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1. INTRODUCTION

For years, National Weather Service (NWS) forecasters have used Model Output Statistics (MOS) guidance (Glahn and Lowry 1972) as an aid in producing text forecast products issued to the user community. However, the methods forecasters use to generate products have changed because of requirements to produce the official NWS 7-day forecasts on high-resolution grids. These gridded, or digital, forecasts are put into a National Digital Forecast Database (NDFD; Glahn and Ruth 2003). NWS forecasters need supporting guidance available on a grid, at a resolution comparable to the grid resolution used at the local forecast office. One approach to the problem of providing guidance on the required grid is to objectively analyze forecasts at MOS stations. Initial testing and development resulted in a prototype gridded MOS system over the western CONUS (Dallavalle and Glahn 2005). The first set of operational Global Forecast System (GFS)-based gridded MOS guidance using this method became available in the National Digital Guidance Database (NDGD) in August 2006 over the conterminous U.S. (CONUS) on a 5-km grid. Since the initial CONUS implementation in 2006, more weather elements have been added and the geographic coverage has expanded to include an Alaska domain. Gridded MOS has become a useful resource to NWS forecasters for initializing forecasts, particularly in the forecast periods from days 4 through 7. Emphasis is placed in the later time periods on only making changes to the MOS grids when and where the forecasters see an obvious opportunity to improve over the guidance.

The gridded MOS guidance has demonstrated many of the positive attributes of its parent station-based MOS, while including options for tailoring the grid point values to best reflect the terrain.

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Since the original implementation, gridded MOS has undergone several adaptations to improve consistency as well as regional applicability. MDL developers have welcomed assessments of gridded MOS from local forecasters in order to make adjustments to provide guidance which is both representative of the local area, and compatible with the process for generating forecasts for NDFD. Some of the improvements resulting from forecaster feedback include: removal of unrepresentative forecasts from the analysis, expansion of the grid coverage, and modifications to the land/water mask.

In this paper, we discuss the current state of the gridded MOS suite, as well as ongoing enhancements to the operational GFS-based MOS guidance, and the process used to diagnose potential errors in the analysis. Challenges encountered in gathering and processing the data necessary to support the development on a high-resolution grid are described. In addition, current and future development activities are presented.

2. CURRENT STATE OF GRIDDED MOS

2.1 Development Techniques

There are two methods currently in use to produce MOS guidance on a grid. The main method employed to produce the weather fields in the gridded MOS guidance is based on an objective technique to analyze the MOS station-based forecasts to points. A scheme of successive corrections has been extended to analyze site-specific MOS forecasts to the desired grid (Glahn et al. 2009). This scheme is similar to the approach implemented by Cressman (1959), but it has been expanded to account for differences between land and water forecast points, and it can account for changes in an element's values due to vertical changes in the elevation. The vertical correction is commonly associated with decreasing temperatures as elevation is increasing. However there are cases where the elevation correction can take on positive values over limited areas, as with tem-

perature inversions. The current gridded MOS software configuration performs some amount of elevation correction, either positive or negative (snowfall amounts and wind speed may increase with height for example) for every analyzed weather element except the probability of precipitation and wind direction.

The other method uses a generalized operator equation applied over the entire domain. This technique combines all of the stations into a single region to increase the sample size and stability of the equations, which is particularly important for some relatively rare and non-continuous weather elements. A single MOS equation is developed for a given cycle and projection, which may then be applied to any station or grid point. The generalized operator method is used to generate the probability of a thunderstorm equations currently available in NDGD (Shafer and Gilbert 2008; Hughes and Trimarco 2004). Thunderstorm forecast equations are developed on a 40-km grid and the resulting forecasts are then interpolated to the 5-km NDFD grid. These gridded MOS thunderstorm forecasts represent the probability of one or more cloud-to-ground lightning strikes within a 40-km area centered around each 5-km grid point during the given time period.

2.2 Available Weather Elements and Projections

The goal of gridded MOS is to provide guidance on high-resolution grids, which corresponds to all of the elements in NDFD, and provide this guidance at the same time and space resolution needed by the NWS forecasters, while maintaining a level of accuracy and skill comparable to the station-based MOS guidance. GFS-based MOS grids are currently produced on a 5-km grid over the CONUS and a 3-km grid over Alaska from the 0000 and 1200 UTC GFS model runs. Unless otherwise noted, the following gridded elements are available in NDGD on the hour every 3 hours from 6 to 192 hours in advance: daytime maximum (max) and nighttime minimum (min) temperature, 2-m temperature, 2-m dewpoint, relative humidity calculated from the temperature and dewpoint, sky cover, wind direction, wind speed, wind gusts, probability of precipitation over 6- and 12-h time periods, total expected precipitation amount over 6- and 12-h time periods (CONUS only, valid out to 156 hours in advance), probability of thunderstorms over 3-, 6-, and 12-h time periods, and total snowfall amount over a 24-h time period (CONUS only, valid out to 132 hours in ad-

vance). Guidance is available in graphical form on the NDGD web site shown in Figure 1 (<http://www.weather.gov/mdl/synop/gridded/sector/s/index.php>) and it is also encoded and transmitted in GRIB2 format.

For all weather elements except the thunderstorms, MOS guidance is developed for specific observing locations. For continuous variables such as temperature and wind speed, the historical sample of observations and model data is adequate to derive single-station MOS equations for each projection, cycle, and season. For many discontinuous elements, a larger sample composed of several stations combined outweighs the slight loss of specific characteristics at an observing site. Variables such as the probability of precipitation and snowfall amounts are developed for groups of stations with similar characteristics within a geographic area. These groups of stations are referred to as regions. Using relative frequencies or other geoclimatic variables specific to each observing site provides additional site-specific information.

2.3 Cycle Averaging

Cycle averaging was implemented to reduce the impacts of model flip-flops and pulsing in small areas between cycles. These oscillations between cycles may be attributed to several factors; the numerical weather prediction models themselves have some temporal inconsistencies between model runs, samples available for the 0000 and 1200 UTC MOS developments vary for some elements, not every station has a forecast for a particular element at all projections, and finally even when stations and sample sizes are matched between cycles, there is no guarantee the unique regression equations will yield consistent forecasts.

An "ensemble of two" approach minimizes the oscillation from run to run for an analyses made from only one run. It is a simple 50%/50% weighting of the current cycle and the previous cycle 12 hours earlier. So, for instance, the 36-h forecast from one cycle is blended together with the 48-h forecast from the previous cycle. Tests have shown that cycle averaging makes little difference in the accuracy or bias of the gridded MOS forecast (Ruth et al. 2009).

Cycle averaging is used for all of the station-based gridded MOS elements except the wind speeds, gusts and direction. The gridded wind

averaging was turned off after forecasters noticed cases of unrealistic wind patterns, described in more detail in Section 5.

3. POST-PROCESSING

A limited amount of internal grid consistency checking (i.e. quality control) has been implemented. Before the station values are offered to the analysis software, the station forecasts are checked for consistency. Some inconsistency is introduced to the grids due to the analysis procedures and the large differences in the number of stations available from element to element (Figures 2-6). Post-processing algorithms assure the temperatures are greater than or equal to the dewpoint temperatures; wind gust grids are greater than or equal to the wind speed grids assuring the maximum wind speeds are used in the gust grids; probability fields are checked for legitimate values, negative values are set to 0, high values cannot exceed 100%.

A few of the weather elements available in the gridded MOS guidance are generated through a series of post-processing steps. The wind direction is computed from the u- and v-wind components, with added checks for calm wind conditions. The relative humidity grids are computed from the temperature and dewpoint grids. The percent opaque sky cover grids are computed from categorical and probabilistic sky cover forecasts.

METAR observing sites generally report most of the sensible weather elements needed for the MOS system. We have increased the density of surface sites in the MOS system by expanding our archives to include buoys, coastal-automated marine networks (C-MAN), mesonets and cooperative observer (COOP) reports. The complication from this expansion is the variability in the number of sensible weather elements reported, and the reliability and quality of the observations. This is particularly evident in the geographic distribution of temperature and dewpoint stations when compared to the max/min stations.

A more thorough consistency package is being written which will reduce the discrepancies between the max/min grids and the 3-h temperature grids caused mainly by the difference in the type and number of available MOS stations. As we refresh our MOS equations and enhance the post-processing algorithms, promoting consistency in the final output grids is a high priority.

4. CHARACTERISTICS

Gridded MOS has several strengths, one being a lack of discontinuities between WFO boundaries, evident in some forecast fields in NDFD. The use of vertical elevation differences to adjust some gridded MOS fields results in realistic features which correspond well to the influencing terrain. The lapse rate used in the gridded MOS analysis is not limited to a standard lapse rate, but rather the data themselves determine the amount of vertical correction to apply with changing elevation. These characteristics enable gridded MOS to be a suitable backup for NDFD when holes are caused by a missing WFO forecast for an extended length of time.

A few characteristics may be viewed by some users as deficiencies and we will address these here. We realize a perfect analysis scheme does not exist. GFS-based gridded MOS is based on a global model, therefore it is still synoptic-scale guidance which has been analyzed to a high resolution grid. In strong surface-based inversions and in extreme or rare events, large errors may be present in the gridded MOS guidance, similar to errors seen in the traditional station-based guidance. Even though gridded MOS output is the result of an analysis of the station-based MOS forecasts, values at grid points near MOS station locations may not return the same values found in the station-based MOS messages, which is partially a result of cycle averaging.

A radius of influence is used to determine which station-based MOS forecasts affect the forecast at a particular grid point. Considerable experimentation was used to determine the optimal number of passes and the optimal radius of influence for each pass. Four passes through the data were found to be necessary and sufficient to capture the desired detail (Glahn et al. 2009). Allowing too large of a radius resulted in an overly smooth field (Fig. 7). Likewise, restricting the radius of influence too greatly resulted in the appearance of spots (also referred to as measles, streaks, holes, or bull's eyes) in the analysis (Fig. 8). Similar features are also caused by stations with unrepresentative observations. An example grid is shown (Fig. 9) generated with the same radius of influence currently in use for our operational products.

In Alaska, where observing stations are sparse and not evenly distributed throughout the domain, one radius of influence setting for all stations pro-

duced poor results. A variable radius feature was implemented which allowed the gridded MOS analysis program to adjust for varying station densities. This feature is planned for CONUS implementation at a later date.

5. FORECASTER FEEDBACK

In order for gridded MOS to have the maximum value for the local forecaster, collaboration between MOS developers and local forecasters is essential. Detailed knowledge of the local area and weather patterns is held by the local forecaster, so adjusting for these details requires collaboration between the local experts and the MOS team.

5.1 GIS Enabled Collaboration

Gridded MOS is dependent on geophysical, or constant data created objectively for the entire grid area with the use of geographic information systems (GIS) (Sheets et al. 2005). The analysis from station MOS to gridded MOS uses the constant data to tailor gridded MOS to terrain and match land/water grid points with stations of the same characteristic (Glahn et al. 2009). Constant information, used as a grid mask, also sets the domain of the generated output (Sheets 2008). The objective process for creating these masks is an efficient method for producing constant files, but may fail to capture details which local forecasters expect to see at 5-km resolution. GIS has also proven to be a crucial tool in the interaction between local forecasters and the MOS team working to make gridded MOS a more valuable guidance product in the digital forecast preparation process. The computing system used in NWS WFOs to generate forecasts is different from system used to develop and implement MOS products, so GIS provides a means to share files in formats readable by both systems. Furthermore, GIS is the tool by which many of the modifications requested by the field are made.

An example of collaboration which provided enhancements to an analysis mask was a request from the field to expand the output coverage. The ability to view the guidance over neighboring areas is a point of concern for NWS forecasters. Near national borders, some of these neighboring areas may not have been included in the original gridded MOS domain. Forecasters at the Juneau, AK, forecast office requested the coverage be expanded along the border with Canada, so we

worked together to expand the domain of gridded MOS for Alaska to fully support their operations.

5.2 Unrepresentative Stations

The analysis of some MOS station forecasts to the grid highlights stations which provide observations that are inconsistent with their neighboring MOS stations. These stations can be identified based on features of the plotted forecasts, such as the bull's eyes, streaks, and holes previously discussed. Even when the MOS team identifies these features as suspect, it is best to confirm with the local forecasters that the patterns are atypical for this location. In some cases there are stations that are consistent reporters, but have an element or two for which their observations are not reliable. These cases are not always evident when examining the grids for these elements at a CONUS or Alaska scale, but are often identified by forecasters using the grids to generate their forecasts. Several NWS WFOs have provided critical feedback regarding suspect stations in their local areas. In one such case, the Paducah, KY, WFO contacted us with concerns of a cold bull's eye in dewpoint temperatures along the eastern portion of their area of responsibility. After plotting the station-based MOS over the gridded MOS, KHSB and KEHR were identified as stations reporting cooler dewpoints than the rest of the area. The MOS team ran the analysis excluding each one and both of the stations. Forecasters reviewed the new results and decided both were poor dewpoint temperature sources, so they were removed from the dewpoint analysis to produce a more realistic grid (Fig. 10).

5.3 Land/water Mask

Another area identified by forecasters which has required some adjustments is the land/water mask, especially in highly populated coastal areas. The grid cells are characterized by the point at their center, so some grid points are classified as water even when a portion of the grid cell may be over land. In some cases, even when the center of the grid cell is over water, if nearby land areas are populated, the forecasts over the entire grid cell needs to represent the forecast over land. The forecasters in Wilmington, NC, notified us that some gridded MOS forecast points along the populated coastline were characteristic of the ocean temperature guidance, so we modified the land/water designations for the indicated grid points (Fig. 11). This change allowed the analysis

to influence these grid points with land station values.

5.4 Strange Wind Patterns

Finally, one of the techniques implemented to provide consistency from one model run to the next, namely the cycle averaging, introduced some peculiar features in the wind guidance. Upton, NY, forecasters noticed odd wind patterns along their coastal areas of responsibility. After comparing the station-based MOS guidance with the gridded guidance over the area, it was determined that the strange areas of convergence and divergence were artifacts of the cycle averaging and not meteorologically plausible. The cycle averaging was turned off for the wind speed, direction and gust grids, which eliminated the peculiar wind fields. Images and more details from this gridded MOS wind case are available at <http://www.weather.gov/mdl/synop/gmos/feb2008/wind.html>.

MDL strives to provide gridded MOS as a locally relevant guidance tool for forecasters. We would not be able to accomplish this without the valuable feedback and collaboration from the forecasters who know their areas of responsibility best.

6. FUTURE WORK

As requirements for more digital weather information continue to increase, the need for expanding and improving gridded forecast guidance is also increasing. Efforts are underway to increase the horizontal grid resolution over the CONUS from 5 km to 2.5 km. Almost half of the 122 NWS forecast offices are already producing gridded forecasts at 2.5 km, which allows the forecasters to more precisely map weather features into complex terrain, both mountainous and coastal areas. Figure 12 shows an example of a 5-km maximum temperature grid over Utah. Figure 13 shows the same MOS forecast data analyzed to 2.5 km.

There is still a need for more weather elements in the gridded MOS suite. The expected weather valid on the hour every 3 hours is a product of the NDFD. This weather grid combines weather type, uncertainty, and intensity information to indicate the expected weather at the indicated hours. Efforts are underway to combine many of the existing gridded MOS fields, and redevelop the MOS precipitation type forecasts to produce a MOS

weather grid. Requirements for probabilistic information are on the rise, particularly for hazardous events. Many of the existing gridded MOS elements have underlying probabilistic information which can be gridded and included in NDGD.

In addition to the GFS-based gridded MOS system described in this paper, requirements have been established to generate a NAM-based gridded MOS system. A new station-based NAM (WRF-NMM) MOS system was implemented in December 2008 to replace the Eta MOS package (Maloney et al. 2009). This initial system was developed for METAR and marine sites. To produce a NAM MOS gridded system of comparable quality and detail to the GFS-based gridded MOS package requires the addition of many more observing sites. Development is in progress to process observations from the cooperative observer network and mesonet sites over the same time period as the NAM (WRF-NMM) model output is available.

Work is also in progress to expand the available elements over Alaska. Grids of max/min, temperature, dewpoint, sky cover, relative humidity, wind speed and direction, wind gusts, the probability of precipitation, and the probability of thunderstorms are already available on a 3-km grid covering Alaska. New elements to be implemented include snowfall amount and precipitation amount grids. We are also in the early stages to develop gridded MOS systems over Hawaii and Puerto Rico.

It is a continuous process to incorporate MOS stations into the MOS system to provide better coverage and more realistic detail over the gridded domains. It is a time consuming effort to obtain observational data from diverse networks, gather and confirm station metadata, and develop quality control procedures to prepare the datasets for incorporation into the MOS system for equation development. As numerical models evolve and available developmental samples change, it is also desirable to refresh the existing sets of equations to ensure we maintain a skillful system with minimal bias and error.

7. CONCLUSIONS

Gridded MOS is adapting to the needs of the forecasters. A new procedure was recently implemented by the NWS to use the GFS-based gridded MOS to automatically fill in holes in the NDFD when NWS Weather Forecast Offices are

not able to send their grids for extended periods. More elements will be added, horizontal resolution will be increased, and coverage will continue to be expanded. It maintains a level of accuracy comparable to station-based MOS while being analyzed to the NDFD 5-km grid. Forecaster feedback had led to improvements since the initial implementation in August 2006. As both capabilities and expectations increase, we will continue to expand and improve gridded MOS as a valuable resource to forecasters. More online documentation can be found at (<http://www.weather.gov/mdl/synop/gmos.php>).

8. ACKNOWLEDGMENTS

Gridded MOS is a product of the hard work of many people in MDL. We thank all of the MOS developers for their efforts. We thank Marc Sac-cucci for his efforts to make gridded MOS images available on the web and Dave Ruth for his assistance in identifying suspect areas in gridded MOS. We also thank the WFOs in Caribou, ME; Wilmington, NC; Boston, MA; Paducah, KY; Cleveland, OH; Burlington, VT; Mobile, AL; Oxnard, CA; Upton, NY; and Juneau, AK for their feedback. A general thanks is extended to all NWS Regional Headquarters for their support of gridded MOS and to the WFOs for collaborating with us to make gridded MOS better.

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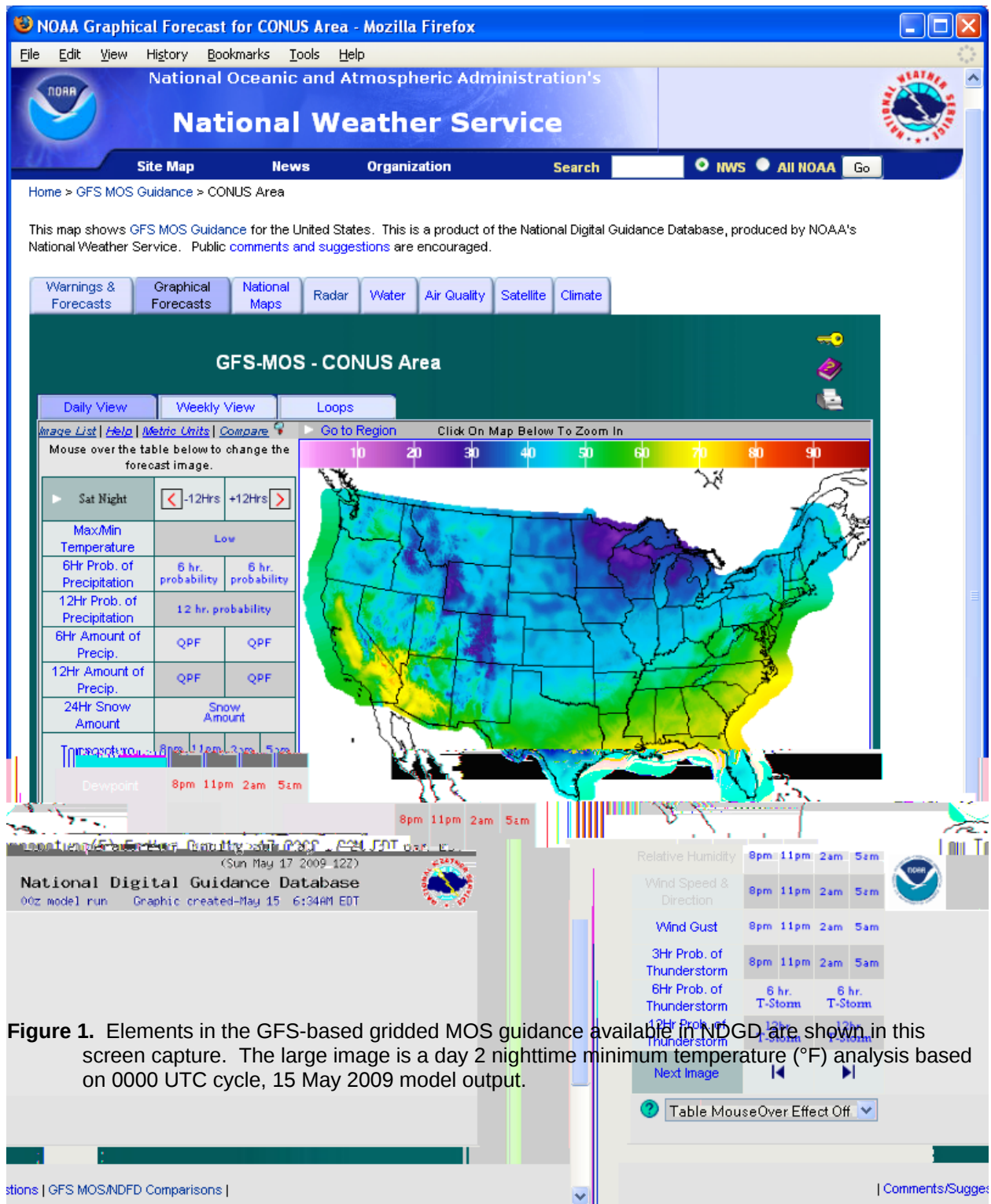


Figure 1. Elements in the GFS-based gridded MOS guidance available in NDGD are shown in this screen capture. The large image is a day 2 nighttime minimum temperature ($^{\circ}\text{F}$) analysis based on 0000 UTC cycle, 15 May 2009 model output.

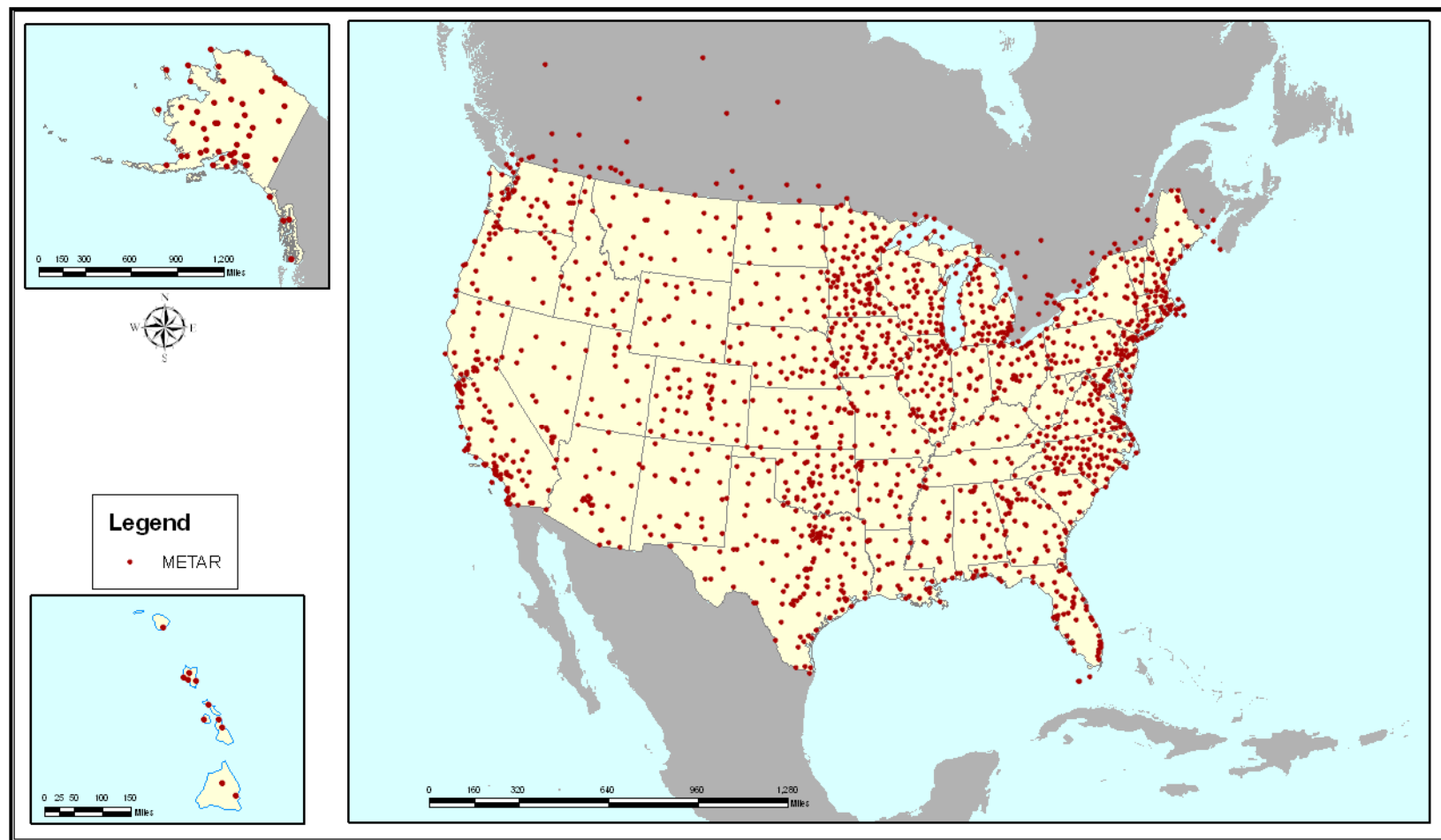


Figure 2. METAR stations available for the analysis of the GFS MOS probability of precipitation and expected precipitation amount grids.

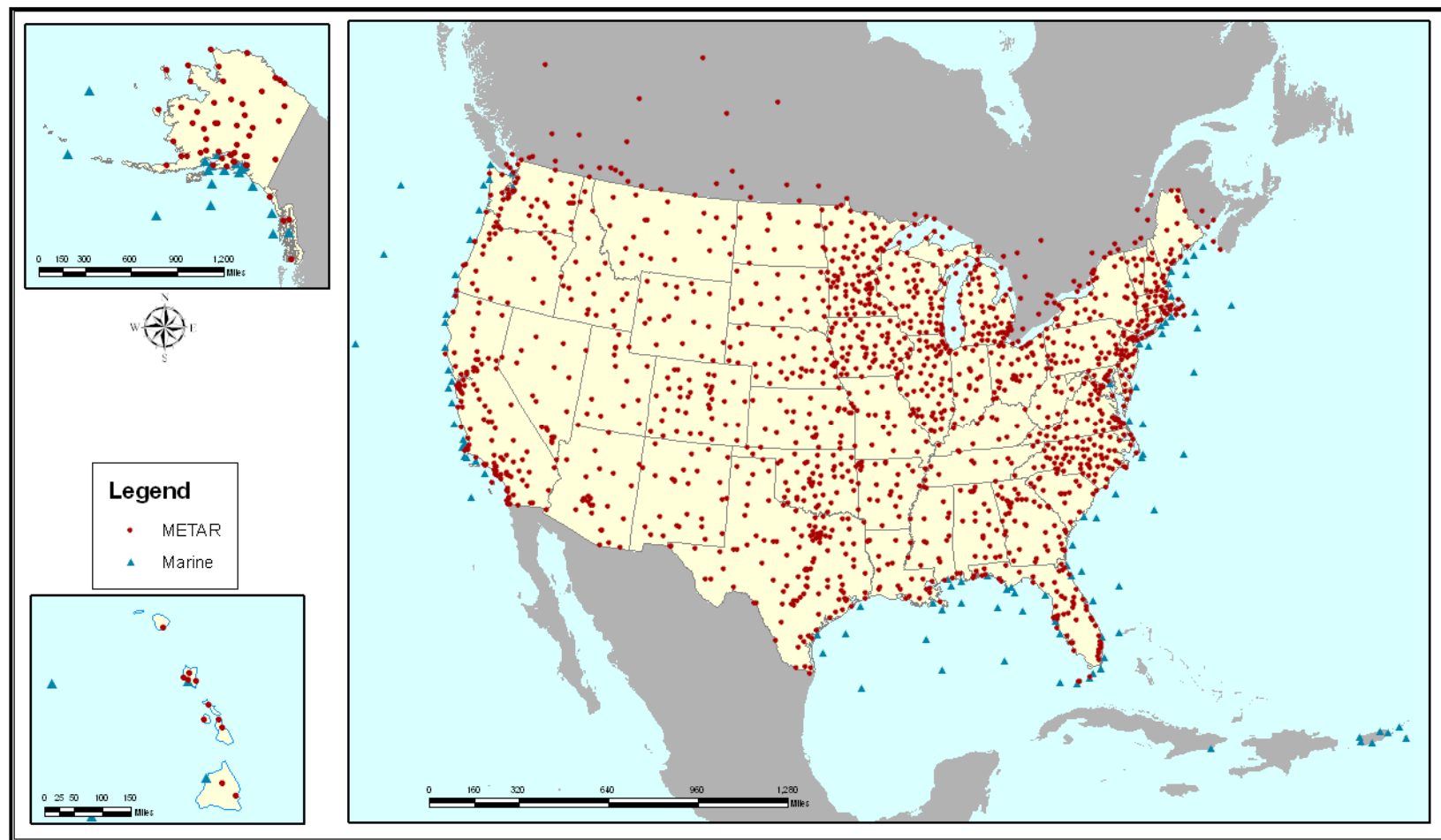


Figure 3. METAR, buoy and C-MAN sites available for the analysis of the GFS MOS sky cover and wind gust grids.

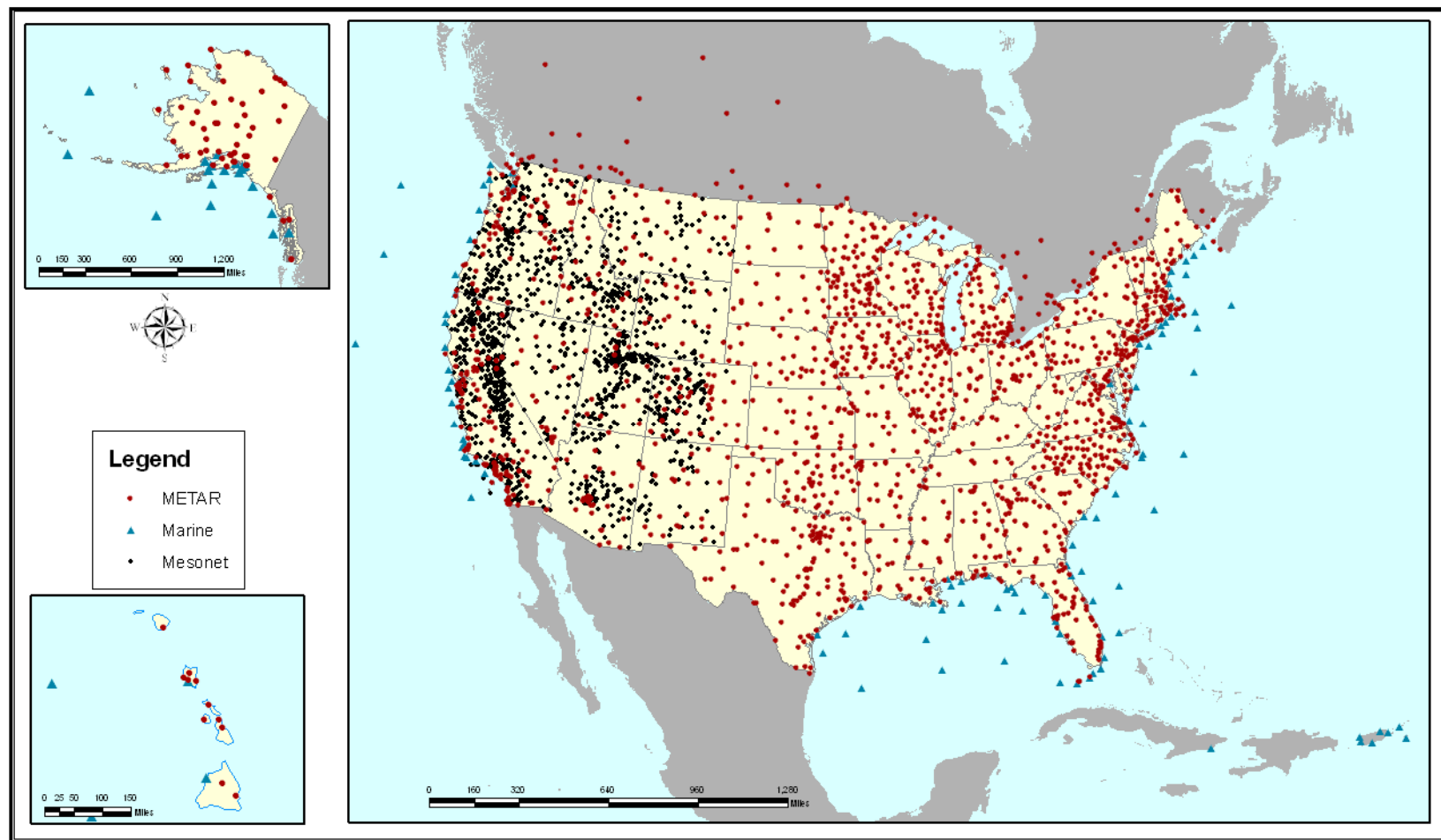


Figure 4. METAR, buoy, C-MAN, and mesonet sites available for the analysis of the GFS MOS wind direction, wind speed, 2-m temperature, 2-m dewpoint, and relative humidity grids.

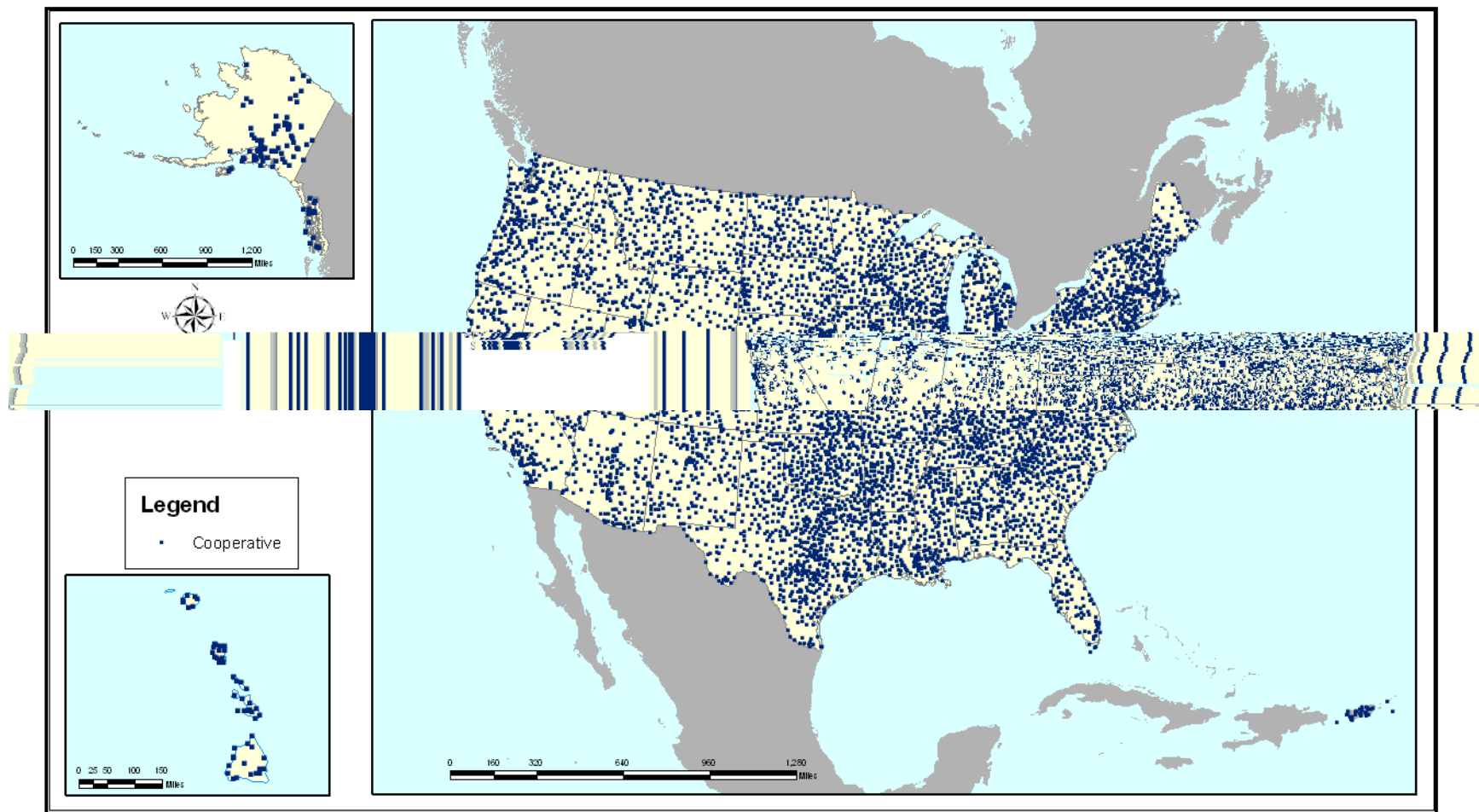


Figure 5. COOP sites available for the analysis of the GFS MOS 24-h snowfall amount grids.

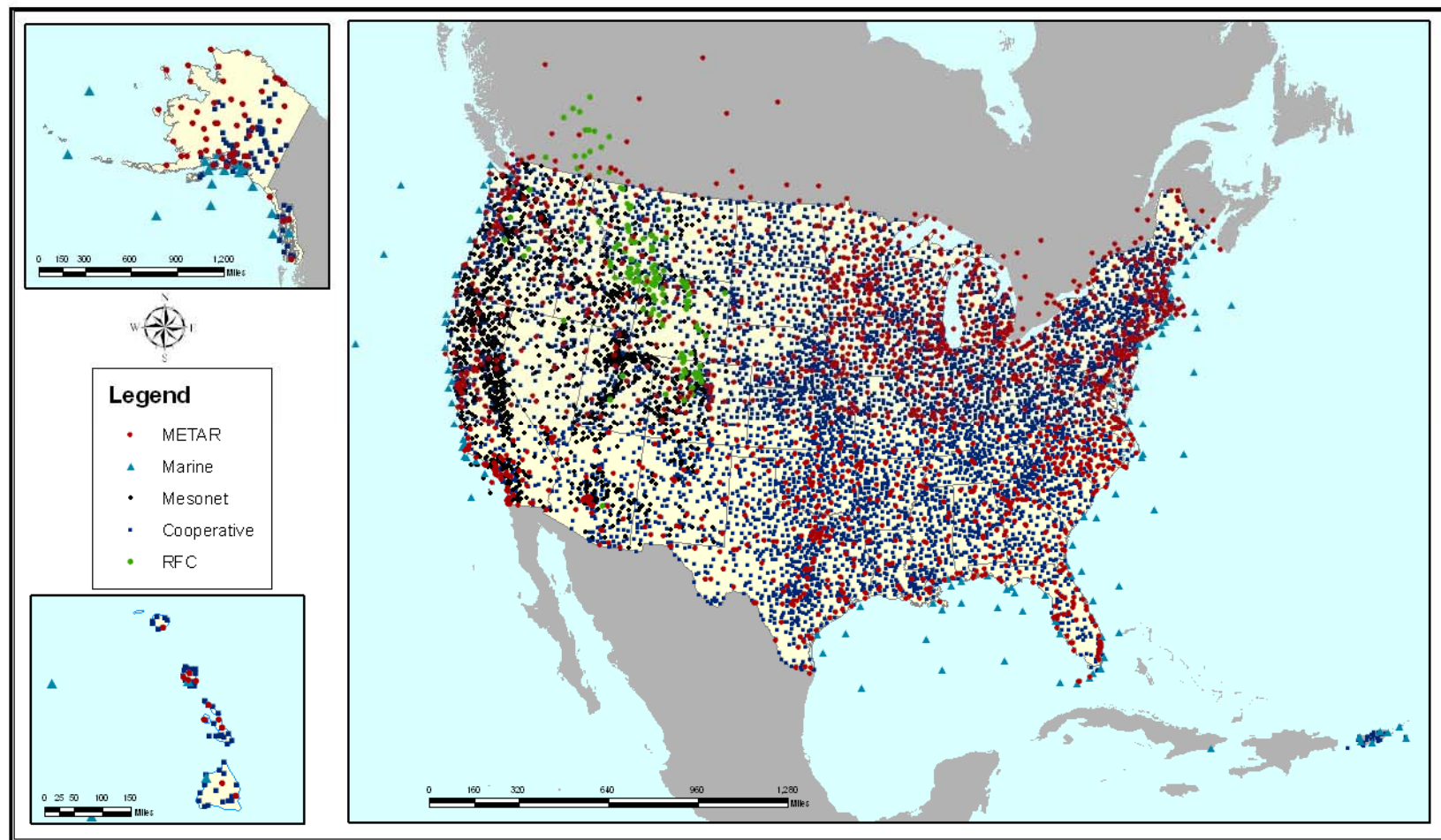


Figure 6. MOS stations from METAR, buoy, C-MAN, mesonet, and COOP networks, and a few special observing sites provided by the River Forecast Centers are available for the analysis of the daytime maximum and nighttime minimum temperature grids. There are over 10,500 total observing sites included in the GFS MOS system.

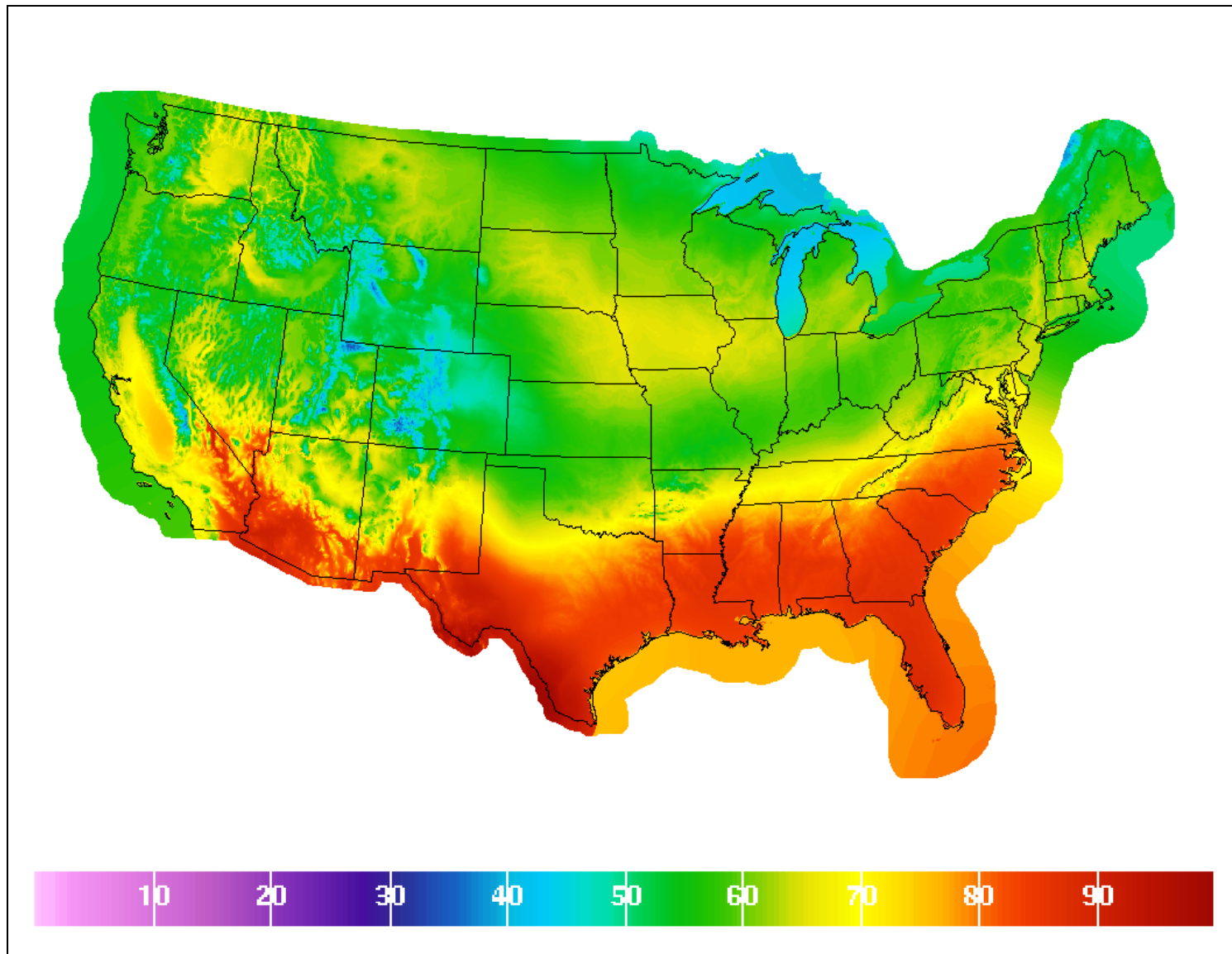


Figure 7. Radius of influence used in this day 2 analysis of maximum temperature was set to twice the normal radius currently used in the gridded MOS operational process, resulting in an overly smooth grid. This analysis is based on 1200 UTC model data from 01 May 2009.

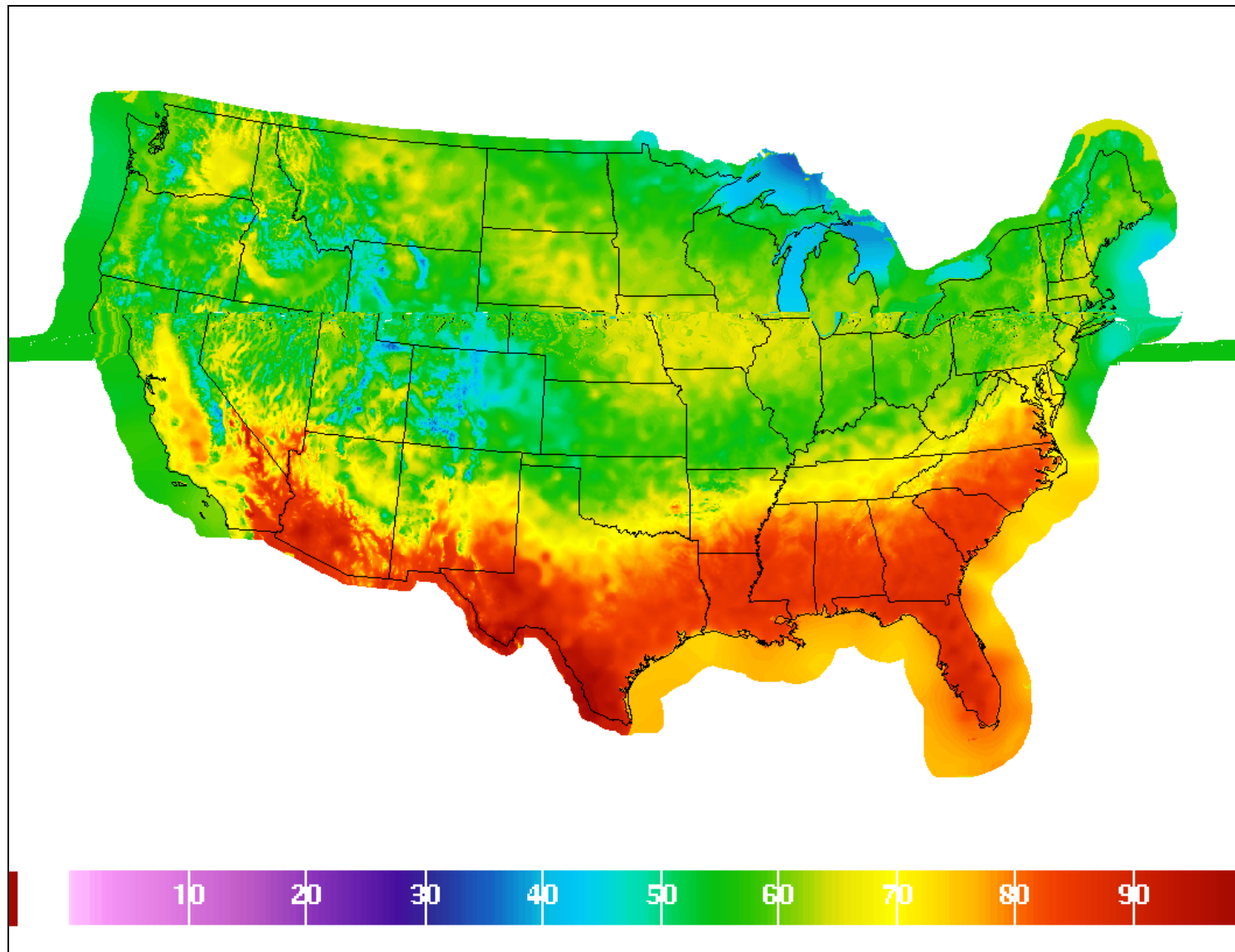


Figure 8. Same as Fig 7. except the radius of influence was set to half the normal radius of influence used in the gridded MOS operational processing, resulting in a “spotty” analysis.

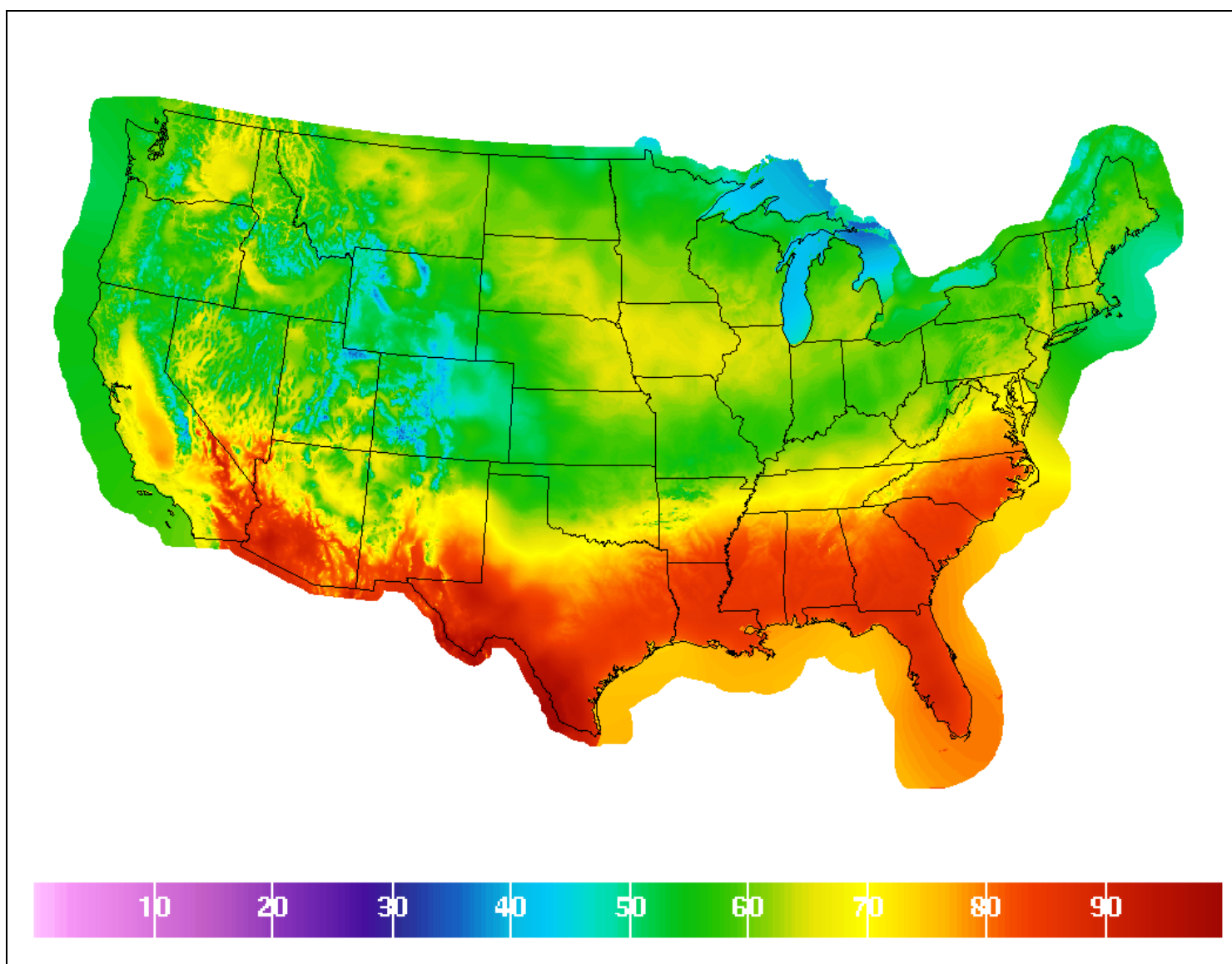


Figure 9. Same as Fig 7. except the radius of influence was set to the normal radius of influence used in the gridded MOS operational processing.

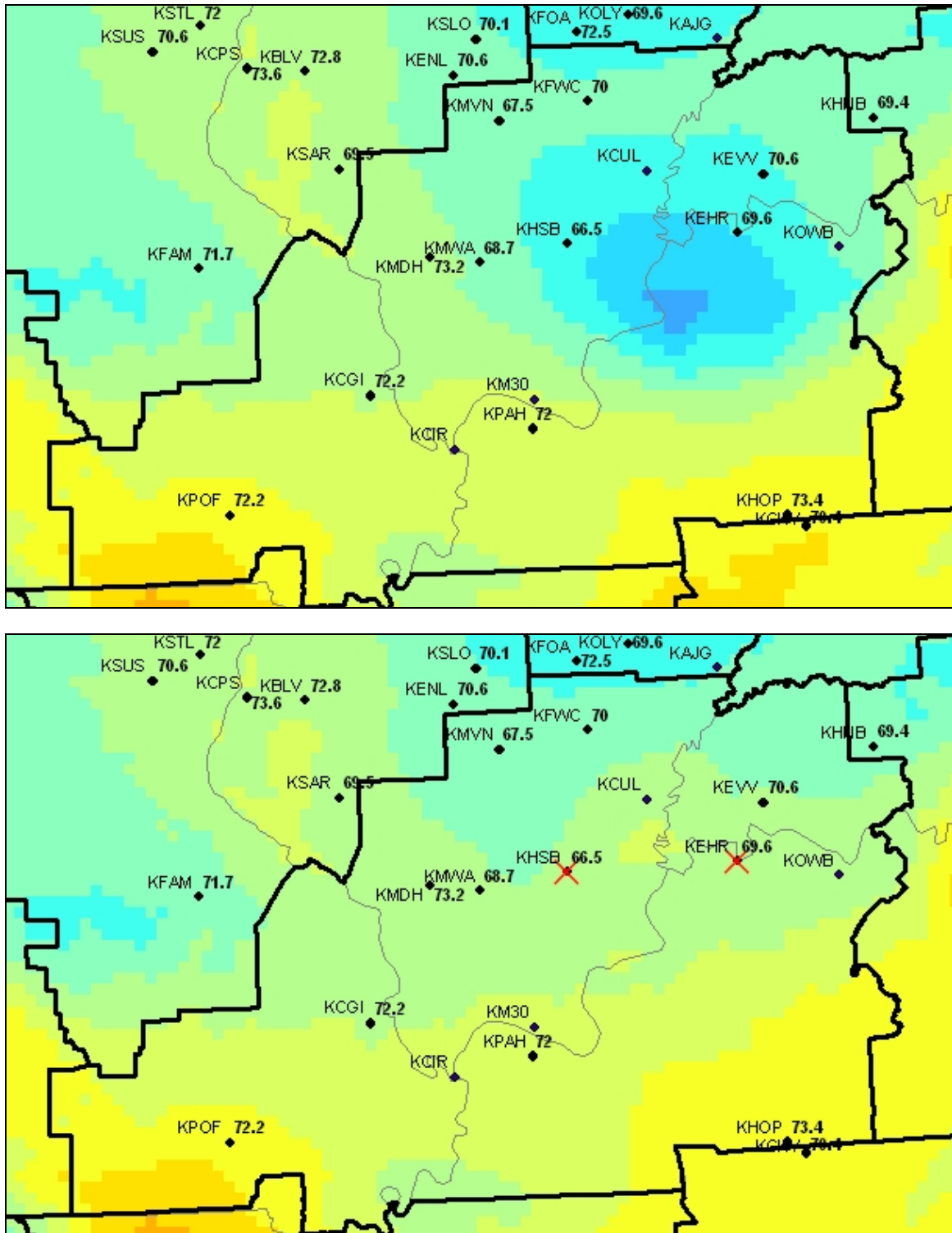


Figure 10. Example of the impact on the dewpoint analysis when unrepresentative stations are removed. The top image shows a cold bull's eye. In the bottom image the cold spot is gone after stations KHSB and KEHR were removed from the gridded MOS dewpoint processing, at the request of NWS forecasters in Paducah, KY.

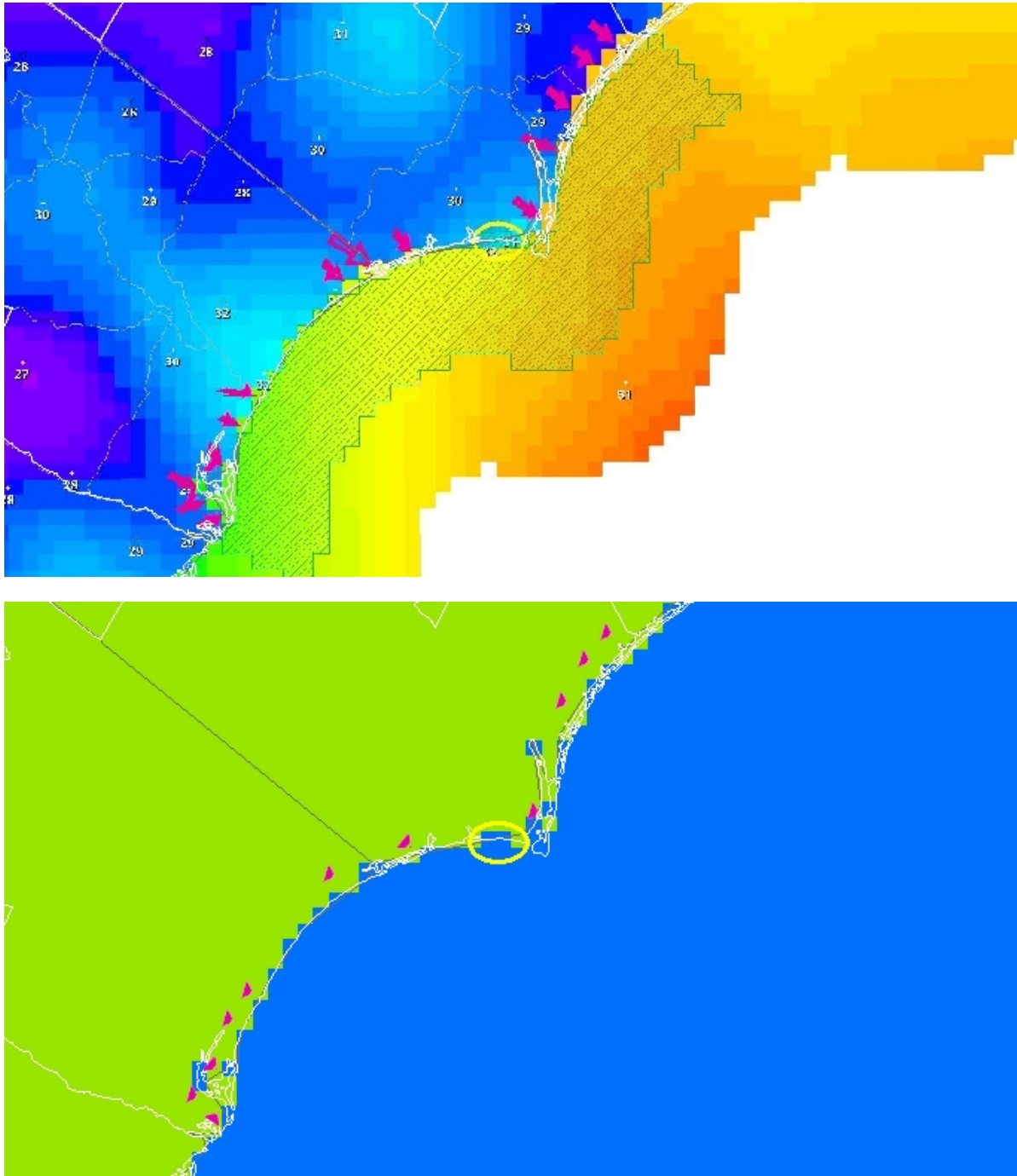


Figure 11. Example of suspect land/water designations. The red arrows in the top figure are pointing to grid points originally designated water, the yellow ellipse shows grid points originally designated as land. At the request of forecasters in Wilmington, NC, those same grid points were reclassified (shown in the bottom figure) in the gridded MOS land/water mask used in the analysis.

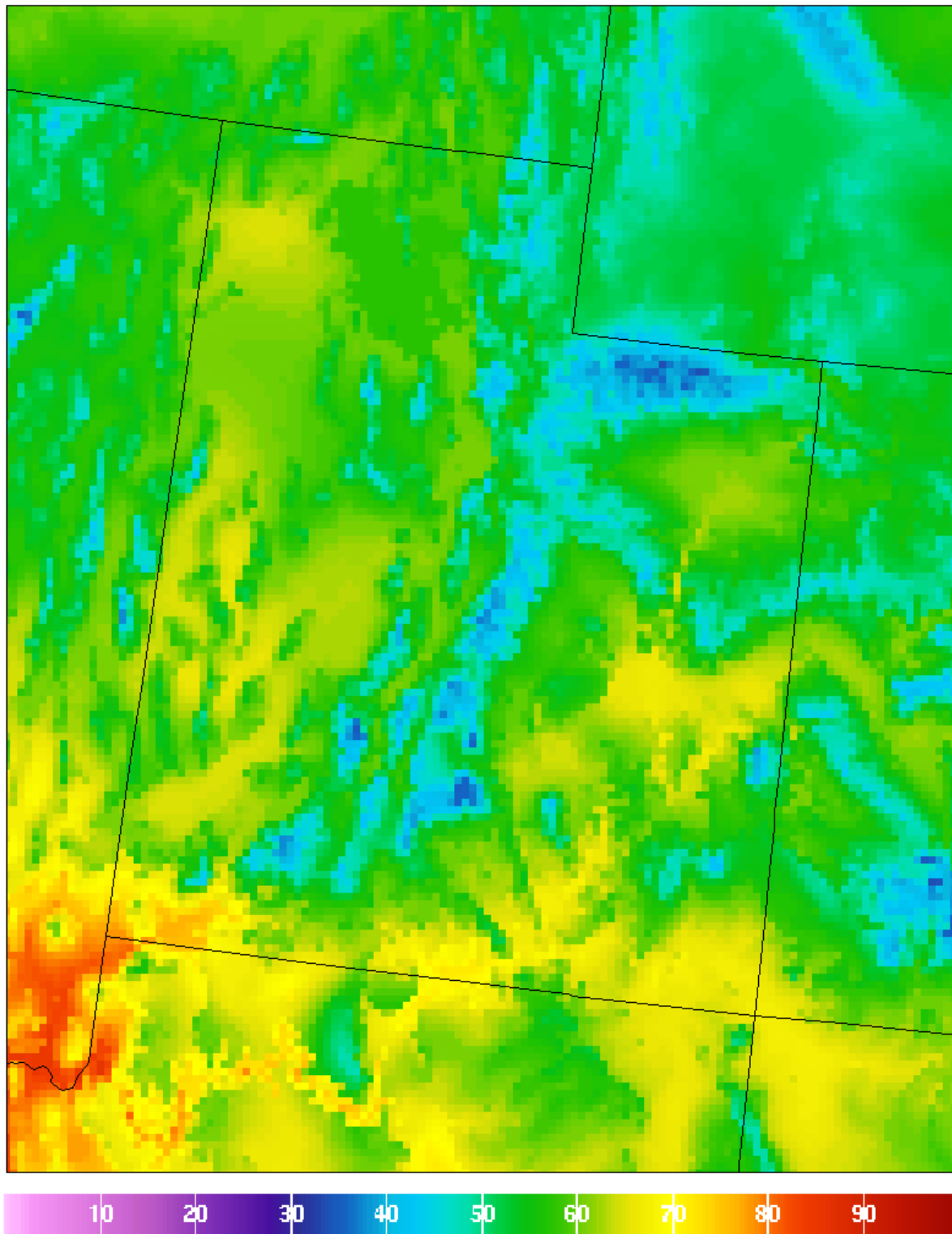


Figure 12. Gridded MOS day 2 daytime maximum temperature output to a 5-km grid based on 1200 UTC model data from 01 May 2009.

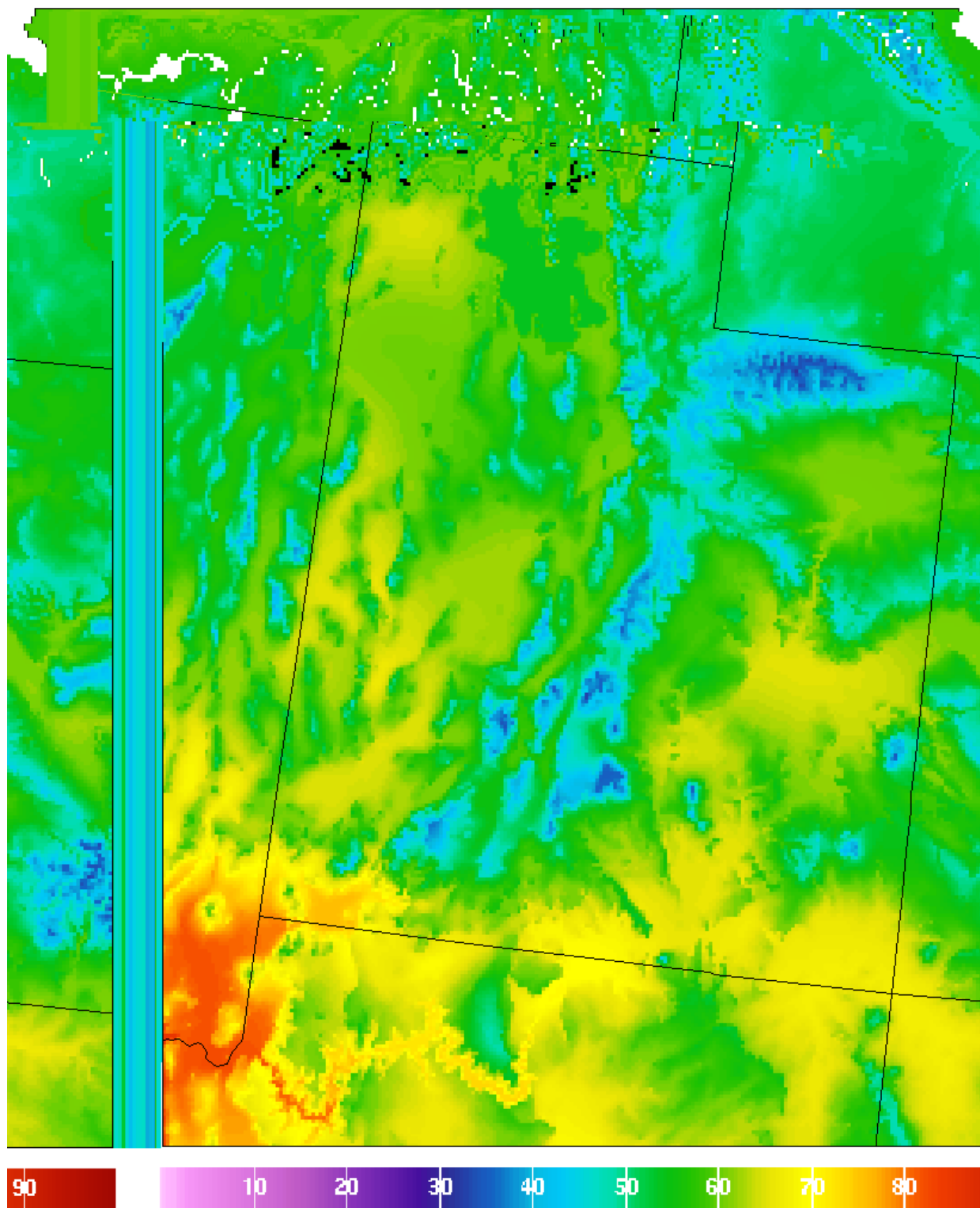


Figure 13. Analysis of the same MOS data as for Fig. 12 except output to a 2.5-km grid.