RESEARCH SERIES

# NORTHEAST REGIONAL CLIMATE CENTER

## A Method to Produce Serially Complete Daily Maximum and Minimum Temperature Data for the Northeast

Arthur T. DeGaetano
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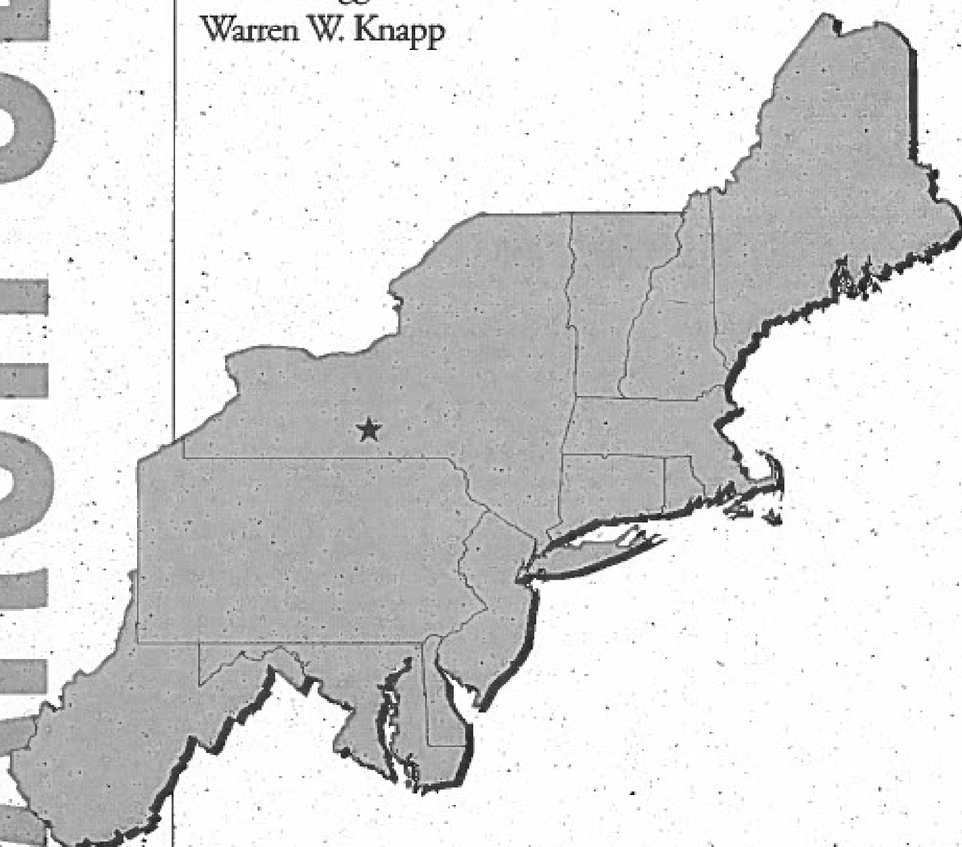

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# INTRODUCTION

Serially complete daily climatic data sets are required for many modeling and statistical applications. Efforts to identify and estimate missing data values on the national or regional scale in the United States, however, have been limited. One notable exception is the serially complete data set that was developed by the National Climatic Data Center (NCDC) to improve the comparability and consistency of daily 1951-1980 temperature normal and freeze/frost date statistics at selected Cooperative Network stations. The availability of this data set has not been widely advertised and therefore its use has been limited.

# PREVIOUS WORK

The difficulty in obtaining serially complete climate data has led numerous researchers to develop and use a variety of procedures to estimate missing daily temperature data. Thus an assortment of data sets, each fitting a particular need and location, have been produced. Kemp et al. (1983) compared seven methods for estimating maximum and minimum temperatures. The seven methods were broadly classified into three categories: 1) within-station, 2) regression-based, and 3) between-station techniques.

Within-station techniques rely on temperature data recorded on previous and subsequent days to estimate missing data values. An example of this approach would be the replacement of a missing maximum temperature on 20 June with the average of the maximum temperatures recorded on 19 June and 21 June (Landsberg, 1958; Oliver, 1973). Similarly, averages can be calculated using temperatures encompassing more than one day on either side of the missing day. Although these methods are satisfactory when calculating monthly or longer period averages, individual daily estimates show significant errors. Using four years of data at four stations in northern Idaho, Kemp et al. (1983) randomly selected 20 daily maximum and minimum temperatures for each month and found that within-station methods produced mean daily absolute minimum temperature errors that ranged from 8°F in January to 4°F during several other months. Mean absolute errors for maximum temperatures were as high as 5°F during May.

Regression-based methods of data estimation tend to be more accurate than within-station methods (Kemp et al., 1983). In the regression-based approach, available data from several adjacent stations are used to develop linear regression equations which are subsequently used as a basis for estimating missing data values. In some cases, weighting factors are applied based on the correlation between the station with missing data and those used for reconstruction. Using regression-based methods, Kemp et al. found that the mean absolute error associated with minimum temperatures was reduced by 50% and ranged from 4°F in January to 2°F during several months. The highest mean absolute maximum temperature deviation was also reduced to just 3°F and occurred in October. While such methods are useful over limited areas, they are computationally intensive and therefore not feasible when data estimates are needed for a large number of stations or over a long period of time.

Adjacent stations are also used in methods classified as between-station techniques. Kemp et al. (1983) described such a method which assumes that the difference between daily temperatures at adjacent stations is equal to the difference between the monthly average temperatures of the sites. Using data from the same 4 northern Idaho stations mentioned above, the mean absolute errors produced by this method tended to be lower than those which resulted from the within-station methods, and were only slightly higher than those resulting from the regression-based methods. For minimum temperatures, mean absolute errors ranged from 4°F in January to as low as 2°F during several months. Mean absolute errors for maximum temperature were as high as 3°F during October.

Steurer (1985) developed a similar between-station method which was used to create a serially complete data set of daily maximum and minimum temperatures in the United States from 1951 through 1980. A total of 3106 stations representing those selected for the 1951-1980 normals project (NOAA, 1983) comprised this data set. Steurer's method assumes that, on a given day, stations within a climate division will experience temperatures which deviate from their monthly normal by similar amounts. His method involves three stages which include: 1) identification and elimination of erroneous data, 2) interpolation, and 3) quality control.

In the error screening stage, temperature values which exceed 5 absolute standard departures are considered questionable. Steurer defined the standard departure, STD, for station j as:

$$STD_j = (X_j - \overline{X}_j)/S_j \qquad (1)$$

where j represents any station within the network, $X_j$ is the daily maximum or minimum temperature and $\overline{X}_j$ and $S_j$ are estimates of the long term mean daily maximum or minimum temperature and its standard deviation, respectively. For estimates of these quantities, Steurer makes use of mean monthly average temperatures and monthly standard deviations ignoring any missing or questionable data values. Daily temperature normals and standard deviations for the second and third weeks of a month are assumed to equal the monthly value. Estimates of $\overline{X}_j$ and $S_j$ for days during the first (last) week of a month are obtained by averaging the current and preceding (succeeding) monthly means and pooling the corresponding monthly variances. Questionable values are compared to corresponding daily temperatures at other stations within the same climate division and flagged as erroneous if, based on an involved scheme, significant differences are evident.

In the second stage of Steurer's method, missing and flagged values are determined by interpolation using all available data from stations within the same climate division. For a given date and climate division, a daily average standard departure, $STD_{avg}$, is computed using the equation:

$$STD_{avg} = \left( \sum_{j=1}^{N} STD_j \right) / N \qquad (2)$$

where N is the number of stations that have valid daily temperature data present. At least 3 stations are required for each interpolation to assure that a representative value of $STD_{avg}$ is produced. If three stations can not be found within a division, stations from an adjacent division are used to calculate $STD_{avg}$. Estimates of missing and flagged data, $X_i$, are calculated using the formula:

$$X_i = STD_{avg}(S_i) + \overline{X}_i \qquad (3)$$

where i represents the station with flagged or missing data.

Once estimates are calculated for all missing and flagged temperature values, a final quality control stage is implemented. In this stage, flagged values are compared to corresponding estimates to determine whether the two values are statistically similar. To determine statistical significance of the estimate, STD is calculated for the flagged temperature value and used to compute a value Z, defined as:

$$Z = | STD_{avg} - STD_i | . \tag{4}$$

If Z is greater than 3, the estimate is retained. Otherwise the original flagged value is assumed valid since it is not statistically different from the estimate.

Adopting the general principles used by Steurer (1985), the Northeast Regional Climate Center (NRCC) has developed and implemented a procedure to create a serially complete temperature data set for nearly 400 stations in the northeastern United States. In contrast to Steurer's procedure, our procedure uses nearest available station data to reconstruct missing temperature values rather than using data from any station in the same climate division. Because climate divisions often have areas on the order of thousands of square miles and somewhat arbitrary boundaries, this modification limits the stations used in the interpolation procedure to those which are nearest the missing-data site and thereby maximizes the probability that all stations were influenced by the same meteorological conditions on a given day.

Our procedure also considers and accounts for differences in observation time between the missing-data station and those used in estimation. Although Steurer noted the existence of observation time bias in his serially complete data set, he made no attempt to limit its effect when estimating missing values. In our procedure, only stations with observation times similar to that of the missing-data station are used.

## ESTIMATION PROCEDURE

The initial step in the creation of the Northeast Serially Complete Data Set was the screening of data at each of the 439 northeastern stations for which 1961-1990 normals were calculated by NCDC. Stations which had more than 10% of their daily temperature observations missing over the 1961-1990 period were omitted from the serially complete data set. This reduced the total number of usable stations to 391.

The daily temperature data at each of these stations were then validated using an error checking procedure described by Robinson (1993). In this procedure, daily temperature data are flagged as erroneous when any of the following conditions occur:

1. Maximum or minimum temperature is greater than prescribed maximum for the state or lower than prescribed state minimum. In the Northeast, prescribed maxima range from 105° to 110° and minima range from -17° for Delaware to -52° for New York.
2. Maximum temperature is less than the minimum temperature.
3. Minimum temperature exceeds the prior day's maximum temperature.
4. Maximum temperature exceeds the minimum temperature by more than 60°F.

Flagged data are treated as missing in all subsequent analyses. Therefore estimates are calculated for these temperature data, but neither the flagged data nor their estimates are used to reconstruct missing data values.

To estimate a missing or flagged maximum or minimum temperature observation at a particular site, say Ithaca, NY, the observation times of all normals stations within a 0.1° of latitude radius of Ithaca are compared with that of Ithaca. Stations with similar observation times are retained for use in data estimation. For comparison purposes, observation times were grouped as morning, 1:00–11:00 local time (LT); afternoon, 12:00–20:00 LT; and midnight, 21:00–24:00 LT. This is similar to the grouping of observation times that Karl et al. (1986) used to estimate observation time bias in monthly mean temperatures. If less than three stations with similar observation times are identified, the search radius is increased by increments of 0.1° of latitude until at least three stations are found or the radius exceeds 1°.

Generally the required number of stations with similar observation times can be found within 1° of latitude of most sites in the Northeast. However, when the missing-data station has a midnight observation time, this criteria can not be met in some instances. In such cases, the search is repeated using morning observing stations for missing maximum temperatures and afternoon observing stations for missing minimum temperatures. When morning observations serve as replacements, however, the maximum temperature from the subsequent day is used to reflect its actual date of occurrence.

In data sparse regions, it still may not be possible to identify at least three normals stations with similar observation times. In these cases, the search is repeated with the minimum number of stations required for estimation reduced to two and the maximum search radius increased to 1.5° of latitude. These relaxed criteria were required at five stations in the Northeast. In the unlikely event that two stations with the same observation time are still unavailable, the observation time requirement is waived and the closest three or more stations within a maximum radius of 1.5° of latitude are used in the reconstruction. This selection criterion was only necessary at Eastport, ME. A logic flow diagram illustrating this station selection procedure is shown in Figure 1.

Once the appropriate number of stations have been identified, $STD_{avg}$ is calculated using Equations 1 and 2 and the daily temperature observations at these sites. In the majority of cases, the temperatures used as estimators will have been recorded on the same calendar day as the missing or erroneous temperature value. However when a morning maximum temperature observation is used to estimate the temperature at a station with a midnight or afternoon observation time, the temperature recorded for the day after that of missing temperature must be used. Alternatively, when an afternoon or midnight observation is used to estimate the maximum temperature at a station with a morning observation schedule, the temperature recorded during the previous day must be used. These adjustments are necessary because the maximum temperature reported for a given day by a morning observer has most often occurred during the previous day.

Ideally, daily values of $\overline{X}_j$ should be used to calculate the daily $STD_j$ at each station (Eq. 1). Although Steurer assumed biweekly temperature averages, based on linear interpolation from monthly values, provide appropriate surrogates for these daily values, a more reliable method of estimating daily temperature normals is described by Epstein (1990). In Epstein's procedure, the daily climatology of maximum or minimum temperatures is given with a high degree of accuracy by the sum of harmonic components based on the 12 monthly means. Therefore, Epstein's method is used to calculate $\overline{X}_j$ in Equation 1. Daily estimates of $S_j$, however, continue to be derived using monthly or pooled variances. Once $STD_{avg}$ has been

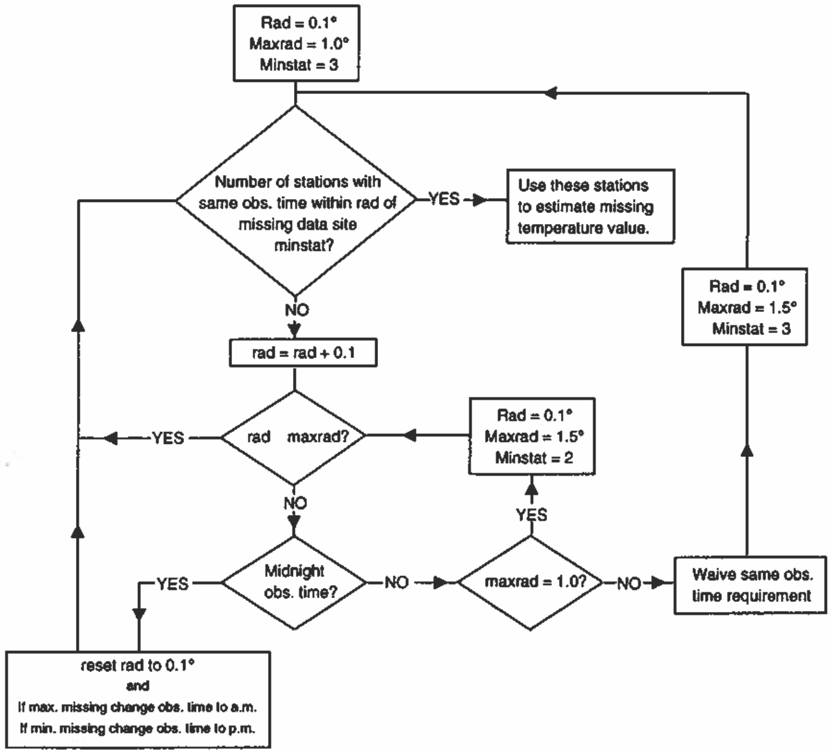


**Figure 1. Flow chart showing the procedure used to select stations for use in the modified estimation procedure. Rad is the search radius increment; Maxrad is the maximum search radius; and minstat is the minimum number of stations used to estimate a missing temperature value.**

obtained and $\overline{X}_i$ is estimated using Epstein's procedure, an estimate for the missing temperature value is calculated using Equation 3.

As a final quality check, the entire serially complete data set was subjected to Robinson's validation procedure. A small percentage of the interpolated data values were flagged as erroneous in this final quality control stage. In some cases, the interpolated maximum (minimum) temperature was less than (exceeded) the actual or interpolated minimum (maximum) temperature, while in other instances the interpolated minimum (maximum) temperature exceeded (was less than) the prior days' maximum (minimum) temperature. The interpolated temperatures were manually adjusted in these cases so that they were consistent with the corresponding observed values.

## VALIDATION

To assess the accuracy of the temperature values generated by our procedure, estimates were calculated for non-missing daily temperature observations at 12 sites in the northeastern United States. Daily estimates were produced for the months of January, April, July and October of 1991 and 1992 at a 12 station network comprised of 3 stations from each of four states; Maine, Maryland, New York and West Virginia. Within each state, the stations were selected to represent each of the three observation time categories. On an annual basis, the selected years reflect anomalously warm and cold conditions, respectively. At each site, monthly values of mean errors (ME), mean absolute errors (MAE) and root mean square

**Table 1. Mean error (ME), mean absolute error (MAE) and root mean square error (RMSE) associated with maximum and minimum temperature estimates for three stations within the indicated states. Errors have units of °F. Mx Pos and Mx Neg indicate the maximum positive and maximum negative temperature errors, respectively.**

**MAINE**

| | MAXIMUM TEMPERATURE | | | | | MINIMUM TEMPERATURE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| MONTH | ME | MAE | RMSE | Mx Pos | Mx Neg | ME | MAE | RMSE | Mx Pos | Mx Neg |
| January | -0.5 | 2.7 | 4.4 | 11 | -24 | -0.2 | 3.5 | 4.5 | 9 | -17 |
| April | -0.3 | 2.0 | 2.6 | 5 | -11 | 0.4 | 1.8 | 2.4 | 10 | -7 |
| July | -0.9 | 2.1 | 3.1 | 8 | -12 | -0.2 | 1.7 | 2.5 | 14 | -6 |
| October | -0.6 | 1.7 | 2.4 | 9 | -8 | 0.0 | 2.3 | 3.0 | 9 | -8 |

**MARYLAND**

| | MAXIMUM TEMPERATURE | | | | | MINIMUM TEMPERATURE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| MONTH | ME | MAE | RMSE | Mx Pos | Mx Neg | ME | MAE | RMSE | Mx Pos | Mx Neg |
| January | 0.0 | 1.9 | 2.4 | 6 | -7 | -0.3 | 2.3 | 2.9 | 8 | -10 |
| April | 0.6 | 2.3 | 3.1 | 8 | -11 | 0.1 | 2.3 | 2.9 | 7 | -7 |
| July | -0.2 | 1.4 | 2.0 | 6 | -7 | -0.5 | 1.9 | 2.4 | 9 | -5 |
| October | 0.5 | 1.7 | 2.3 | 9 | -6 | -0.3 | 2.0 | 2.7 | 7 | -8 |

**NEW YORK**

| | MAXIMUM TEMPERATURE | | | | | MINIMUM TEMPERATURE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| MONTH | ME | MAE | RMSE | Mx Pos | Mx Neg | ME | MAE | RMSE | Mx Pos | Mx Neg |
| January | -0.7 | 1.8 | 2.5 | 8 | -10 | 0.8 | 2.8 | 3.6 | 10 | -12 |
| April | 0.2 | 1.4 | 1.8 | 5 | -5 | 1.1 | 2.4 | 3.1 | 9 | -10 |
| July | 0.4 | 1.2 | 1.6 | 4 | -5 | 1.3 | 2.7 | 3.3 | 12 | -6 |
| October | -0.2 | 1.3 | 1.8 | 4 | -10 | 1.2 | 2.9 | 3.4 | 9 | -8 |

**WEST VIRGINIA**

| | MAXIMUM TEMPERATURE | | | | | MINIMUM TEMPERATURE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| MONTH | ME | MAE | RMSE | Mx Pos | Mx Neg | ME | MAE | RMSE | Mx Pos | Mx Neg |
| January | -0.7 | 2.4 | 3.1 | 7 | -10 | 0.5 | 2.7 | 3.5 | 8 | -15 |
| April | 0.0 | 1.7 | 2.5 | 9 | -9 | 1.1 | 3.0 | 3.8 | 11 | -9 |
| July | -0.4 | 1.4 | 2.0 | 4 | -11 | 0.5 | 2.5 | 3.1 | 9 | -8 |
| October | -0.8 | 2.0 | 2.6 | 8 | -7 | 0.3 | 3.1 | 3.9 | 12 | -10 |

errors (RMSE) were computed for the differences between the actual temperature observation and the estimated value. A summary of these values for each state is given in Table 1.

For maximum temperature, the largest mean errors on an annual average basis occurred in Maine and West Virginia. The smallest average mean errors occurred at the Maryland stations. Mean absolute errors ranged from 2.7° in Maine to 1.2° in New York. The maximum error in estimated maximum temperature was 24°F at Caribou, Maine. Further examination of this case showed that a strong cold front had passed two of the three stations used to estimate Caribou's maximum temperature. Caribou, however, remained on the warm side of the front until the next day. Observations show that maximum temperatures after the frontal passage were 30 to 40° colder than those recorded prior to its passage.

Mean absolute errors for estimated minimum temperatures tended to be greater than those associated with maximum temperatures. Generally the largest MAE values occurred at stations in West Virginia. However the largest individual MAE value, 3.5°, occurred during January in Maine. Interestingly, the smallest MAE, 1.7°, also occurred in Maine, but during July. Mean errors for minimum temperatures had approximately the same value as those associated with maximum temperatures, except for those at the New York stations. The highest minimum temperature error, 17°, occurred at Eastport, which is located off the Maine coast. Due to a lack of adjacent stations with similar observation schedules, temperature estimates for this site neglected observation time differences.

The estimation procedure was also verified with daily data for Worcester, MA for the period 1951-1980. Worcester was the only station in the northeastern United States at which Steurer tested his estimation procedure. Use of the Worcester data therefore allows the estimates produced with our procedure to be directly compared with those obtained using Steurer's method. The results are compared in Table 2.

Table 2 shows that use of the modified procedure improves the accuracy of temperature estimates, particularly for maximum temperature. MAE values for maximum temperatures are reduced by 42 to 45% compared to Steurer's method. Likewise maximum errors are reduced by as much as 10°F. Although MAE improved only slightly for minimum temperature, the maximum errors associated with minimum temperature estimates are consistently lower using the modified procedure. During individual months, MAE are reduced by 17% in January and 9% in October, but increased by 5% in July and 11% in April.

**Table 2. Mean absolute error (MAE) and maximum positive and negative errors for Worcester, MA based on Steurer's estimation method and the NRCC procedure. Errors have units of °F. Mx Pos and Mx Neg indicate the maximum positive and maximum negative temperature errors, respectively.**

**MAXIMUM TEMPERATURE**

| | NRCC PROCEDURE | | | STEURER'S PROCEDURE | | |
|---|---|---|---|---|---|---|
| MONTH | MAE | Mx Pos | Mx Neg | MAE | Mx Pos | Mx Neg |
| January | 1.9 | 18 | -15 | 3.3 | 21 | -25 |
| April | 2.0 | 10 | -12 | 3.6 | 16 | -15 |
| July | 1.4 | 7 | -9 | 2.4 | 11 | -14 |
| October | 1.8 | 8 | -9 | 3.1 | 12 | -16 |

**MINIMUM TEMPERATURE**

| | NRCC PROCEDURE | | | STEURER'S PROCEDURE | | |
|---|---|---|---|---|---|---|
| MONTH | MAE | Mx Pos | Mx Neg | MAE | Mx Pos | Mx Neg |
| January | 3.0 | 16 | -13 | 3.6 | 17 | -18 |
| April | 2.7 | 10 | -12 | 2.4 | 12 | -13 |
| July | 2.0 | 7 | -9 | 1.9 | 9 | -10 |
| October | 3.0 | 9 | -15 | 3.3 | 13 | -13 |

## CONCLUSIONS

Since numerous modeling and statistical applications require serially complete temperature data, a method to estimate missing and erroneous temperature data has been developed and implemented by NRCC for Cooperative Network Stations in the northeastern United States. The estimation procedure uses the same general principles used by Steurer (1985). However, compared to Steurer's methods, our procedure significantly improves the accuracy of maximum temperatures estimates and reduces maximum errors by as much as 10°F. This improved accuracy can be attributed to our requirement that observations used in estimating missing temperatures be taken at a time close to the observation time used at the missing-data station. In addition, the stations used in reconstruction are selected based on minimum distance from the missing-data station rather than by their inclusion in the same climate division. Since climate divisions are often based on political rather than climatic boundaries, the distance approach increases the probability that stations used for estimation have experienced the same meteorological conditions on any given day.

Based on the results of validation analyses, it appears that the magnitude of MAE for maximum temperature is influenced by station density. Where several adjacent stations with similar observation times could be found, errors tended to be small, on the order of 1.5°F. In data sparse regions, however, MAE errors increased to approximately 2.5°F.

The accuracy of minimum temperature estimates is also improved somewhat with our procedure. The relatively small increase in the accuracy of minimum temperature estimates most likely results from two factors. Temperature biases resulting from observation time differences tend to be smaller for minimum temperatures than those associated with maximum temperatures (DeGaetano and Knapp, 1993). In addition, most morning observations in the region are taken at a late enough hour (07:00 - 08:00) that observation time bias associated with minimum temperature is minimal. In contrast, the majority of afternoon observations are taken near the time when observation time bias is at a maximum. This contributes to the improvement in accuracy obtained when observation time was considered in estimating maximum temperatures.

Microclimatic differences between the stations used in the estimation process and the missing-data site may also account for the limited improvement in the minimum temperature estimates. It is likely that, on a given day, the departure of the minimum temperature from normal will be influenced by microclimatic features over short distances. These effects should be most prevalent in mountainous terrain, where temperature inversions and cold air drainage can produce sharp minimum temperature gradients. The results of validation analyses appear to support this conclusion, since the largest MAE values were associated with stations from primarily mountainous areas of West Virginia.

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