be a mapping to the target grid, which for the NDFD is Lambert Conformal over the CONUS, polar stereographic over Alaska, and Mercator over the Pacific region and Puerto Rico.

Several statistical techniques could be used to provide the link between the observations and the model output, but we have used least squares regression almost exclusively after much experimentation a number of years ago. We have settled on this approach because it is relatively simple, and the nonlinearity among the model variables and the surface weather variables can be assessed meteorologically and taken into account by "computed predictors." In this discussion, the term "equations" will embody those relationships.

However, for the guidance to be optimally useful it has to be on the same grid that the WFOs use. Three methods for doing this easily come to mind:

1) Forecast equations are produced from data taken at the observing sites, applied at those same sites, and the resulting forecasts somehow mapped to a grid;

2) Forecast equations are produced from data taken at the observing sites, and applied at gridpoints; and

3) Forecast equations are produced from data at gridpoints and applied at those same gridpoints.

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[1] *Corresponding author address:* Bob Glahn, 1325 East-West Highway, Room 10214, Silver Spring, MD 20910-3283; e-mail: harry.glahn@noaa.gov

The first of these usually yields the most accurate and skillful results for the observation locations. The site local climatology and other specific characteristics are built into the site-specific (SS) equations. The problem remains of mapping to a grid.

To apply 3) requires predictand data at gridpoints, and usually those are not available. Exceptions are data that can be used for precipitation occurrence and amount, cloud cover, and variables related to severe weather. For thunderstorms, either the occurrence of lightning (Hughes 2001) or a combination of lightning and radar data can be used to define the event. Charba and Liang (2005) discuss the collection and quality control of radar data. For precipitation, high resolution estimates obtained from radar and gauges can be used (Antolik 2004). For cloud cover, satellite data and routine surface observations can be used to augment each other. For severe weather, usually a manual observation (report by a human) is used to define the event. For all of these sources, assumptions have to be made, and the data still have to be put on the target grid. Surface temperature and dewpoint have no good grid-oriented surrogates.

For 2), one can use observing site data, group data from several sites together, and develop Regional Operator (RO) equations which can be applied to any location, even a gridpoint, within that region. The region can cover the entire CONUS, in which case the RO equations become Generalized Operator (GO) equations. In so doing, observations from the site (persistence) can not be used, because these observations are not available at gridpoints. When RO equations are applied, because the equations are different for different regions, discontinuities can exist at the regional boundaries (see Glahn and Wiedenfeld 2006). This cannot be ignored. Simple smoothing will usually not suffice. GO equations do not have such boundaries. Even though topographic and climatic features can be partially captured by RO and GO equations, the accuracy and skill at specific observation points will not, in general, equal that of the SS equations. Even so, for many variables, it has not proven practical to use SS equations with available sample sizes because of the highly non-normal predictand distributions.

To date, we are using all three methods in producing grids to support 7-day forecasting. However, only Method 1) is currently being used to provide grids for experimental use; 2) has not been developed to the quality needed, and work on 3) has only begun.

3. DATA COLLECTION AND PREPARATION

As our first effort, we have developed our gridded guidance over an area of the western United States encompassing Idaho, Utah, Arizona, all states to the west, and portions of bordering states to the east; this so-called "western tile" is shown in Fig. 1. We chose this area primarily for two reasons--several data sources were available from which data could be obtained that provided a relatively dense network, and we wanted to develop in such a way that serious mountains could be accommodated. Below we briefly describe the data obtained and processed; a more detailed discussion is in Dallavalle and Glahn (2005).

3.1 *METAR*

Routine observations, usually taken at airports, are designated here as METAR reports, the code form in which they are normally available. These are high quality, and contain most weather elements we need; there are about 300 over the western tile.

3.2 *Buoys and Coastal-Automated Marine Network (C-MAN)*

These observations, about 121 in number over the CONUS, Alaska, and Hawaii provide air temperature, wind speed and direction, and sometimes dewpoint (but not over the western tile); about 30 of these marine sites are in the near coastal waters of the Pacific and Puget Sound. Maximum (max) and minimum (min) temperature can be inferred. For details of developing MOS for marine sites, see McAloon (2005).

3.3 *Cooperative Observer (CO-OP) Reports*

Cooperative observer reports are available, generally for daily max and min temperature, 24-h snowfall amount, and daily precipitation amount. These data are not available in real-time, so cannot be used as predictors (persistence). They also require considerable quality control and preparation. The max and min are not for the periods (daytime and nighttime) desired, and inferences have to be made. Possible instrument siting errors and relocation of observing sites are additional problems. All told, we obtained a sufficient record at about 5500 sites in the United States, of which about 1325 are over the western tile.

3.4 *RFC Data*

We call these RFC data for want of a better term, because the data were provided by certain River Forecast Centers (RFC) over the West. These sites, approximately 80 in number, provide only max and min temperature.

3.5 *MesoWest Data*

Some types of data in the MesoWest network (Horel et al. 2002) were used, generally those from RAWS (Remote Automated Weather Stations) and SNOTEL (Snowpack Telemetry) sites. These data were judged to be of a high enough quality we could use them in development. MesoWest sites number about 1175. Generally, observations for these sites include temperature, relative humidity, and wind speed and direction. Dewpoint, the daytime max, and the nighttime min are derived from the available data.

3.6 *Remote Sensing Data*

MDL has established an archive of satellite cloud observations, and we are also preparing high resolution precipitation estimates that will be used in development of GO or RO precipitation occurrence and amount equations. Especially the precipitation estimates require much quality control work for the data to be useful for development. Use of such data is discussed by Hughes (2001) and Antolik (2004). These data will be used in future work.

4. EQUATION DEVELOPMENT

SS equations were developed for max and min temperature out to 7 days and temperature and dewpoint at 3-hourly intervals also out to 7 days. The predictors were predominantly from the National Centers for Environmental Prediction's (NCEP) Global Spectral Model (GSM) at or near the valid times of the predictands. Dallavalle et al. (2004) and McAloon (2005) give details of such equation development.

5. MAPPING TO A GRID

Many methods for interpolating from a quasi-random set of points to a regularly spaced grid have been used to provide the initial fields for numerical weather prediction 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 fine mesh 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 discussed in this paper, 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 BCDG technique as presently implemented has many options (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, data over water. That is the situation here; the data points over land are relatively dense but are extremely sparse (half a dozen buoys) in the Pacific near-shore coastal waters. BCDG treats this situation by (1) using different analysis parameters over land and water, and (2) by 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. A similar, but separate, process deals with inland waters (i.e., lakes).

BCDG, in a series of 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. This 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. 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.

There are more observations for max and min temperature than for spot temperatures and dewpoint. The more the stations, the better the forecasts can be mapped to the grid. The BCD technique allows very close fitting to the data, but too close a fit will exhibit bull's eyes and may not provide good gridpoint values at locations not in close proximity to the data points. In order to help determine the quality of the analyses, withheld data tests were made.

We used a sample of MOS forecasts made on each 15th of the month from April 2004 through March 2005 from the 0000 UTC run of the GSM. For each of the 12 days in the sample, 15 analyses were made in which 10 stations were randomly withheld. The randomization was such that data from each area of the grid was approximately evenly sampled. Then the mean absolute error of the analysis was determined for those withheld stations, as well as for the analysis points. In each case, the analysis was characterized by linear interpolation into the 5-km grid to the observation sites. So, there were two interpolations necessary--one furnishing the grid, and then interpolating into the grid to get the "analysis" value. There is error in each process.

These analyses were made with the radii of influence being 30, 20, 10, 5, and 3 grid lengths for five passes on the 5-km grid. The "first guess" analysis was just the average of all the forecasts used in the analysis. Because we don't expect any MOS forecast to be grossly "in error," the quality control throwout criteria were set so that no forecasts were discarded on the final pass. The lapse rates used for each station in making corrections to the gridpoints were calculated by dividing the sum of the differences between the MOS forecast at the station and about 50 surrounding stations by the sum of the vertical distances between the same stations. This is usually negative, indicating a decrease in temperature with elevation. However, in some instances, predominantly at coastal stations where the temperature is influenced by the ocean, the values were positive, indicating higher temperatures in the hills to the east. We found it was necessary to restrict the use of these positive values to within a few grid lengths of the station, and eventually we got better results by setting these lapse rates to zero. An example of the temperature analysis both with and without the elevation correction is shown in Figs. 2 and 3.

The results of the withheld data tests are shown in Table 1. The percentage of withheld stations was quite low being about 0.4 to 1.0 percent (4 to 10 per thousand), so the analyses were not materially affected by withholding the stations. The analyses with the radii of influence stated above fit the data rather closely; the average "errors" were just over a degree, including the error of interpolating into the grid to find the analyzed value at the station. The corresponding average errors at the withheld stations were about 3 degrees. Analyses with larger radii of influence or with fewer passes give a smoother field and may actually be better guidance to forecasters. Interestingly, the error at withheld stations was rather insensitive to analysis parameters; the "best" set of such parameters will likely be determined by pattern and eye-appeal, rather than by "error" statistics. An example of an analysis stopped after three passes, corresponding to the 5-pass analysis shown in Fig. 3, is shown in Fig. 4.

6. CURRENT WORK AND FUTURE PLANS

The prototype grids for the western tile for max and min temperature and spot temperature and dewpoint are available on the NWS ftp server, and are in the National Digital Guidance Database (NDGD). We will transmit these grids in GRIB2 format over AWIPS by early 2006. We will extend this work both to other elements and to the entire CONUS, and later to the other areas in the NDFD. The elements will include probability of precipitation, 24-h snow amount, probability of thunderstorms, sky cover, precipitation type, and wind. Each of these elements presents unique challenges in rough terrain. The known deficiencies of the MOS forecasts (e.g., the difficulty of forecasting cold air in valleys) will show up even more so on grids and graphics than in text bulletins. We hope the feedback on the grids and the infrastructure we are building to deal with them will allow us to better correct some of these deficiencies than in the past.

Work is in progress to incorporate more stations into the MOS system to provide better coverage over the CONUS. Obtaining data and quality controlling them from diverse networks, entering them into the MOS system, and deriving the necessary equations are quite time consuming. We will also be doing a direct comparison among the gridded MOS forecasts, the forecasts from the Hydrometeorological Prediction Center, and the official NDFD forecasts at stations not used in the production of the forecasts.

7. ACKNOWLEDGMENTS

Many persons in MDL contribute to this work on a daily basis. We are documenting their work as well as ours; we thank them all.

8. REFERENCES

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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 “Number of Stations” denotes the number of sites in the analysis area for which MOS guidance values were available.

Variable	**Projection (h)**	**Number of Stations in Analysis**	**Number of Stations Withheld**	**MAE (all stations in analysis)**	**MAE (withheld stations)**
Dewpoint	27	179,460	1800	1.06	2.81
Temperature	27	247,950	1800	1.20	2.75
Max Temp.	Tomorrow	472,861	1799	1.30	3.00
Min Temp.	Tomorrow Night	473,311	1799	1.14	3.25

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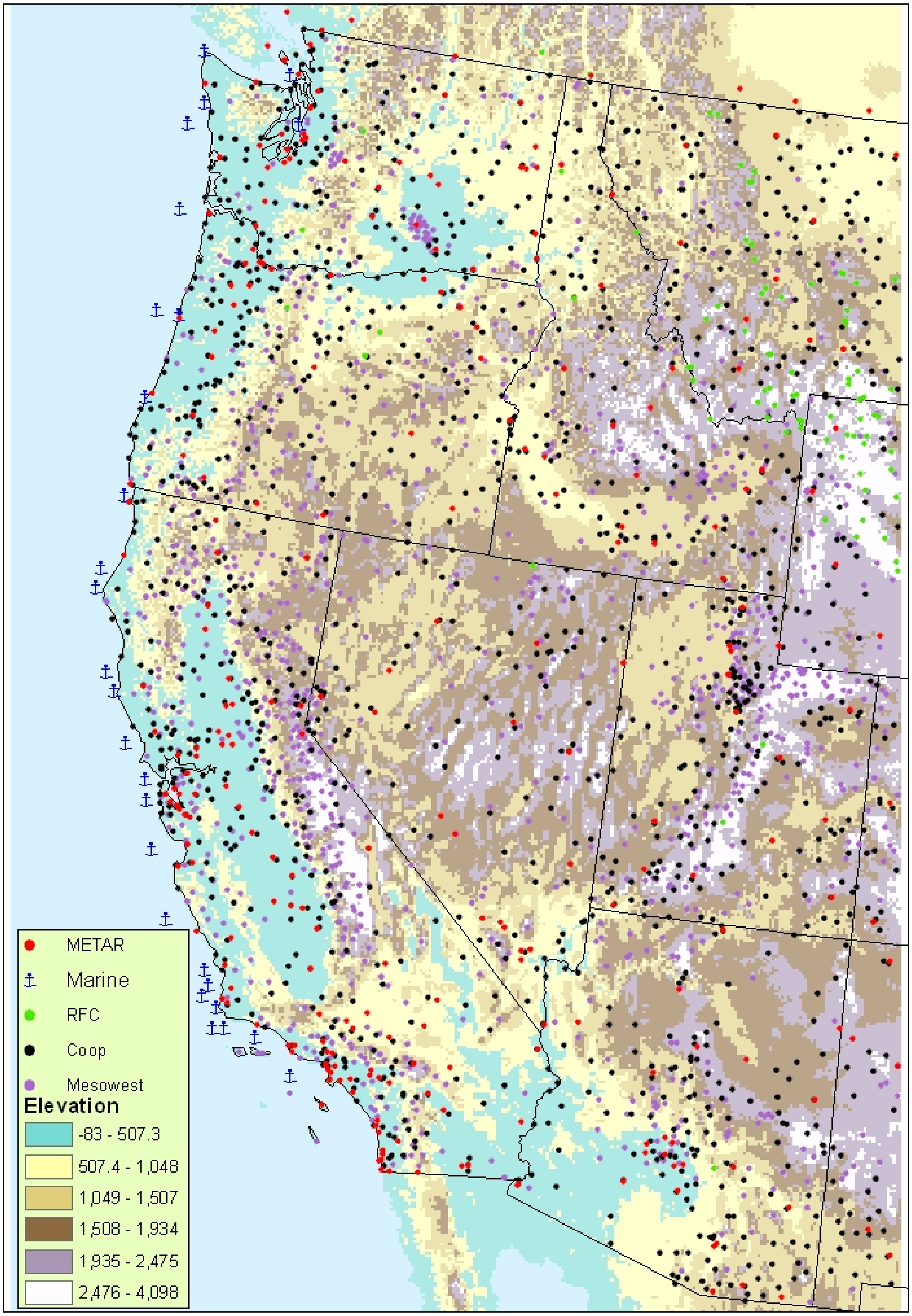

Figure 1. Terrain elevation (m) and MOS stations for the western CONUS. The origin of the data used for the various station sets is described in the text.

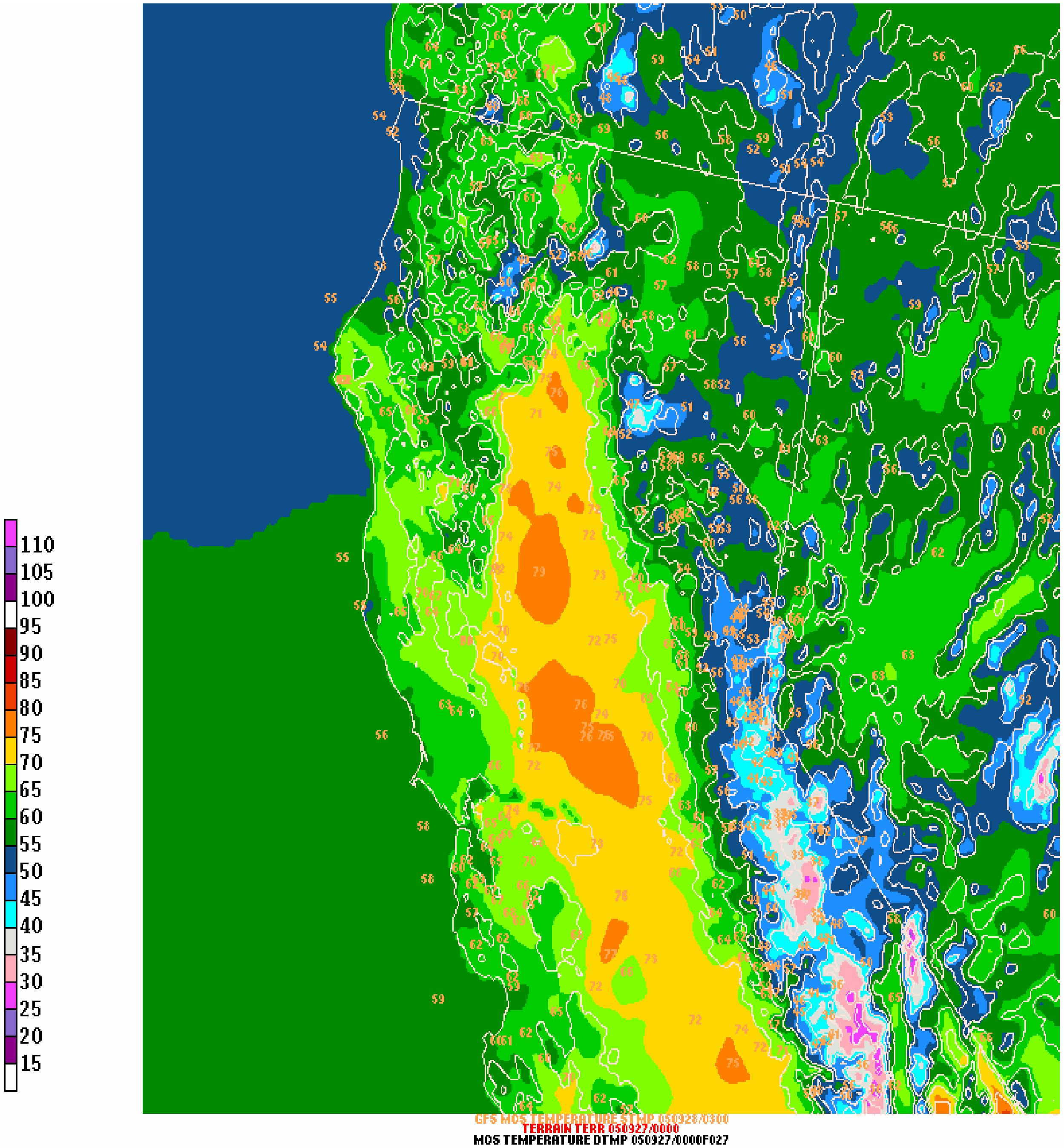

Figure 2. Analysis of MOS temperature guidance (° F), 27-h projection, 0000 UTC cycle, September 27, 2005. The analysis was generated by using the terrain correction described in the text. Contours shown are 500-m elevation isohyets. Plotted values denote MOS guidance at specific sites.

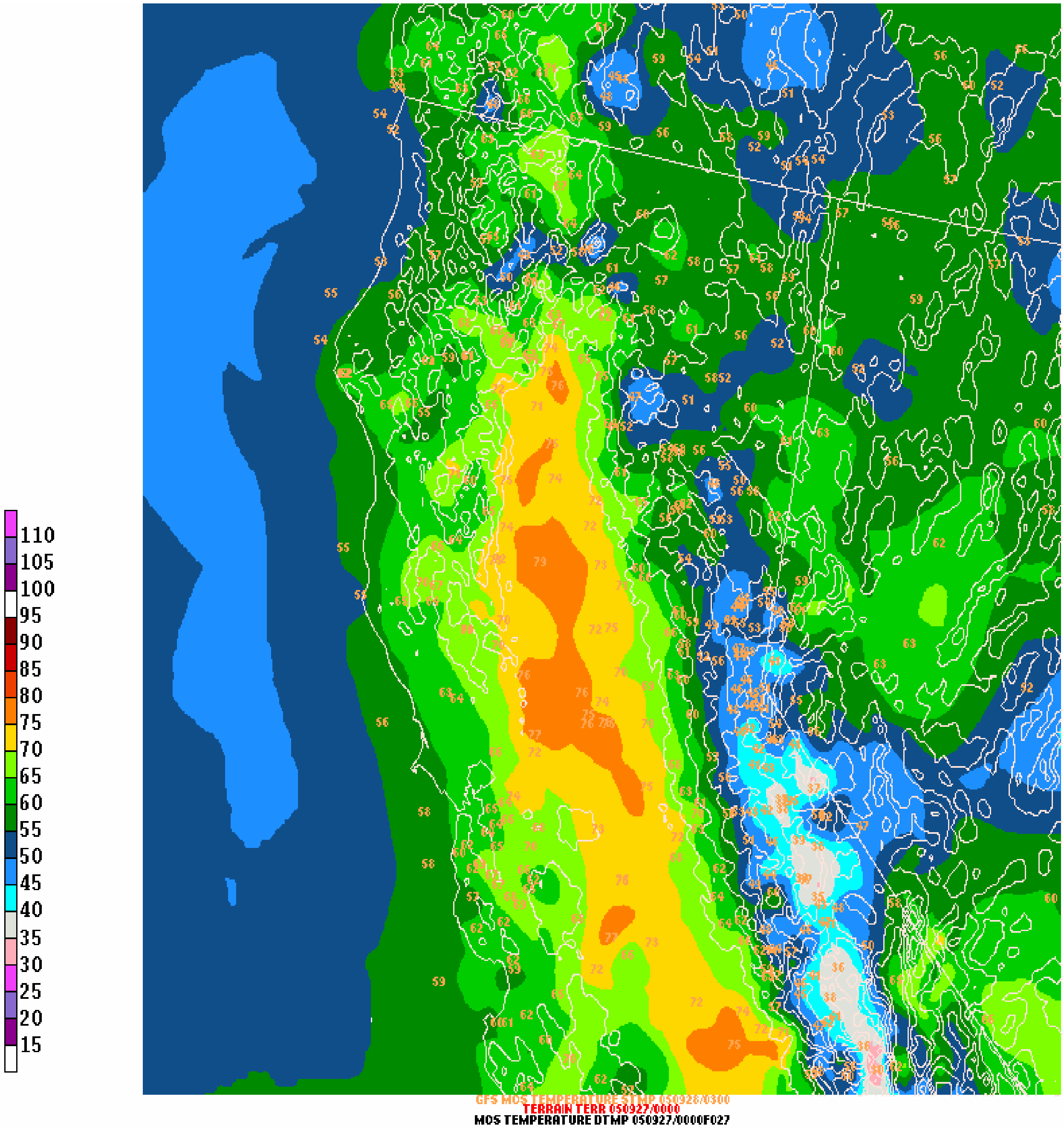

Figure 3. Same as Fig. 2, except no terrain correction was used in the analysis, and there was no distinction between land and water. Note that we are not concerned with the area in the Pacific beyond the NDFD boundary.

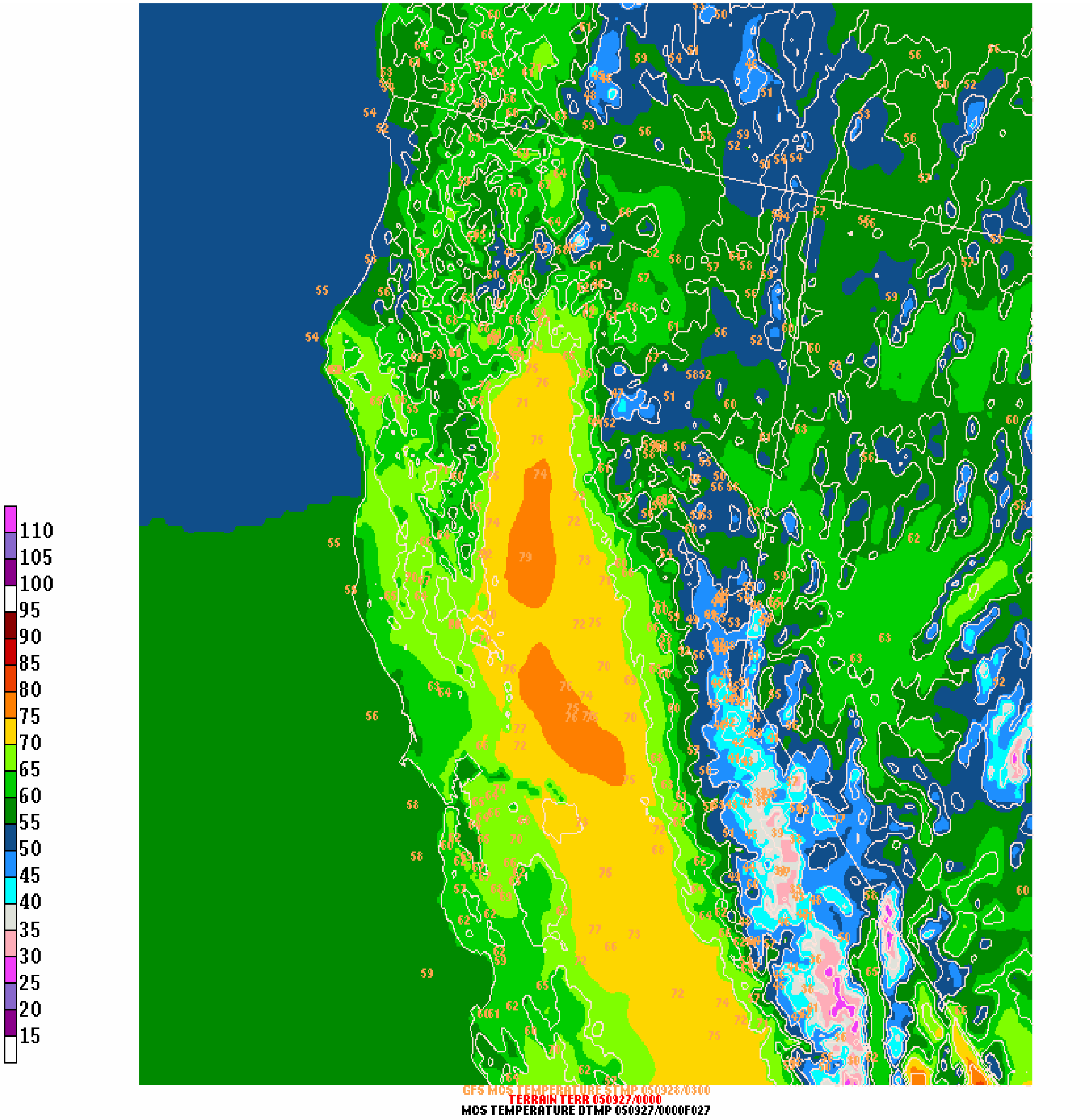

Figure 4. Same as Fig. 2, except only three analysis passes through the data were used.