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DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

AN EVALUATION OF THE NATIONAL METEOROLOGICAL CENTER'S EXPERIMENTAL BOUNDARY LAYER MODEL

Paul D. Polger
Development Division

National Meteorological Center
Suitland, Md.
December 1974

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AN EVALUATION OF THE NATIONAL METEOROLOGICAL CENTER'S EXPERIMENTAL PLANETARY BOUNDARY LAYER MODEL

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ABSTRACT. For almost a year, the National Meteorological Center (NMC) experimented with a planetary boundary layer model (PBL) to determine its utility in NMC operations. The PBL model is similar to the operational boundary layer model used by the Air Force Global Weather Central (AFGWC). The PBL model has eight levels, surface to 1600 m, and a horizontal grid mesh of 190.5 km over the contiguous United States. Forecasts were based on 0000 G.m.t. data and were run to 24 hours. The parameters forecast by the PBL model include temperature, winds, relative humidity, freezing levels, precipitation type, and severe weather indices. The results show that the NMC PBL model has potential for providing useful forecasts of ceiling/visibility combination, rain vs. snow delineation, and areas of severe weather and temperature changes over the eastern two-thirds of the United States. The PBL model does not perform well over the mountain region or during the summer months.

1. INTRODUCTION

In September 1971, an effort was undertaken at the NMC to examine the feasibility of combining a PBL model with the NMC limited-area fine-mesh (LFM), primitive equation (PE) model. In such a system, the LFM model is run first to provide initial and forecast values necessary to operate the PBL model. The model that evolved is similar to the one that has been in operational use by the AFGWC since December 1969. The AFGWC boundary layer model (Hadeen 1970) was adapted from a model for forecasting synoptic-scale low cloudiness developed by Gerrity (1967).

The implementation of the PBL model at NMC required development of an objective analysis code for processing surface and upper-air observations and transposing the LFM model data required as boundary conditions. The actual forecast model was adapted from the AFGWC boundary layer forecast model and modified to operate with the NMC computer system. Finally, to facilitate the production of output, the graphics were generated on microfilm. The above efforts have been documented by Gross et al. (1972).

Once the major components of the PBL model project had been completed, several test cases were carried out to obtain a preliminary evaluation of the model's performance (Gerrity et al. 1972). The results of these preliminary tests of the LFM-PBL model concurred, in general, with the expectations assumed at the onset of the study. Although some inadequacies in the analysis and prediction schemes were suggested by the results of the preliminary tests, further modification was set aside until experience could be gained from a more extensive evaluation. The approach to be used in conducting this evaluation was the next matter of concern.

In conjunction with compiling statistics on the basic forecast variables, it was desired that subjective and, where possible, objective evaluations should be obtained by disseminating information to potential users on as near a real-time basis as possible. To that end, the PBL model was run in an experimental, semioperational framework beginning in the fall of 1972. The forecasts were run out to 24 hours once a day, using the 0000 G.m.t. data cycle. The forecasts were normally completed 9 hours after the observation time, and then distributed to users outside of NMC by means of a facsimile transmission. Internal distribution to the NMC Forecast Division was accomplished through hard copies from the microfilm, which was processed on an operational basis.

2. FORECAST MODEL AND ANALYSIS

A detailed discussion of the PBL model, including a derivation of the model equations, has been given in the previously mentioned papers by Gerrity (1967) and Hadeen (1970). For our purposes, only a cursory examination of the model physics and analysis technique will be presented in this test.

The PBL model forecast area is a subset of the LFM model forecast region and is shown by the innermost rectangle of figure 1. The horizontal area is divided into a 29 x 27 grid point network with a grid interval of 190.5 km, true at 60°N. The vertical structure, figure 2, is divided into 8 levels from the surface of the terrain up to 1600 m above the surface. The forecast variables are the horizontal and vertical wind components, temperature, specific humidity, and specific moisture. The specific moisture accounts for liquid water after the air becomes saturated, since the model has no mechanism for precipitation.

The model has two regions in the vertical; a surface contact layer 50 m deep and a transition layer 1550 m deep. The winds within the transition layer are computed diagnostically assuming a balance of the coriolis, pressure gradient, and eddy viscous forces. The eddy viscosity coefficient, calculated by applying stability-dependent, constant-flux profile formulas within the surface contact layer, is taken to be invariant with height within the transition layer. In addition, calculations within the contact layer specify the heat and moisture flux at the lower boundary of the transition layer.

The assumption that the eddy fluxes within the contact layer are constant with respect to height is the basis for the development of a similarity theory of the structure of the atmosphere within this layer. The results of similarity theory and numerous empirical studies imply two primary turbulence regimes, free and forced convection, which occur in the air layer near the ground. In the PBL model, a third regime is introduced to account for the case of a strong stable stratification.

The surface temperature is formulated to allow for changes principally through advection and radiation. The radiation changes are calculated as a function of local time and length of day, and then scaled down by the presence of clouds inferred from the relative humidity forecasts of the PBL and LFM models. The surface specific humidity is calculated empirically and allowed to change principally through advection.

The PBL model analysis program generates the initial data and boundary conditions for the forecast model. The initial fields are temperature, specific humidity, and a parameter designed to simulate surface moisture. Also included in the analysis code are certain fixed fields such as elevation, roughness length, and latitude and longitude. The boundary conditions, which are the horizontal wind components and the cloudiness at the top of the model, are derived from the LFM model forecast data.

In the analysis of temperature and specific humidity, the fields are built up from the relatively data-dense surface level to the more sparse upper data levels. Upper-air data are obtained from conventional radiosondes including significant level data, while surface data include both land and ship reports. Lapse rates are analyzed at the levels above the surface and then anchored at the ground to a detailed surface analysis. Analyzing lapse rates enhances the control of vertical stability.

3. MODEL OUTPUT

After the completion of the forecast and analysis codes, the remaining task was to develop an output package. This was accomplished by using the data available at the multiple levels of the PBL model and adapting the data to a sophisticated microfilm program, which enabled the development of output formats that maximized the information content.

The forecast parameters included the temperature, relative humidity, vertical velocity, horizontal wind speed and direction, multiple freezing levels, severe weather indices, air pollution indices, and turbulence indices. When any of the above parameters required data above the PBL model levels, the information was specified from the LFM model initial and forecast values. The initial and forecast values generated by the LFM for use by the PBL model as boundary conditions or output data comprise the only interaction between the two models.

The output that resulted from the above data was processed at the initial, 12-, and 24-hour times for the entire PBL forecast region. The horizontal depictions included (1) 50 m vector wind and surface temperature, (2) mean relative humidity 50 to 1600 m and precipitation type, (3) mean relative humidity 50 to 300 m, vertical velocity, and temperatures at 300 m, (4) mean relative humidity 600 to 1600 m, vertical velocity, and temperature at 1600 m, (6) mixing height and total wind speed, (7) relative concentration of pollutants, (8) best lifted index (Fujita 1970) and a modified total-total index (Miller 1972). In addition, a vertical depiction was developed which presented forecast values at hourly intervals out to 24 hours. The variables predicted at each level of these PBL model time cross sections are the temperature, relative humidity, vector wind, and freezing levels.

4. EVALUATION

The evaluation of the PBL model was divided into four major areas: (1) studies performed by the Forecast Division (FD) of the NMC which involved verification of ceiling/visibility forecasts and rain vs. snow forecasts; (2) NSSFC study of the severe weather indices generated by the PBL model; (3) study by several Weather Service Forecast Offices (WSFO) of the time cross sections; (4) study of basic statistics of temperature and relative humidity prepared by the Development Division of the NMC.

A. Ceiling/Visibility and Rain Versus Snow

A test program for ceiling/visibility category forecasts derived from the PBL model 24-hour mean relative humidity prognoses was conducted by the FD during the period February 28 to May 31, 1973. The program was designed to assess the usefulness of the PBL model as guidance in preparing low-level significant weather forecasts. The 24-hour PBL model mean relative humidity prognoses were converted into ceiling/visibility category forecasts at a 60-station FD verification network over the United States using the following criteria:

- Forecasts of category 1 (ceiling ≤ 1000 feet and visibility ≤ 3 miles) were assumed at all stations in the areas where the mean relative humidity for the layer 50 to 300 m was forecast to be 90 percent or more.
- Forecasts of category 2 (ceiling 1000 to 5000 feet and visibility ≥ 3 miles) were assumed at stations in the areas where the mean relative humidity for the layer 600 to 1600 m was forecast to be 80 to 89 percent.
- Forecasts of category 3 (ceiling > 5000 feet and visibility ≥ 3 miles) were assumed at stations outside the above areas.

A utility score was determined using the FD verification matrix shown in table 1, which grants more credit for correct forecasts in categories that occur less frequently. The evaluation was divided into three test periods. The results, which were prepared independently of the FD forecast, are given in table 2. Note that the differences between the utility scores decrease in the last of the three test periods. Experience with objective forecast techniques tested by FD has shown that the objective methods tend to do better when the frequency of category 3 is greater, which is the case as the season shifts from winter to spring.

Table 1.--Verification matrix employed for the computation of a utility score

		Category forecast		
		1	2	3
Category observed	1	1.0	.2	0
	2	.3	.7	.1
	3	0	.2	.4

Table 2.--Utility scores for the PBL model vs. the FD, determined from the verification matrix in table 1. The maximum score possible is given by MAX POS. The scores are for three test periods in 1973

	2/28-4/5	4/11-4/28	5/1-5/31
FD	392	256	386
PBL	338	241	381
MAX POS	551	317	460

Considering the simplicity of the criteria used to delineate categories utilizing the PBL model output, the differences in the forecasts suggest that the model has potential for supplying valuable guidance in forecasting ceiling/visibility combinations.

The verification of the rain/snow line forecast was accomplished by comparing the 24-hr PBL model forecasts to the FD forecasts and an objective forecast of the conditional probability of frozen precipitation (POFP) developed by Bocchieri and Glahn (1974). For the PBL model, a conditional precipitation type forecast is calculated at each gridpoint. The criteria for determining the conditional precipitation type were derived subjectively by analyzing soundings taken during different types of precipitation occurrences. The criteria were applied to a prognostic vertical temperature profile constructed by merging temperature forecasts from the 8 levels of the PBL model and the tropospheric levels of the LFM model. The forecasts discriminate between rain, snow, freezing rain, sleet, and mixed rain/snow. For the purpose of verification, only the delineation between rain (rain or mixed rain/snow) and snow (snow, sleet, or freezing rain) was taken into account. The forecasts were compared utilizing independent evaluations of the PBL model vs. the FD and POFP forecasts. The intent was not to determine the skill of one forecast method over another, since relatively few cases were considered, but rather (as with the ceiling/visibility test program) to obtain a measure of the usefulness of the PBL model output. In the comparison of the PBL model vs. the POFP for 29 cases, the PBL model forecasts were judged better for 56 percent and equal for 10 percent of the cases. In comparison to the FD forecasts, the PBL model forecasts were judged better for 50 percent and equal for 16 percent of the cases.

B. Severe Weather Indices

The verification of the severe weather indices generated by the PBL model was carried out at the NSSFC (Mogil 1974). The two indices evaluated were the Best Lifted Index (BLI) and a Modified Total-Total (MTT).

The concept of the BLI was introduced by Fujita (1970) who noted that a lifted index computed from a fixed level such as the surface might misrepresent the stability of the air mass. This results from the fact that the base of an updraft or unstable layer will vary from point to point in the lowest level of the troposphere. The PBL model, with 8 levels in the lowest 1600 m of the atmosphere, provides the resolution necessary to obtain the BLI from the model parameters. The BLI is the most unstable value of the lifted index computed from the 8 levels of the PBL model used in conjunction with the LFM model tropospheric data.

The MTT index is defined as the sum of the temperature and dewpoint in ^{o}C at the 900-m level of the PBL model, minus twice the temperature at 500 mb from the LFM model. The modification was to use 900-m values of temperature and dewpoint, rather than 850-mb values as originally employed by Miller (1972) to compute the total-total. The result of the change is a shift in threshold values for severe weather.

Severe weather forecasts were verified on a digitized radar (DR) data grid over much of the eastern two-thirds of the United States for grid squares roughly 95 km on a side. The forecasts were verified using both DR data and the SELS Severe Weather Log. The results of the verifications for the 1973 spring period are given in table 3. The verification period was composed of 39 forecast days during which an average of 24.6 severe weather reports were recorded daily. Of the 39 days, 31 were considered important severe weather days during which 10 or more severe weather reports were recorded in the SELS log.

Table 3.--Percentage frequency (f(%)) of severe weather associated with the MTT and BLI. The number of squares covered by a given index value or range of values is given by N.

MTT	N	f(%)	BLI	N	f(%)
≤ 41	2709	.37	≥ -1	6371	.24
42-44	2748	.73	-2	2392	1.09
45-47	4538	1.04	-3	3094	1.07
48-50	6541	1.77	-4	3533	1.57
51-53	5543	3.23	-5	3173	1.76
54-56	3096	5.52	-6	2698	3.78
≥ 57	1622	7.60	-7	1943	5.04
			-8	1326	5.67
			≤ 9	2267	9.00

The values shown in table 3 indicate the direct relations between the values of the BLI and MTT, and severe weather frequency. For the BLI and MTT, 80 percent of the occurrences of severe weather were recorded for values less than minus 6 and greater than 50, respectively. It should be noted that both indices had a bias toward overforecasting the anticipated area of severe weather, particularly in the Gulf States.

C. Time Cross Sections

The time cross sections were designed to depict the vertical structure of the atmosphere through the 8 levels of the PBL model and indicate changes in this structure with time. An example of a PBL model time cross section (TCS) is shown in figure 3. The time runs from right to left, zero to 24 hours. The solid contours are temperature in degrees Celsius, the dashed lines are relative humidity in percent, and the vector winds are in knots. The surface temperature in °F is shown at the bottom of the chart, with the freezing levels--including those from the LFM model troposphere forecasts, shown at the top of the TCS. The elevation in feet above sea level for the particular grid point location of the TCS is given at the right margin. It is important to note that because of the horizontal resolution of the PBL model grid network, grid point values were not interpolated to the actual location of Weather Service Forecast cities.

The results for two of the WSFOs, which participated in the evaluation and verified the TCS over an extended period, will be discussed in this section. A subjective evaluation was performed for the grid point closest to New York City, and an objective study was conducted for the grid point closest to Sioux Falls, S. Dak.

To evaluate the TCS at New York City, weather elements were delineated into several categories which included ceiling $\leq$ 5000 ft, onset or ending of ceiling $\leq$ 5000 ft, onset or ending of precipitation, and temperature changes $\geq$ 25°F in 12 hours. These elements were then evaluated relative to how well the observed element corresponded to the PBL model predictors which included relative humidity, temperature stratification, change of wind direction, trend of relative humidity, change of wind speed, and freezing levels. The verification was carried out for 103 cases between December 1972 and May 1973. Of a total of 1108 responses relating the PBL model predictors to the observed weather, 42 percent were recorded as well related, 23 percent were moderately related, and 35 percent were poorly related. In individual categories, the relative humidity factors proved to be the best related--while the wind factors were the PBL model predictors most poorly related to the observed weather.

The relative humidity forecasts from the PBL model previously discussed in connection with ceiling/visibility category forecasts at NMC were also investigated at the grid point nearest Sioux Falls, S. Dak. For 100 cases during the period November 30, 1972, and April 30, 1973, the PBL mean relative humidity forecasts for the layer from the surface to approximately 2500 ft above the ground level were compared to the occurrence of ceilings at or below 2500 ft and those below 1000 ft. The frequency of ceilings for both the 1000-ft level and the 2500-ft level, which includes the values of the lower level, are shown in figure 4. The frequency of ceilings is directly proportional to the mean relative humidity of the PBL model. During the same test period, a comparison of the PBL model 24-hour surface temperature forecast to the observed value at Sioux Falls resulted in a root-mean-square (rms) error of 4.11°C.

Additional statistics were compiled from upper air observations taken at Huron, S. Dak. The error and bias were determined for temperature, relative humidity, wind direction, and wind speed. For the purpose of verification, the data from the Huron upper air sounding was always within 50 m of the appropriate level of the TCS. The results are shown in table 4. It will be seen later that the rms errors of temperature and humidity are comparable to those calculated for the region over the eastern two-thirds of the United States. The freezing level at Huron was also evaluated and found to have an rms error of 930 ft with a positive bias of 514 ft.

Table 4.--PBL time cross section for Sioux Falls, S. Dak., verified at 24 hours against Huron, S. Dak. sounding. The rms errors are given by the top number, with the bias in parenthesis below.

	Temperature (°C)	Relative humidity (%)	Wind direction (deg)	Wind speed (kt)
Surface	3.24	14.9	64.3	5.75
	(.61)	(-3.88)	(2.80)	(-4.14)
300 m	3.44	15.0	80.3	9.75
	(.10)	(-6.50)	(41.5)	(1.15)
900 m	3.76	18.0	87.6	10.2
	(.85)	(-7.7)	(27.2)	(-.35)
1600 m	4.42	17.5	61.0	9.43
	(2.68)	(-8.75)	(26.6)	(-1.02)

D. Basic Statistics

The statistics compiled on the PBL model temperature and relative humidity forecasts are summarized in table 5. They are based on 24-hour forecasts valid at 0000 G.m.t. and are verified against the 0000 G.m.t. PBL model analysis, which is independent of the forecast. The verification area was divided into two regions, which included the eastern two-thirds of the United States as one region and the Western Mountain States as the other. The forecasts were verified at the surface and 300, 600, and 1600 m for the forecast temperature change, forecast relative humidity changes, and the corresponding observed changes. The values shown in table 5 are mean values computed for 168 cases over a 10-month period from November 1972 through August 1973. The statistics are presented in terms of rms error, bias, and the percent difference between the rms error of forecast changes and the rms of observed changes.

The mountain region yields consistently poor results for both forecast parameters as indicated by the bottom row of table 5. For the region over the eastern two-thirds of the United States, the temperature change forecasts have an average error of approximately 3°C, except at 1600 m where there is a large bias in the forecasts. The results of the relative humidity change forecasts are mixed, but on the average there is an improvement over the observed rms change--which is essentially the error of persistence. The bias of the observed changes, not shown, is small as would be anticipated when averaged over the 10-

month verification period. The biases of forecast values were relatively small except for the 1600-m temperature, as noted above, and for the surface relative humidity.

Table 5.--Statistics of PBL model temperature and relative humidity change forecasts based on 168 cases between November 1972 and August 1973. The statistics given for the surface and 300, 600, and 1600 m are compiled only over the eastern two-thirds of the United States. The statistics for the mountain region are averaged over all the aforementioned levels.

	Temperature				Relative humidity			
	rmse fcst chg	rms obs chg	pct diff	fcst chg bias	rmse fcst chg	rms obs chg	pct diff	fcst chg bias
1600 m	3.74	3.48	-7.5	2.90	21.2	25.9	18.1	-3.9
600 m	2.69	3.27	17.7	-.18	18.5	18.0	-2.8	3.3
300 m	2.87	3.16	9.2	.22	15.6	15.8	1.3	-2.0
Surface	3.04	3.19	4.7	.39	15.1	13.8	-9.4	-5.4
Mtn. reg.	4.32	3.37	-28.2	.65	20.9	17.6	-18.7	.9

The characteristics of monthly variations in performance are presented in figure 5, which shows the percent increase or decrease of the rms error of forecast temperature and relative humidity changes vs. the rms of the observed changes. The computation which includes the 300- and 600-m levels over the nonmountain region indicates that the PBL model does not skillfully forecast changes of temperature and relative humidity during the summer months due, in part, to the persistence of that season. Similar statistics were not compiled for the wind components because the initial values are determined diagnostically rather than being analyzed from observations.

5. SUMMARY OF THE EVALUATION

The development of a planetary boundary layer forecast capability at NMC was approached from the viewpoint of testing an existing boundary layer model to determine its usefulness as a forecast tool within the NMC operational framework. The NMC PBL model was adapted from the AFGWC boundary layer model, which evolved from a model conceived for the prediction of synoptic-scale low cloudiness (Gerrity 1967). Previous evaluations by Gerrity (op cit) and Diercks (1970) of these boundary layer models, which are similar to the NMC PBL model, suggested several problem areas with regard to model performance. However, the intention set forth at the onset of the feasibility study precluded extensive development of the basic model. Hence, only minor adjustments were introduced during the coding of the PBL model for the NMC computer system. For example, a modification to the radiational component of the temperature change altered the original formulation which yielded a minimum temperature at 3 a.m. local standard time (l.s.t.) and a maximum temperature at 3 p.m. l.s.t., without regard to latitude or season. The modified formulation yields a minimum temperature at sunrise and a maximum temperature 2 hours before sunset. Modifications, such as the one just described, are simple in nature and did not resolve basic model deficiencies.

The experience gained from operating the PBL model for an extended test period suggests that it should be possible to improve the forecasts without developing a new model substantially different in character from the present version. The statistics indicate an effort should be directed at the elimination of important biases, such as those of the temperature at 1600 m and the surface relative humidity. Inherent in this effort would be an improved formulation of the surface temperature and parameterization of the cloud cover. It should also be possible to refine the procedure for diagnostically determining the wind field which the limited evaluation has shown to possess a degree of inaccuracy that, in turn, adversely affects advection-dependent parameters. This study of the PBL model and the earlier study by Diercks (1970) on the AFGWC boundary layer model show the deficiency of the model's capability to make forecasts for the mountain region.

The results of the evaluation show that the NMC PBL model has the potential of providing useful forecast information and that improved forecasts are likely through improved analysis and modeling techniques. In particular, the verification indicates that the PBL model has skill in forecasting ceiling/visibility combinations, rain vs. snow delineation, areas of severe weather, and temperature changes over the eastern two-thirds of the United States. The time cross section, presently limited by the lack of local detail, is a useful forecast tool if one considers the forecast trends rather than a special spatial or temporal prognostication. The PBL model does not perform well over the mountain region or during the summer months.

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I wish to express gratitude to Dr. Joseph Gerrity for his help in analyzing the results, and to Mrs. Mary Daigle for typing the manuscript. In addition, thanks are due to those in the National Weather Service whose participation in the evaluations made this study possible.

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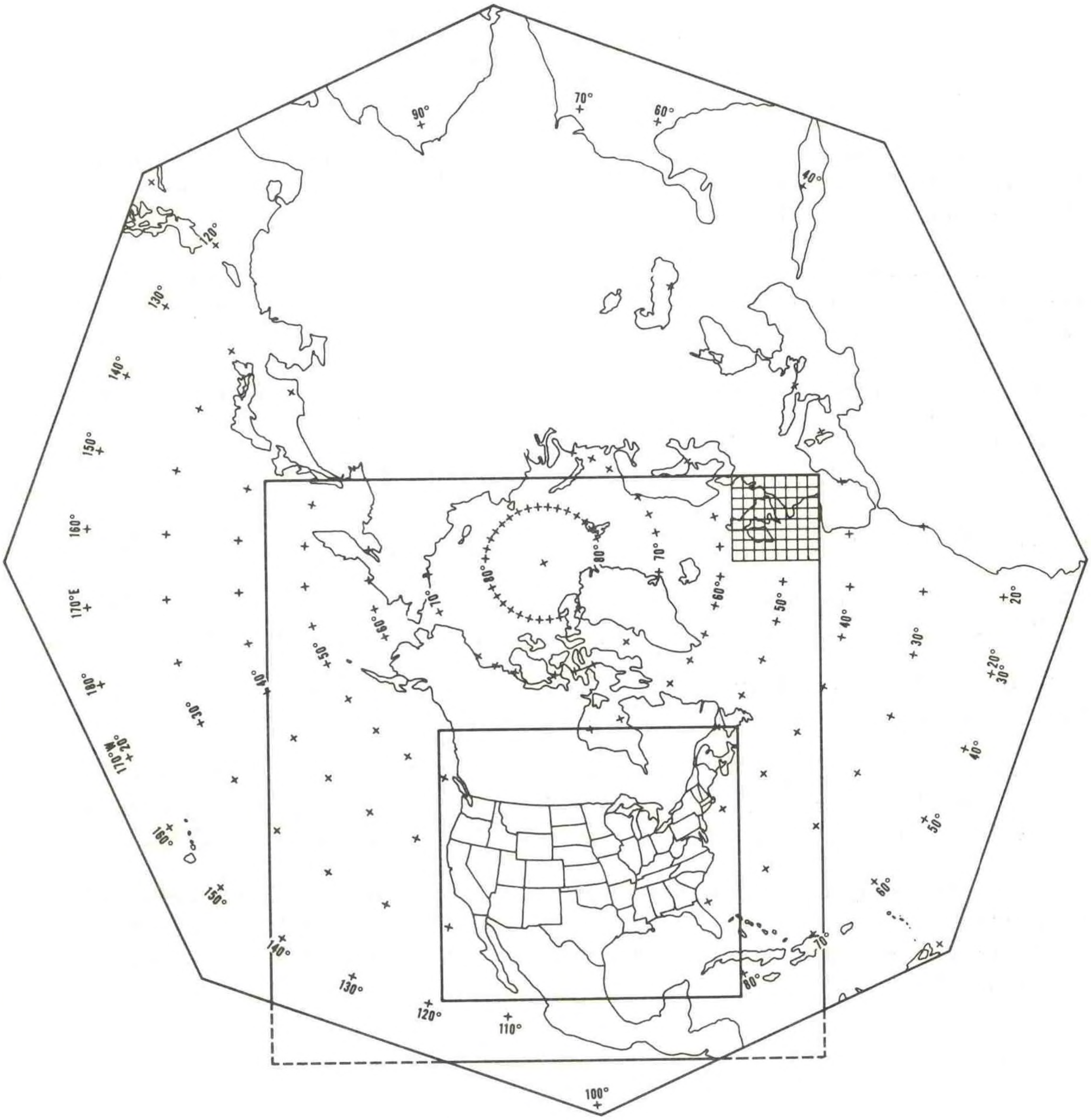

Figure 1.--Forecast areas for the PBL model (inner rectangle) and the LFM model (outer rectangle).

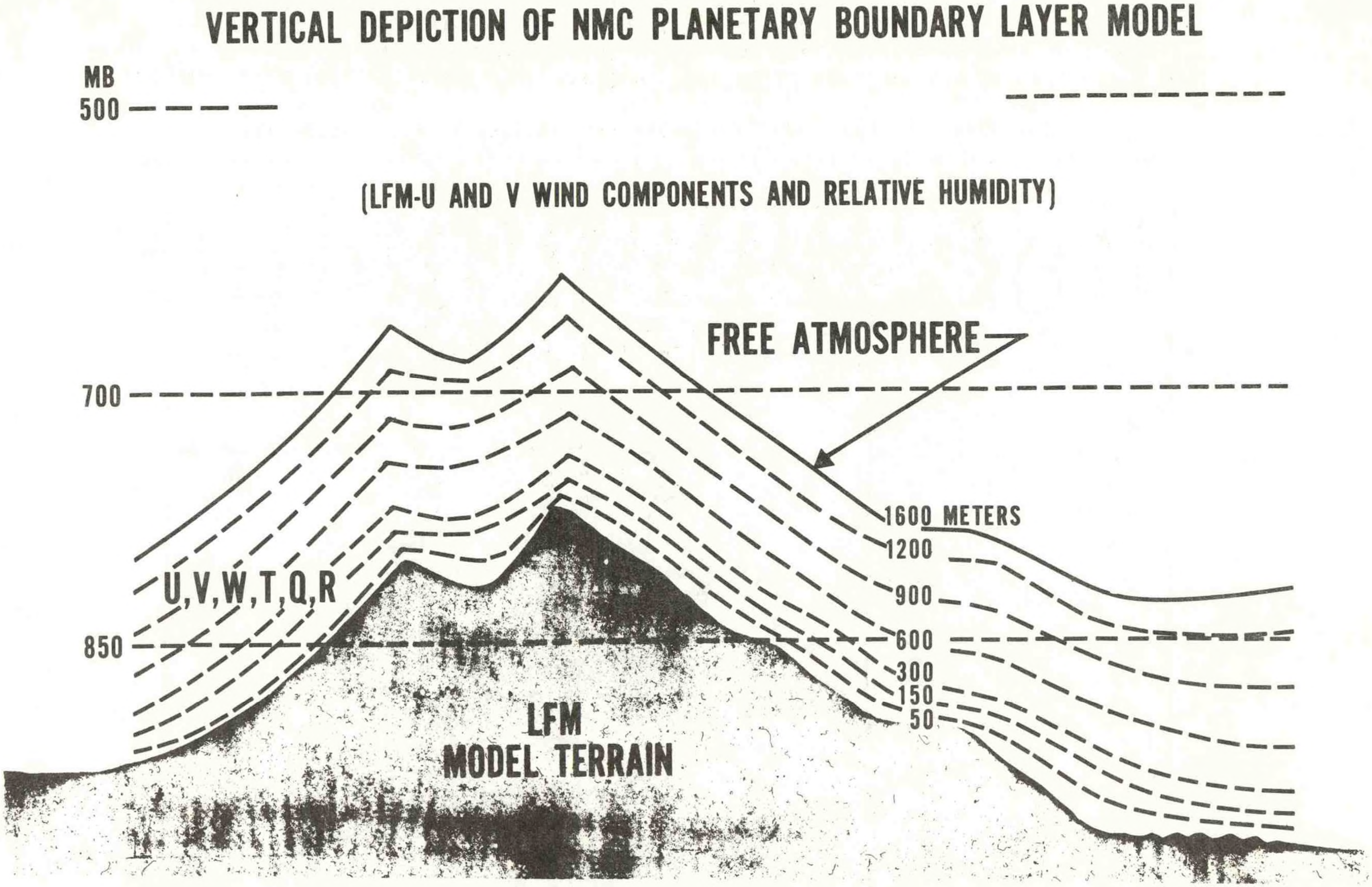

Figure 2.--Vertical depiction of the PBL model. The forecast variables are the horizontal (U,V) and vertical (W) wind components, temperature (T), specific humidity (Q), and specific moisture (R).

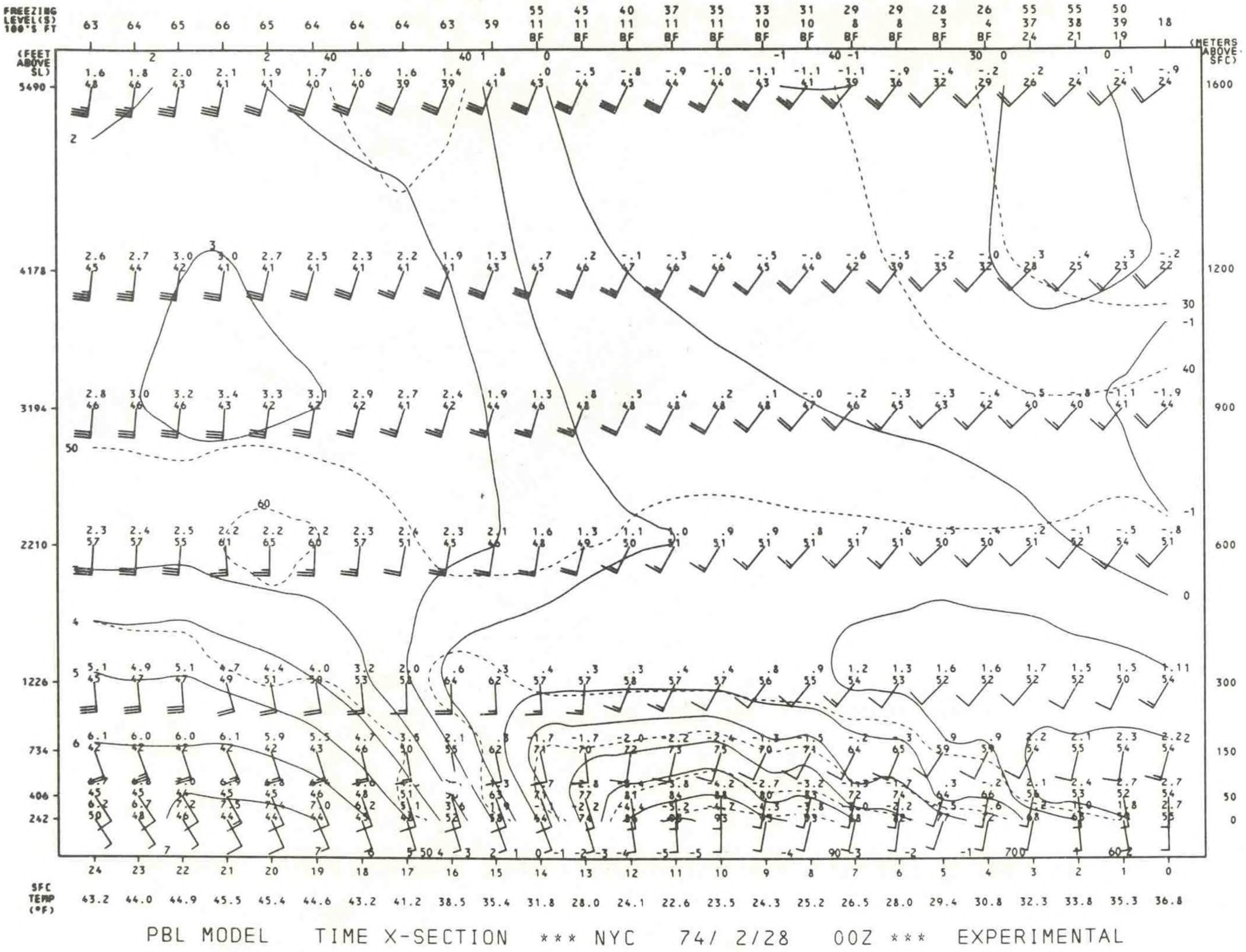

Figure 3.--A forecast time cross section. The solid contours are temperature (°C), the dashed lines are relative humidity (%), and the vector winds are in knots. The surface temperature (°F) is shown at the bottom of the chart, with freezing levels--including those from the LFM model tropospheric forecasts--at the top of the TCs.

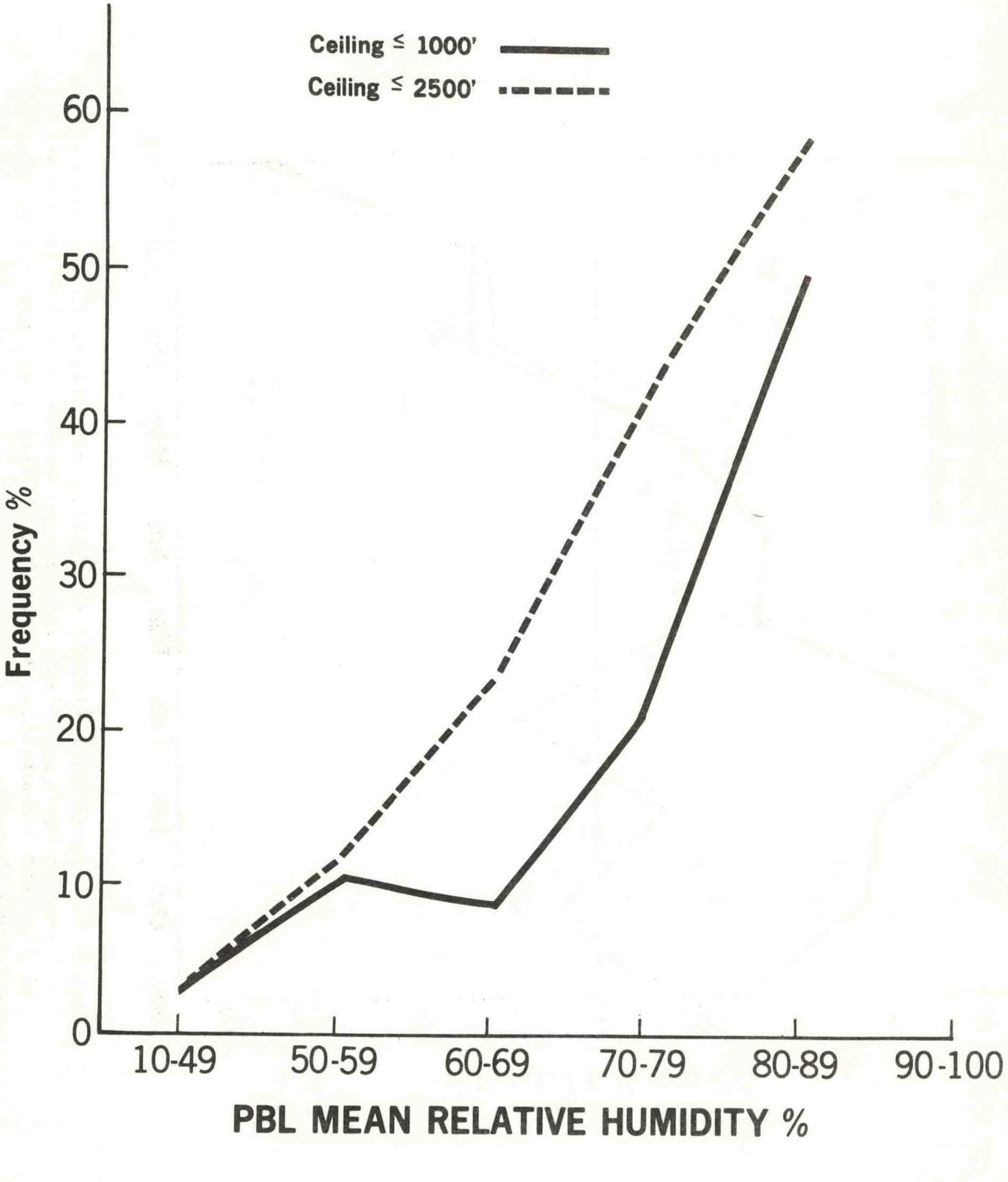

Figure 4.--The frequency of ceilings ≤ 2,500 feet related to the mean relative humidity from the PBL model time cross section for Sioux Falls, S. Dak. Data are averaged for 100 cases during the period November 30, 1972, and April 30, 1973.

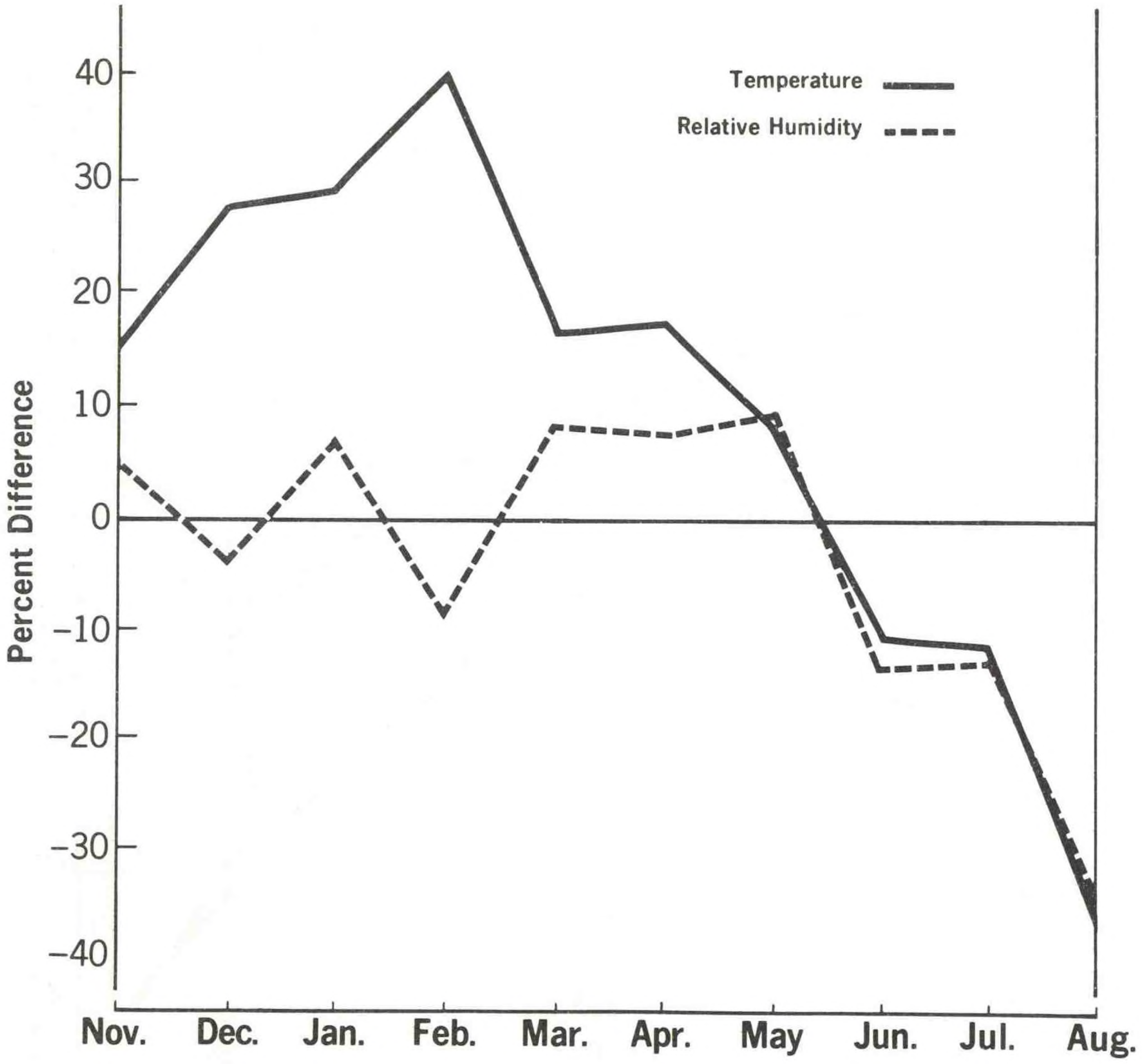

Figure 5.--The characteristics of monthly variations in performance as shown by the percentage increase or decrease of the rms error of forecast temperature and relative humidity vs. the rms of the observed changes.

(Continued from inside front cover)

NOAA Technical Memoranda

NWS NMC 49	A Study of Non-Linear Computational Instability for a Two-Dimensional Model. Paul D. Polger, February 1971. (COM-71-00246)
NWS NMC 50	Recent Research in Numerical Methods at the National Meteorological Center. Ronald D. McPherson, April 1971.
NWS NMC 51	Updating Asynoptic Data for Use in Objective Analysis. Armand J. Desmarais, December 1972. (COM-73-10078)
NWS NMC 52	Toward Developing a Quality Control System for Rawinsonde Reports. Frederick G. Finger and Arthur R. Thomas, February 1973. (COM-73-10673)
NWS NMC 53	A Semi-Implicit Version of the Shuman-Hovermale Model. Joseph P. Gerrity, Jr., Ronald D. McPherson, and Stephen Scolnik. July 1973. (COM-73-11323)
NWS NMC 54	Status Report on a Semi-Implicit Version of the Shuman-Hovermale Model. Kenneth Campana, March 1974.