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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service

Use of Surface Observations in Boundary-Layer Analysis

H. MICHAEL MOGIL AND WILLIAM D. BONNER

Systems
Development
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USE OF SURFACE OBSERVATIONS IN BOUNDARY-LAYER ANALYSIS

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Systems Development Office
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USE OF SURFACE OBSERVATIONS IN BOUNDARY-LAYER ANALYSIS[1]

H. Michael Mogil and William D. Bonner
Techniques Development Laboratory

ABSTRACT. Methods of objective analysis have been developed that use surface reports to enhance the resolution of radiosonde data. Experiments performed compare the accuracy of two such methods with the accuracy obtained from direct analysis of radiosonde data. One method relates layer-mean quantities to surface values by analysis of ratios; the other relates point values aloft to surface values by analysis of lapse rates. Parameters examined include:

1) Mean potential temperature and mean mixing ratio within layers extending from the surface to 50 and 100 mb above the ground.

2) Temperature and mixing ratio at specific pressure levels to 200 mb above the ground.

Results show that the use of surface data reduces the errors in analysis of temperature and moisture at 0000 but not at 1200 GMT. The improvement in error reduction decreases with height and is significant only within the lowest 150 mb. Reduction of error is greater for moisture than for temperature. Methods using surface data appear to be valuable only during that portion of the day when surface and lower troposphere temperature or moisture are highly correlated as a result of vertical mixing.

INTRODUCTION

Significant horizontal variations in low-level temperature and moisture often occur on scales which are not adequately defined by the existing radiosonde network. Because surface stations are much closer together and

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[1] This Technical Memorandum was presented as a paper for the Seventh Conference on Severe Local Storms held at Kansas City, Mo., on October 5-7, 1971.

surface and upper air observations are correlated, it should be possible to use surface reports to obtain better estimates of temperature and moisture aloft.

Several methods have been proposed for incorporating surface data into boundary-layer analyses. Inman (1970) used surface mixing ratios (w_o) to estimate mean mixing ratios ($\overline{w}$) within the lowest 100 mb. At each radiosonde station, he computed a ratio:

$$\gamma = \frac{\overline{w}}{w_o} \quad . \tag{1}$$

Inman interpolated ratios to the locations of surface stations and obtained estimates of $\overline{w}$ by multiplying the surface mixing ratio by γ (1). The basic assumption is that features appearing at the surface are reflected through some distance aloft and that the ratio field can be adequately defined by the radiosonde network. Although Inman's technique is designed for moisture analysis, the same approach can be used for analysis of mean temperature or potential temperature.

A similar technique, developed by Gerrity (1967), is used in the Air Force boundary-layer model (Hadeen 1970). In this case, temperature and dew point at specific levels above the ground are estimated by first determining lapse rates from radiosonde reports. Interpolated lapse rates are than applied to surface reports, yielding values of temperature and dew point aloft.

Both methods are designed to enhance the resolution of boundary-layer moisture or temperature analyses. They are simple in concept and easy to apply. The only question is: How well do they work?

We ran an experiment to test the accuracy of these methods against the accuracy obtained from radiosonde data alone. The experiment also tests the relative accuracy of analysis by first- and second-degree polynomials (Panofsky 1949) and by weighting functions which give additional weight to upwind and downwind observations (Endlich and Mancuso 1968; Inman 1970).

APPROACH

We selected four test stations: Topeka, Kans.; Jackson, Miss.; Cape Hatteras, N. C.; and Pittsburgh, Pa. Topeka is the station of principal interest because of its proximity to the mean position of the low-level jet (Bonner 1968) and its location within the severe storms region of the Central States (Pautz 1969).

We treated each of these radiosonde stations as if they reported only surface data. Values aloft were withheld and used only to verify results of the different analysis techniques. Although this treatment reduces by one the number of available upper air observations in a particular region, it should have little effect upon relative errors among the methods tested.

Different analyses were performed on the same data sample consisting of 44 to 64 nonwinter days at each station.

Parameters examined included:

1) Mean mixing ratio within the lowest 50 and 100 mb.

2) Mean potential temperature within the same layers.

3) Dew point at 50, 100, and 200-mb levels above the ground.

4) Temperature at the same levels.

Each parameter was examined by:

1) Direct analysis using radiosonde data only.

2) A ratio or lapse-rate approach.

Layer-mean quantities were analyzed by use of both isotropic and along-wind weighting.

METHOD

Basic Analysis Scheme

Interpolations were performed by fitting a first- or second-degree polynomial to radiosonde data by the method of least squares.

First-degree polynomials used data from the five closest radiosonde stations. This method, described by Endlich and Mancuso (1968), is currently in use in the operational three-dimensional trajectory model of the Techniques Development Laboratory (Reap 1968).

Second-degree polynomials used data from the nearest 10 radiosonde stations. This method, and methods using surface data, can reproduce a maximum or minimum at the verifying station and should, theoretically, give better results than use of first-degree polynomials with direct analysis.

Weighting Function

The isotropic weighting function W_1 is given by:

$$W_1 = \frac{C^2}{R^2 + C^2} \qquad (2)$$

where R is the distance between the observation and the grid point or verifying station. With R in National Meteorological Center (NMC) grid units, the constant C^2 was assigned a value of 0.75 (Reap 1968).

A weighting function W_2 was defined, following Endlich and Mancuso (1968), as:

$$W_2 = \frac{C^2}{(R + R^*)^2 + C^2} \leq W_1 \qquad (3)$$

where

$$R^* \equiv \vec{k} \bullet \frac{\vec{R} \times \vec{V}}{|\vec{V}|} \quad . \qquad (4)$$

Thus, if $\vec{R}$, the position vector with respect to the grid point, is parallel to the wind, $R^* = 0$ and $W_2 = W_1$. If $\vec{R}$ is perpendicular to $\vec{V}$, $R^* = R$ and

$$W_2 = \frac{C^2}{4R^2 + C^2} \quad . \qquad (5)$$

The function W_2 gives relatively greater weight to "along-wind" observations. It reflects the tendency of fields to elongate in the direction of the wind through transport by horizontal advection.

Weighting functions W_1 and W_2 are graphed in figure 1.

Layer-Mean Quantities and Lapse Rates

Mean quantities used in the ratio approach were pressure-weighted means of the form:

$$\theta = \frac{\sum_{j=1}^{n-1} (\theta_j + \theta_{j+1})(P_j - P_{j+1})}{\sum_{j=1}^{n-1} (P_j - P_{j+1})} \qquad (6)$$

where θ is, in this case, potential temperature; P is pressure; and n is the number of reports in the layer, including an interpolated value at the top of the layer.

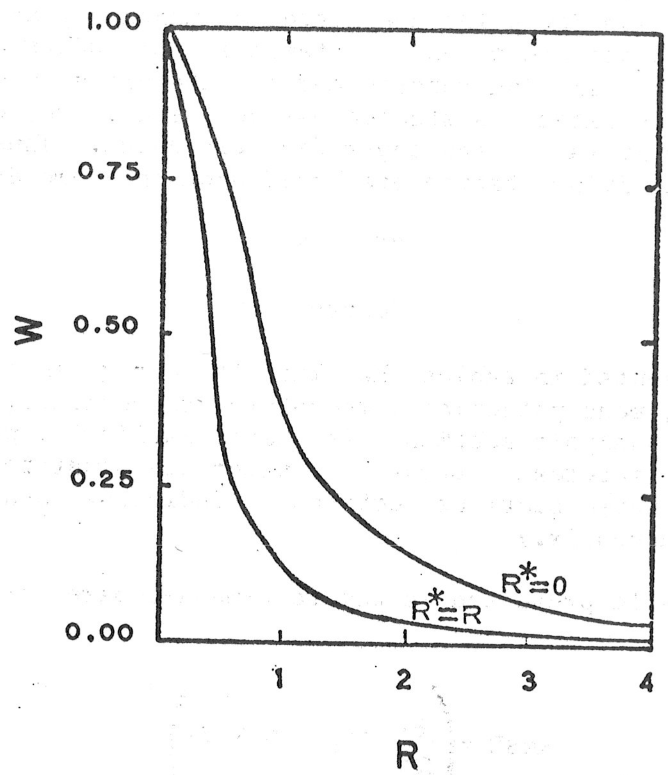

Figure 1.--Weighting function from equation (3) showing relative weights given along-wind ($R^* = 0$) and crosswind ($R^* = R$) observations. C^2 is equal to 0.75 and R is distance in NMC grid units between the observation and the verifying station (from Reap 1968).

Lapse rates were determined simply from the surface value of temperature or dew point and from the value obtained by linear interpolation at the layer top.

Data Source

Radiosonde data were obtained from the archived NMC B3 tapes. On these tapes, temperature and dew point are listed at mandatory and significant levels; low-level winds are given at intervals of 1,000 ft above sea level. Data were checked for missing reports and for the presence of strongly superadiabatic lapse rates. A station was not used if any of the data were missing or if it failed the superadiabatic check. Thus, all analyses at a particular verifying station are based upon the same data set.

RESULTS

General

Results are presented in tables that list the errors in specification of mean mixing ratio, mean potential temperature, temperature, and dew point for the different analysis schemes. As stated earlier, Topeka is the station of primary interest. Errors are presented separately for Topeka and for the other three stations combined. (Individual station errors are tabulated in the appendix.)

The error statistic presented is the root-mean-square error, defined as:

$$\mathrm{RMSE} = \left(\sum_{j=1}^{m} (A_j - O_j)^2/m \right)^{\frac{1}{2}} \qquad (7)$$

where m is the number of cases and A_j and O_j are the analyzed and observed values at the verifying station. Tests of significance are based upon the standard deviation error. This is approximately equal to RMSE, provided the mean algebraic error or bias is small.

With the lapse rate or ratio techniques, smallest errors were associated with the simplest analysis scheme--first-degree polynomials with isotropic weighting. Tables 1 to 4 compare the errors for the lapse rate or ratio technique with errors associated with direct analysis using:

- first- and second-degree polynomials, and

- isotropic and along-wind weighting.

Mean Mixing Ratio

Table 1 shows results relating to the mean mixing ratio. At 0000 GMT, root-mean-square errors in specification of $\overline{w}$ by direct analysis are approximately 3 g kg^{-1} for Topeka and 2.5 g kg^{-1} for the pooled sample from the other three stations. Use of Inman's ratio technique reduces this error by roughly a factor of two. This difference is significant at the 1-percent level for both layers at Topeka and at the 5-percent level for the 50-mb-deep layer in the pooled sample.[2] Among direct-analyses techniques, lowest errors are associated with use of second-degree polynomials at Topeka and first-degree polynomials at other stations. Errors with along-wind weighting (W_2) are as large or larger than those associated with the simple isotropic weighting-function W_1.

At 1200 GMT, errors for direct analysis are, in general, much smaller then at 0000 GMT. The only significant difference among the various analysis methods at 1200 GMT appears to be between ratio and direct techniques in the lowest 50 mb at Topeka. In all other cases, minimum errors are associated with direct analysis using second-degree polynomials. There appears to be no advantage in using along-wind weighting.

Mean Potential Temperature

Results (table 2) are similar to those for $\overline{w}$. At 0000 GMT, the ratio technique gives significant improvement over direct analysis at Topeka and at the other three stations combined. Improvement is greatest within the lowest 50 mb at Topeka where root-mean-square errors are reduced from roughly 3°C with direct analysis to less than 1°C with use of ratios and surface data.

At 1200 GMT, lowest errors at Topeka are associated with the ratio technique.

At both times, errors with W_2 are generally as large or larger than those associated with W_1. For the combined data, direct-analysis errors are lower for first-degree than for second-degree polynomials.

Dew Point at Specific Levels

Results are summarized in table 3. For calculations at specific levels, only the isotropic weighting function W_1 was used. Thus, comparisons are between first- and second-degree polynomials and between direct-analysis and lapse-rate techniques.

At 0000 GMT, results for Topeka show a significant reduction in error

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[2] A two-tailed F-test was used to test the significance of differences between direct and lapse rate or ratio methods for analyses, using a first-degree polynomial and W_1.

Table 1.--Root-mean-square errors (g kg^{-1}) in analysis of mean mixing ratio ($\overline{w}$). Combined data refer to pooled sample from all stations except Topeka. W_1 and W_2 refer to isotropic and along-wind weighting, respectively. Asterisks denote significance of difference between standard deviations of error for ratio technique and direct analysis, first degree, W_1; * means significant at 5-percent level, ** at 1-percent level

Layer thickness	Direct analysis 1st degree W_1	Direct analysis 1st degree W_2	Direct analysis 2nd degree W_1	Direct analysis 2nd degree W_2	Ratio method 1st degree W_1
mb	Topeka--0000 GMT (62 cases)				
50	3.16	3.09	2.81	2.80	1.35**
100	2.85	2.73	2.51	2.50	1.27**
	Combined data--0000 GMT (169 cases)				
50	2.32	2.45	2.63	2.79	1.66*
100	2.12	2.24	2.53	2.64	1.76
	Topeka--1200 GMT (54 cases)				
50	1.97	1.98	1.73	1.67	1.20**
100	1.77	1.75	1.60	1.54	1.79
	Combined data--1200 GMT (144 cases)				
50	1.91	1.93	1.78	1.82	1.86
100	1.81	1.82	1.77	1.85	2.03

Table 2.--Root-mean-square errors (°C) in analysis of mean potential temperature ($\bar{\theta}$). Combined data refer to pooled sample from all stations except Topeka. W_1 and W_2 refer to isotropic and along-wind weighting, respectively. Double asterisks denote significance of difference at 1-percent level between standard deviations of error for ratio technique and direct analysis, first degree, W_1

Layer thickness	Direct analysis 1st degree W_1	Direct analysis 1st degree W_2	Direct analysis 2nd degree W_1	Direct analysis 2nd degree W_2	Ratio method 1st degree W_1
mb			Topeka--0000 GMT (62 cases)		
50	3.03	2.99	3.02	3.06	.92**
100	2.81	2.70	2.57	2.58	1.08**
			Combined data--0000 GMT (169 cases)		
50	2.53	2.64	3.14	3.18	1.27**
100	2.22	2.34	2.66	2.76	1.55**
			Topeka--1200 GMT (54 cases)		
50	2.53	2.55	2.51	2.49	1.84
100	2.15	2.16	2.13	2.08	1.95
			Combined data--1200 GMT (144 cases)		
50	3.16	3.04	3.58	3.79	3.24
100	2.62	2.55	3.04	3.19	3.10

Table 3.--Root-mean-square errors (°C) in analysis of dew point at selected levels. Combined data refer to pooled sample from all stations except Topeka. All analyses use isotropic weighting (W_1). Asterisks denote significance of difference between standard deviations of error for lapse rate and direct analysis, first degree, W_1; * means significant at 5-percent level, ** at 1-percent level

Pressure level (above ground)	Direct analysis 1st degree	Direct analysis 2nd degree	Lapse rate 1st degree
mb	Topeka--0000 GMT (62 cases)		
50	4.45	3.86	2.07**
100	4.45	3.96	2.63*
200	5.82	5.86	5.71
	Combined data--0000 GMT (169 cases)		
50	3.67	4.14	2.88
100	4.33	5.45	4.05
200	7.09	7.50	7.10
	Topeka--1200 GMT (54 cases)		
50	3.59	3.42	3.50
100	4.52	4.97	4.84
200	5.52	6.34	5.51
	Combined data--1200 GMT (144 cases)		
50	4.53	4.42	4.54
100	5.01	5.90	5.27
200	7.76	9.00	7.37

with use of the lapse-rate technique. At 50 mb above the ground, errors are roughly 4°C with use of direct analysis and approximately 2°C with use of lapse rates and surface data. Errors increase with height, becoming approximately the same as those with direct analysis at 200 mb above the ground. Results for the pooled sample are similar, but differences are not statistically significant and the superiority of the lapse-rate technique disappears near 100 mb above the ground. With direct analysis, second-degree polynomials are better at Topeka and first-degree polynomials are better for the combined data.

At 1200 GMT, errors are roughly the same for all techniques. Nothing is gained by the use of surface data.

Temperature at Specific Levels

At 0000 GMT, lowest errors in temperature analysis are associated with the lapse-rate technique only at the pressure level 50 mb above the ground (table 4). At Topeka, this difference is significant at the 1-percent level. Errors are nearly 3°C with direct analysis, slightly more than 1°C with lapse rates and surface data. At 200 mb above the ground, errors with the lapse-rate approach are significantly larger than those with direct analysis.

At 1200 GMT, lowest errors are associated with direct analysis, using second-degree polynomials at Topeka and first-degree polynomials at other stations. The lapse-rate approach is significantly worse than direct analysis at levels 100 and 200 mb above the ground.

CONCLUSIONS

Tests of the various analysis techniques indicate that:

1) Use of surface reports through Inman's ratio technique yields improved estimates of mean mixing ratio and mean potential temperature in layers 50- and 100-mb-deep at 0000 GMT. At 1200 GMT, improvement is apparent only at Topeka and is significant only for the 50-mb-deep layer.

2) Use of surface reports through analysis of lapse rates yields improved estimates of dew point to levels between 100 and 200 mb above the ground at 0000 GMT. The improvement in temperature is restricted to the lowest 50 mb. The lapse-rate technique should not be used with 1200 GMT data.

3) In the boundary layer over the central and eastern United States, isotropic weighting gives results as good or better than use of the more complicated along-wind weighting function described by Endlich and Mancuso. In a further stratification of the data at Topeka, we found this result to be true for high- (greater than 20 kt) as well as low-wind speed cases.

4) For the combined sample, better results were obtained from

Table 4.--Root-mean-square errors (°C) in analysis of temperature at selected levels. Combined data refer to pooled sample from all stations except Topeka. All analyses use isotropic weighting (W_1). Asterisks denote significance of difference between standard deviations of error for lapse rate and direct analysis, first degree, W_1; * means significant at 5-percent level, ** at 1-percent level

Pressure level (above ground)	Direct Analysis 1st degree	Direct Analysis 2nd degree	Lapse rate 1st degree
mb	Topeka--0000 GMT (62 cases)		
50	2.97	2.87	1.13**
100	2.33	1.91	2.01
200	2.04**	1.79	3.07
	Combined data--0000 GMT (169 cases)		
50	2.00	2.40	1.76
100	1.72	1.99	2.29
200	1.61**	1.63	2.87
	Topeka--1200 GMT (54 cases)		
50	2.33	2.09	2.35
100	1.93**	1.81	2.61
200	2.36*	2.33	3.49
	Combined data--1200 GMT (144 cases)		
50	3.89	3.94	4.24
100	2.04**	2.13	3.00
200	1.69**	1.84	3.28

direct analysis with first-degree than with second-degree polynomials. At Topeka, the reverse was true.

In general, it appears that improved boundary-layer analyses can be obtained with ratio or lapse-rate techniques only during that portion of the day when surface and lower tropospheric variables are highly correlated as a result of vertical mixing. Improvement within the lowest 50 mb at Topeka at 1200 GMT (see tables 1 and 2) may result from breakdown of the nocturnal inversion and mixing within the lowest layers through mechanical turbulence associated with the development of the low-level jet (Kaimal and Izumi 1965; Bonner and Winninghoff 1969). The improvement with use of second-degree polynomials in direct analysis at Topeka may reflect the climatology of the region: the frequent occurrence of warm, moist tongues near Topeka, which are poorly defined by a least-squares plane surface,fit.

In the trajectory model (Reap 1968), parcels terminating at the surface generally originate at levels within the lowest 100 mb. Thus, use of the lapse-rate technique at 0000 GMT should increase the accuracy of the initial analysis and of the surface temperature and dew point forecasts made by the trajectory model. Root-mean-square errors in tables 3 and 4 can be used to estimate relative weights or reliabilities to be given surface observations in the analysis scheme. Reliability should vary with altitude--ranging from 1 at the surface to 0 at levels where root-mean-square errors from lapse-rate and direct-analysis techniques are essentially the same. At these levels, no useful information is provided by the surface report.

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APPENDIX

Table 1A.--Root-mean-square errors in analysis of mean mixing ratio ($\overline{w}$). Errors are for individual stations of the pooled sample. W_1 and W_2 refer to isotropic and along-wind weighting, respectively. Asterisks denote significance of difference between standard deviations of error for ratio technique and direct analysis, first degree, W_1; * means significant at 5-percent level, ** at 1-percent level.

0000 GMT						1200 GMT				
Direct analysis				Ratio method		Direct analysis				Ratio method
1st degree		2nd degree		1st degree	Layer thickness	1st degree		2nd degree		1st degree
W_1	W_2	W_1	W_2	W_1		W_1	W_2	W_1	W_2	W_1
Cape Hatteras (57 cases)					mb	Cape Hatteras (49 cases)				
2.95	3.17	3.69	4.04	2.13*	50	2.52	2.53	2.14	2.24	2.04
2.67	2.89	3.66	3.90	2.28	100	2.47	2.46	2.27	2.34	2.68
Jackson (48 cases)						Jackson (44 cases)				
2.24	2.37	2.25	2.22	1.82	50	1.43	1.40	1.37	1.43	1.71
2.09	2.17	2.02	1.96	1.84	100	1.42	1.44	1.41	1.55	1.54
Pittsburgh (64 cases)						Pittsburgh (51 cases)				
1.65	1.61	1.53	1.53	.85**	50	1.57	1.62	1.71	1.66	1.81
1.51	1.50	1.40	1.43	1.00**	100	1.29	1.32	1.49	1.52	1.65

Table 2A.--Root-mean-square errors in analysis of mean potential temperature ($\overline{\theta}$). Errors are for individual stations of the pooled sample. W_1 and W_2 refer to isotropic and along-wind weighting, respectively. Asterisks denote significance of difference between standard deviations of error for ratio technique and direct analysis, first degree, W_1; * means significant at 5-percent level, ** at 1-percent level

0000 GMT						1200 GMT				
Direct analysis				Ratio method		Direct analysis				Ratio method
1st degree		2nd degree		1st degree	Layer thickness	1st degree		2nd degree		1st degree
W_1	W_2	W_1	W_2	W_1		W_1	W_2	W_1	W_2	W_1
Cape Hatteras (57 cases)					mb	Cape Hatteras (49 cases)				
2.79	3.10	4.25	4.30	1.45**	50	3.15	2.62	3.93	4.54	3.21
2.49	2.80	3.59	3.75	1.73**	100	2.60	2.22	3.39	3.72	3.44
Jackson (48 cases)						Jackson (44 cases)				
1.94	1.99	2.01	2.18	1.19**	50	1.20	1.20	1.17	1.30	1.35
1.74	1.78	1.77	1.95	1.47	100	1.08**	1.13	1.21	1.35	1.55
Pittsburgh (64 cases)						Pittsburgh (51 cases)				
2.66	2.61	2.64	2.57	1.14**	50	4.17	4.26	4.49	4.39	4.26
2.28	2.25	2.20	2.17	1.45**	100	3.45	3.53	3.72	3.72	3.70

Table 3A.--Root-mean-square errors in analysis of dew point at selected levels. Errors are for individual stations of the pooled sample. All analyses use isotropic weighting (W_1). Asterisks denote significance of difference between standard deviations of error lapse rate and direct analysis, first degree, W_1; * means significant at 5-percent level, ** at 1-percent level

0000 GMT				1200 GMT		
Direct analysis 1st degree	Direct analysis 2nd degree	Lapse rate 1st degree	Pressure level (above ground)	Direct analysis 1st degree	Direct analysis 2nd degree	Lapse rate 1st degree
	Cape Hatteras (57 cases)		mb		Cape Hatteras (49 cases)	
4.45	6.00	3.92	50	4.35	3.71	3.86
5.38	7.98	5.30	100	6.79	8.63	7.29
8.82	9.84	9.31	200	9.86	12.00	9.33
	Jackson (48 cases)				Jackson (44 cases)	
3.47	2.88	2.45*	50	3.16	2.88	2.76
4.37	3.77	3.59	100	4.70	4.63	4.29
3.85	4.33	4.03	200	5.95	5.71	5.66
	Pittsburgh (64 cases)				Pittsburgh (51 cases)	
2.98	2.64	1.91**	50	5.57	5.89	6.12
3.05	3.31	2.92	100	2.74	3.25	3.40
7.04	7.15	6.61	200	6.80	7.89	6.49

Table 4A.--Root-mean-square errors in analysis of temperature at fixed levels. Errors are for individual stations of the pooled sample. All analyses use isotropic weighting (W_1). Asterisks denote significance of difference between standard deviations of error lapse rate and direct analysis, first degree, W_1; * means significant at 5-percent level, ** at 1-percent level

0000 GMT				1200 GMT		
Direct analysis 1st degree	Direct analysis 2nd degree	Lapse rate 1st degree	Pressure level (above ground)	Direct analysis 1st degree	Direct analysis 2nd degree	Lapse rate 1st degree
	Cape Hatteras (57 cases)		mb		Cape Hatteras (49 cases)	
2.43	3.21	2.02*	50	2.97	3.08	4.02
1.89*	2.54	2.57	100	2.08**	2.38	3.81
1.81**	1.97	3.26	200	1.87**	2.28	4.54
	Jackson (48 cases)				Jackson (44 cases)	
1.65	1.76	1.61	50	1.33	1.54	1.66
1.45**	1.59	1.98	100	1.33**	1.30	2.34
1.20**	1.25	2.42	200	1.20**	1.40	2.33
	Pittsburgh (64 cases)				Pittsburgh (51 cases)	
1.81	1.94	1.61	50	5.72	5.72	5.74
1.76*	1.67	2.25	100	2.46	2.42	2.61
1.68**	1.54	2.79	200	1.86*	1.71	2.43

(Continued from inside front cover)

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