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A REPORT ON EXPERIMENTS WITH THE AFGWC BOUNDARY LAYER MODEL.(U)
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Experiments were carried out to find means of improving the forecast performance of the AFGWC Boundary Layer Model. The results suggest that modifications in the methods of estimating eddy diffusivity and surface specific humidity may yield a slight improvement in the forecast accuracy while requiring less computation. It is also demonstrated that doubling the time step from 30 to 60 min does not significantly degrade the forecast accuracy. Suggestions on further modifications under less restrictive operational conditions are also included.

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A Report on Experiments With the AFGWC Boundary Layer Model

1. INTRODUCTION

This is a summary report of the efforts undertaken to investigate the Air Force Global Weather Central's Boundary Layer Model (designated as AFGWC-BLM hereafter) for possible improvements in its production of forecasts.

A comprehensive description of the model may be found in Hadeen[1] and Hadeen and Friend.[2] The approach taken and the procedures employed in the investigation have been described in detail by Yang.[3] In essence, we defined our objective to be improvement of forecast accuracy and/or forecast efficiency. Regarding the objective analysis at the time of observation as the assumed truth, the root-mean-square (rms) errors of forecast over the set of computational grid points have been chosen as the measure of accuracy. A combination of required central memory and computation time in the production of forecasts is understood to characterize the efficiency.

(Received for publication 20 October 1978)

1. Hadeen, K. D. (1970) AFGWC Boundary Layer Model, AFGWC Technical Memorandum 70-5, Air Force Global Weather Central, Air Weather Service, Offutt AFB, Nebraska.
2. Hadeen, K. D., and Friend, A. L. (1972) The Air Force global weather central operational boundary layer model, Boundary Layer Meteorology, 3:98-112.
3. Yang, C. (1976) A Proposed Procedure for Diagnosis and Improvement of Dynamical Prediction Models, AFGL-TR-76-0079.

For reasons of the operational constraints at AFGWC we sought only improvements that would require neither additional capacity in the central memory nor extra computational time. Furthermore, we limited our consideration to modifications that could be implemented on the prognostic phase of the program.

A number of synoptic samples, as represented by objective analyses made at 0Z and 12Z, and the corresponding forecasts produced by the operational AFGWC-BLM over the North American region, the so-called U.S. Window, were collected randomly during the period between April 1975 and December 1976. These analyses, serving both as the initial conditions and as the verification data, and the accompanying operational forecasts, constituted the test bed and the frame of reference, respectively, of the entire investigation. The dates and the forecast categories included in these samples are listed in Table 1.

These synoptic samples were conveniently divided into two groups; Sample Group I consisting of Time Blocks 1 through 5 and Sample Group II consisting of Time Blocks 6 through 12. All the modifications considered were first run on Sample Group I and only those that were deemed worth further investigation were tried on Sample Group II to test the inferences drawn on the basis of the earlier experiments.

Effects of various modifications to AFGWC-BLM on forecasts were analyzed by comparing characteristics of the resulting forecast errors obtained on these synoptic samples. The merit of a modification was inferred on the basis of these analyses. Because of the amounts of time and cost involved in the production and analysis of forecasts, the study was carried out in a number of stages, in which the modifications were imposed sequentially on the basis of the inferences obtained in earlier stages of the investigation.

The progress of the study is most conveniently described in five stages by chronological order. Each may be characterized by the chief concern during the stage. They are:

(1) Orientation with the operational model,
(2) Computational resolution,
(3) Vertical structure,
(4) Humidity forecasts,
(5) Tests on independent samples.

In the following, the objective, procedure, and the major findings of the investigation in each stage will be presented.

Table 1. Synoptic Samples

Sample Group	Time Block	Date	Forecast Category			
			12h/12Z	24h/12Z	12h/0Z	24h/0Z
I	1	1 Apr 75	x	x		
		2 Apr 75	x		x	x
	2	29 Apr 75	x	x		
		30 Apr 75	x	x	x	x
		1 May 75			x	
	3	14 Jul 75	x	x		
		15 Jul 75	x	x	x	x
		16 Jul 75			x	
	4	8 Sep 75	x	x		
		9 Sep 75	x	x	x	x
		10 Sep 75			x	
	5	15 Oct 75		x		
		16 Oct 75	x	x		
		17 Oct 75			x	
II	6	16 Dec 75	x	x		
		17 Dec 75			x	
	7	13 Jan 76	x	x		
		14 Jan 76	x	x	x	x
		15 Jan 76			x	
	8	23 Mar 76	x			
		24 Mar 76				x
		25 Mar 76			x	
	9	14 Jul 76	x	x		
		15 Jul 76	x		x	x
	10	26 Oct 76	x	x		
		27 Oct 76	x		x	x
	11	9 Nov 76	x	x		
		10 Nov 76	x		x	x
	12	14 Dec 76	x	x		
		15 Dec 76	x		x	x

2. THE OPERATIONAL MODEL

As we studied the logical structure of the operational model to search for areas of potential improvement, we also carried out various statistical analyses on its forecast products to learn about the characteristics of its forecast errors. Figure 1 presents the vertical profiles of the sample averages on Sample Group I of the rms forecast errors. The variables include the air temperature, the specific humidity of air, and the U- and V- components of the horizontal wind.

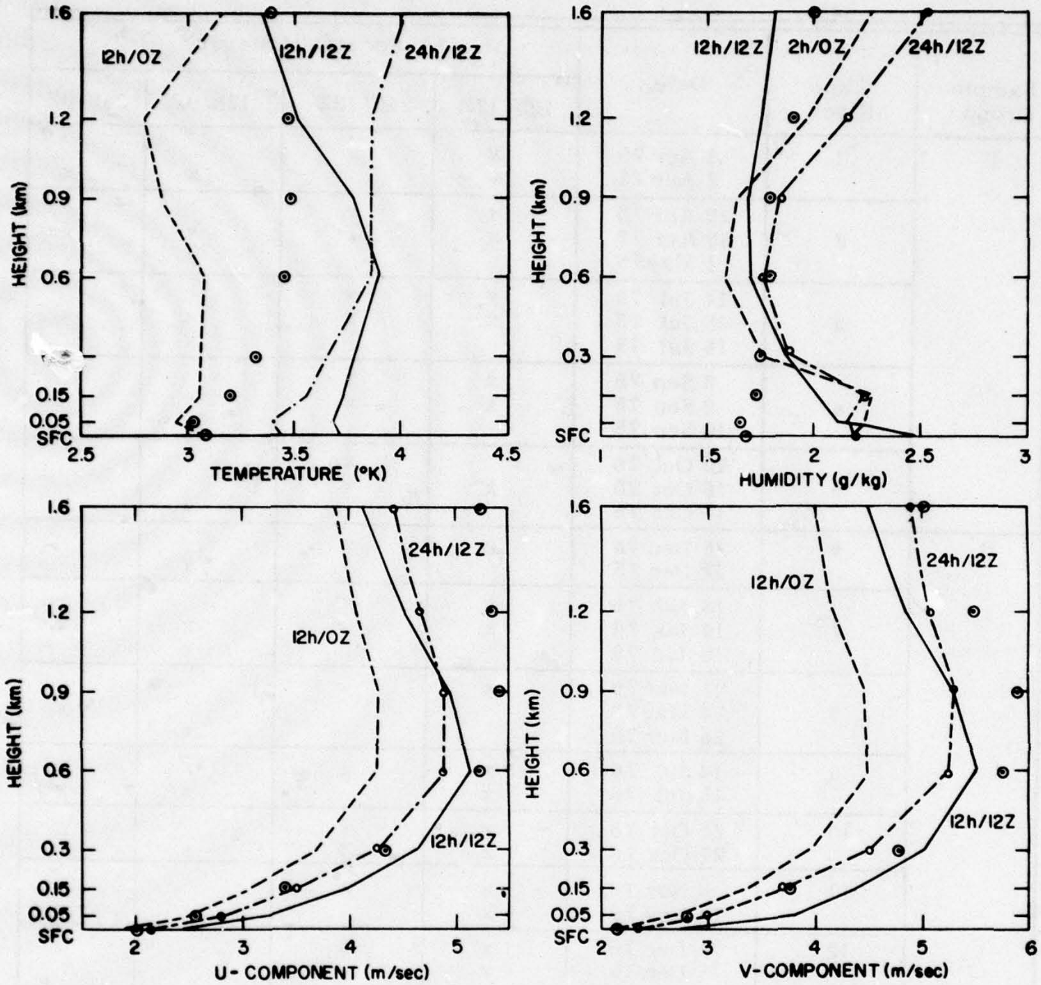


Figure 1. The RMS Errors of Forecast of the AFGWC-BLM Operational Model, Sample Group I

Because of apparent differences in the characteristics of forecast errors, we thought it advantageous to distinguish forecast categories not only by the range of forecast (either 12-hr or 24-hr forecast) but also by the time at which the forecast is prepared (either 0Z or 12Z). Thus, we have four categories, designated by 12h/12Z, 12h/0Z, 24h/12Z and 24h/0Z, respectively. The last category, 24h/0Z, however, was not included in Figure 1 because there were only four cases in Sample Group I and we did not consider it to be compatible with the other categories.

Figure 1 also includes the vertical profiles of the rms forecast errors of the persistence forecasts in category 24h/12Z. They are represented by unconnected dotted circles.

No attempt was made at this point to relate any of the statistical characteristics observed in the forecast errors with the structure of the model. There were nevertheless some noteworthy features in the geographical distributions that were believed to be due to causes extraneous to the model structure. For example, the temperature forecast error was generally larger in the western half of the domain. This error was believed to be principally due to the more complicated topography of the region compared to that of the other half. The specific humidity forecast error was largest in the southwest quadrant and the smallest in the northeast quadrant. The higher temperature and, therefore, larger moisture content in the south and the rugged terrain in the west were believed to produce such a characteristic.

We also calculated correlation coefficients to examine the degree of association and kind of relationship that might exist between any pair of the forecast errors of different variables. Table 2 lists the values of correlation coefficients between the rms errors for all six pairs of the four variables, temperature (T), specific humidity (H), and U- and V- components of the wind. Although the small number of sample cases considered makes it dubious to attach much significance to these values, Table 2 nevertheless shows clearly that specific humidity was the odd member of the group. It is also evident from the table that (U, V) is the most consistent pair of all, in both levels and categories.

Table 2 also shows that no single variable may represent any other very well in the rms forecast error. It suggests that a vector representation with each predicted variable as a component may be required to express adequately the comprehensive accuracy of a forecast of the model. On the basis of relative importance and reliability of the variables considered, however, we have chosen air temperature as the primary variable with which effects of modifications are to be evaluated first.

3. COMPUTATIONAL RESOLUTION

We carried out a study on the effects of reducing computational resolution on the forecast accuracy in order to best cope with the imposed constraint that modifications should not create additional demand on the computer beyond the limit currently allotted by GWC for the routine operation of AFGWC-BLM.

We had anticipated that improvement in the forecast accuracy would most likely result from more sophistication in the model or from more refinement in the computation. Although common sense told us that reduction in computational resolution

Table 2. Correlation Coefficients Between the RMS Forecast Errors of the Operational Model, Sample Group I

Forecast Category	Pair	Level 0	1	2	3	4	5	6	7
12h/12Z	(T, H)	-.52	-.15	.25	.29	.22	-.19	-.53	-.40
	(T, U)	.58	.47	.66	.67	.62	.51	.52	.42
	(T, V)	.55	.74	.79	.76	.59	.66	.77	.23
	(H, U)	-.20	-.69	.39	.03	.03	-.19	-.16	-.04
	(H, V)	-.66	-.14	.14	-.15	-.51	-.56	-.42	-.30
	(U, V)	.53	.56	.60	.55	.57	.67	.74	.81
12h/0Z	(T, H)	-.42	-.43	-.63	.04	.02	.53	.44	.28
	(T, U)	.37	.30	.23	.07	.03	-.28	-.33	-.16
	(T, V)	.27	.38	.10	.54	.53	.36	.21	.05
	(H, U)	-.20	-.45	-.56	-.21	.28	.23	.14	.16
	(H, V)	.24	-.20	-.27	-.14	-.30	.21	.65	.63
	(U, V)	.40	.46	.32	.24	.22	.27	.39	.55
24h/12Z	(T, H)	-.11	-.02	.03	.22	-.29	-.40	-.47	-.19
	(T, U)	.42	.38	.27	.36	.46	.48	.64	.75
	(T, V)	.24	.28	.20	.62	.79	.70	.54	.42
	(H, U)	-.78	-.82	-.84	-.30	.09	.03	.01	.14
	(H, V)	-.74	-.75	-.63	-.47	-.33	-.41	-.39	-.21
	(U, V)	.69	.69	.76	.76	.69	.62	.56	.65

in any reasonable numerical model would result in degradation of accuracy of the solutions sought, we wanted to find out how it would affect the forecast accuracy as it was defined in this work. Such knowledge could be profitably used in the event that improvement could be attained by a trade-off, for example, between reduction in computational resolution and refinement in some other logical structure of the model.

Toward such an end, we ran AFGWC-BLM on Sample Group I with four different computational resolutions. They are: (0) the operational resolution, denoted by (Δx, Δt), with the fine-mesh horizontal grid interval (190.5 km at 60N) and 30-min time step; (1) version (Δx, $2\Delta t$), with the fine-mesh horizontal grid interval and 60-min time step; (2) version ($2\Delta x$, Δt), with twice the fine-mesh horizontal grid interval and 30-min time step; and (3) version ($2\Delta x$, $2\Delta t$), with both the horizontal grid interval and time step twice those of the operational versions. With no change elsewhere in the model the three alternatives (1), (2), and (3) reduce the amount of required computation time to 1/2, 1/4, and 1/8 of that of (0) respectively. In addition, alternatives (2) and (3) reduce the required storage to 1/4 of that required by (0).

To detect any substantial difference among different versions, monitoring of pertinent variables and parameters during the course of forecast runs was made by counting the number of times each variable or parameter reached the bounds that were dictated by the packing design of the model. The number of counts was referred to as the overflow count. No significant differences among the different versions were noted in the patterns of these overflow counts, dispelling our earlier concern about computational instability.

Comparisons of the geographical distributions of errors of the temperature forecasts and the quadrant statistics of individual cases among the four versions also indicated that all were in a large measure comparable. Figure 2 gives one such example and shows agreement of the four in the gross features. The high degree of association among the four versions through the widely varying synoptic samples may be gathered from Table 3 that lists the values of correlation coefficients. Based on these observations we considered it reasonable to ascribe the differences in forecast error, as represented by the differences in the rms error over the entire domain, to the differences in computational resolution.

The vertical profiles of the averages of the rms temperature forecast errors are presented in Figure 3 for three categories, (a) 12h/12Z, (b) 12h/0Z, and (c) 24h/12Z. Two significant features may be noted in these figures. The first is the closeness of version (Δx, $2\Delta t$) to the operational one in all categories. None of the differences observed between these two versions was statistically significant. The second is the contrast between category 12h/12Z on one hand and categories 12h/0Z and 24h/12Z on the other in versions ($2\Delta x$, Δt) and ($2\Delta x$, $2\Delta t$). While there were hardly any differences of statistical significance from the operational version in category 12h/12Z, larger errors observed in the middle levels in the other categories were significant.

We could find no satisfactory reason to explain these characteristics; however, we suspected that the differences might be due to the differences in the vertical structure of either the real atmosphere or the model or both between day and night. This speculation eventually led to an inquiry on the modeling of eddy diffusivity which will be described in the next section. We conclude this stage by noting that version (Δx, $2\Delta t$) would be a strong candidate for replacing the operational version pending confirmation by more sample experiments.

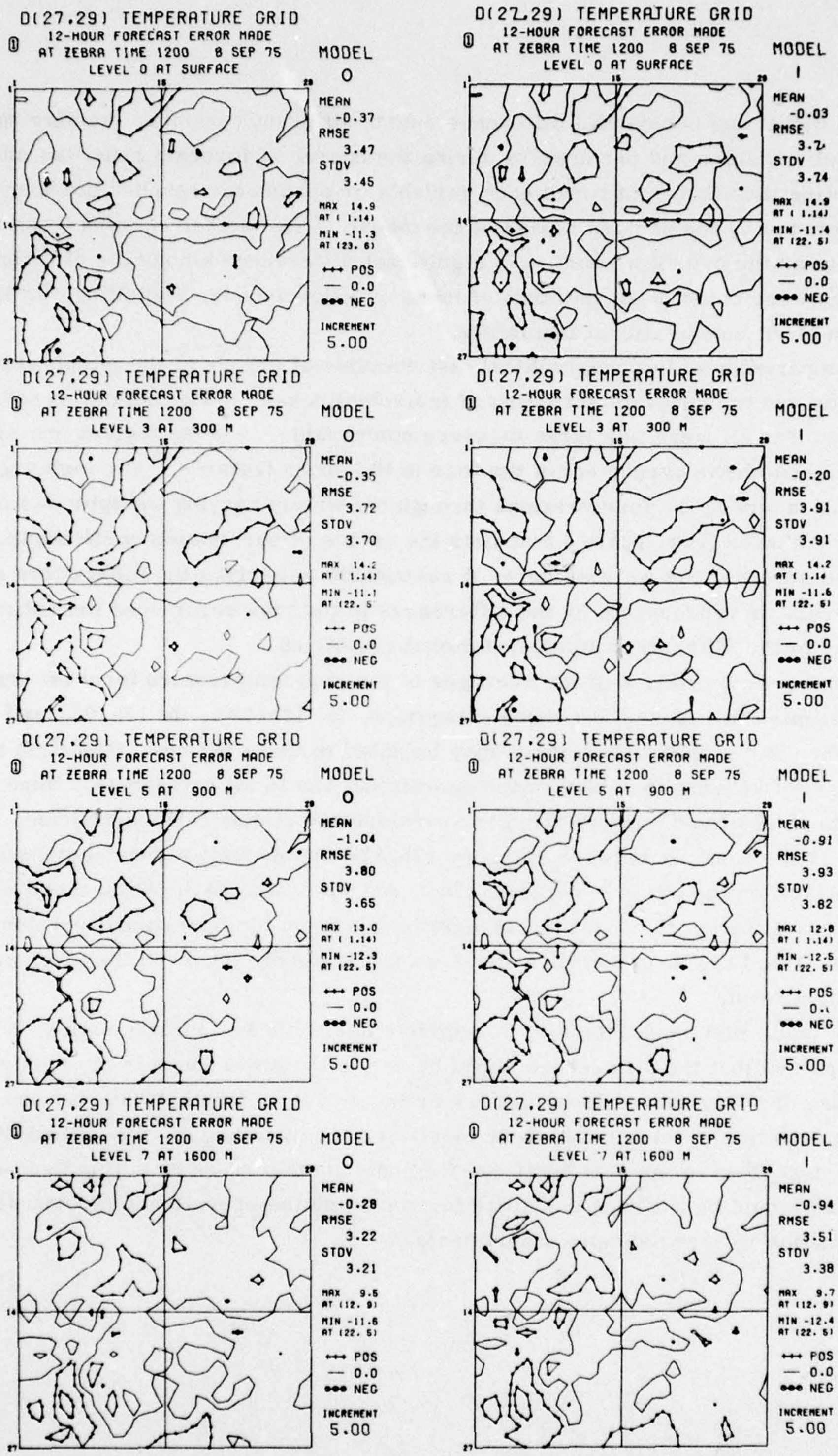
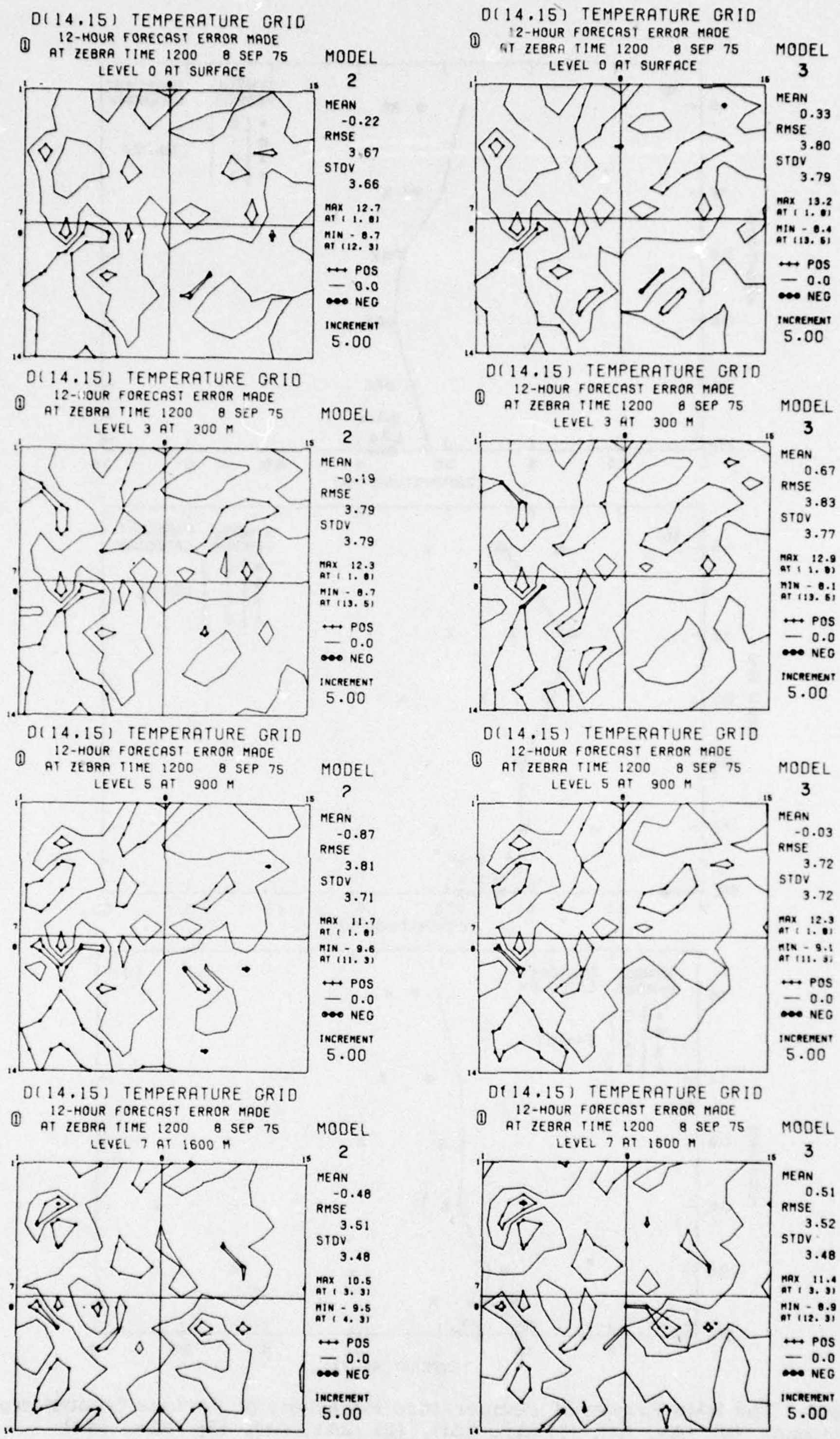


Figure 2. Contour Maps of Errors of Temperature Forecasts



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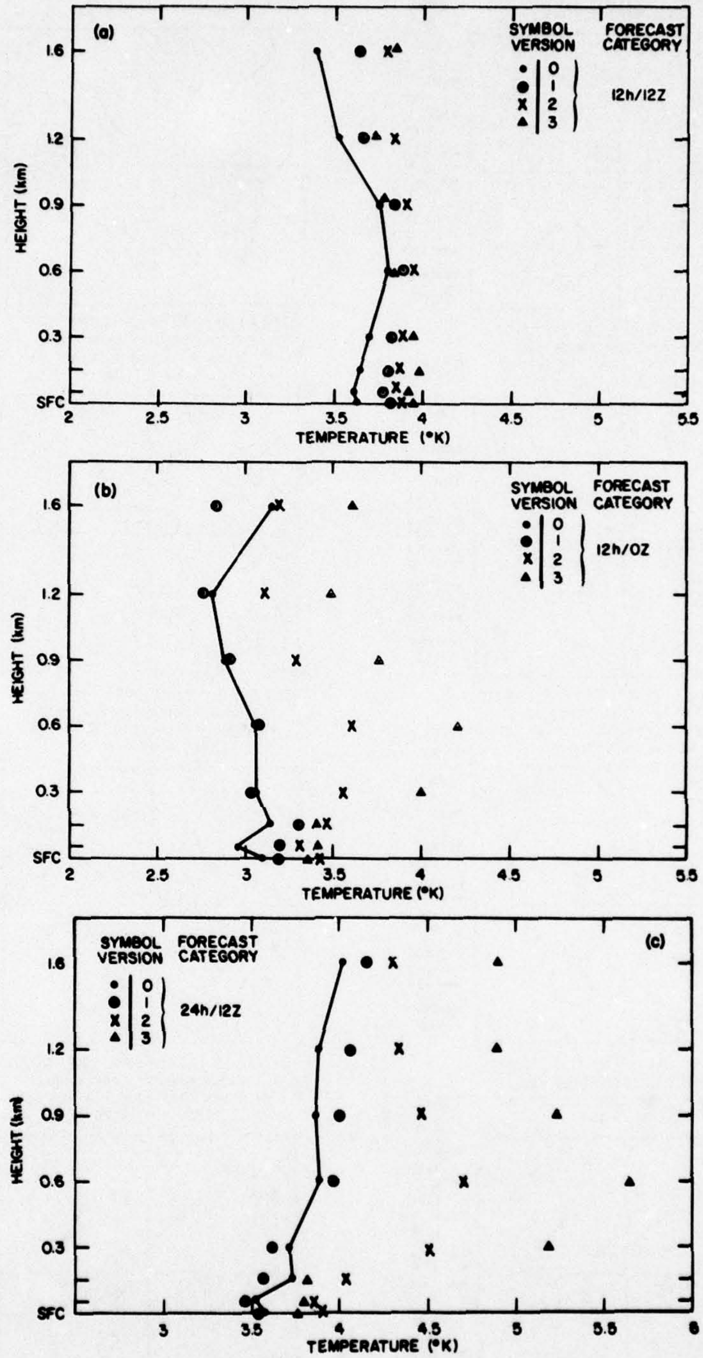

Figure 3. The RMS Errors of Temperature Forecasts of Various Computational Resolutions. (0) (Δx, Δt), (1) (Δx, $2\Delta t$), (2) ($2\Delta x$, Δt), (3) ($2\Delta x$, $2\Delta t$)

Table 3. Correlation Coefficients of the RMS Temperature Forecast Errors of Different Computational Resolutions, Sample Group I

Forecast Category	Pair	Level 0	1	2	3	4	5	6	7
12h/12Z (9)	(0, 1)	.98	.99	.99	.98	.99	.98	.94	.92
	(2, 3)	.99	.98	.96	.97	.97	.93	.93	.93
	(0, 2)	.98	.98	.98	.97	.95	.93	.87	.83
	(0, 3)	.97	.97	.94	.92	.87	.77	.69	.84
12h/0Z (8)	(0, 1)	.97	.97	.98	1.00	1.00	.99	.95	.92
	(2, 3)	.96	.96	.93	.92	.95	.91	.90	.89
	(0, 2)	.90	.88	.94	.93	.95	.86	.78	.74
	(0, 3)	.96	.89	.94	.95	.98	.93	.89	.88
24h/12Z (9)	(0, 1)	.98	.99	.99	.96	.91	.95	.97	.90
	(2, 3)	.97	.98	.92	.88	.87	.83	.90	.90
	(0, 2)	.76	.70	.78	.56	.69	.72	.75	.79
	(0, 3)	.81	.67	.70	.41	.40	.30	.44	.54

4. VERTICAL STRUCTURE

4.1 Eddy Diffusivity

The unique feature of AFGWC-BLM is found in its modeling of the vertical structure of the planetary boundary layer. A great deal of attention is given to model the surface layer in a manner that is supposed to conform to the best available observational evidence gathered in the fifties and early sixties.[4] Direct extensions of the surface-layer modeling are made in estimating the eddy transfers in the layer above the surface layer. On the other hand, the horizontal structure of the model is very much similar to that employed in the prediction model of the free atmosphere that also provides the required upper boundary condition of the wind for the boundary layer.

AFGWC-BLM employs the concept of eddy diffusivity in modeling the eddy transfers within the planetary boundary layer. It distinguishes and calculates at each time step two eddy diffusivities, one for momentum and the other for heat and moisture. The value of the eddy diffusivity for momentum is assumed constant throughout the entire depth of the planetary boundary layer on a grid point at a given time and is calculated with the knowledge of wind and temperature in the surface layer. The value of the eddy diffusivity for heat and moisture, on the other hand, is assumed to vary with height and is dependent on the local Richardson number.

4. Gerrity, J.P., Jr. (1967) A physical-numerical model for the prediction of synoptic-scale low cloudiness, Monthly Weather Review, 95:261-282.

An impetus for examining the method of estimating eddy diffusivities was provided by the monitoring of overflow counts during the experiments on computational resolution. It was noted then that, regardless of the resolution, approximately 75 percent of the values of the eddy diffusivity for heat and moisture calculated were reaching either the lower (10^3 cm^2 sec^{-1}) or the upper bound (10^6 cm^2 sec^{-1}). This meant that in spite of all the computation entailed, the values of the eddy diffusivity actually employed in three quarters of all the grid points at any time step were determined by the artificial bounds imposed by storage restriction rather than by any physical assumption of the model. Examples of such vertical profiles at a grid point and on two observation times twelve hours apart are shown in Figure 4. Also included in the figures are the profiles proposed as their replacements.

The proposed method of estimating eddy diffusivity may be stated as follows:

(1) There is no change in the determination of eddy diffusivity in the surface layer;

(2) There is no change in the evaluation of the eddy diffusivity for momentum;

(3) (a) In the layer above the surface layer, the lapse rate of the entire depth is estimated singly by the temperatures at the top (z= 1. 6 km) and the bottom (z=. 05 km);

(b) If the lapse rate equals or exceeds the dry adiabatic lapse rate, the value of the eddy diffusivity for heat and moisture is constant and equal to the value obtained in the surface layer;

(c) If the lapse rate is less than the dry adiabatic lapse rate, the eddy diffusivity for heat and moisture decreases linearly with height in such a way that the value at the top (z= 1. 6 km) is one-hundredth the value in the surface layer (z=. 05 km).

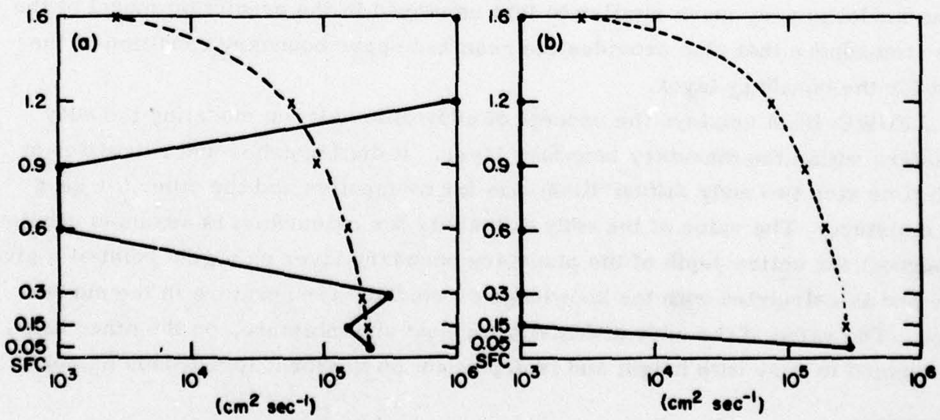

Figure 4. Examples of Vertical Profiles of Eddy Diffusivity for Heat and Moisture. (a) date = 9/9/75, hour = 0Z, location (8, 7); (b) date = 9/9/75, hour = 12z, location (8, 7). Solid line = operational; broken line = proposed

It should be noted that, according to (3) above, the eddy diffusivity for heat and moisture has the same value as that for momentum under the lapse conditions. On the other hand, under stable stratifications the eddy transfer of heat and moisture is more inhibited than that of momentum.

This new method of estimation greatly simplifies the computation required in evaluating the eddy diffusivity. It smoothed the profiles of the eddy diffusivity for heat and moisture both in space and in time, as shown by the examples of Figure 4, and it reduced the fraction of the overflow counts to as little as 6 percent. All of these features are obviously desirable from the standpoint of efficiency. However, the most crucial aspect which has caused us to prefer this method to the operational procedure was the improvement it brought to the forecast accuracy, as measured by the rms errors of the temperature forecasts. Figure 5 shows the summary of the statistics obtained with Sample Group I. The rms errors of the operational version are represented by dots with two arms of equal length, $2s/\sqrt{n}$, where s is the standard deviation and n the number of samples. The width indicates the range of statistical insignificance of differences in the sample averages of the rms errors. The rms errors of two versions with the new eddy diffusivity are also shown in these figures. Symbol x is used to mark those of the version with 30-min time step while symbol ⊙ is for those of the version with 60-min time step.

4.2 Virtual Temperature

AFGWC-BLM employs the Ekman-layer model in prescribing the horizontal wind within the planetary boundary layer. The wind is determined such that it brings about a balance between the Coriolis force due to the geostrophic component of the wind and the frictional drag force induced by the eddy transfer of momentum. The geostrophic wind is calculated using the hydrostatic equation and the ideal gas law of dry air.

Since moisture is more plentiful and is more variable in distribution within the planetary boundary layer than any other region in the atmosphere, it is important to account accurately for any effect the presence and the distribution of moisture may bring about. One such effect appears in the ideal gas law and can be accounted for if the dry-bulb temperature T is replaced by the virtual temperature T_v, defined by

$$T_v = T(1 + 0.61q)$$

where q is the specific humidity of the air.

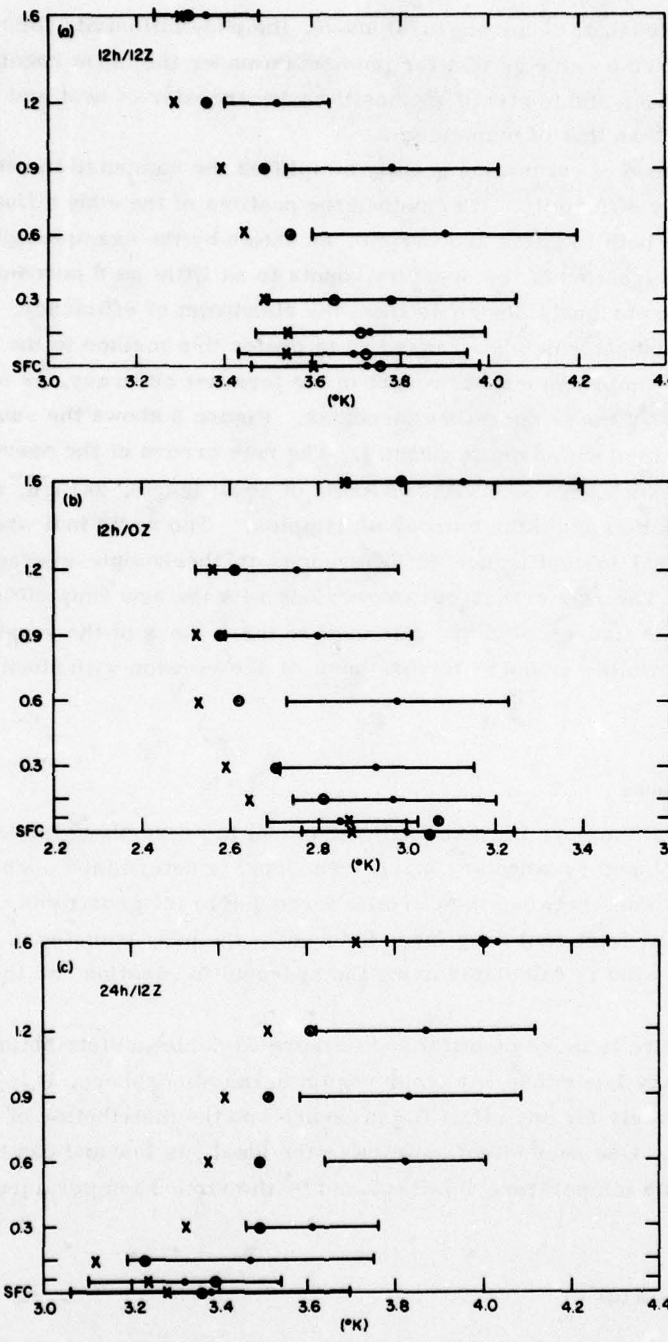

Figure 5. The RMS Errors of Temperature Forecasts. • = operational eddy diffusivity, x = the suggested eddy diffusivity with 30-min time step, ⊙ = the suggested eddy diffusivity with 60-min time step

We implemented this modification in the determination of the geostrophic wind. The procedure requires unpacking of specific humidity and one multiplication operation in addition to those needed in the operational version. As it appears in Table 4, the effect of this modification on the error of temperature forecast is practically non-existent. A spectral analysis of the differences of the forecast errors demonstrated further that differences in individual cases were largely of small scales and did not have any organized structure.

In view of the fact that this modification needed additional computation and yet failed to produce any desirable effect in forecast we decided not to install this modification in future experiments.

4.3 Vertical Differencing

As demonstrated by Yang[5] in an earlier study with steady-state problems, the finite-difference formula employed in the operational version for approximating terms such as $\frac{d}{dz}[K(z)\frac{dT}{dZ}]$ has an undesirable characteristic and may yield large errors in numerical solutions under unfavorable circumstances. Since such discretization errors are also potentially present in the time-varying system, we thought it wise to replace it by an alternate form which preserved the divergence form of the differential expression and insured the non-singularity of the coefficient matrix.

The effect of this modification on the values of the rms errors of temperature forecasts, as seen in Table 4, is statistically insignificant at all levels and in all forecast categories. Nevertheless, we judged the modification worthwhile on the basis of the theoretical reason, particularly since the modification would not need any additional core or time for its implementation.

When the inferences regarding the merits of these modifications were confirmed valid in the results obtained using Sample Group II, we concluded this stage of investigation by adopting the modifications on eddy diffusivity and vertical differencing.

5. HUMIDITY FORECASTS

Having installed modifications that had been chosen on the ground of analyses on the temperature forecasts, we next turned our attention to examining the effects of these changes on the humidity forecasts. We hoped to find improvement in the humidity forecasts similar to that observed in the temperature forecasts. This would not only fulfill our utilitarian objective but also uphold our conjecture that the observed improvement in the temperature forecasts had been due to a better representation of the eddy transfer processes in the real atmosphere.

5. Yang, C. (1977) A Study of the Error of Discretization in the Air Force Global Weather Central Boundary Layer Model, AFGL-TR-77-0091.

As it turned out, however, the changes in the humidity forecasts were not as pleasing as those in the temperature forecasts. As shown by ⊙ in Figure 6, the reduction in the rms errors at low levels in categories 12h/0Z and 24h/12Z were offset by larger errors at higher levels. Also, the errors in low levels in category 12h/12Z were significantly larger than those of the operational model, represented here by dots. The two arms of equal length on the sides of the dots represent the range of statistical insignificance of deviations, as those in Figure 5 did.

In devising a modification within the existing structure which might improve upon these performances, we wanted to accomplish it, if possible, without losing the advantage gained on the temperature forecast. We therefore looked for the areas where we could act to induce changes directly in specific humidity. There were two: one was in the determination of the surface specific humidity, and the other in the determination of the vapor flux within the surface layer. We chose the first strictly for expediency, with little attention to any rigorous physical or mathematical reasoning.

AFGWC-BLM, following Gerrity,[4] makes use of the so-called "percent wetted area," originally devised by Halstead et al,[6] in estimating the surface specific humidity. This quantity, evaluated at the initial time of the forecast, is held constant throughout the range of forecast, and is supposed to reflect the effect of the complex process of moisture exchange between the underlying soil and the air. Although such a model has a certain conceptual appeal, it lacks a creditable verification in the real atmosphere, particularly in a surrounding as wide and varied as the domain of the present model.

The alternate we have adopted after a few trial experiments is very simple. The surface specific humidity is extrapolated linearly from the values of specific humidity at the levels above. Thus,

$$q_0 = q_1 + (q_1 - q_2)\frac{z_1 - z_0}{z_2 - z_1}$$

where subscripts 0, 1 and 2 denote the surface level, 50 m and 150 m level, respectively. This procedure makes no presumption on the physical process determining the surface specific humidity.

The rms errors of the humidity forecasts produced by this version are represented by ⊙ in Figure 6. That our objective has been met by this contrivance is quite obvious. We concluded this stage by replacing the operational procedure with the suggested alternate after noting that the effect of this change on the temperature forecast was indeed insignificant everywhere in all categories (Figure 7).

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Table 4. Sample Means and Standard Deviations (in parentheses) of the RMS Errors of Temperature Forecasts. O′ = operational, H = the virtual temperature modification, V = the alternate finite-differencing

(1) Sample Group I

Forecast Category	Model	Level 0	1	2	3	4	5	6	7
12h/12Z (9)	O'	3.60(.36)	3.54(.34)	3.54(.35)	3.49(.36)	3.44(.36)	3.39(.31)	3.28(.24)	3.30(.22)
	H	3.60(.37)	3.53(.35)	3.53(.36)	3.48(.37)	3.42(.36)	3.38(.31)	3.27(.24)	3.30(.22)
	V	3.60(.36)	3.54(.36)	3.53(.36)	3.49(.37)	3.43(.36)	3.38(.31)	3.27(.24)	3.30(.23)
12h/0Z (7)	O'	2.87(.24)	2.87(.18)	2.64(.28)	2.59(.30)	2.53(.31)	2.52(.29)	2.56(.30)	2.86(.32)
	H	2.88(.23)	2.88(.17)	2.65(.27)	2.60(.29)	2.55(.30)	2.53(.29)	2.58(.30)	2.88(.32)
	V	2.87(.24)	2.75(.17)	2.58(.26)	2.60(.30)	2.53(.31)	2.52(.30)	2.56(.31)	2.87(.33)
24h/12Z (8)	O'	3.28(.40)	3.24(.36)	3.12(.40)	3.32(.33)	3.37(.41)	3.41(.49)	3.51(.50)	3.61(.50)
	H	3.27(.39)	3.23(.35)	3.11(.38)	3.31(.32)	3.35(.40)	3.40(.49)	3.50(.50)	3.71(.50)
	V	3.29(.42)	3.17(.38)	3.10(.41)	3.35(.33)	3.36(.41)	3.38(.49)	3.48(.50)	3.71(.49)

(2) Sample Group II

Forecast Category	Model	Level 0	1	2	3	4	5	6	7
12h/12Z (12)	O'	4.18(.53)	4.09(.47)	3.97(.38)	3.79(.34)	3.48(.32)	3.28(.30)	3.14(.31)	3.12(.33)
	H	4.17(.54)	4.08(.47)	3.96(.39)	3.78(.35)	3.47(.32)	3.27(.30)	3.13(.31)	3.13(.33)
	V	4.17(.54)	4.07(.46)	3.97(.39)	3.79(.35)	3.48(.32)	3.27(.30)	3.12(.30)	3.12(.32)
12h/0Z (8)	O'	3.64(.54)	3.49(.55)	3.25(.50)	3.04(.34)	2.80(.30)	2.70(.26)	2.73(.28)	2.87(.32)
	H	3.64(.54)	3.49(.49)	3.26(.50)	3.05(.34)	2.81(.31)	2.70(.26)	2.73(.28)	2.87(.32)
	V	3.64(.54)	3.44(.49)	3.25(.48)	3.03(.32)	2.79(.31)	2.68(.25)	2.72(.27)	2.87(.31)
24h/12Z (7)	O'	4.45(.82)	4.31(.71)	4.18(.63)	4.19(.42)	3.92(.24)	3.75(.26)	3.66(.30)	3.57(.30(
	H	4.44(.81)	4.29(.70)	4.16(.63)	4.17(.43)	3.90(.25)	3.73(.28)	3.65(.31)	3.58(.31)
	V	4.41(.81)	4.25(.72)	4.17(.63)	4.22(.42)	3.93(.24)	3.73(.25)	3.65(.28)	3.56(.29)

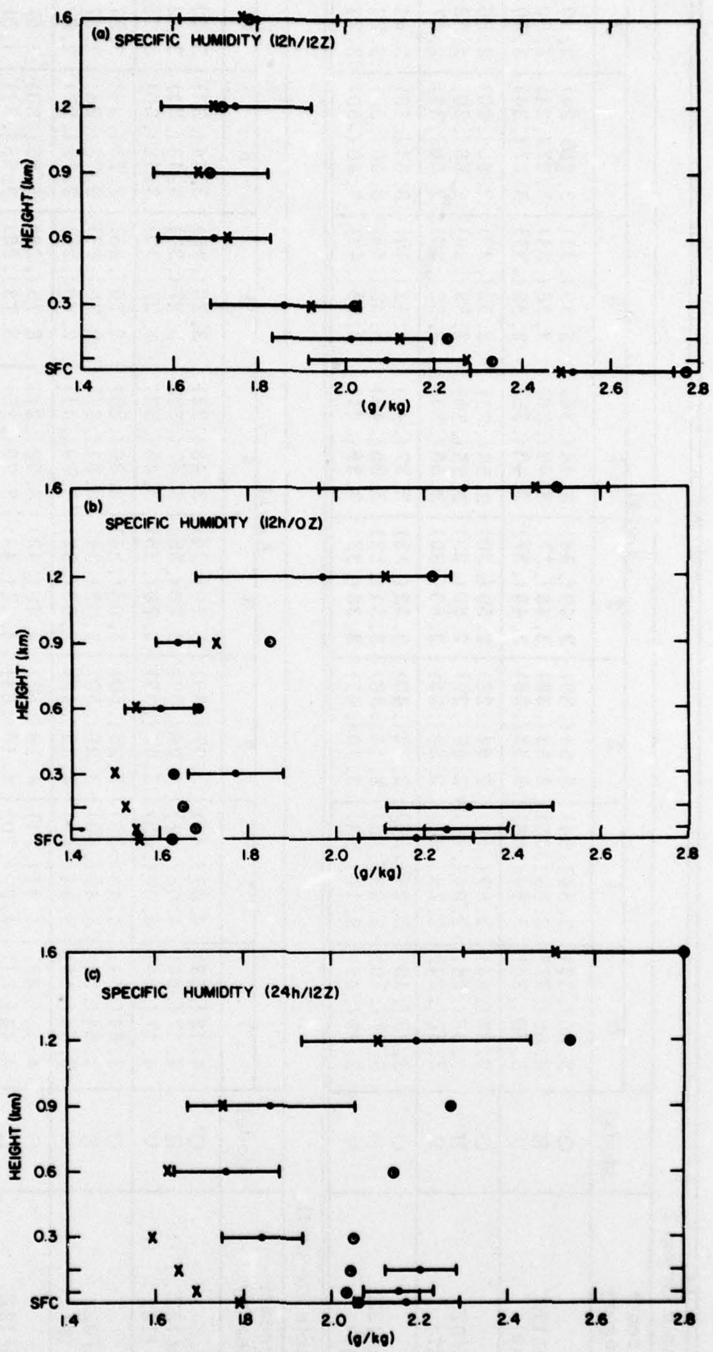


Figure 6. The RMS Errors of Humidity Forecasts. • = the suggested eddy diffusivity, ⊙ = the suggested eddy diffusivity and vertical differencing, x = the suggested eddy diffusivity, vertical differencing and surface specific humidity

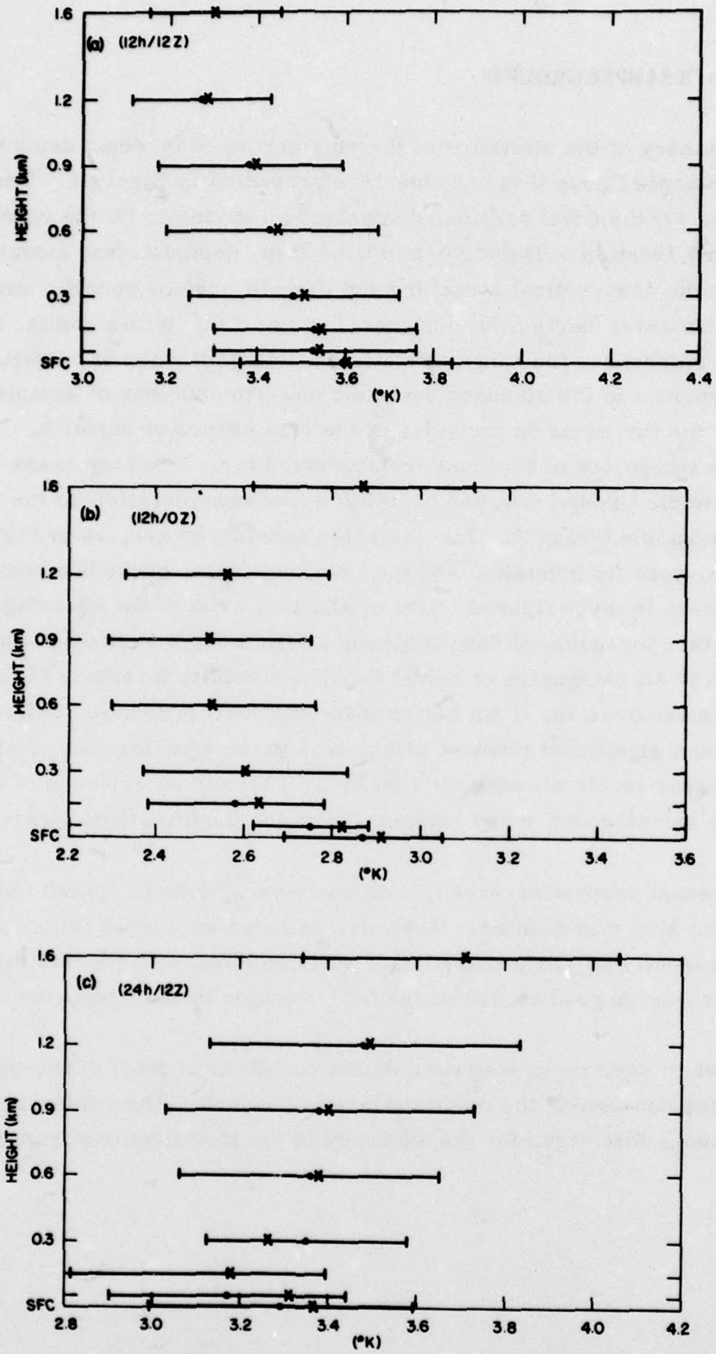


Figure 7. The RMS Errors of Temperature Forecasts. • = the suggested eddy diffusivity and vertical differencing, x = the suggested eddy diffusivity, vertical differencing, and surface specific humidity

6. A TEST WITH SAMPLE GROUP II

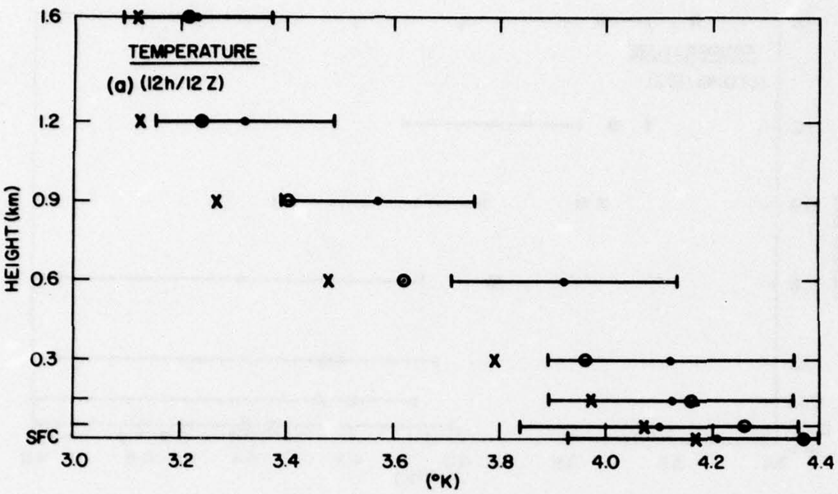
The summary of the statistics of the rms errors of forecast using the synoptic samples in Sample Group II (see Table 1) is presented in Figure 8. Three models included are: (1) the GWC version, designated as model A; (2) the version with the new diffusivity (Section 4.1) and 60-min time step, designated as model B; and (3) the version with the new vertical structure and the new surface specific humidity; and with 30-min time step (Section 5), designated as model C. With model A, the GWC version, as the reference, the range of statistical insignificance of deviations, defined by $2s/\sqrt{n}$, where s is the standard deviation and n the number of sample cases, is indicated by the two arms on the sides of the rms errors of model A.

All four categories of forecast are accounted for. The four cases of category 24h/0Z in Sample Group I that had been left out of consideration so far were added to the six in Sample Group II. The variables considered are, as in Figure 1, air temperature, specific humidity, and the two components of the horizontal wind.

We observe in these figures, first of all, that most of the advantages noted in the temperature forecasts of Sample Group I with the new vertical structure are still present in all categories of model C. The humidity forecasts of the same model are as accurate as, if not better than, the GWC products. Moreover, there appears to be a significant positive effect even in the wind forecasts, although it is only in the lower levels of category 12h/12Z. There is no evidence of any adverse effect in any variable and in any category from the modifications incorporated in model C.

The forecast errors increased, with some exceptions in specific humidity, when the time step was doubled. However, as noted earlier in Stage 2, the degradation was apparently so slight that when it was combined with the new diffusivity the performance was as good as that of the GWC version in all categories and in all variables.

Needless to say, these statistics do not constitute a proof of the correctness of the inferences concerning the modifications introduced. The evidence can only provide the reasons that argue for the adequacy of the modifications from the standpoint of utility.



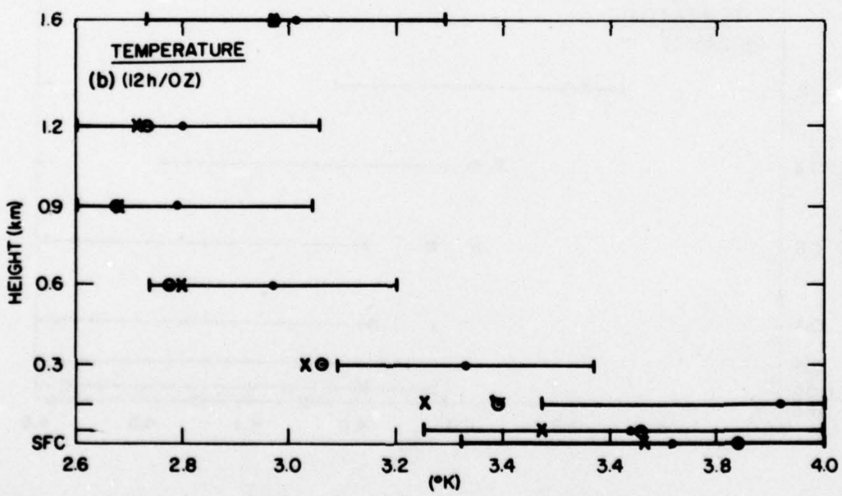
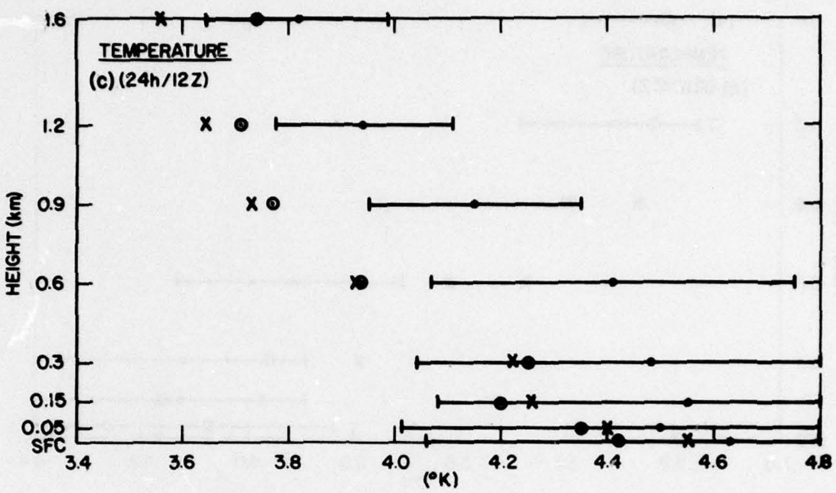


Figure 8. The RMS Errors of Forecast, Sample Group II. • = the AFGWC operational version, x = the suggested eddy diffusivity, vertical differencing, and surface specific humidity, ⊙ = the suggested eddy diffusivity and 60-min time step



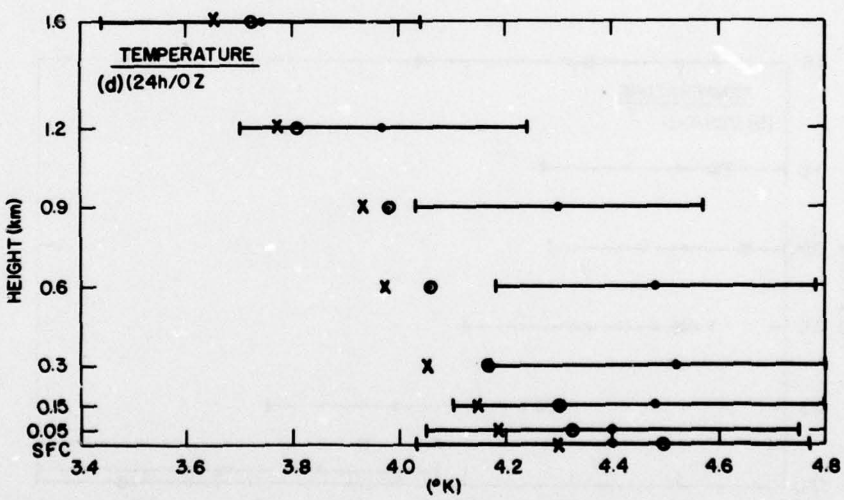
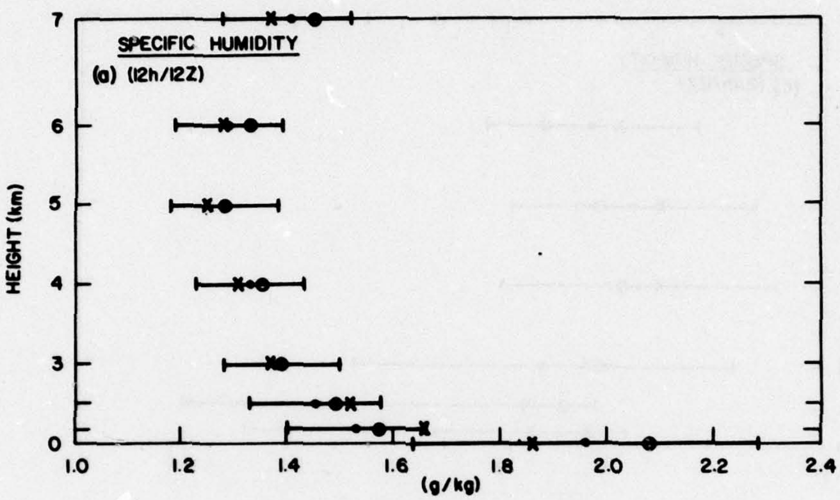
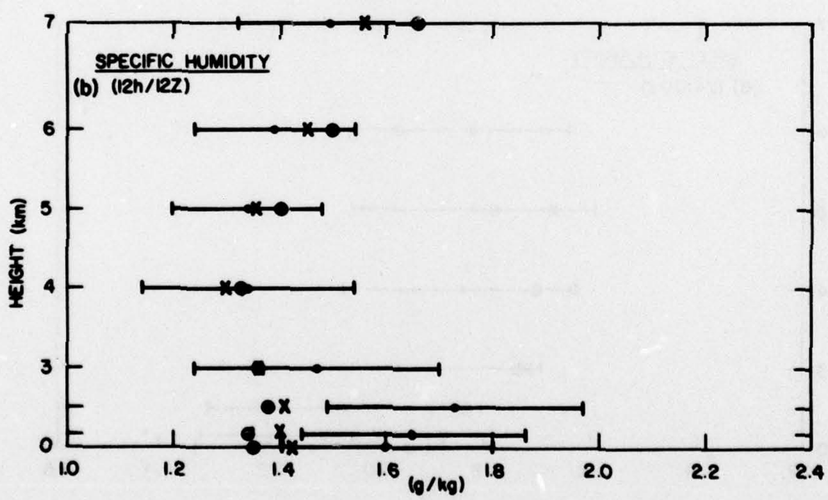


Figure 8. (Cont)





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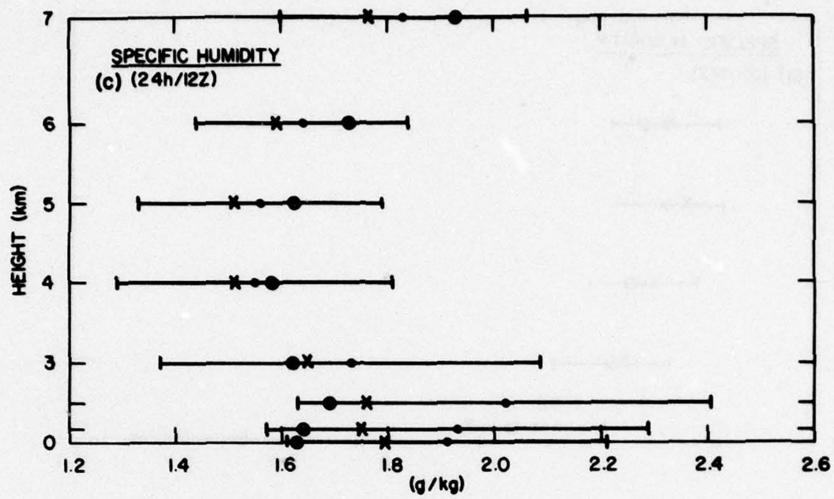


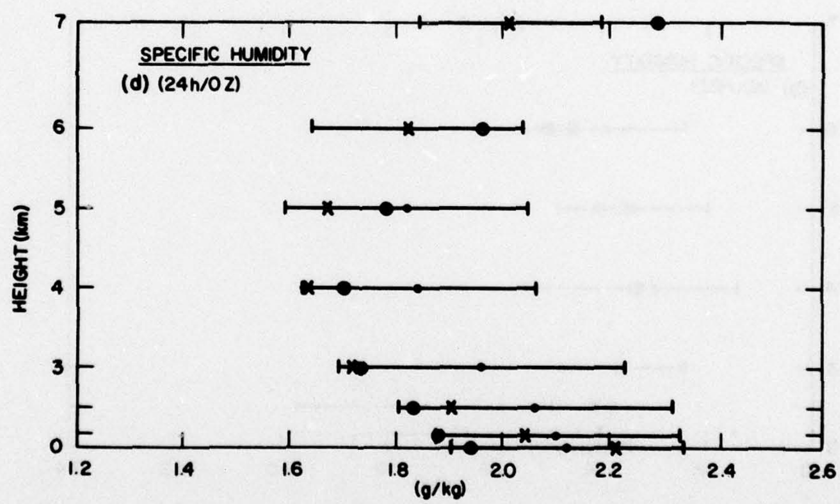
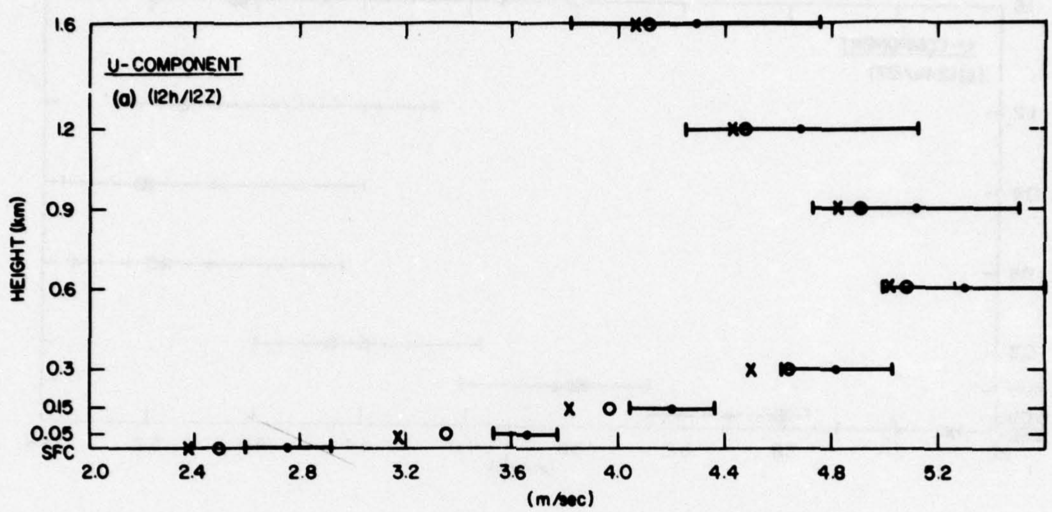


Figure 8. (Cont)



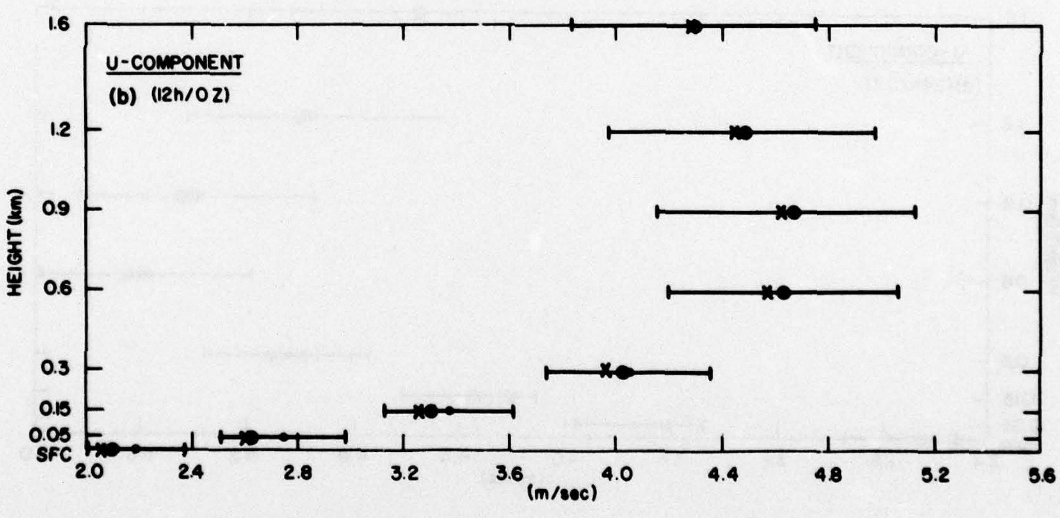
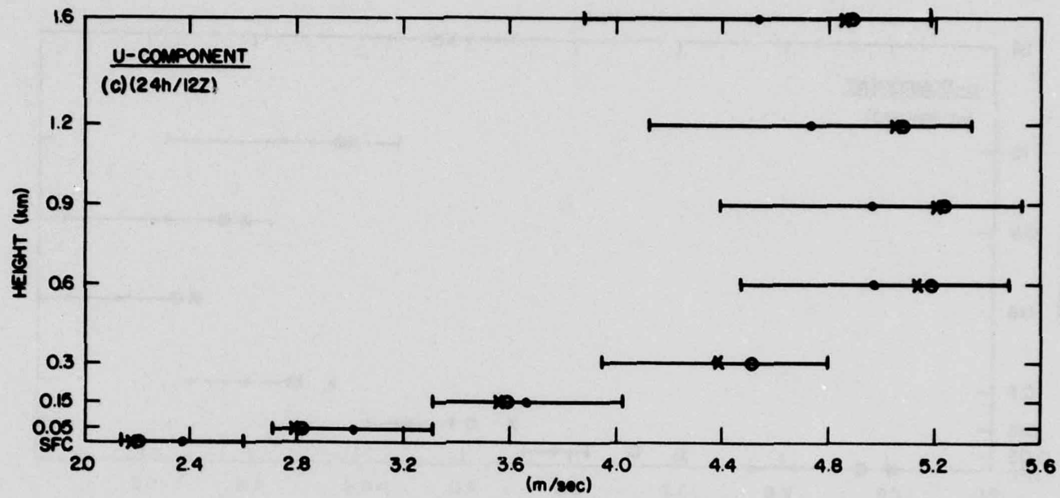


Figure 8. (Cont)



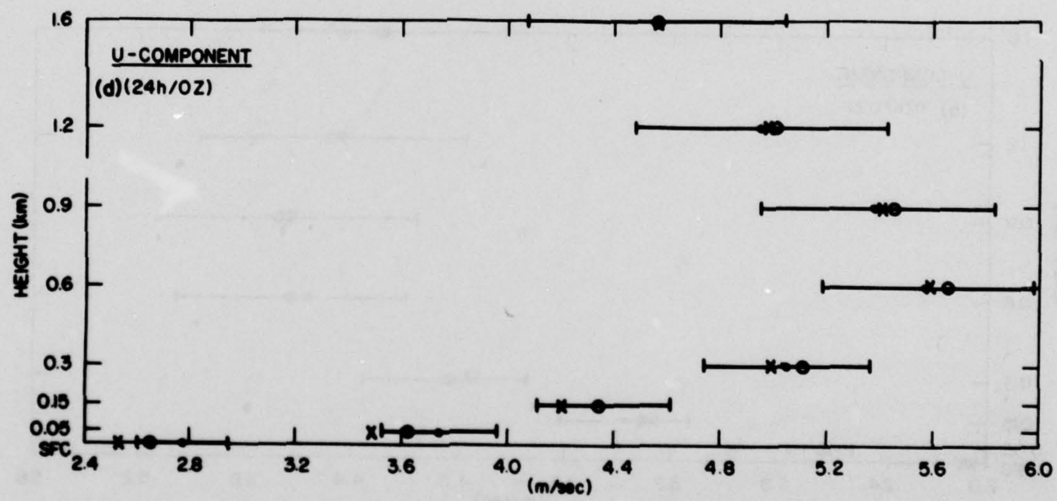
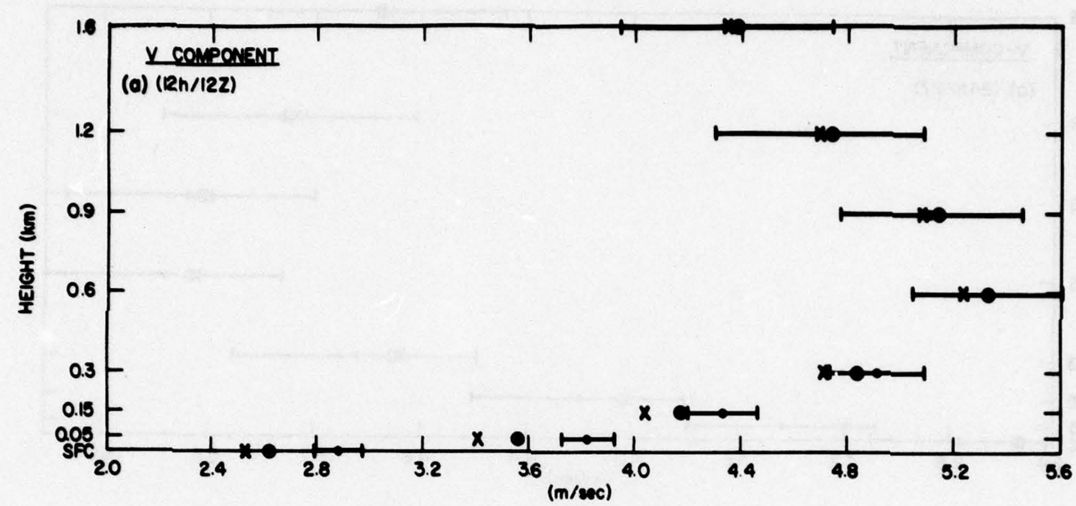


Figure 3. (Cont)



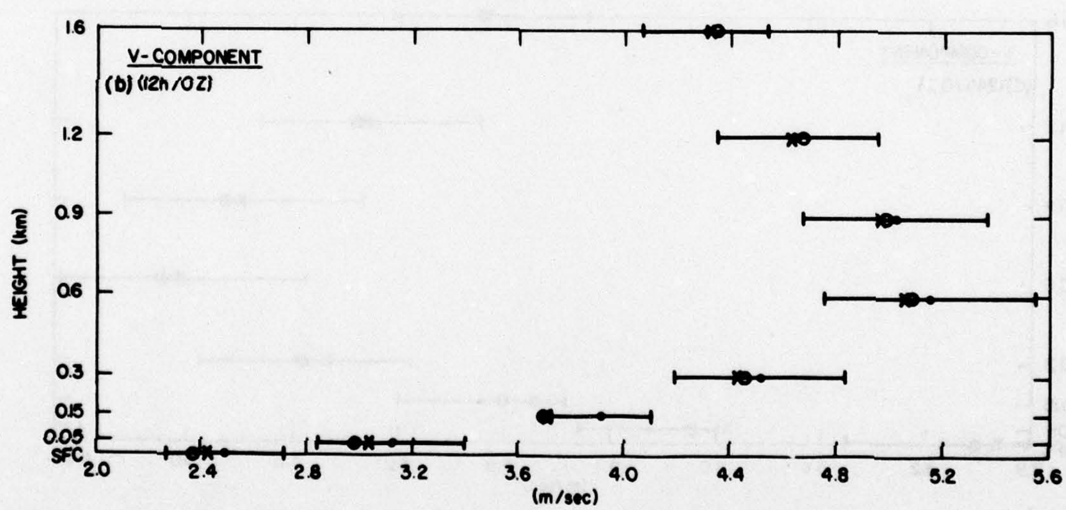


Figure 8. (Cont)

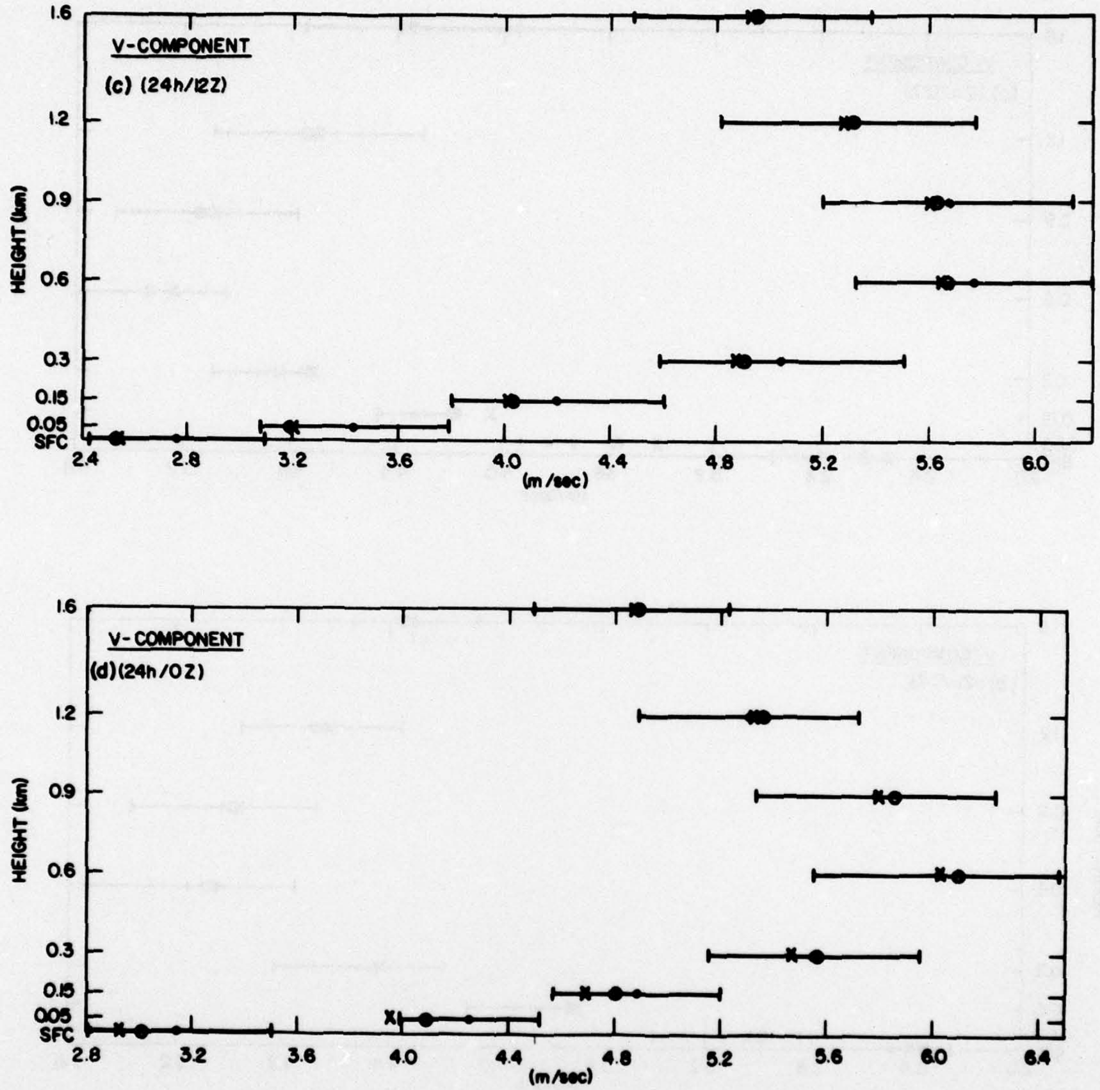


Figure 8. (Cont)

7. CONCLUSION

We have obtained two major conclusions from the experiments described in the foregoing sections and from various studies made in association with these experiments.

First of all, these experiments have demonstrated that some improvement in the forecast accuracy could be made with alternatives that are simpler in concept and less laborious in computation than the operational version. The examples are the suggested method of eddy diffusivity (Section 4) and the alternate estimate of surface specific humidity (Section 5). Secondly, a version with 1-hr time step is likely to deliver as accurate forecasts as the operational version with half as much computation.

The modifications suggested on the basis of these experiments may be readily incorporated into the operational version. However, since the measure of accuracy employed at AFGWC for quality control is different from the one used in this investigation, it is necessary to carry out more experiments in the operational setting to test the validity of these suggestions in reference to the operational criterion.

On the other hand, extensive and major reorganizations of the model are believed necessary in order that a greater increase in the forecast accuracy can be obtained. Such a reorganization is best made by taking both the diagnostic and prognostic phases into consideration. Any attempt at reorganization involving only the prognostic phase would require more core memory and/or computation time.

One such modification which may bring forth a significant improvement is suggested in the method of determining the radiational effect on the surface temperature. The current model assumes the same hours of sunrise and sunset everywhere all year around and varies only the temperature amplitude in accordance with the climatological data. A better approximation can be made by using available astronomical and geographical data to include the spatial and temporal variations of this effect. This, it is believed, would improve, at least, the temperature forecast at all levels since there is a strong coherence in the forecast error along the vertical direction. This modification requires an expansion in the core memory for storing pertinent astronomical and geographical data and an extension in the computation time for including the subprogram of computing the hours of daylight.

Another modification is suggested in the subprogram employed to store the numerical values of variables and parameters. There is no provision made to accommodate those that exceed the maximum value allowable by the allocated number of bits. As a result, values other than those calculated are stored and steep gradients are erroneously created in the vicinity whenever there is an overflow. Although such overflows do not occur frequently, they are nevertheless detrimental from the standpoint of simulation when they do. The corrective measure required additional core storage. This may also contribute to an increase in the forecast accuracy.

We are concluding this study with the belief that we have considered all of the major aspects in the prognostic phase that could be modified within the limits imposed by the operational constraints and would likely lead to some improvement in the forecast performance of AFGWC-BLM.

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