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10A.4 ALGORITHMS FOR EFFECTIVE OBJECTIVE ANALYSIS OF SURFACE WEATHER VARIABLES

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1. INTRODUCTION

Analysis of surface weather variables, the interpolation from quasi-random points to a regularly spaced grid, presents many challenges. The Meteorological Development Laboratory uses a highly specialized form of the successive correction objective analysis method popularized by George Cressman in the late 1950's (Cressman 1959). The successive correction method remains as one of the best procedures for analysis of surface weather elements. It starts from a first guess grid, then corrects each grid point according to the data in its vicinity in a series of passes over the data; that is, more than one corrective pass can be made, usually with a smaller radius of influence for successive passes. However, there are many differences in data characteristics, geography, and topography that must be dealt with, including sparse data areas, land/water boundaries, rough terrain, and categorical variables rather than quasi-continuous variables.

This paper describes methods we have devised to deal with these and other challenges. For instance, our analysis package can compute an expected change in the variable as a function of elevation from either the surface data being analyzed, upper air data from a model forecast, or a combination of both. A different radius of influence can be used for each data point, or a constant one that depends only on pass number. There are four choices for the first guess, and several of the analysis options, such as throw-out criteria in quality controlling the data, vary by first guess choice. Land and water can be treated together or separately. There are options for smoothing the grid, including a terrain-following smoother, a spot remover, and a ray smoother for water areas that can variably smooth depending on distance from the coast. The number of corrective passes can vary, and there are three types of correction that can be made in combination with bi-linear, bi-quadratic, or terrain-related interpolation. Provision is made to give special emphasis to the range of values of interest to users; for instance, the careful analysis of ceiling heights below 1000 ft is much more important than a 1000-ft range up at 10,000 ft.

Grids of observations (Im et al. 2010), as well as of MOS (Glahn et al. 2009) and Localized Aviation MOS Program (LAMP; Ghirardelli and Glahn 2010) forecasts, are provided in the National Digital Guidance Database (NDGD; see Ruth et al. 2009) approximately 30 minutes after each hour. This follows the recommendation from a 2004 workshop on mesoscale analysis (Horel and Colman 2005), "Thus, the NWS has an immediate and critical need to produce real-time and retrospective analyses at both a high spatial and temporal resolution in order to create the National Digital Forecast Database (NDFD) forecasts as well as to verify their accuracy." (See Glahn and Ruth 2003 for a description of the NDFD.) They state these analyses should be available "within roughly 30 minutes of the valid time." The techniques used to produce not only these grids of observations, but forecasts derived from them, are presented in this paper.

2. THE SUCCESSIVE CORRECTION METHOD

Dr. George Cressman (1959), who was Director of the Joint Center for Numerical Weather Prediction Unit (JNWPU), was quick to realize an analysis method developed by Bergthorssen and Doos (1955) was superior to any other method in existence for analyzing upper air variables (e.g., 500-mb geopotential height or 850-mb temperature) such as the use of polynomial fitting pioneered by Panofsky (1949) and Gilchrist and Cressman (1954). [JNWPU was the forerunner of the U.S. Weather Bureau's National Meteorological Center (NMC), now the National Weather Service's (NWS) National Centers for Environmental Prediction (NCEP)] This method, called

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here and previously (Glahn et al. 1985) the Bergthorssen-Cressman-Doos (BCD) method, was used to initialize early atmospheric models. Later, the same method without much if any change was used for surface weather variables. A very similar technique was devised by Barnes (1964) and has been used extensively in a variety of applications (e.g., Achtemeier 1989).

The process starts with a “first guess,” but many times it can be just a constant field (the same value at each grid point, the value being unimportant). Each grid point is corrected by the stations in its vicinity, vicinity being defined by a radius of influence, and the correction depending on (1) the difference between the station value and the value interpolated from the grid at that station location and (2) the distance between the two points. (“Stations” is used here for convenience, but the data points can be, of course, defined by various processes, and not necessarily be at the location of a station.) That is, the total change to the gridpoint value is based on a weighted average of the changes suggested by all the stations within the radius of influence. After each grid point has been corrected, another pass is made with a smaller radius of influence. In this way, fewer stations, the closest, will affect a grid point, and thereby detail is added. A smoothing pass is sometimes applied, especially after the last pass, to filter out very high frequency noise either present in the data or introduced by the analysis procedure.

In analyzing upper air data (e.g., geopotential height, temperature, wind), dynamic consistency and restraints can be effectively used in three dimensions, and even in time, and the process is now called data assimilation. This process is not as effective at the surface of the earth for various reasons. First, the dynamic coupling between observations is not as strong, and the processes obtaining in the boundary layer are not as well known or modeled as they are at higher elevations. Another important difference is that the scale of processes indicated by the surface data are more closely tied to the earth’s surface, especially the elevation of the terrain, than at higher elevations. Data assimilation is expensive when used over large areas on time and space scales for which analyses of surface variables are needed. The BCD method provides a framework that is reasonably inexpensive that can be tailored to specific situations.

The basic BCD method has been so extensively tailored for use by the Meteorological Development Laboratory that we call the tailored method BCDG to distinguish it from the original formulation. Specific extensions are given in the next section.

3. EXTENSIONS INCLUDED IN BCDG

3.1 *Type of Correction*

Three types of correction to the grid points are possible: (1) the average of the individual differences between the station value and the grid interpolated to the station, (2) the same as (1), except the differences are weighted by a quadratic function of the distance between the station and the datum so that the closer stations furnish more correction, and (3) the same as (2) except that the average is divided by the average of the weights used in the individual corrections. The original BCD formulation was (2), and the weighting function used by Cressman (1959), among other possibilities considered, was mainly for computational efficiency. Testing over many applications (e.g., Glahn et al. 1969, 1985) has shown that (3) is best for most applications, with some specific controls. For instance, if only one station is within the radius of influence on a particular pass, (3) would devolve to (1), and might be very disruptive, especially if the grid point were at the edge of the circle defined by the station’s radius of influence. Formula and more detail are given in Glahn et al. (2009).

3.2 *Type of First Guess*

For many applications, a constant first guess is satisfactory and even best. This may seem counterintuitive. The correction process requires that interpolation be made into the grid at each data point. The difference between that interpolation and the datum is then applied (see Section 3.1) to the grid points. The assumption that the difference between the interpolated value and the data value can be applied to a grid point some distance away may hold as well or better for a constant grid as for another first guess grid, unless the first guess grid already represents the data quite well. For instance, consider the analysis of surface temperature on a 2.5-km grid in the vicinity of a strong, rapidly moving cold front. A data point behind the front will likely be colder than an analysis produced 1 hour previously. This will indicate a strong cooling within the radius of influence, but that cooling would not be appropriate either ahead of the front or in an area behind where the front was an hour ago. The same problem exists with a constant first guess, or a smoothed grid like that produced after the first pass, but the change would not be as great and would not be as disruptive.

The use of a first guess from a numerical model works well over ocean areas where the data density is low; it may be that there are *no* data points, and the model field is imperative. For this reason, BCDG can use a consent first guess, either a specified constant or the average of all observations over land, but some other source over water.

3.3 *Radii of Influence*

The radius of influence used on each pass is of critical importance. Usually, four or sometimes five or six passes are made over the data in order to capture the detail of the observations. For the first pass, the radius has to be large enough that every grid point is corrected by at least one, and preferably several, stations. Over an area with highly variable data densities, the first pass radius may have to be quite large. We have found when analyzing temperature on a grid with 2.5-km grid length (a 2.5−km grid) over the conterminous United States (CONUS), a first pass radius of 84 grid lengths is necessary for good results. In data dense regions, this is wasteful of computer time, because a smaller radius would be sufficient, and the computer time involved is directly proportional to the area of the circle defined by the radius.

Therefore, we devised a “variable radius” method whereby each station has its own radius of influence. In this way, stations in sparse data regions can have large radii, and stations in dense data regions can have much smaller radii. This capability is necessary for Alaska because of the extreme data variability from the tip of the Aleutian Islands to the Arctic Ocean. The calculation of the individual radii is done in a preprocessor by assuring that each grid point is affected by a specified number of stations on the first pass; this is possible, based on the grid to be used and the data points to be available. If the receipt of data can vary, allowance must be made for that possibility. An override feature in the preprocessor is provided so that specific stations can be given specific radii. This is useful in Puget Sound in keeping the several observations there from unduly spreading into the Pacific Ocean. It is also imperative over the Gulf of Alaska and the Bering Sea in order to use the few observations in a near optimum fashion.

One difficulty with the variable radius and the method of calculating it is that in extremely dense data areas, such as a cluster of mesonet sites around a large city, the radii can be very small, even for a station slightly outside the cluster. A very small radius on the last pass may introduce noise, so a capability exists to use the variable radius method, but to switch to a constant radius for the last one or more passes.

3.4 *Land/Water Separation*

Many surface variables, in fact most, show different characteristics over water than over land. There may be fairly dense observations over land near shore and inland, but none to few over the adjacent water. In analyzing MOS probability of precipitation or precipitation amount, there are no data points over the ocean, so the land values are just extended out over the water. However, for temperature, there are MOS forecasts and observations over the water, although they are much more sparse than over the adjacent land. Temperatures over large bodies of water may be quite different than over nearby land. BCDG can analyze land and water separately, thereby creating the actual discontinuity (at the spatial scale analyzed) at the shore. Stations are defined as ocean, land, inland water, or both inland water and land. Grid points are also defined as ocean, land, or inland water. Data points are allowed to affect only grid points of the same designation. For this process to work, the body of water must have at least one data point that would represent (affect) it. Even if analyzed separately, some bleeding across the water/land boundary can be allowed within one grid length of the boundary.

In Fig. 1, differences can be noted over water depending on whether water and land were analyzed separately or together. For instance, note the temperatures over the Pacific Ocean off the coast of northern California and over southern Lake Michigan.

3.5 *Quality Control Criteria*

Any analysis system must have a good method to deduce whether an observation is incorrect, or is so far different from others in the vicinity that it should not be used in the analysis. There should be quality control (QC) procedures prior to the analysis, but discard criteria would likely be based on gross limit checks (e.g., temperature > 130 °F), location checks (checked against a dictionary of locations), checks against other variables at the same location and time (e.g., dewpoint > temperature), and time series checks (e.g., hourly temperature change > 50 °F). All these are good, but do not well address the spatial continuity needed for an analysis. BCDG has a rather elaborate scheme for tossing out data, the philosophy being to be as sure as possible the datum is not usable before tossing it on the current pass. The criteria for discard vary by pass, weather element, and first guess type, and data can be given only partial weight specified by a dictionary based on historical information. This QC method is described in detail in Im et al. (2010). In addition, there is cross checking for some weather elements, both during the analysis and after. For instance, even if the temperature and dewpoint observations are consistent, the gridpoint values may not be. So after the analyses, any dewpoint value at a grid point that exceeds the temperature at that point is set to the analyzed temperature.

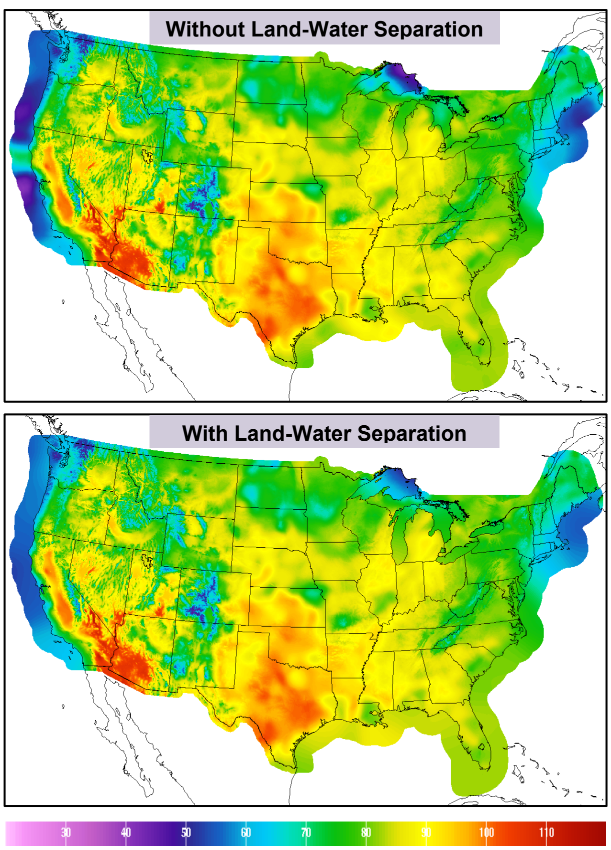

FIG. 1. Analyses of temperature observations (°F) without (top) and with (bottom) land-water separation for 0000 UTC 25 June 2009.

3.6 *Types of Smoothing*

Some smoothing of the analyzed grid is usually desirable. While BCDG can smooth after any pass, we have generally used smoothing only after the last pass. The reason for smoothing is to eliminate the small scale features that are probably not real, and that an experienced analyst would not put in. The undesirable features are not at the data points, unless the data point is in question and is not in agreement with other values in the vicinity, but rather between the points. Most smoothing methods will smooth all grid points whether or not they are near observations. Even a basic smoother such as used by Cressman (1959), extended by Thomasell and Welsh (1962), and explained in detail in Glahn et al. (2009) smoothes every grid point the same, even if the data point is essentially at the grid point, and regardless of the terrain.

One attempt at not smoothing the detail caused by the terrain was the development of the "terrain following" smoother. This is described in Glahn et al. (2009); it essentially uses the basic smoother, but smoothes only along equal terrain contours. This is a very local smoother, and does not make large changes.

More recently, a "spot remover" has been developed. The first step is to calculate for each grid point the distance D between it and the closest station. Then smoothing is done over a circular area of radius R . We have found R = 1.25 X D is a good value. All grid points within that radius contribute to the smoothed value at the grid point, provided the elevation difference between the grid point being smoothed and another is $\leq$ a specified value C. This elevation threshold allows most of the elevation detail in the analysis to remain and may even enhance it. Distance weighting can be applied such that the gridpoint values closer to a station will have more weight than those farther away. For temperature which varies rather smoothly, distance weighting is not applied. This has proved to be very effective at removing blemishes between stations. Subtle differences can be seen in Fig. 2 before and after the smoothing, for instance in northwest New Mexico and northeast Arizona. A value of C = 25 m was used.

For ceiling height which can vary from unlimited at one station to 100 ft at a neighboring station and 5,000 ft at another neighbor, the transition is likely precipitous, and this can be achieved by using weighting of, say, $1/(D^3)$. This will make very abrupt transitions from one height to another near the midpoint between the neighboring stations. In Fig. 3, some arcs and concentric circles before smoothing are essentially eliminated. Such circles can be caused by differing data values at stations close together (e.g., on the Georgia-South Carolina border). Other significant differences can be noted, especially over the Appalachian Mountain region. The values at the stations are well preserved, but areas between the stations are dramatically affected. A value of C = 75 m was used.

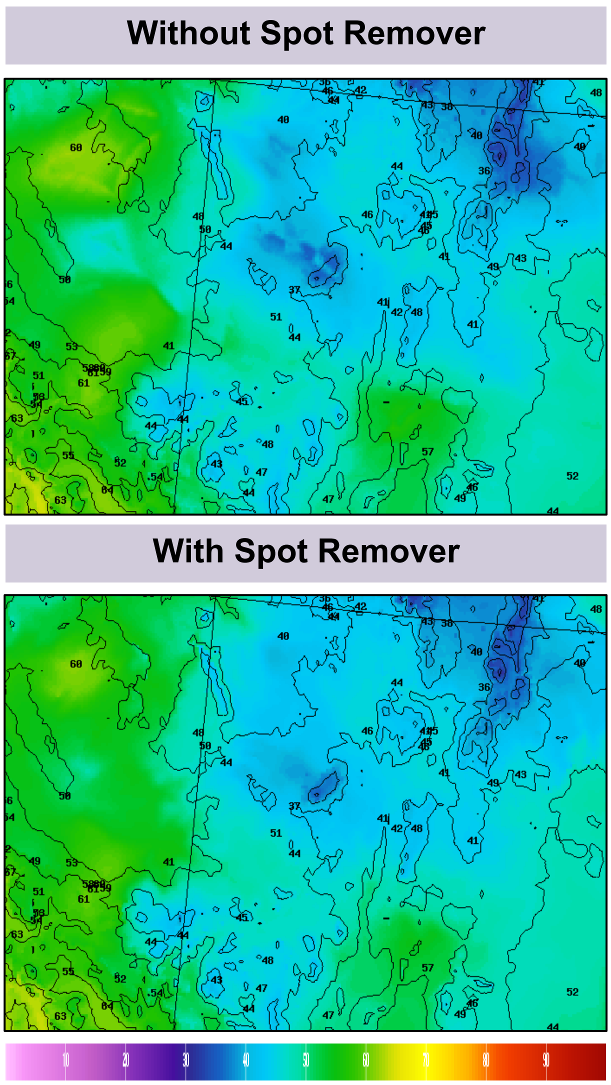

FIG. 2. Analyses of 1-h temperature LAMP prediction (°F) without (top) and with (bottom) spot remover for 1500 UTC 27 October 2009. The area shown is northwest New Mexico and adjoining Arizona.

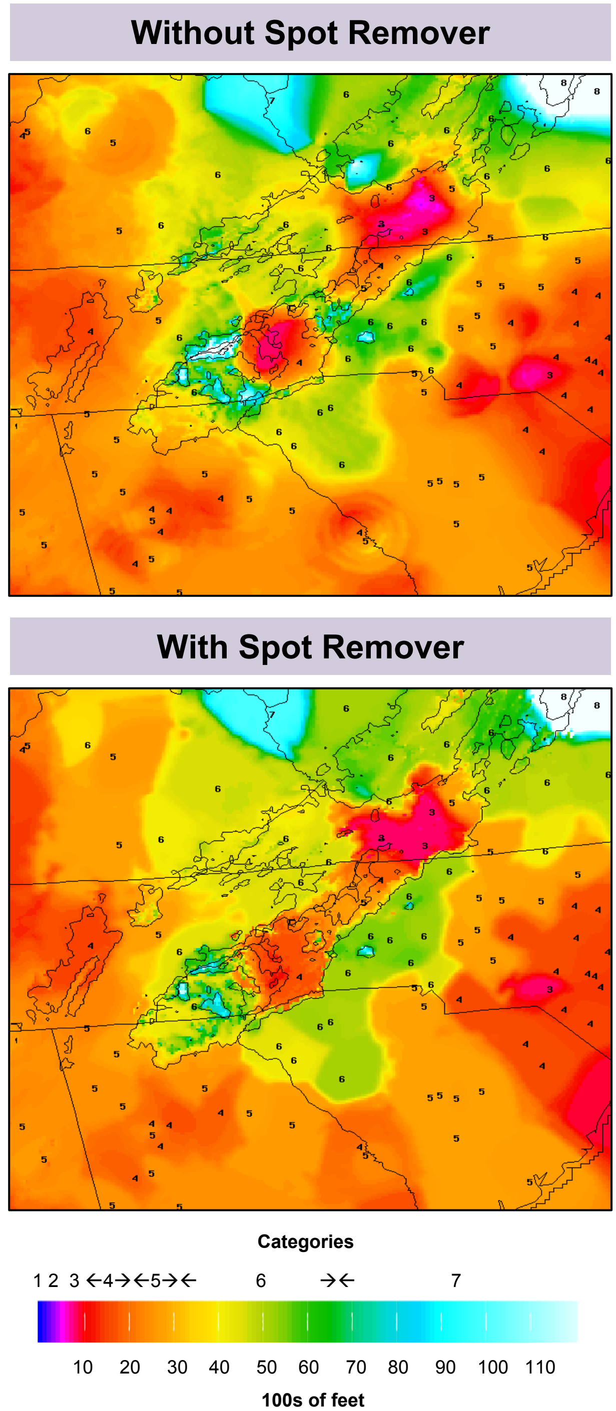

FIG. 3. Analyses of 4-h ceiling height LAMP prediction without (top) and with (bottom) spot remover for 1500 UTC 6 October 2009.

Another smoother used over the ocean in the Alaskan area is a “ray smoother.” A grid point is smoothed along rays emanating from the grid point in 16 directions out to some specified distance within the confines of the grid. A ray is stopped when it first encounters a land point. This was necessary (1) to not smooth across the Aleutian chain between Bristol Bay and the Pacific Ocean, (2) to keep temperatures within Prince William Sound fairly well isolated from the Gulf of Alaska, and (3) to keep the temperatures in the inland waterways in southeast Alaska from being unduly affected by those in the open ocean, and vice versa.

Still another ray smoother is used over water when there are no data points over the water, and the analysis consists of land values extended out. Such an extension many times gives odd patterns, and the analysis away from the shore cannot be considered very good. Still, values are needed, and the values near shore may be reasonable. The desire is to keep the values near shore intact, but to heavily smooth away from shore. This is done by using a mask composed of the distance to land at each ocean point, and smoothing with the ray smoother, but doing so in a manner that the values near the coast are preserved, but the values farther out have full, heavy smoothing.

3.7 *Variation with Elevation*

Most variables show some variation with elevation, some in a complicated way not easy to determine. Surface temperature usually changes profoundly, but while presenting difficulties, is probably the easiest to deal with. The objective is to gauge how the difference between a station and its interpolated value should be applied to a grid point at a different elevation. Even on a 2.5 km grid, the elevation difference can be significant. One method might be to use a climatologically derived (e.g., the standard atmosphere) lapse rate, but this is rather crude, and certainly would not represent many synoptic situations. A better method is to use a model field, forecast to be valid at the time as the data being analyzed. This is a viable method, although the free air temperature may not well represent the 2 m temperature. The procedure is not to just use the free air temperature, interpolated in three-dimensional space, at the grid point, but to compute a vertical gradient, which can be called a “lapse rate,” between a surface-based 2-m temperature and a free air point above it, and to apply that lapse rate in the correction process. This free air point above the station is at the elevation of the highest grid point to be affected by the station.

Another method is to compute a lapse rate to be used at a station based on the average difference in temperature divided by the average elevation difference (making sure the signs are kept straight) over a large number of stations in the vicinity of the base station. For efficiency, the set of stations is determined by a preprocessor. This lets the data determine what the effect of elevation should be. For instance, while the temperature usually decreases with elevation, near the west coast of California the temperature may be cooler than that on the low mountains inland, giving an increase of temperature with height. This is real, but might hold only during part of the day, and would be hard to determine by other methods. BCDG uses this “unusual” lapse rate, but limits its areal extent to a specified number of grid lengths. This data-derived method is used over the CONUS, but because of the scarcity of stations does not do well over Alaska or Hawaii, and the upper-air method is used there.

Fig. 4 shows a marked difference when the lapse rate adjustment is or is not used. The Grand Canyon stands out when the adjustment is used, even though there are no data within the canyon. Mountains and the ridge-valley structure in the West are clearly visible when the lapse rate is used.

3.8 *Methods of Interpolation*

As stated above, it is necessary to interpolate into the analysis to get a value at the station. BCDG can use bi-linear, bi-quadratic, or nearest neighbor to find that needed value. The nearest neighbor is used by some processes at this space scale (e.g., Ruth et al. 2009) and may be adequate, but even at 2.5 km there can be significant elevation differences between a station in a valley and the mountains on either side. Linear interpolation in complex terrain is probably better than a higher order such as bi-quadratic. This usually works well, but it was found that there are certain situations where standard interpolation is not viable when the data-derived lapse rate option is used. For instance, for temperature, a station located such that all four points around it are at higher elevations, the interpolated value would likely be colder than the station. This would indicate the grid points should be made warmer. Then with the lapse rate, low elevations can become warmer, even very close to the station.

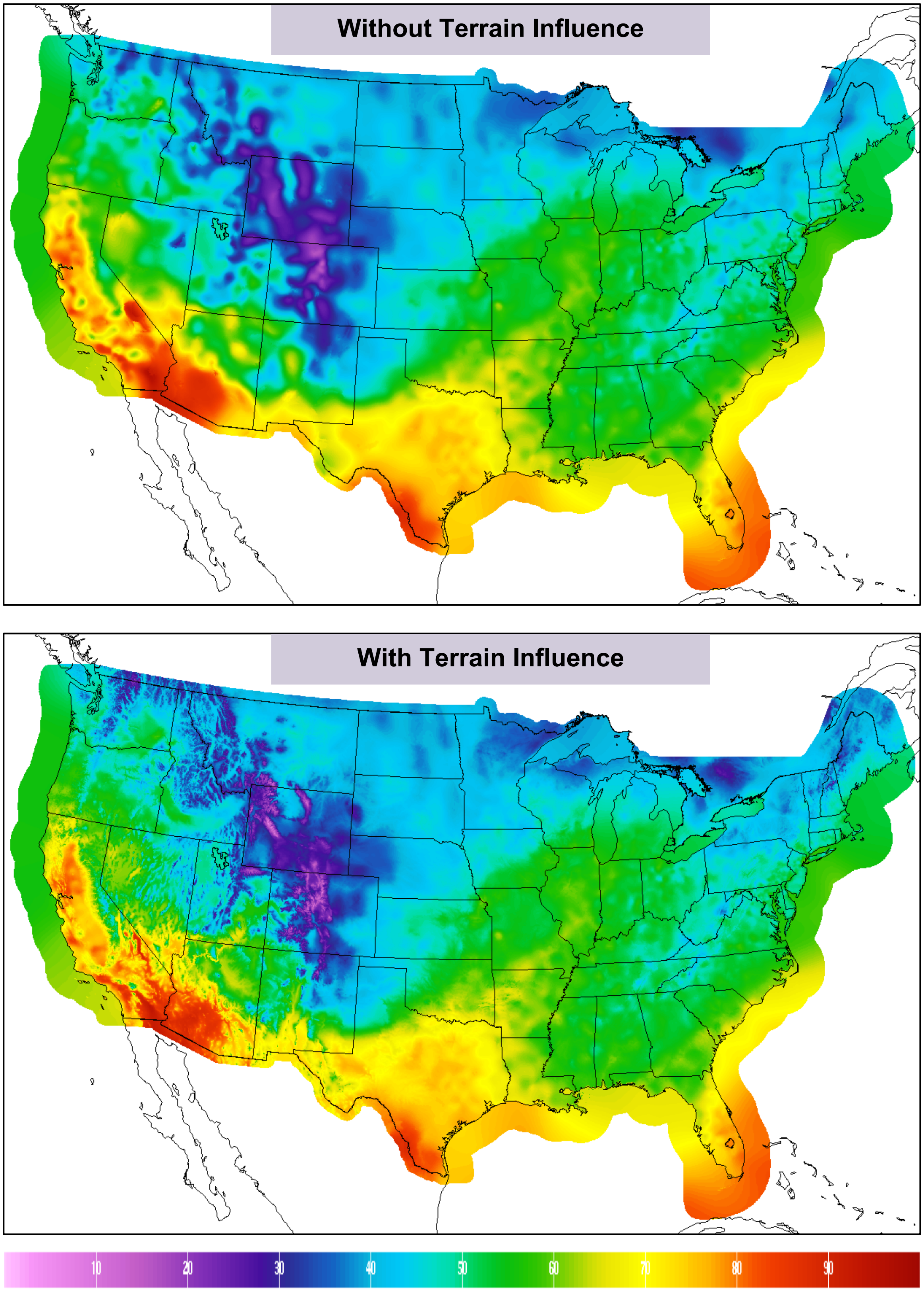

FIG. 4. Analyses of temperature observations (°F) without (top) and with (bottom) terrain influence for 0000 UTC 26 October 2009.

On the next pass, the same thing would happen, and the cumulative result is a "hot spot." A similar problem can occur when the station is at a considerably higher elevation than the surrounding grid points, and a "cold spot" can occur. To address this problem, instead of interpolating to the station from the surrounding four points, the point is found that has an elevation closest to the station. The lapse rate is then used to get the "interpolated" value at the station. This works quite well.

3.9 *Bogus Values*

The distribution of stations may be so perverse that one or more values have to be manufactured from other information to feed to the analysis process, it by itself not being fully able to provide acceptable results. The area north of the Brooks Range in Alaska is particularly problematic. Almost no reports exist in the vast expanse between the Books Range and the Arctic seacoast, and there are only a very few stations near the coast. Many bogus points are inserted north of the Brooks Range both inland and along the coast that are weighted averages of existing stations. The values along the coast are necessary to get a good demarcation between water and land.

Another example is along the west coast of Alaska. A first guess is used from an NCEP model, but the resolution smears the land/water boundary. The land grid points can be corrected with the land stations, but there are no water stations with which to do the correction. Several bogus points over water close to the shore are manufactured by bringing in the gridpoint temperatures farther out in the ocean toward the shore. Fig. 5 shows the improvement by using bogus stations over Alaska. Note the area north of the Brooks Range and the delineation of the west coast.

3.10 *Procedures for Variables with Highly Skewed Distributions*

Some variables present special problems. Examples are ceiling height, visibility, sky cover, and snow amount. While these variables are not categorical, the way they are dealt with in meteorology almost makes them so. For instance, sky cover is dealt with in aviation as clear, few, scattered, broken, and overcast. In addition, the relationships between sky cover and variables forecast by numerical models are very non-linear. So, in post-processing, instead of dealing with sky cover as a continuous variable, it is many times dealt with as categorical, and each category is treated as an "event." It is best to define the event as < some specified coverage, or > some specified coverage, but not as a "slice." The MOS process can yield the probability of the event, and by using the probabilities and the event definitions, an "expected value," or some "best category" forecast can be derived. In addition, the event probabilities form a crude, but legitimate, cumulative distribution function, after some checks for consistency are applied.

Ceiling height is a major problem because not only are the low heights rare, but it is those rare events that are important. The aviation industry is very concerned whether the ceiling is 100 ft or 1,000 ft, but doesn't care nearly as much whether it is 3,500 ft or 4,500 ft. Therefore, objective forecasting methods and analysis of ceiling height observations or forecasts must tailor processes to those considerations. MOS and LAMP forecasts are in terms of probabilities of cumulative from below categories, and a "best category" forecast is derived to be such that the categorical bias is not far from unity. That is, we want to make about as many ≤ 200 ft forecasts as occur, even though some metric such as Heidke skill score computed over several categories might be better if we never forecast that category.

The analysis of LAMP forecasts requires some transformation of ceiling height so that the low values will have the necessary effect on the analysis. For LAMP forecasts, the categorical values are used along with the probabilities to give a continuous value to analyze that ranges from 1 through 9, the latter representing a high probability of unlimited. These scaled values are then analyzed. Such an analysis can be "choppy" because the height values can vary drastically at neighboring stations, and the gridpoint values between stations sometimes show arcs caused by the influence of a particular station at its radius of influence. The spot remover is applied so that the arcs and spots are effectively removed, the values very near the stations remain at the station value, and the changes between the stations are rather abrupt. After the analysis, the values are converted back to continuous height values in feet.

The analysis of observations, in distinction to the forecasts which are categorical, also requires scaling, and the same scaling used for forecasts is applied. The difference is that the forecasts

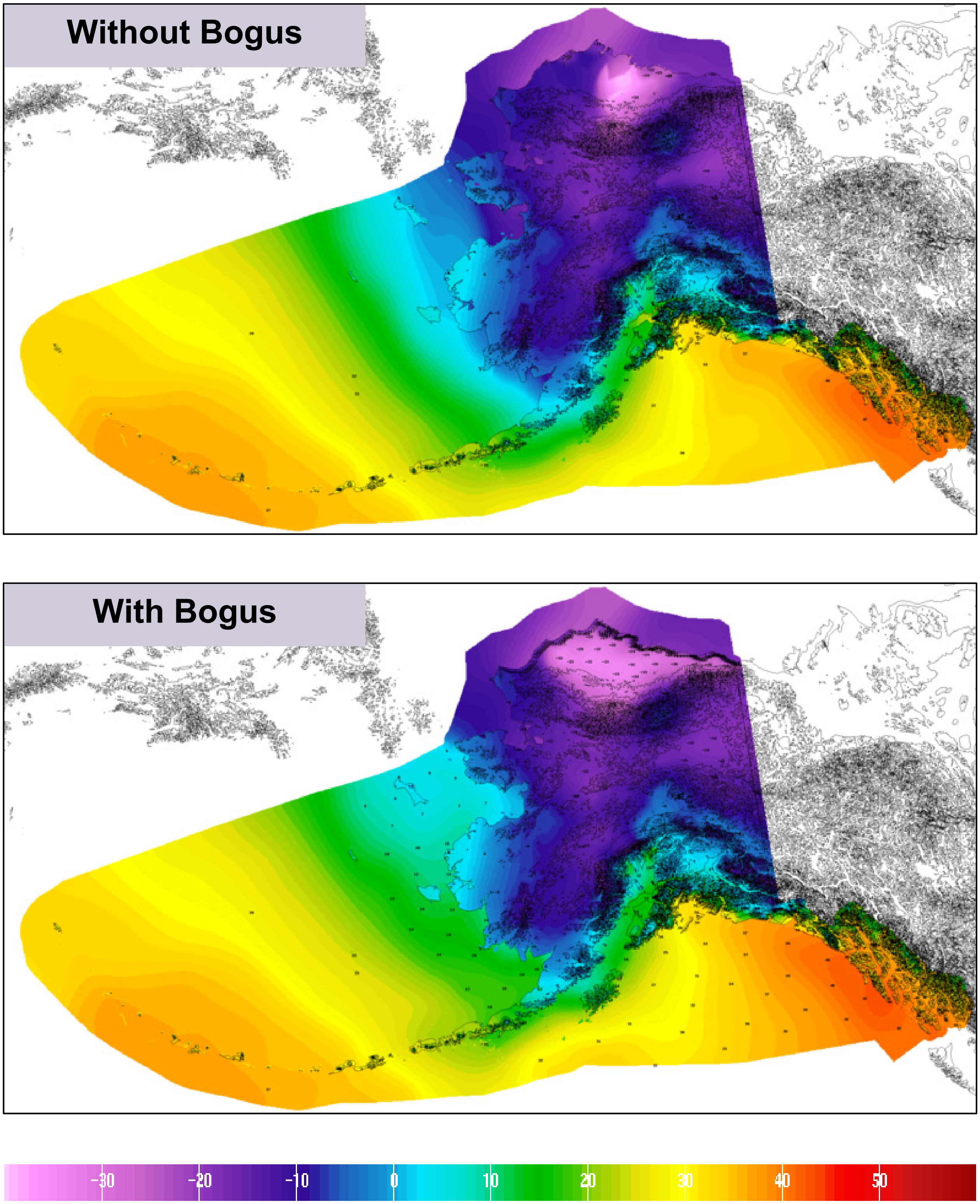

FIG. 5. Analyses of 66-h maximum temperature MOS predictions (°F) without (top) and with (bottom) bogus values for 1200 UTC 1 January 2007.

consist of categorical forecasts and probabilities of the categories, while the observations are essentially continuous. The observations are put into categories, but linearly scaled within the category depending on the actual ceiling. This, then, gives a continuous range over the values 1 through 9, and the analysis process is the same as with forecasts.

In summary, for a variable like ceiling height, unless the values are scaled, the rare low values will not be well represented on the grid, because the larger number of much higher values will overpower them.

3.11 *Augmentation with Similar Data*

Augmentation is a way of manufacturing or using values from other datasets. For instance, we do not have LAMP forecasts at mesonet sites. The reason is partly because LAMP is targeted for aviation interests and the mesonet stations do not observe ceiling height and visibility. Another reason is that many mesonet stations have become available after the LAMP station set was established some years ago. There are more MOS stations having temperature forecasts than LAMP, so LAMP analyses can be augmented by MOS. MOS is a forecast of the same element valid at the same time, although made earlier and therefore not as accurate, especially for the 1- to 12-h LAMP projections. For the augmentation technique, a preprocessor is run which determines a set of stations around a MOS station that has both MOS and LAMP forecasts. Then for an analysis, the MOS station is used, but modified with a delta which is the average difference between the surrounding MOS and LAMP stations. That is, the general temperature forecast by LAMP over the area is maintained, and at the same time the additional detail in the MOS forecasts is used. This helps to maintain a consistent pattern from hour to hour.

Fig. 6 shows an analysis over northwestern New Mexico and the adjacent Arizona, both with and without MOS augmentation of LAMP temperature forecasts. LAMP forecasts are fairly sparse in the area, and the lapse rate has caused an adjustment that is not borne out by the MOS forecasts. The analysis generally remains true to the LAMP forecasts, but is assisted in sparse data regions by older MOS forecasts.

In the analysis of surface observations of temperature and dewpoint, only about half the total stations report at any given hour by our data cutoff time of 26 minutes after the hour. The observations at the previous hour are used in the analysis, after being "corrected" by the change in the past hour in the immediate vicinity. This maintains a more consistent set of stations from hour to hour, and thereby a more consistent analysis (see Im et al. 2010 for details). With a data cutoff time of 26 minutes after the hour, the need expressed by Horel and Coleman (2005) is met.

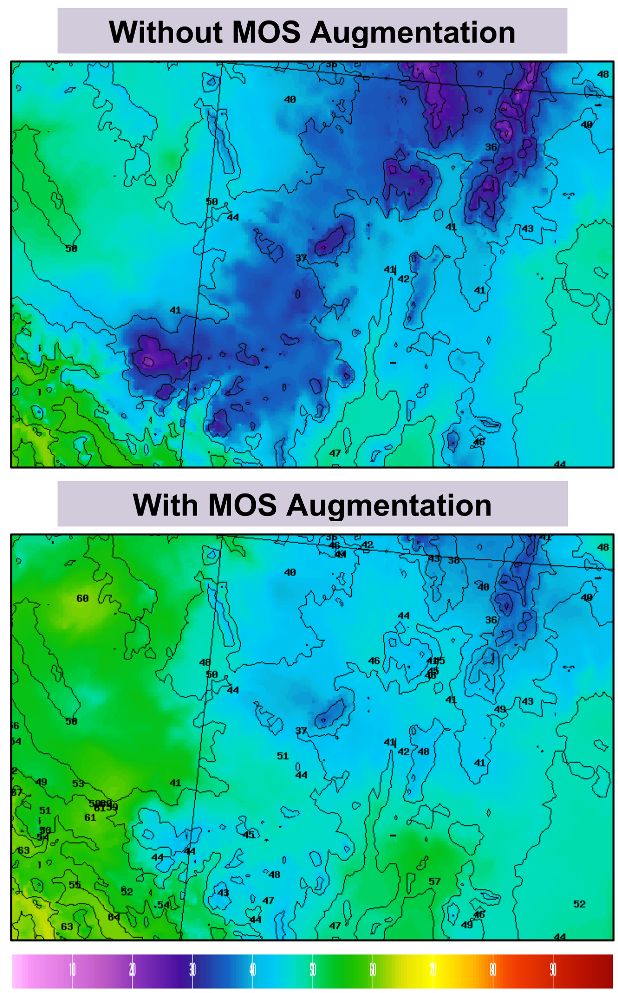

FIG. 6. Analyses of 1-h temperature LAMP prediction (°F) without (top) and with (bottom) MOS augmentation for 1500 UTC 27 October 2009.

4. SUMMARY

The analysis of surface-based weather elements requires many specialized techniques within some basic method. The ones presented here are part of BCDG, a highly specialized form of a much used successive correction technique, but some of the techniques are applicable to other methods. For instance, the spot remover and ray smoothers need not be unique to BCDG.

Analyses of LAMP forecasts and of observations of ceiling height, visibility, temperature, and dewpoint are in the NCEP job stream, and the grids are in the NDGD. Images from the grids can be found at http://www.mdl.nws.noaa.gov/~glmp/glmp_expr.php. This web site also has information on how the grids can be downloaded. They can be compared with the Real-Time Mesoscale Analysis (RTMA) produced at NCEP (De Pondeca 2007).

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