Use of Mesoscale Climatology in Mountainous Terrain to Improve the Spatial Representation of Mean Monthly Temperatures

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ABSTRACT

Using regularly collected climatological data, mean monthly temperatures as a function of elevation are estimated for the period 1958–73 over a portion of Virginia and West Virginia. These data can be used to make improved climatological maps of mean temperature distribution over the region. The application of this method to other geographical regions is straightforward.

1. Introduction

Climatological data are an essential ingredient in the planning and management of a wide variety of human activities, as well as a component in the explanation for the distribution of soil types, vegetation and animal life. In mountainous terrain, for example, it is well known that plant life is distributed such that species which favor colder, moister climates are found at higher elevations [see, e.g., Odum, 1971, p. 403).

Conventional climatological analyses for individual states, such as those presented in *Climates of the States* (1974, Vols. 1 and 2) and *Climate and Man* (1941), do not take sufficient advantage of the variations with elevation of meteorological parameters in their preparation of maps which are disseminated to the public. Rather, elevation influences are considered through the contouring of values at individual observation sites with terrain contours taken into account only very crudely. The work by Alemán and García (1974, p. 360) is the only example known to the authors where terrain effects have been explicitly considered in the preparation of climatological maps. In their paper they mentioned the equivalence of topographic contours and mean temperatures over Mexico as a first approximation and applied this result to define climatic regimes and to draw contoured fields of mean temperature in the country. They presented results based on a very smoothed contouring of the Mexican terrain, however, and did not apply the technique to local regions.

The neglect of the application of this technique to describe mesoscale climatological variations in mountainous regions is surprising, particularly since Conrad and Pollak (1962, 88–89, 272–276) described over 26 years ago how temperature can be related to terrain elevation.[1] In this paper we utilize and extend the methodology, as discussed by Alemán and García and by Conrad and Pollak, to describe monthly mean temperatures over mountainous terrain for a limited geographic region using standard climatological data and terrain contours. A portion of northwestern Virginia and east-central West Virginia is used as the illustrative example. Information presented in this manner will have useful applications in such areas as insulation engineering, ecology, forestry, water management, as well as in weather forecasting. In ecology, for instance, this information will aid in explaining the observed distributions of flora and fauna in irregular terrain, while workers in forestry and water resources can utilize the information to help estimate evaporation and evapotranspiration at different elevations in a region.

It should be straightforward to extend the method discussed in this paper to maximum and minimum temperatures, and to any other geographic region of comparable size.

2. Methods and Results

An example of a map of mean temperatures over a limited region of Virginia for January 1961 as reproduced from *Climatological Data Virginia* (1961) and *West Virginia* (1961) is presented in Fig. 1. A reference to a topographic map of the region (such as the U. S. Dept. of the Interior Geological Survey, 1:24000 maps, Reston, Va. 22092) illustrates that terrain contours

[1] The edition of Conrad and Pollak's book referenced was published in 1962 but the original copyrighted material was published in the book of the same name in 1950.

are not considered in the analysis. One would not know from Fig. 1, for instance, that a major mountain ridge runs northeast–southwest between Waynesboro and Charlottesville. Using mesoscale climatology, however, this analysis can be improved to give a more realistic representation of mean temperature distribution.

To do this, monthly mean temperatures for climatological data sites located in the region represented in Fig. 1 were tabulated for 1958–73 as a function of elevation. The data were obtained from the Virginia and West Virginia climatological data publications of the National Climatic Center. Latitude effects were ignored. The map in Fig. 2 gives an example of the typical horizontal data coverage. Linear regressions were applied to each month's data in the form of

$$T(Z)=A_0+A_1Z, \quad (1)$$

where Fig. 3 is a representative example. As shown by Conrad and Pollak (1950, p. 88), a quadratic form may be more appropriate in regions of persistent low-level inversions where the maximum temperature occurs at an intermediate elevation. Similarly, in mountainous areas where upslope clouds and precipitation are frequent at high elevations, a nonlinear fit will probably apply better (due to effects of the release of latent heat).

The average monthly values for the period 1958–73 of the intercept A_0, slope A_1, regression coefficient r, standard error of the estimate S_e and uncertainty of estimate, defined as S_e/A_1, are given in Table 1. As evident from the averages, the correlations are highest in the summer, undoubtedly due to the more homogeneous weather regime during the warmer season. During the winter, polar and arctic fronts occasionally are situated over the area, creating large horizontal contrasts, while low-level inversions are more frequent.

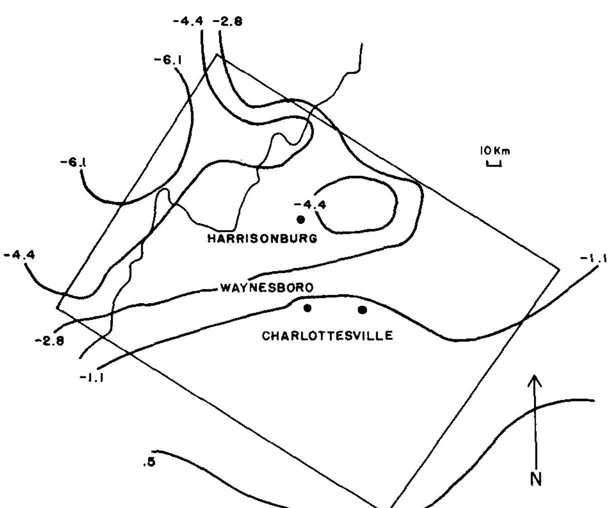

FIG. 1. The daily mean temperature for January 1961 over portions of West Virginia and Virginia as reproduced from *Climatological Data, Virginia and West Virginia* (1961).

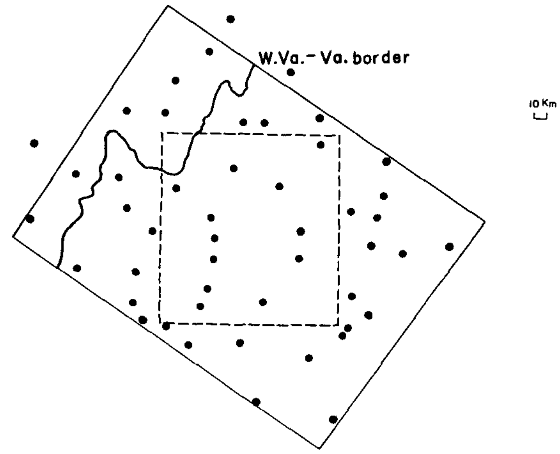

FIG. 2. Climatological data sites available for January 1963 for a portion of Virginia and West Virginia. The region shown in Fig. 4 is indicated by the dashed line.

The change of temperature with height (A_1) is also greatest during the summer, which can be attributed to the less stable lapse rate typically found in the warmer season due to the strong solar heating of the ground. The secondary maximum in the magnitude of the lapse rate in March may be due to the warming of the lower levels as the equinox approaches, but with the very cold winter temperatures aloft creating a greater likelihood of strong vertical mixing. In May the upper levels have warmed, but the lower levels have not heated to their July values.

The magnitude of the lapse rate found in this region is close to that generally quoted in climatological references. Baldwin (1973, p. 4) gives a value of $-6.01°C\ km^{-1}$, while Blumenstock and Price (1967, p. 618) in their paper on the climate of the island of Hawaii reported a decrease in mean monthly temperatures upslope of $5.46°C\ km^{-1}$, although they added that actual monthly means vary from $-1.85°C\ km^{-1}$ to $-10.93°C\ km^{-1}$, depending on local differences in cloudiness and exposure to the trade winds. No such radical variations in lapse rates were found in our study, with the maximum magnitude of $8.23°C\ km^{-1}$ in March 1960 and a minimum of $3.43°C\ km^{-1}$ in February 1962. Snow (1975, p. 153) found lapse rates in the Columbia Andes ranging from $-4.5°C\ km^{-1}$ at elevations <1 km to values of $-7.0°C\ km^{-1}$ from 4 to 5 km. The values at the intermediate levels varied from $6.5°C\ km^{-1}$ between 1 and 2 km, $5.0°C\ km^{-1}$ between 2 and 3 km to $6.0°C\ km^{-1}$ between 3 and 4 km.

The goodness of fit of the linear regression, as described by the magnitude of the standard error of estimate along with the slope of the regression, determines the resolution with which we can apply this climatological data to describe the mean temperature distribution over a limited geographic area. In the summer, for instance (Table 1) more confidence in the mean temperature for a given elevation is possible because the

TABLE 1. The monthly mean values of lapse rate A_1, sea level value A_0, correlation coefficient for the linear regression r, standard error of estimates S_e and uncertainty in elevation $|S_e/A_1|$ for the period 1958–73.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
A_0 (°C)	1.88	2.92	8.01	14.03	18.70	23.14	25.23	24.63	20.95	14.79	9.19	3.57
A_1 (°C km^{-1})	−5.56	−6.02	−6.41	−6.17	−5.89	−6.33	−6.61	−6.40	−5.67	−5.17	−5.47	−5.23
r	−0.88	−0.91	−0.93	−0.93	−0.94	−0.95	−0.95	−0.96	−0.93	−0.90	−0.91	−0.89
S_e (°C)	0.9	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.8
Uncertainty in elevation (m) ($\|S_e/A_1\|$)	171	145	129	122	109	102	98	99	126	157	146	159

standard error is less and the lapse rate is greater. The largest uncertainty in elevation (309 m) was for February, 1962 due to a comparatively small lapse rate of −3.4°C km^{-1} and a standard error of 1.1°C. Fortunately, for most of the period of study, the uncertainty was much less because the lapse rate was greater. The mean uncertainties ranged from 171 m in January to 98 m in July.

The display in Fig. 4 illustrates how this information can be applied to improve the analysis for January 1961 over a portion of the region given in Fig. 1. To obtain the improved mean temperature mapping, terrain contours obtained from U. S. Geological Survey topographic maps (scale of 1:24000) were digitized at 5 km intervals and then smoothed. The estimated mean temperatures corresponding to a given elevation were then displayed in place of elevation.[2] For January 1961 the uncertainty of estimate was 193 m so that contour labels for 1.2°C intervals (corresponding to 200 m) are statistically useful for this month. (Approximately 68% of the observed mean temperatures at a given elevation in the region would be expected to be within 1.2°C of the predicted mean.) Only 14 of the 204 months analyzed for the period 1958–74 had larger uncertainties of estimate, so most maps presented in this fashion would have smaller, statistically significant contour intervals.

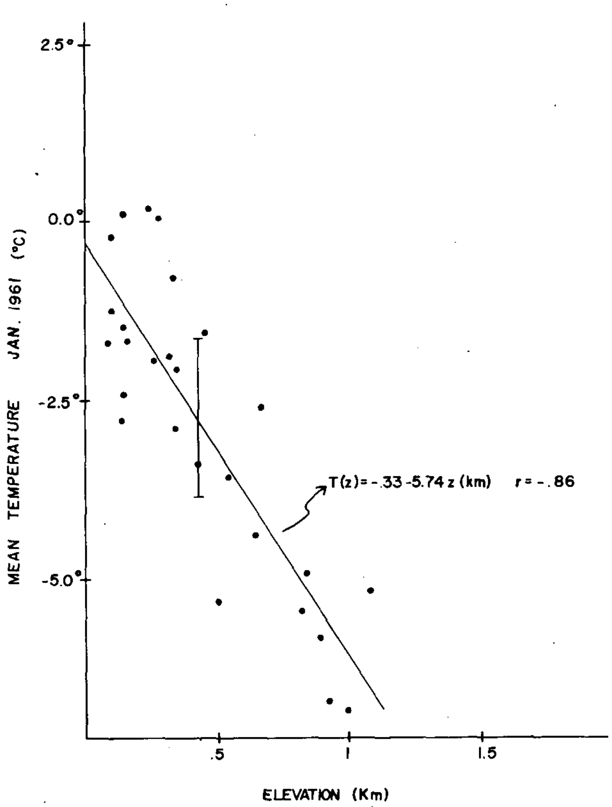

FIG. 3. Temperatures as a function of elevation for a portion of Virginia and West Virginia for January 1961.

The improvement in resolution compared with Fig. 1 is obvious and illustrates, for example, the marked colder environment in the Blue Ridge Mountains (which run along the southwest to northeast diagonal of the figure). In Fig. 1, the mountains are essentially ignored except for point observation sites in the mountains.

An alternate mode to distribute this information to users is given in Table 2, where the mean temperatures at selected heights are indicated for each month. Such a table would permit a user to refer directly to a standard topographic map, using the standard error of estimate to indicate confidence in the value.

The method outlined in this paper, however, has a limitation of which prospective users must be aware. The standard error will not be reduced appreciably by a denser data network since microscale influences will create mean temperature variations over short distances. Whittaker and Niering (1968, P. 532, 540), for instance, describe the variation in vegetation type as a function of slope aspect for various soil characteristics in the Santa Catalina Mountains in Arizona. Due to lower mean temperatures and a consequential reduction in evapotranspiration, for a given elevation the more mesic vegetation prefers north-northeast slopes, while the more xeric plants dominate the south-southwest slope.

Geiger (1965) and Schroeder and Buck (1970) discuss the relation between aspect and temperature at considerable length. Additional improvements in the

[2] Although not considered in preparing Fig. 4, one of the reviewers suggested contouring for the observed temperature as well as the terrain contours might improve the accuracy further.

resolution and accuracy of mesoscale mappings of mean temperature will require the consideration of slope orientation; such that, for example, south facing slopes will be warmer in the mean than north slopes at the same elevation.

3. Summary and conclusions

A method is described for improving the analysis of monthly mean temperatures in mountainous terrain for a limited geographic region. The technique is based on plotting mean monthly temperatures as a function of elevation, fitting the data points with linear regressions, and plotting the estimated mean temperatures on a topographic map in place of elevation. The standard error is used to estimate the statistical reliability of the result. The highest correlations were found in the summer, while the smallest lapse rates were generally found in the fall and early winter. Climatological data displayed in this manner will be extremely useful for segments of our society such as builders, in their design of insulation for homes; ecologists, in the explanation of animal and vegetation distributions, as well as for meteorologists in the improvement of the spatial resolution in weather forecasts.

This method of presenting mesoscale climatological mean temperatures should be useful in any hilly or mountainous region of the world, as well as for other terrain features such as around urban areas, in regions with lakes and along seacoasts. The technique is readily automated using digitized topography and computerized analysis routines and will be a useful addition to the Automation of Field Operations and Services (AFOS) programs of the National Weather Service. Precipitation, including snowfall, should also be amenable to this technique providing the direction of the prevailing wind, slope orientation and upstream barriers are considered, in addition to elevation. Bryson and Hare (1974, p. 99), for example, mention work by Walker (1961), who has attempted to categorize mean annual precipitation over British Columbia using observed values, and estimates of vertical motion derived from mountain wave theory.

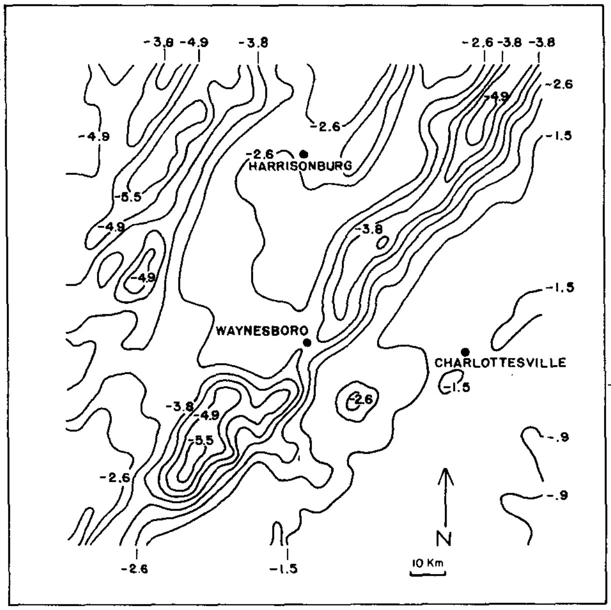

FIG. 4. The daily mean temperature for January 1961 over a portion of the region illustrated in Figs. 1 and 2, where the information content has been improved using topographic contours (unequal isotherm interval is due to rounding error in converting °F to °C)

Finally, although this paper deals with climatological mean data, the approach of displaying weather data with high spatial resolution needs much more study. Since topographic features, such as mountains, lakes, urban areas, etc., are fixed in space, surface meteorological information (including daily forecasts) should

TABLE 2. 1958–1973 mean temperature and standard error (°C) at selected heights over a portion of west-central Virginia and east-central West Virginia (Fig. 1).

Elevation (km)	Annual range of mean temperatures	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
0	23.1	2.1	2.9	8.0	14.0	18.7	23.1	25.2	24.6	21.0	14.8	9.2	3.6
0.152	23.0	1.2	2.0	7.1	13.1	17.8	22.2	24.2	23.7	20.1	14.0	8.4	2.8
0.305	22.8	.4	1.1	6.1	12.2	16.9	21.2	23.2	22.7	19.2	13.2	7.5	2.0
0.457	22.7	−.5	0.2	5.2	11.2	16.0	20.3	22.2	21.7	18.4	12.4	6.7	1.2
0.610	22.5	−1.3	−0.7	4.2	10.3	15.1	19.3	21.2	20.7	17.5	11.6	5.9	0.4
0.762	22.3	−2.1	−1.6	3.3	9.3	14.2	18.3	20.2	19.8	16.6	10.9	5.0	−0.4
0.914	22.2	−3.0	−2.5	2.3	8.4	13.3	17.4	19.2	18.8	15.8	10.1	4.2	−1.2
1.067	22.0	−3.8	−3.3	1.4	7.5	12.4	16.4	18.2	17.8	14.9	9.3	3.4	−2.0
1.220	21.9	−4.7	−4.2	0.4	6 5	11.5	15.4	17.2	16.8	14.1	8.5	2.5	−2.8
1.372	21.7	−5.5	−5.1	−0.5	5.6	10.6	14.5	16.2	15.9	13.2	7.7	1.7	−3.6
1.524	21.6	−6.4	−6.0	−1.5	4.6	9.7	13.5	15.2	14.9	12.3	6.9	0.9	−4.4
Standard error of estimate		0.9	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.8

include these terrain influences more quantitatively in the output products which are disseminated to industry, the military and the public. Maximum temperatures, for example, for a given day under a certain synoptic weather regime could be displayed on television or in the newspaper in the manner presented in Fig. 4. Researchers and operational meteorologists are urged to test this approach.

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