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REAL-TIME OBJECTIVE ANALYSIS OF SURFACE DATA AT THE METEOROLOGICAL DEVELOPMENT LABORATORY

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1. INTRODUCTION

As part of the Localized Aviation Model Output Statistics (MOS; Glahn and Lowry 1972) Program (LAMP; Ghirardelli 2005), the Meteorological Development Laboratory (MDL) is analyzing surface data reports on an hourly basis. The analysis scheme used by MDL for gridding MOS forecasts (Glahn et al. 2009) has been tailored to analyze surface observations. MDL is making the analyses to assess the accuracy of gridded MOS and LAMP forecasts. In addition to providing verification grids for gridded MOS and LAMP forecasts, it is our goal to add gridded LAMP nowcasts to the gridded LAMP forecast suite. These accurate high-resolution analyses will eventually help forecasters create and verify the National Digital Forecast Database (NDFD; Glahn and Ruth 2003).

Real-time and retrospective analyses at both a high spatial and temporal resolution are required to establish an Analysis of Record (AOR; Horel and Colman 2005), and to create the NDFD forecasts as well as to verify their accuracy. As a first step, a prototype Real-Time Mesoscale Analysis (RTMA; De Pondeca et al. 2007a; Benjamin et al. 2007) was produced at the National Centers for Environmental Prediction (NCEP) in collaboration with the Earth System Research Laboratory (ESRL). It represents a fast-track, proof-of-concept of the AOR program and establishes a benchmark for future AOR efforts (De Pondeca et al. 2007b). In addition to RTMA, MDL analyses can be used to judge the quality of an AOR.

High quality surface weather observations and effective quality control processes are critical to generate high-resolution objective analyses. The hourly surface observations for the analyses are obtained from NCEP in real time and are additionally quality controlled at MDL. While performing analyses of the surface observations, we found various issues such as inconsistent site information for stationary stations, redundant stations reporting data at the same locations with different station names and types, simultaneous multiple reports with different station types, stations repeatedly reporting the same values, and spatial and temporal discontinuities in the analyses.

In this paper, we describe the intensive effort needed to 1) assure the metadata are correct for each location, 2) develop efficient quality control procedures, 3) assign a representative land, ocean, or inland water flag to each station, and 4) alleviate spatial and temporal discontinuities in the analyses. This paper focuses on the analyses of temperature and dewpoint over the conterminous United States (CONUS) on the 5-km resolution NDFD grid with surface observations archived since August 2007.

2. THE BCDG ANALYSIS METHOD

In support of NDFD, MDL has produced gridded MOS forecasts since 2006 (Glahn et al. 2009). The objective analysis scheme used to produce gridded MOS is based on the successive correction technique called Bergthorssen-Cressman-Doos (BCD; Glahn et al. 1985; Cressman 1959; Bergthorssen and Doos 1955). This successive correction technique consists of making multiple passes over the data, correcting each grid point on each pass by comparing with the data in the immediate vicinity. For gridded MOS, this BCD technique was modified by implementing the following specific features:

1) separate analysis systems for land, inland water, and ocean combined into one, to accommodate the different characteristics associated with land and water,
2) computation on-the-fly of vertical change of a weather element with elevation, so that the vertical change varies with the location, time of day, day of the year, and synoptic situation,

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3) a variable radius of influence (R) for land and for water points for each specific corrective pass to account for highly varying data densities,
4) error detection which employs a buddy check when a datum is in serious question, and
5) a terrain-following smoother.

With theses major extensions, the BCD scheme was thereafter called Bergthorssen-Cressman-Doos-Glahn (BCDG; Glahn et al. 2009).

The BCDG analysis system has many options that can be used to tune the system based on data density relative to gridpoint density, variation in data density over the grid, choice of first-guess field, number of corrective passes, smoothness versus detail desired in the analysis, and error characteristics of the data. In analyzing surface observation data, BCDG's error checking capability is an essential part of the analysis of the data. The BCDG software performs this error checking on each pass based on an acceptable difference (threshold) between the station value and the value interpolated from the analysis. Based on considerable testing and meteorological judgment, we have determined the threshold values for each pass. The procedures of BCDG's error checking are summarized in Fig. 1. On each pass, the difference between a station's value (S) and the value interpolated from the 1^{st} guess or previous pass analysis (I_S) is computed before making an analysis. If the difference is less than or equal to the threshold (Th) specified for each pass, S is accepted for that pass, but if it exceeds 1.5 times the threshold, S is discarded; if it exceeds the threshold, but is less than or equal to 1.5 times the threshold, then the two closest neighbors' values to S (N_1 and N_2) are found to perform buddy checks before S is discarded. The differences of N_1 from its interpolated value (I_{N1}) and N_2 from its interpolated value (I_{N2}) are computed. If either one of the two neighbors' differences is greater than 0.6 times the threshold, and the differences of both S and its neighbor are of the same sign, then S is accepted. If not accepted, one more check is performed. If either one of the two neighbors' differences is less than or equal to 0.6 times the threshold and the difference between S and the neighbor's value *adjusted for terrain* (A_{N1} or A_{N2} accordingly) is within 0.6 times the threshold, S is accepted. Otherwise, S is not used on this pass.

More detailed information on the BCDG technique such as the gridpoint correction algorithm, determination of vertical change with elevation, and accommodation for land and water can be found in Glahn et al. (2009). Based on extensive experimentation performed at MDL, we adopted the BCDG options used in gridded MOS, which incorporate a first-guess grid composed of the average value of the element, a four-pass setup to capture the desired detail in the analysis, limitation of unusual lapse rates when the computed vertical change is of the opposite sign than expected, and a terrain-following smoother.

3. DATA COLLECTION AND INITIAL QUALITY CONTROL

Hourly surface observations are obtained from NCEP in real time and are additionally quality controlled at MDL. The first set of quality control checks at MDL ensures that all temperature and dewpoint observations are in an acceptable range for the station's geographical area, and the temperatures are greater than or equal to the dewpoints (Glahn and Dallavalle 2000; Allen 2001). In preparing input observation data to be used in the hourly analyses, we collect data observed between 15 minutes prior and subsequent to the analysis hour. If more than one observation is reported for a station, we select the report closest to 10 minutes prior to the analysis hour. The analysis system for temperature and dewpoint assimilates six types of observations obtained from METAR (roughly translated as Aviation Routine Weather Report; OFCM 1995), mesonet, synoptic, moored buoy, Coastal-Automated Marine Network (C-MAN), and tide gauge stations.

3.1 *METAR*

METAR reports typically come from airports or permanent weather observation stations. Observations are taken by automated devices or trained personnel. Some stations have automated observations augmented by human observers. METAR reports are of high quality, and we have found that they are more reliable than all other observational data sets.

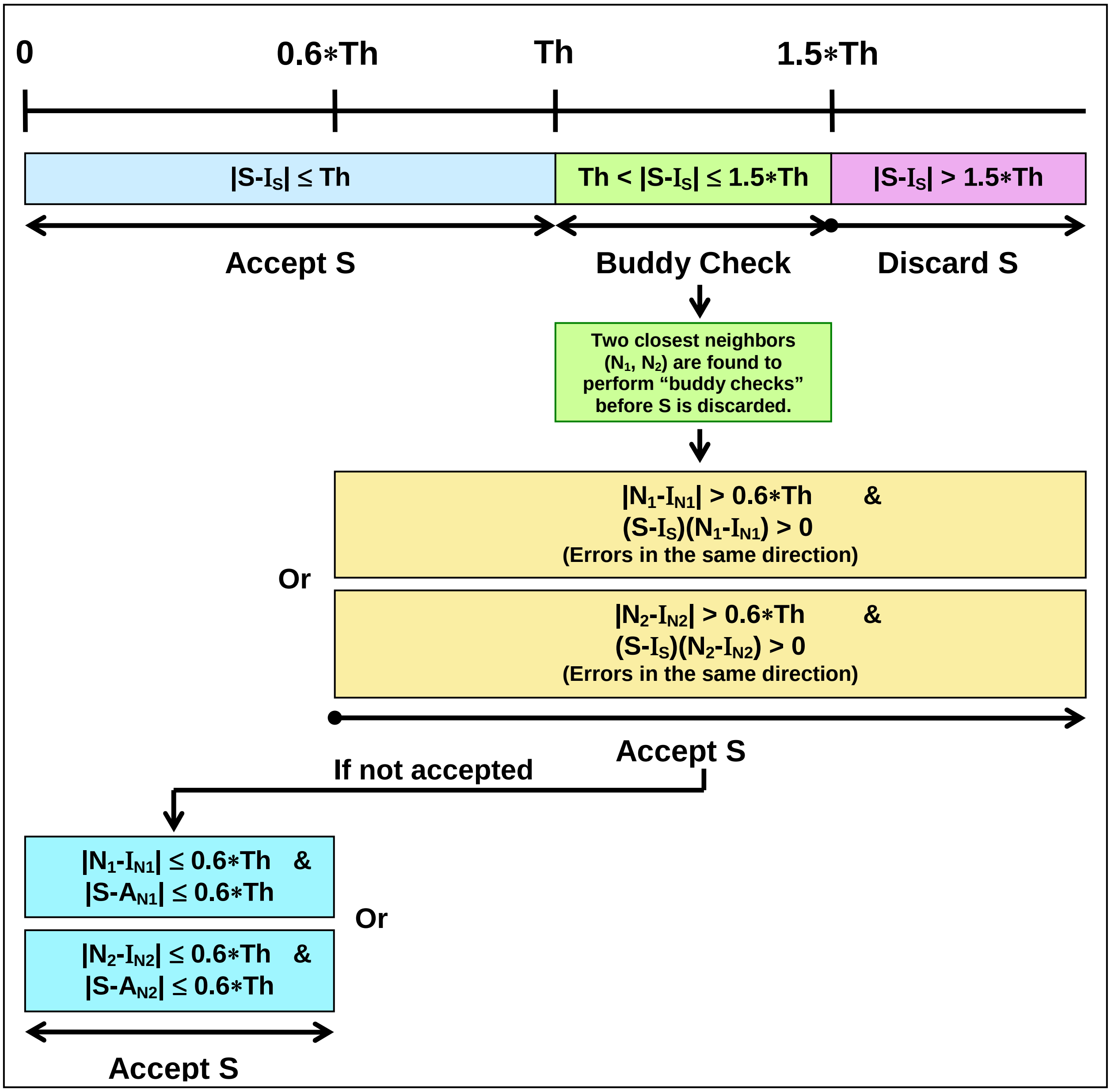

FIG. 1. BCDG's error checking procedures.

3.2 *Mesonet*

Mesonet observations are obtained from local, state, and federal agencies and private mesonet sites. These sites are quite dense compared to METAR sites. In fact, over 80% of the stations used in the BCDG analysis consist of mesonet type stations.

3.3 *Synoptic*

Synoptic data are comprised of manual and automatic observations, and are available every 3 or 6 hours. In many cases, these data are redundant to the METAR data at the same location (this issue will be discussed in section 4.2).

3.4 *Buoy, C-MAN, and tide gauge*

We use observations obtained from moored buoy, C-MAN, and tide gauge stations. These stations provide high quality observations over water for the oceans, the Gulf of Mexico, and major lakes (i.e., the Great Lakes, the Great Salt Lake, and Lake Okeechobee in this study).

MDL maintains a static station dictionary which contains station information such as station identifier, station type, latitude, longitude, elevation, land/water flag, and quality flag. The total number of stations that can report weather elements of interest is on the order of 20,000 over the CONUS; however, on any given hour, only about half that number of stations report. Because site information changes from time to time (Allen 2001), upkeep of the station dictionary is required.

4. UPGRADED FEATURES

While performing analyses of surface data, we considered various issues such as inconsistently reported latitude/longitude/elevation for a stationary station (a station whose location is fixed, unlike a drifting buoy or ship), redundant stations reporting data at the same locations with different station names and types, questionable land/water assignments on the coastlines, simultaneous multiple reports with different station types, stations which keep reporting the same values, and spatial and temporal discontinuities in the analyses. The following sub-sections describe the methods used to resolve these issues.

4.1 Questionable latitude/longitude/elevation reports for stationary stations

While making the static station dictionary based on the information available from the observation reports, we found that 98.4% of stationary stations had reported only at the same fixed locations. However, 1.6% of these so-called stationary stations had reported at different latitude, longitude, and/or elevations. 97.5% of these stations turned out to be mesonet type stations. Because of this unexpected behavior, we determined the metadata for these stations were questionable. Sometimes these station location discrepancies were very large, and as such, we had to establish specific criteria to handle these questionable reports. We determined acceptable limits for latitude, longitude, and elevation as 0.01°, 0.01°, and 280 ft, respectively. The elevation threshold of 280 ft was determined after we made an assumption that 1°F is an allowable error range in a temperature analysis (1°F corresponds to a change in elevation of 280 ft in the standard atmosphere of 3.65×10^{-3} °F ft^{-1}). One exception to the thresholds for latitude and longitude was made for moored buoys. Since moored buoys provide valuable observations over the ocean and lake regions, but the density of observation sites is low, we did not want to unduly diminish the number of these sites. Consequently, the threshold for the latitude/longitude discrepancy for moored buoys was relaxed to 1°. When making the station dictionary and applying theses rules, 38.5% of the questionable stations were removed from the dictionary. The remaining (i.e., 61.5%) questionable stations were retained in the dictionary and were thoroughly investigated to determine the true latitude, longitude, and elevation values. While searching for the true values of latitude, longitude, and elevation, the selection priority was given to 1) matching with online sources of geographic information, 2) the most frequently reported values, and 3) the most recently reported values. Finally, with the site information available from the completed station dictionary, initial screening of the real-time data was performed before starting the analysis. The screening procedure was executed in such a way that if the reporting location of the real-time observation deviated from the position in the station dictionary by greater than the threshold specified for that station type, the observation was not used in the analysis.

4.2 Redundant stations reporting data at the same locations with different station names and types

Exploring the horizontal distributions of each type of station revealed that there were redundant stations that were reporting data at exactly the same locations, but with different station names and types. As an example, stations KEYW (METAR type station) and 72201 (synoptic type station) were reporting observations at the same latitude, longitude, and elevation (24.55°N, 81.75°W, 3.3 ft). These observations were from the same reporting station, but with different station names, which resulted in double weighting at that point in the analysis. Therefore, one of the redundant stations had to be removed. We decided to remove redundant synoptic stations because synoptic stations provide less frequent observations than METAR stations. As a consequence, 45.1% of the synoptic stations were removed from the dictionary and were not used in the analysis.

Figure 2 shows the horizontal distribution of the total observing stations for temperature and dewpoint used in the station dictionary. Stations are heterogeneously distributed with highly variable station density over the CONUS, and are made up of mesonet (82.5%), METAR (13.0%), synoptic (2.4%), C-MAN (0.8%), moored buoy (0.7%), and tide gauge (0.6%) stations.

4.3 Stations reporting unchanging values

Each individual station in the station dictionary has its own quality flag for each element. To determine the quality flag, we used the reject station lists provided by Global Systems Division (GSD) of ESRL and National Weather Service (NWS) Weather Forecast Offices (WFO) as part of the Advanced Weather Interactive Processing System (AWIPS) configuration. In addition to these master reject lists, we made a second reject list. This list included stations that continued to report unchanging observation values (e.g., zero values for temperature and missing for dewpoint simultaneously) for a considerably long period of time (on the order of months).

4.4 Questionable land/water assignments near the coastlines

The BCDG scheme restricts the influence of stations to grid points of the same type so that land station points influence only land grid points, ocean water station points influence only ocean water grid points, and inland water station points influence only inland water grid points. Following the processes described in Sheets (2008), each grid point was designated as land, ocean, or inland water, with high resolution Geographic Information System (GIS) capabilities and the high resolution coastal and lake shape files available in AWIPS and by additional strategic hand edits. Because the BCDG analysis differentiates between land and water, it is essential that each reporting location be tagged as either land, ocean, or inland water. This was primarily accomplished by extracting land/water values from the land/water grids at the station points.

However, for some stations near the coastlines, additional modifications were required. An example of this procedure near the coastline is shown in Fig. 3. If we consider only the land/water grid points, black circled stations seem to be water stations; however, if we consider the coastline

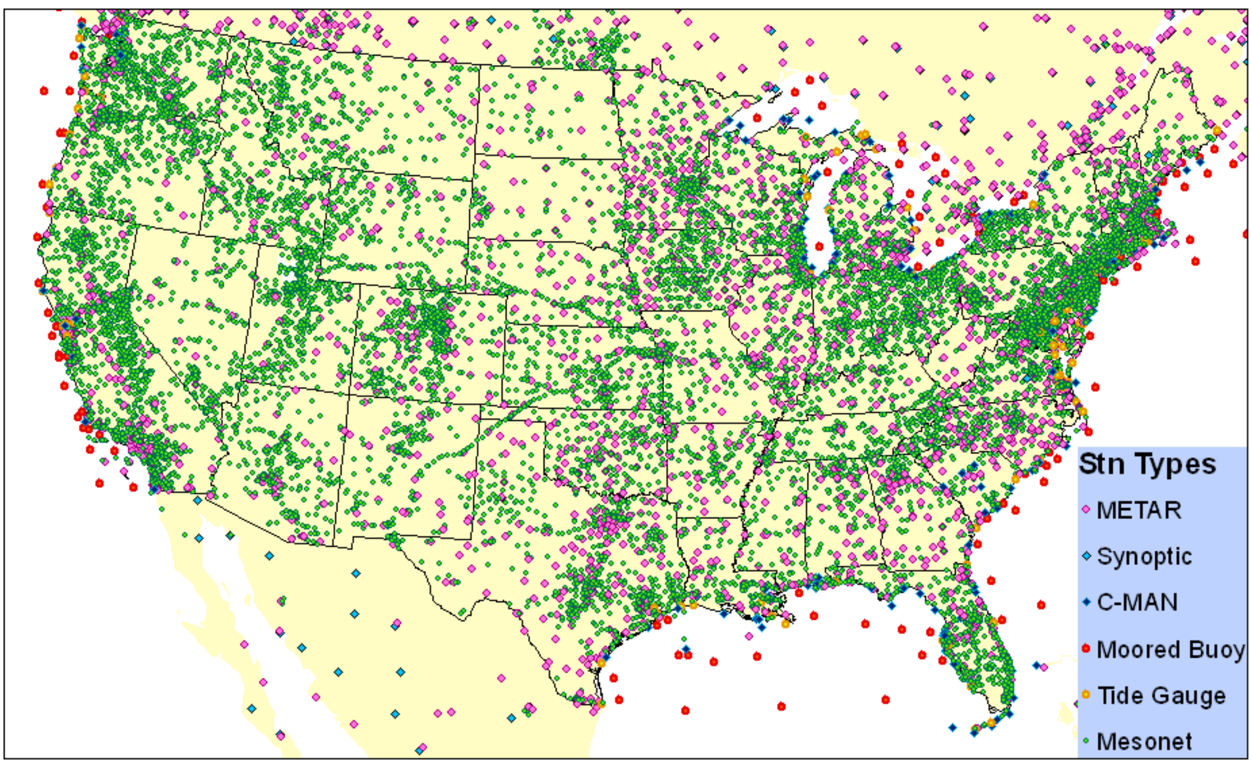

FIG. 2. Horizontal distribution of surface observing stations for temperature and dewpoint.

map overlaid on the land/water grid points and stations, these same stations seem to be land stations. This indicates the land/water assignments for these black circled stations were questionable, and so these stations were removed. In addition, if these land/water designations turned out to be questionable in the analysis as indicated by persistent bull's eye futures or spatial/temporal discontinuities, then the land/water values of the stations were changed to more representative values or the quality flags of the stations were modified to remove the stations.

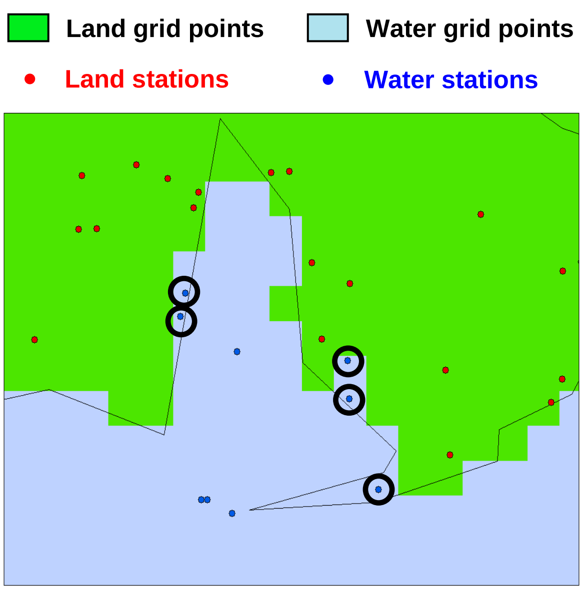

FIG. 3. An example of land/water designation and suspicious stations marked with black circles. The thin black line is the coastline from AWIPS shape file.

4.5 Simultaneous multiple reports from one station with different station types

Inspection of real-time observation data revealed that some stations reported observations with different station types at the same reporting time. Despite having different station types, observations reported from the same station as well as at the same time should be identical. However, sometimes the differences between the observations were too large to be acceptable (see Table 1 for examples). Hence, another quality-check process was implemented. If the difference between the observation values from the same station at the same time was greater than 1°F, all the observations involved were removed. Otherwise, one of the observations was arbitrarily accepted. Among the resultant pairs rejected, 93.6%, 6.2%, and 0.2% were mesonet–C-MAN, mesonet–tide gauge, and mesonet–METAR, respectively.

Table 1. Temperature and dewpoint examples for simultaneous multiple reports with different station types for which the values are not identical.

Temperature Examples				
Station ID	Station type	Day month year	Hour:Min (UTC)	T (°F)
ACXS1	Mesonet	22 Mar 2009	12:45	48
ACXS1	C-MAN	22 Mar 2009	12:45	45
SJOM4	Mesonet	22 May 2009	03:50	76
SJOM4	C-MAN	22 May 2009	03:50	62
NBLP1	Mesonet	15 May 2009	22:48	32
NBLP1	Tide Gauge	15 May 2009	22:48	73
KVDW	Mesonet	09 Jan 2009	20:52	21
KVDW	METAR	09 Jan 2009	20:52	32

Dewpoint Examples				
Station ID	Station type	Day month year	Hour:Min (UTC)	Td (°F)
ELXC1	C-MAN	05 Dec 2008	22:45	39
ELXC1	Mesonet	05 Dec 2008	22:45	37
ACXS1	C-MAN	06 Mar 2009	12:45	46
ACXS1	Mesonet	06 Mar 2009	12:45	50
NAXR1	C-MAN	18 Apr 2009	05:45	28
NAXR1	Mesonet	18 Apr 2009	05:45	26

4.6 Station-specific R: variable R for land and override R for ocean/lakes

To handle highly variable data densities over the analysis domain (Fig. 2), a specific radius of influence (R) was computed for every station. This station-specific R was also computed to optimize the desired detail or smoothness in the analysis.

For every station, the first pass R (the largest R) was determined such that every grid point would have a correction made for it; the last pass R (the smallest R) must be such that the analysis shows the details that a skilled meteorologist would accept as real. The procedures to obtain the optimum R satisfying the above requirements are as follows: for every grid point, up to 50 stations nearest it within a radius of 115 grid lengths are found along with the distances of the stations to the grid point, and then among all the distances saved with the stations, the largest distance for every station is selected. This largest distance for the station becomes the first pass R for that station. The subsequent values of R on the 2^{nd}, 3^{rd}, and 4^{th} passes are determined by the products of the first pass R and 0.74, 0.54, and 0.41, respectively.

The maximum number of stations (50) and the grid length (115 grid lengths) used in deriving R were determined by considerable experimentation performed for all available land stations. This method works efficiently for higher density of land stations. For water stations, other methods were used to accommodate very sparse observations and frequent problems of missing observations. To ensure each water grid point has more than one water station within R on at least the first pass, an override R option for ocean and inland water stations was introduced. In general, a small R was assigned to the stations near coastlines, lake shorelines, the Puget Sound, and the Chesapeake Bay, and a larger R was assigned to the stations in very sparse data regions.

4.7 Throwout criteria for inland water

A critical part of the objective analysis technique is to quality control erroneous data in the analysis. As illustrated in Fig. 1, the BCDG scheme has an elaborate data checking mechanism which requires the datum to be within tolerance when compared to the existing pass of the analysis. If the tolerance is not met, before tossing the datum, a buddy check is performed to see if at least one of the datum's two buddies agrees with it. The data throwout (or acceptance) threshold criteria had been determined depending on analysis pass and month of the year, but not on the station land/water type (i.e., land, ocean, and inland water).

In analyzing observations, the observational data reports over the Great Lakes, in particular, were found to be highly variable in space and time. In summer, buoy reports are available over the lakes; in winter they are not available, and consequently, the stations around the edges of the lakes are used extensively. When observations are present from both the edge stations and buoys, and big differences between these observations are detected, the buoys over deep water are tossed. An example is provided in the left panel of Fig. 4. The stations marked with red circles were tossed, which resulted in a poor analysis that only represented edge station characteristics.

In order to accommodate the larger variability in observations over inland water, the threshold criteria were increased by a factor of 1.5 for inland water. The altered criteria prevented undesired tossing of data that were representative over deep water, and produced a more representative analysis (right panel of Fig. 4).

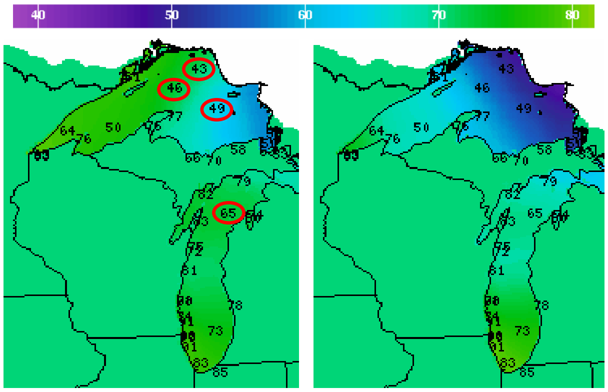

FIG. 4. Analyses of temperature (°F) with tossed data marked with red circles (left), and using all the data (right) over inland waters of Lake Superior and Lake Michigan at 0000 UTC 25 June 2009.

4.8 Augmentation of missing stations at the analysis hour using previous hour observations

As emphasized in Horel and Colman (2005), a real-time analysis should be available within roughly 30 minutes of the valid time to satisfy the ongoing needs of the various communities. However, not all of the available surface observation data (observed within $\pm$15 minutes of the analysis hour) are delivered by 30 minutes past the hour. To address the issue of observations missing at the analysis time, a new feature was added to the BCDG scheme. This is the capability to use an observation from the previous hour if the site did not report an observation at the analysis time. An adjustment was made to the previous hour's observation in order to account for a possible temporal change from the previous to the analysis hour. The temporal change was computed by using surrounding stations which had both previous and analysis hour values. The average of the differences between the previous and the analysis hour values at the surrounding stations was added to the previous hour's observation to approximate the analysis hour's observation at the station whose real observation was missing. These adjusted observations were then used to augment the analysis hour observations which were available at the analysis time.

Figure 5 shows examples of temperature analyses for the western CONUS. The left panel shows the analysis which assimilated only analysis hour data delivered by the analysis time (in which 10,537 reports were available for the whole CONUS domain). If we had waited for one more hour to collect more data, we would have produced the analysis shown in the middle panel (12,155 reports available by this time). This is more representative and closer to the truth. The areas that indicate the most distinguishable differences between these analyses are marked with red circles. The right panel shows the analysis in which the augmentation method was utilized to handle observations that were missing at the analysis time. The analysis assimilating both the adjusted previous hour and the analysis hour observations delivered by analysis time (total 12,464 reports) shows similar features as the analysis shown in the middle panel. As seen in the right panel of Fig. 5, the augmenting capability implemented in the BCDG scheme improves the analysis by capturing more detailed features in the mountainous regions and depicting more representative temperatures over the Great Salt Lake.

5. ANALYSIS MAPS AND CURRENT STATUS

On the basis of the upgraded features and techniques described in the preceding section, real-time hourly objective analyses of temperature and dewpoint are being produced for the CONUS on the 5-km NDFD grid. In addition, a post-processing step is necessary to ensure inter-element consistency. Specifically, the temperature must be greater than or equal to the dewpoint. Even though the temperature and dewpoint observations are consistent at each observation point, this does not guarantee the temperature and dewpoint are consistent at each grid point. This can be caused by either the temperature or the dewpoint being missing at a site (there are fewer dewpoint observations than temperature observations), the computed vertical change being generally different for temperature and dewpoint, or the analysis process not being perfect. BCDG checks each grid point and in instances where the dewpoint exceeds the temperature, the dewpoint is set to the temperature.

Figure 6 displays examples of the analyses made for 0000 UTC 21 August 2009. As seen in Fig. 6, both the analyses of temperature and dewpoint are capturing well-defined terrain, major lakes, and coastal and ocean areas as well as synoptic and mesoscale features.

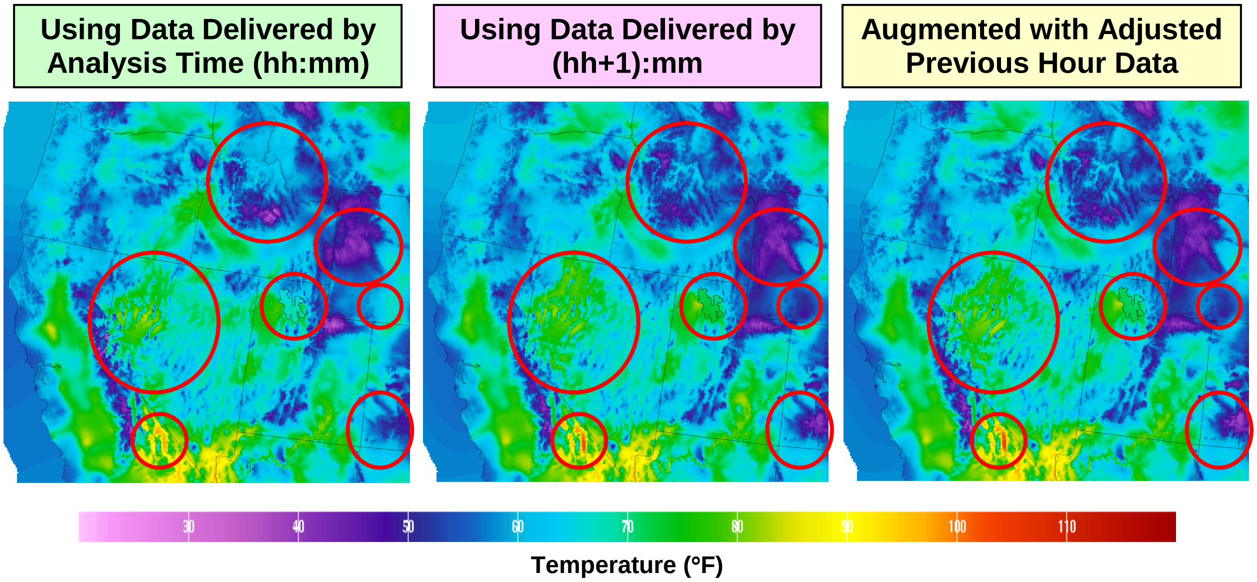

FIG. 5. Analyses of temperature for 0700 UTC 12 August 2009 over the western CONUS, with analysis hour data delivered by 0726 UTC (left), with analysis hour data delivered by 0826 UTC (middle), and with the analysis hour data and the adjusted previous hour data delivered by 0726 UTC (right).

Real-time hourly objective analyses of temperature and dewpoint are now being produced and evaluated internally at MDL. In conjunction with the element analyses, the errors involved in these analyses are being estimated by Glahn and Im (2010) and are likewise being assessed internally at MDL.

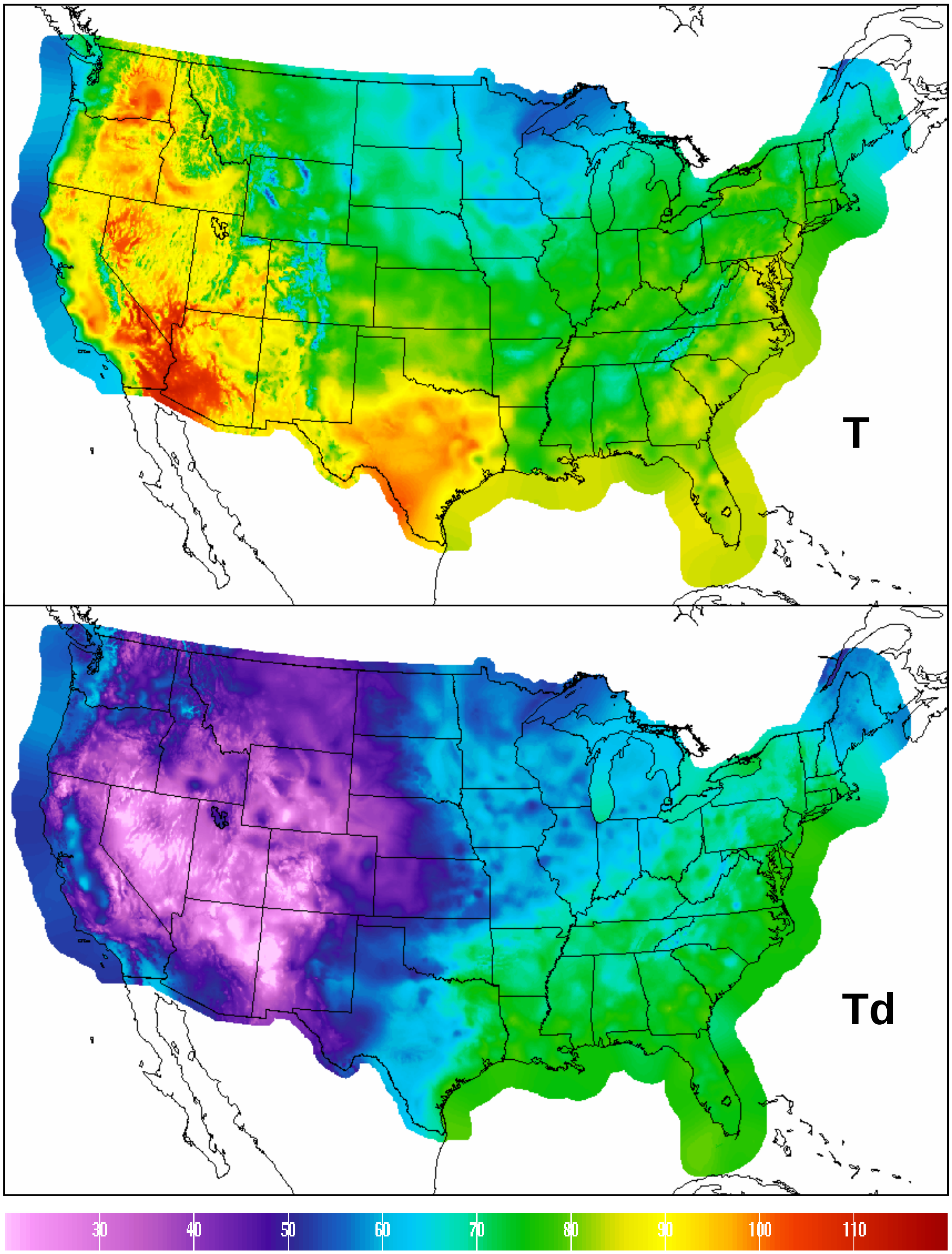

FIG. 6. Analyses of temperature (top) and dewpoint (bottom) (°F) produced for 0000 UTC 21 August 2009.

6. SUMMARY AND FUTURE ENHANCEMENTS

The BCDG analysis method developed to analyze point data in rough terrain and in regions with high data variability is being used by MDL to produce real-time analyses of hourly surface observations. A critical part of the analysis of the surface data is the error checking procedure which ensures that obviously incorrect data are not assimilated into the analysis. This paper describes intensive quality control procedures developed for pre-analysis (e.g., in making the station dictionary and preparing observation data), during-analysis (buddy checks), and post-analysis (the inter-element consistency check) steps.

While making the station dictionary and preparing observation data, issues of questionable site information, redundant stations reporting data at the same locations with different station names and types, stations repeatedly reporting the same values, suspicious land/water assignments near the coastlines, and simultaneous multiple reports with different station types were identified and resolved. At the analysis step, the BCDG program performs efficient quality control procedures such as buddy checks to decide whether to accept or throw out a suspicious datum.

In addition, to address spatial and temporal discontinuities of the analyses that are caused by observation data unevenly distributed over the analysis domain and not delivered (transmitted) on time and unpredictable data availability (missing problem), new features were added to the analysis package. One of the features is the capability to use an observation from the previous hour if the station did not report at the analysis hour. Adjustments are made to the previous hour's observations in order to account for possible diurnal changes from the previous to the analysis hour. These adjusted previous hour observations are then used to augment the analysis hour observations. To handle the heterogeneous distribution of the observations, a station-specific R computed for each individual station was implemented; this benefits the analysis especially in very sparse data regions and deep waters.

The purpose of the BCDG analysis is to provide verification grids for gridded MOS and LAMP forecasts, and to add gridded LAMP nowcasts to the LAMP forecast suite. The analyses will be put into the National Digital Guidance Database (NDGD) to be used by forecasters and for verifying the NDFD forecasts. This paper focuses on the analyses of temperature and dewpoint over the CONUS on the 5-km NDFD grid, and real-time hourly objective analyses are currently being produced and evaluated internally at MDL. In the near future experimental analyses, and later operational analyses, will be available online (http://www.nws.noaa.gov/mdl/gfslamp/gfslamp.shtml). While only a few variables are currently being analyzed at MDL, the analysis product suite will be extended to include other weather elements on the 2.5-km NDFD grid. The analysis area will also be extended to include Alaska and Hawaii.

Future work for technical improvements involves developing a dynamic station dictionary to include observations available from drifting buoys and ships as well as newly (recently) added stations, and a methodology to accommodate wind directions when assigning stations as land, ocean, or inland water, near the coastlines and lake shorelines.

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