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EVALUATION OF TECHNIQUES FOR LONG-RANGE FORECASTING OF AIR TEMPERATURE AND ICE FORMATION

Jeffery C. Rogers

Great Lakes Environmental Research Laboratory
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UNITED STATES
DEPARTMENT OF COMMERCE
Elliot L. Richardson, Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION
Robert M. White, Administrator

Environmental Research
Laboratories
Wilmot N. Hess, Director

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EVALUATION OF TECHNIQUES FOR LONG-RANGE FORECASTING OF AIR TEMPERATURE AND ICE FORMATION

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Four techniques for making long-range air temperature forecasts were evaluated by using wintertime (November through February) data from around Lakes Superior, Huron, and Michigan. The purpose of the evaluation was to find a technique for forecasting air temperature which could be applied to ice forecasting on the Lakes. The four techniques analyzed were:

(1) The use of cycles and oscillations

(2) The extrapolation and kinematic process used by the National Meteorological Center which results in forecasts in the *Average Monthly Weather Outlook*

(3) Conditional probabilities

(4) A Markov chain equation.

The analysis of techniques (1) and (4) consisted of predicting a monthly mean temperature and comparing the standard error of estimate (SE) of the difference between predicted and actual temperatures to the SE for climatological predictions. The evaluation of techniques (1), (2), and (3) also consisted of predicting monthly temperature categories and then comparing them to one another. The forecast categories were below normal, normal, and above normal temperatures.

Based on the evaluations, it was found that only the quasi-biennial oscillation [technique (1)] category forecasts and the *Average Monthly Weather Outlook* [technique (2)] category forecasts predicted with any skill. Individually, the accuracy of the techniques is only slightly better than chance; however an improved temperature forecasting system for application to ice forecasting could be established by combining them.-

1. INTRODUCTION

One of the major concerns regarding Great Lakes and St. Lawrence Seaway navigation is the development of long-range forecasts of the opening and closing dates of harbors, bays, and rivers due to ice cover. The major advantage of such ice forecasts would be to maximize the number of shipping days on the Lakes and Seaway. At the present time closing and opening dates due to ice are determined several months in advance without taking into account the meteorological and hydrological factors which influence those dates. As a result, shippers are seldom able to take advantage of mild winters and do not receive enough warning prior to cold and early winters.

The prediction of the date of ice formation may be accomplished in three ways:

(1) By establishing a climatological forecast date. This is simply the average date of ice formation in past years and it is applied to each upcoming winter.

(2) By developing long-range water temperature forecasts. These forecasts combine radiation and heat budget parameters in predicting when the water temperature will reach 32°F.

(3) By developing long-range air temperature forecasts. Subfreezing air is the primary factor which causes water to freeze. One common measure of subfreezing air temperature is the accumulation of freezing degree-days (defined as the difference between the mean daily air temperature and 32°F given that T_{mean} is less than 32°F). Although Richards (1964) and Snider (1974) have helped establish the number of freezing degree-days (FDD's) needed to form ice cover on many parts of the Great Lakes, a suitable method for making long-range air temperature, or FDD, forecasts has not yet been perfected.

The purpose of this report is to present the results of an investigation undertaken to develop and evaluate long-range air temperature forecasting techniques. The report will concentrate on attempts to predict air temperature for stations around Lakes Superior, Huron, and Michigan during the winter months of January and February. The adequacy of each forecasting technique evaluated here will be determined by comparing the standard error of estimate (SE) of prediction results to the SE of climatological temperature values. While no direct application to ice forecasting will be made, the results contained herein will be applied to the ongoing effort to develop ice forecasting techniques at the Great Lakes Environmental Research Laboratory.

2. LONG-RANGE FORECASTING TECHNIQUES

Barry and Perry (1973) identify six techniques used throughout the world to make long-range forecasts of meteorological phenomena. They are as follows: (1) cycles and oscillations, (2) extrapolation and kinematic procedures, (3) synoptic persistence, (4) teleconnections, (5) analogues, and (6) ocean-atmosphere interaction. The first three techniques will be evaluated in detail in this report and all six are briefly discussed below.

2.1 Cycles and Oscillations

The annual temperature cycle is the most familiar meteorological cycle known. Since the late nineteenth century, however, meteorologists have known of another cycle with a period of slightly more than 2 years. This cycle, subsequently named the quasi-biennial oscillation (QBO), has been detected in other meteorological parameters, such as precipiation, surface pressure, and alternate year variations in such phenomena as tree rings, varves, and lake levels. The QBO may be seen graphically by plotting 12-month running means of temperature data for several years. This study will attempt to make long-range temperature forecasts at two stations by using the QBO and predicting its future trends.

2.2 Extrapolation and Kinematic Procedures

This is the technique currently used by the National Meteorological Center to produce ***Average Monthly Weather Outlook*** *(AMWO)*. This technique "... [notes] the past and current rate of evolution of mid-tropospheric flow patterns, in particular the major features (ridges, troughs, and centers), and [takes] these developments into account in deriving a forecast 500 or 700 mb chart for time periods of up to a month." (Barry and Perry, 1973, p. 385). From these forecast charts, the anomalies of temperature may be determined and divided into three categories of above, below, or normal temperatures for any region for the upcoming month. Presently, ice forecasters use these categories to determine if FDD accumulations (and hence ice formation) will occur later, earlier, or on approximately the normal climatological date, respectively. The accuracy of the extrapolation and kinematic procedure, as published in the *AMWO*, is evaluated in section 4.

2.3 Synoptic Persistence

Monthly long-range forecasts based upon synoptic persistence involve probabilities between adjacent or between non-adjacent months that the current anomaly of temperature will persist into future month(s). The methods used here to develop synoptic persistence techniques, Markov chain processes, and conditional probabilities are discussed in section 5.

2.4 Teleconnections, Analogues, and Ocean-Atmosphere Interaction

The existence of teleconnections implies that a high correlation constantly exists between temperature conditions in one location and those of the area of study sometime later. They require a worldwide data base generally, as does the analogue technique in which one forecasts the future temperature conditions based upon those which occurred during an analogous situation in the past. The need for a large data base in regard to length of records and locations prohibited the use of these techniques. Knowledge of the fundamentals of ocean-atmosphere interaction is never solely used as a long-range forecasting tool, but rather is incorporated with other procedures, such as the extrapolation and kinematics techniques. It is not considered further in this study.

3. USING THE QBO IN LONG-RANGE TEMPERATURE FORECASTS

The QBO in air temperature at Duluth, Minnesota, since December 1960 is shown in figure 1, where the 12-month running monthly mean temperatures are plotted. Spectral analysis of a similar set of data for Sault Ste. Marie, Michigan, since 1939 revealed a statistically significant periodicity in the 12-month running means of about 26.4 months, consistent with estimates of 2.2 to 2.3 years by other authors. The fact that such a cycle exists in temperature data and may be conveniently displayed by using graphs of 12-month running means implies two things:

(1) Actual monthly mean temperatures during any given month when the running mean is graphically on an upward swing (as during most months from December 1972 through December 1973 in fig. 1) are higher than those of the same month of the previous year.

(2) Act&l monthly mean temperatures during any given month when the running mean is graphically on a downward swing (starting January 1974 in fig. 1) are lower than those of the same month of the previous year.

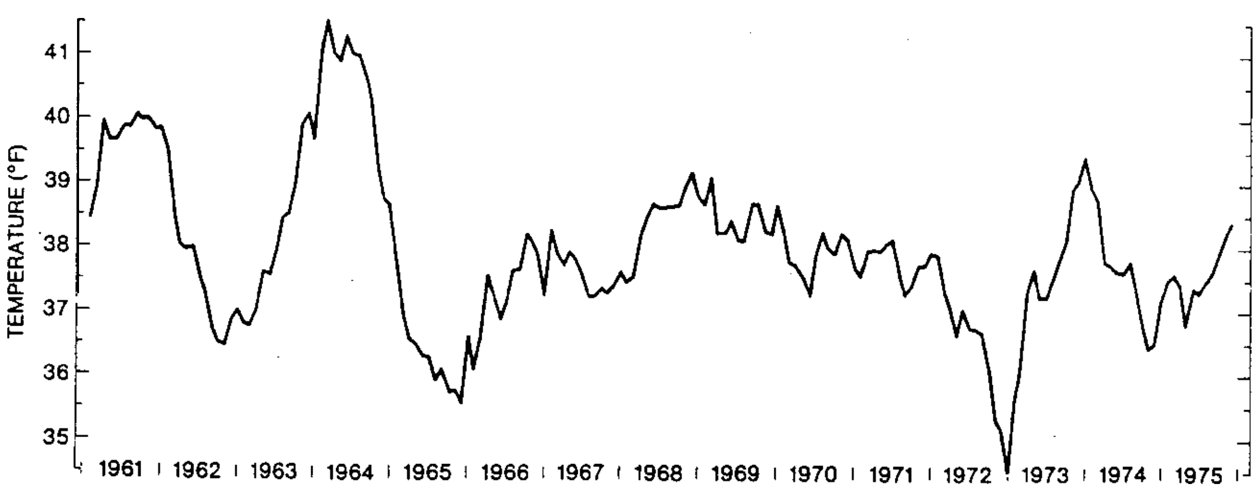

Figure 1. *Twelve-month* ***running monthly mean temperatures at Duluth, Minnesota.***

The basic assumption in using the QBO for long-range forecasting is that the present monthly mean temperature may be accurately forecast by knowing last year's monthly mean temperature and the present direction (upward or downward) of the 12-month running mean plot. At Sault Ste. Marie, numerical temperature values were predicted for the month of January of the years 1939 to 1975. An SE was obtained from the differences between the predicted and actual temperatures and compared to the SE for climatology. At Duluth numerical temperature values as well as three temperature categories (above normal, below normal, and normal) were predicted for all months during the periods January 1962 through December 1964, January 1968 through December 1971, and January 1973 through December 1974. From figure 1, these periods of time at Duluth correspond to periods with a well defined, poorly defined, and well defined QBO cycle, respectively.

The procedure used to make the predictions was:

(1) Graph the most recent movement of the 12-month running mean temperature and determine whether the curve will move up or down next month. Generally it was assumed that the upcoming month would follow the trend of the previous month.

(2) Determine how far the plotted 12-month running mean value will move during the forecast month. This was done simply by computing the average movement in the curve during past years for both the up and down cases for all months and then applying that value to the present forecast month. These monthly average changes in the 12-month running mean ware multiplied by 12 (to turn them into actual monthly temperature changes) and are shown in table 1 for the Duluth evaluation; they ware assumed to be -4.9°F (down) and +6.0°F (up) for Januaries at Sault Ste. Marie.

(3) Obtain the actual monthly temperature for the forecast month 1 year earlier and add the chosen value from table 1 in step (2). This is the numerical temperature forecast for the station. It was also translated into forecast categories at Duluth. Appendix A lists the computations and temperature forecasts.

The results of the predictions were as follows:

(1) Sault Ste. Marie January temperature predictions since 1939 had an SE of 4.2°F, and the climatological forecasts of those months (using 14.3°F as normal) had an SE of 3.9°F, a slight improvement.

(2) Duluth predictions for the three periods (described above) totaling 108 months has an SE of 4.4°F compared to a climatological SE of 3.3°F. However, when the QBO forecasts were translated into categories of above normal or normal temperatures, they were correct in 49 of the 108 months (45.4 percent), which compares favorably to no-skill (chance) category forecasts with 33.3 percent accuracy.

Table 1. ***Average Change in the Monthly Temperature Between Alternate Months During Periods of Upward and Downward Trends in the 1%Month Running Mean Temperatures at Duluth, Minnesota****

Period of Change	Average Change During a Downward Trend (Colder)	Average Change During an Upward Trend (Warmer)
Dec. to Jan.	-4.1°F	+13.3°F
Jan to Feb.	-5.9°F	+5.5°F
Feb. to March	-5.6°F	+8.2°F
March to April	-2.0°F	+3.6°F
April to May	-2.5°F	+2.9°F
May to June	-2.4°F	+3.1°F
June to July	-2.6°F	+3.8°F
July to Aug.	-3.6°F	+2.2°F
Aug. to Sept.	-4.0°F	+2.8°F
Sept. to Oct.	-4.9°F	+4.6°F
Oct. to Nov.	-2.8°F	+1.8°F
Nov. to Dec.	-5.0°F	+4.2°F

* The forecast month is underlined.

There are several factors which may account for the inaccuracy of the QBO predictions:

(1) The period of the QBO is not always 26 months, having varied from 23 to 39 months at Sault Ste. Marie since 1939. This leads to an inability to accurately determine the month when a reversal will occur in the 12-month running mean graph.

(2) Although major reversals in the tendency of the 12-month running means usually occur between November and March, compounding the problem of winter temperature forecasting, there are also short periods (1 to 3 months) of random reversals which may occur at any time. Figure 1 shows these, e.g., during May 1972, May 1973, and July 1974.

(3) The sinusoidal curve of the QBO, when plotted, often breaks down. In figure 1 this happened from 1966 through late 1971, making it very difficult to consistently predict the tendency of the 12-month running means.

4. THE EXTRAPOLATION AND KINEMATIC PROCEDURES

The extrapolation and kinematic processes are used for long-range forecasts issued by the National Meteorological Center and are briefly described in section 2.2. These temperature forecasts are issued semimonthly in the AMWO and consist of one of three forecast categories for any area: below, above, or normal temperatures for the next month. Maps showing the actual temperature category which prevailed over an area are issued in the same publication about 1 1/2 months later. In this study the accuracy of the AMWO forecasts was determined for Duluth, Sault Ste. Marie, and Detroit from April1966 to June 1975. The AMWO forecasts are frequently interpreted and used to forecast expected ice conditions on the Great Lakes during the winter.

Until 1974 two additional categories were forecast in the AMWO, much above normal and much below normal temperatures. If one of those categories occurred in a forecast or verification over any of the three areas studied here, they were simply considered above normal or below normal temperature. If one of the three stations studied here lay on a boundary between two of the forecast categories, the benefit of the doubt was given to the AMWO when the accuracy of the forecast was determined with the verification maps. Missing data prevented the determination of AMWO forecast accuracy at all three stations during August through November 1966, May and June 1967, July and September 1973, and September 1974. In all, 102 months of maps were analyzed.

Table 2 summarizes the number of accurate forecasts for all 102 months and exclusively for the winter months November through February (35 cases) at the three stations. The results indicate that the overall accuracy of the forecasts is generally less than 40 percent, which is slightly better than a no-skill forecast (33.3 percent accuracy). The implications of these results for ice forecasting become apparent: any Ice forecasting technique attempting to predict the formation, areal extent, or breakup of ice on the basis of the AMWO forecasts is limited by the low skill demonstrated in predicting air temperatures.

Table 2. Accuracy of Average Monthly Weather Outlook Long-Range Forecasts

STATION	OVERALL FORECASTS			WINTER FORECASTS		
	Forecasts Attempted	Correct Forecasts	Percent Correct	Forecasts Attempted	Correct Forecasts	Percent Correct
Detroit	102	40	39%	35	15	43%
Sault Ste. Marie	102	36	35%	35	11	31%
Duluth	102	38	37%	35	12	34%

5. USING SYNOPTIC PERSISTENCE IN LONG-RANGE FORECASTING

The use of synoptic persistence in long-range forecasting of air temperature was introduced in section 2.3. The techniques evaluated here to develop such forecasts were conditional probabilities and the Markov chain process.

5.1 Conditional Probabilities in Long-Range Forecasting

Conditional probability forecasting is based on the pattern of change in atmospheric conditions over two adjacent periods of time, such as months, and on the patterns of atmospheric change during two non-adjacent periods. The probabilities involved indicate the likelihood of the occurrence of certain atmospheric conditions after certain preceding events have taken place.

In this study an attempt was made to predict January and February temperatures based on initial temperature conditions in November and December, respectively (2 months prior). Monthly temperatures were collected for those 4 months at Sault Ste. Marie since 1947 and were categorized by type of departure from normal (above normal, below normal, and normal). The categories were structured so that in the 28 years of data each month had 8 cases of above and 8 cases of below normal temperatures and 12 normal cases. Table 3 shows the number of times and percentage of times that a category type of January followed November category temperatures. Table 4 shows the same thing for February temperatures which follow December temperatures.

Table 3. *Conditional* **Probability of a** ***Given January Temperature Category Based on November Temperature Categories During 1947-74***

November Temperature Categories	JANUARY TEMPERATURE CATEGORIES: Below Normal	Normal	Above Normal	Total
Below Normal	1 12%	4 50%	3 38%	8
Normal	6 50%	4 33%	2 17%	12
Above Normal	1 12%	4 50%	3 38%	8

Table 4. ***Conditional Probability*** of a ***Given February Temperature Category Based on December Temperature Categories During 1947-74***

Dece mbr Teera tue Cae gons		—FEBRUARY TEMPERATURE CATEGORIES—			
		Below Normal	Normal	Above Normal	Total
	Below Normal	1 12%	4 50%	3 38%	8
	Normal	6 50%	6 50%	0	12
	Above Normal	1 12%	2 25%	5 62%	8

As they appear in tables 3 and 4, the percentages could be used to predict future January and February temperature categories based on November and December temperatures. For example, if November temperatures at Sault Ste. Marie are below normal, it my be expected that there is a 50-percent chance that the upcoming January temperatures will be normal (table 3) based on the last 28 years of data. Similarly, there would be a 62-percent chance of above normal temperatures in February if the preceding December had above normal temperatures. Although these probabilities suggest one would obtain a prediction accuracy of only 50 to 62 percent in most situations on the basis of past data, this is considerably greater accuracy than seen in the techniques of sections 3 and 4. However, the real test of the accuracy of conditional probabilities lies in making test predictions of January and February temperatures based on data from a period of time separate from the forecast period. As a result, tables similar to tables 3 and 4 were made based on data at Sault Ste. Marie from 1927 to 1955 (28 years) and were used to make 20 predictions of January and February temperatures between 1956 and 1975. The 1927-55 conditional probabilities are shown in tables 5 and 6.

In the 1927 to 1955 data the temperature categories during each month were established around the following normal temperature conditions:

(1) November normal temperatures were between 30.6°F and 34.7°F.

(2) December normal temperatures were between 18.7°F and 23.7°F.

(3) January normal temperatures were between 12.0°F and 17.5°F.

(4) February normal temperatures were between 13.9°F and 17.9°F.

Table 5. ***Conditional Probability of a Given January Temperature Category Based on November Temperature Categories During 1927-54***

		—*JANUARY TEMPERATURE CATEWRIES*-			
		Below Normal	Normal	Above Normal	Total
vember Temperature Categories	Below Normal	2 25%	4 50%	2 25%	8
	Normal	4 33%	6 50%	2 17%	12
	Above Normal	2 25%	2 25%	4 50%	8

Table 6. ***Conditional Probability of a Given February*** Temperature ***Category Based on December Temperature Categories During 1927-54***

		-*FEBRUARY TEMPERATURE CATEWRIES*-			
		Below Normal	Normal	Above Normal	Total
cember Temperature Categories	Below Normal	4 50%	3 38%	1 12%	8
	Normal	2 17%	7 58%	3 25%	12
	Above Normal	2 25%	2 25%	4 50%	8

The boundaries of the three categories were taken as the mid-temperature value between the 8th and 9th and the 20th and 21st temperatures when all 28 were ranked lowest to highest.

The exact procedure used to make the 1956 to 1975 conditional probability predictions "as as follows:

(1) Determine the November and December temperature category preceding the forecast month based on the boundaries listed above.

(2) Use tables 5 and 6 to determine the January and February temperature categories which have the highest probability of following the November and December categories which were determined in (1). For example, from table 5 one would always forecast a normal January if a below normal November occurred and from table 6 one would always forecast a normal February if a normal December occurred.

(3) Determine the accuracy of the January and February 1956 to 1975 forecasts based on the actual temperatures which occurred during those months and using the category boundaries listed above.

With the above procedure it was found that the 1956-75 Sault Ste. Marie January and February temperatures based on conditional probabilities from an independent period of time (1927-55) were accurate only 6 and 7 of 20 times, respectively (30 percent and 35 percent). The actual Sault Ste. Marie forecasts are shown in Appendix B. Similar forecasts of January and February temperatures based on 1927-55 data were made for Detroit and Escanaba, Michigan. At Detroit 8 of 19 (42 percent) correct forecasts were made during both months between 1956 and 1974 and at Escanaba 5 of 20 and 11 of 20 (25 percent and 55 percent) correct forecasts were made during January and February, respectively. Although conditional probabilities are no more accurate or inaccurate than the other techniques evaluated, they do exhibit greater extremes of success and failure at various stations and during various months. The conditional probabilities allow temperature forecasts to be made nearly 2 months in advance compared to the l-month range of the other techniques.

One-month-in-advance forecasts were also attempted at the same stations by the use of conditional probabilities. January and February forecasts based on December and January base data from 1927-1955 were accurate in 30 percent of both months at Sault Ste. Marie from 1956 to 1975, in 37 percent of Januaries and 47 percent of Februaries (7 and 9 of 19 forecasts) at Detroit, and in 20 percent of Januaries and 30 percent of Februaries at Escanaba. These results represent a considerable drop in accuracy from the 2-month-in-advance forecasts and overall display little or no skill.

5.2 The Markov Chain Process in Long-Range Forecasting

The Markov chain process is most frequently used to generate synthetic data on the assumption that the outcome of a given trial depends only on the outcome of the directly preceding trial. In meteorology the use of the Markov chain process has been limited to studies of the probability of persistence of wet and dry spells. Evaluation of probablities in determining air temperatures was discussed in section 5.1 and now the concentration will be on using a Markov chain equation to obtain monthly temperatures, rather than temperature categories. The following equation is used in hydrological studies with Markov chains:

$$X_{t+1} = \bar{X}_{t+1} + \frac{rS_{t+1}}{S_t}\left[X_t - \bar{X}_t\right] + t_i S_{t+1}\left[1-r^2\right]^{1/2} \qquad (1)$$

where X_{t+1} is the upcoming monthly value to be forecast

$\bar{X}_{t+1}$ is the long-term normal value for the same month

$\bar{X}_t$ is the long-term normal value for the antecedent month

r is the correlation coefficient between the past values of X_t and X_{t+1}

s_{t+1} is the standard deviation of month X_{t+1} values

t_i is a standard normal deviate or random number from a normal distribution with a mean of 0 and a standard deviation of 1.

From equation (1) the upcoming monthly temperature is dependent on the long-term normal for that month and two additional terms, one of which is the temperature departure of the preceding month (multiplied by a correlation coefficient) and the other of which is a random variation term. The success of this equation in forecasting monthly temperatures depends on the correlation coefficient. A high correlation coefficient will make the temperature departure from the preceding month a significant factor in the equation (that term represents persistence) and will decrease the importance of the random variation term.

In the evaluation of this equation as a long-range temperature forecasting device, January temperatures were computed for Duluth from 1960 to 1974 and for Sault Ste. Marie from 1970 to 1975. The January forecasts were made by the use of correlations and departures of temperature from the preceding November. The terms in equation (1) now become:

X_{t+1} is the January forecast temperature

$\bar{X}_{t+1}$ is the long-term normal January temperature, which is 6.1°F at Duluth and 14.1°F at Sault Ste. Marie

$\bar{X}_t$ is the long-term normal November temperature, which is 28.4°F for Duluth and 32.8°F for Sault Ste. Marie

r is 0.06 for Duluth and 0.13 for Sault Ste. Marie

S_{t+1} is 5.2°F for Duluth and 4.7°F for Sault Ste. Marie

S_t is 3.8°F for Duluth and 3.2°F for Sault Ste. Marie

t_i varies.

The equation for Duluth may be written as:

$$X_{t+1} = 61°F + \frac{0.06\ (5.2)}{3.8}(X_t - 28.4) + t_i\ (5.2)\ (0.9964)^{1/2}. \qquad (2)$$

The values of t_i, X_t, and X_{t+1} are presented in Appendix C along with the complete compuation of the Duluth and Sault Ste. Marie January temperatures for the periods described. By taking the differences between the January predicted and actual temperatures, one may obtain the SE and compare that to the SE for climatological predictions. The results of that computation reveal an SE of 6.8°F for Duluth and 7.5°F for Sault Ste. Marie, which compare unfavorably to climatological SE's of 5.2°F and 4.7°F, respectively. The low correlation coefficients were primarily responsible for these poor results.

Subsequent analysis of the temperature data revealed that correlations between December and January temperatures were only $r = 0.28$ at Duluth and $r = 0.59$ at Sault Ste. Marie. These values are still too low for the persistence term to be more influential than the random term. Evaluation of equation (1) for various values of r indicates that a value of $r = 0.70$ is needed before persistence becomes equally as important as random variation since $r = 0.70 \approx (1 - 0.70^2)^{1/2}$. Correlations between temperatures of any 2 months of the year are never as high as $r = 0.70$ at Sault Ste. Marie or Duluth. It was also found that removing the random variation term from equation (1) and recomputing the January forecast temperatures only resulted in an SE which was equal to the climatological SE and not a significant improvement.

6. CONCLUSIONS AND RECOMMENDATIONS

Four techniques for making long-range monthly air temperature forecasts have been analyzed using wintertime (November through February) data from around Lakes Superior, Huron, and Michigan. The evaluation was intended to serve as an aid in ice forecasting on the Great Lakes. Once an accurate air temperature forecasting technique is determined, its application to ice forecasting would be relatively easy since the number of freezing degree-days needed to cause ice formation in many harbors, bays, rivers, and over certain parts of the Lakes have already been established (Richards, 1964; Snider, 1974). The four techniques evaluated for accuracy and applicability as long-range temperature forecasting tools were:

(1) The use of the QBO

(2) The published forecasts of the AMWO

(3) Conditional probability

(4) The Markov chain equation.

Techniques (1) and (4) were used to derive monthly temperature values and techniques (1), (2), and (3) were (also) used to make temperature category forecasts.

Throughout the evaluation of these techniques, the purpose was to delineate methods by which the standard long-range forecasting techniques (Barry and Perry, 1973) could be applied. It was also necessary to establish an impartial evaluation of the accuracy of the *AMWO* forecasts so that they could be compared to the other techniques. Several years of data from at least one station was generally used to evaluate the accuracy of the techniques. Although data from more stations would have helped make conclusions more statistically significant, some reasonable tentative conclusions, comparisons, and recommendations may be made.

It was shown in sections 3 and 5.2 that using the QBO and the Markov chain equation did not improve upon climatology forecasts of monthly temperatures. Similar poor results were obtained when attempting temperature category forecasts by using conditional probabilities (section 5.1). Two-month-in-advance conditional probability forecasts fluctuated in accuracy from better than, to worse than no-skill forecasts, with overall improvement on chance at the three stations analyzed. There was no skill exhibited in most of the l-month-in-advance forecasts, however, and that casts doubt upon the usefulness of the technique. Analysis of data from more stations would help resolve this question.

The AMWO forecasts were found to be consistently slightly more accurate than chance at the three stations analyzed. The QBO temperature category forecasts also improved over no-skill forecasts at the one station which was analyzed. Further evidence of the usefulness of a QBO based forecasting technique was given by Rogers (1975), who developed a method for making long-range forecasts of maximum ice extent on the Great Lakes. As a result it is recommended that the *AMWO* forecasts, which presently are used by many ice and weather forecasters, be used in conjunction with analysis of 12-month running mean temperatures at the stations of interest to the forecaster. These 12-month running means, as evaluated in section 3, indicate whether or not a trend exists for current monthly temperatures to be higher or lower than those of the same month of the previous year. This in turn, with the actual temperatures from the past year, will enable one to obtain an additional forecast of the upcoming monthly temperature category. The 12-month running means were accurate during 45 percent of the months at Duluth and would in many cases be capable of determining which temperature category is unlikely to occur during the upcoming month. Combining knowledge derived from the running means with the *AMWO* can give a forecaster a more solid basis upon which his predictions can be made, and over a period of time, this could lead to a forecasting accuracy which would surpass that of the techniques when considered individually.

7. ACKNOWLEDGMENTS

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APPENDIX A. HINDCASTS OF TEMPERATURES FOR SAULT STE. MARIE, MICHIGAN, AND DULUTH, MINNESOTA, BY USE OF THE QBO

Hindcasts for Sault Ste. Marie were made for January 1939 through 1975. The columns shown below indicate the steps used in the QBO forecasting technique to obtain the hindcast date. The most important factor, the expected change in temperature from last years temperature, based on the upward or downward trend of the QBO is as follows: for an upward trend the change averaged 6.0°F, for a downward trend, 4.9°F. Based on the position of the curve in December and the final result (if it was extremely anomalous), some of those temperature changes were revised and are indicated by an asterisk (*).

Table A.2 is a sample of the category (above normal, below normal, or normal temperatures) hindcasts for Duluth from January 1962 through December 1964. The format is the same as for Sault Ste. Marie, above; however, now category hindcast accuracy' is the important factor. Table A.1 is used for the expected curve change values in most cases.

Table A.1. Hindcasts ***of Temperatures by Use of the QBO***

	(A) Mean Temperature Last Year, °F	(B) Expected Change in Temperature Based on QBO, °F	(C) Predicted Mean Temperature °F	(D) Actual Mean Temperature °F	(E) Absolute Error, °F
Jan. 1939	11.9	3.6*	15.5	16.1	0.6
Jan. 1940	16.1	-4.9	11.2	12.2	1.0
Jan. 1941	12.2	6.0	18.2	14.4	3.8
Jan. 1942	14.4	-4.9	9.5	14.5	5.0
Jan. 1943	14.5	-4.9	9.6	11.3	1.7
Jan. 1944	11.3	6.0	17.3	23.7	6.4
Jan. 1945	23.7	-7.2*	16.5	7.2	9.3
Jan. 1946	7.2	6.0	13.2	15.9	2.7
Jan. 1947	15.9	-3.6*	12.3	17.3	5.0
Jan. 1948	17.3	-4.9	12.4	9.6	2.8
Jan. 1949	9.6	6.0	15.6	18.6	3.0
Jan. 1950	18.6	-4.9	13.7	15.4	1.7
Jan. 1951	15.4	1.2"	16.6	14.4	2.2
Jan. 1952	14.4	3.6*	18.0	17.4	0.6
Jan. 1953	17.4	-4.9	12.5	18.8	6.3

	(A)	(B)	(C)	(D)	(E)
Jan. 1954	18.8	-4.9	13.9	11.2	2.7
Jan. 1955	11.2	**3.6***	14.8	16.8	2.0
Jan. 1956	16.8	-4.9	11.9	16.3	4.4
Jan. 1957	16.3	**2.4***	18.7	8.4	10.3
Jan. 1958	8.4	6.0	14.4	17.1	2.7
Jan. 1959	17.1	-4.9	12.2	11.2	1.0
Jan. 1960	11.2	6.0	17.2	18.2	1.0
Jan. 1961	18.2	**-4.9**	13.3	10.7	2.6
Jan. 1962	10.7	3.6"	14.3	10.5	3.8
Jan. 1963	10.5	**3.6***	14.1	8.4	5.7
Jan. 1964	8.4	6.0	14.4	20.6	6.2
Jan. 1965	20.6	-4.9	15.7	12.0	3.7
Jan. 1966	12.0	3.6"	15.6	10.4	5.2
Jan. 1967	10.4	**2.4***	12.8	17.3	4.5
Jan. 1968	17.3	**-3.6***	13.7	11.5	2.2
Jan. 1969	11.5	6.0	17.5	15.5	2.0
Jan. 1970	15.5	-4.9	10.6	9.6	1.0
Jan. 1971	9.6	6.0	15.6	9.6	6.0
Jan. 1972	9.6	6.0	15.6	13.7	1.9
Jan. 1973	13.7	**3.6***	17.3	19.1	1.8
Jan. 1974	19.1	-4.9	14.2	14.5	0.3
Jan. 1975	14.5	**3.6***	18.1	18.4	0.3
Mean				14.3	
SE			4.15	3.91	

* Temperature changes were revised.

Table A.2. *Hindcast* **Categories for** *Duluth,* **Minnesota**

	(A) Mean Temperature Last Year, °F	(B) Expected Curve Change	(C) Predicted Mean Temperature °F	(D) Normal Temperature Range, °F	(E) Hindcast Category	(F) Actual Category
Jan. 62	**7.9**	-4.0	**3.9**	5.7-11.3	Below	Below
Feb. 62	19.7	-6.0	13.7	9.9-14.3	Norm	Below
Mar. 62	29.3	-5.8	23.5	20.7-26.3	Norm	Norm
Apr. 62	35.4	-2.0	33.4	36.7-39.3	Below	Below
May. 62	49.7	-2.5	47.2	47.7-50.5	Below	Norm
June 62	61.3	-2.2	59.1	57.4-60.2	Norm	Below
July 62	65.1	-2.5	62.6	63.2-66.6	Below	Below
Aug. 62	67.6	-3.6	64.1	61.3-64.9	Norm	Norm
Sep. 62	54.6	-4.0	50.6	52.2-56.2	Below	Below
Oct. 62	45.0	-4.9	40.1	43.6-47.0	Below	Norm
Nov. 62	29.1	-2.8	26.3	26.4-30.4	Below	Above
Dec. 62	12.9	2.3	15.2	12.0-16.8	Norm	Norm
Jan. 63	3.4	13.5	16.9	5.7-11.3	Above	Above
Feb. 63	7.5	5.5	13.0	9.9-14.3	Norm	Below
Mar. 63	24.3	8.2	32.5	20.7-26.3	Above	Above
Apr. 63	34.2	3.6	37.8	36.7-39.3	Norm	Above
May 63	50.1	2.9	53.0	47.7-50.5	Above	Norm
June 63	56.8	3.1	59.9	57.4-60.2	Norm	Above
July 63	60.7	3.8	64.5	63.2-66.6	Norm	Above
Aug. 63	61.8	2.2	64.0	61.3-64.9	Norm	Norm
Sept.63	51.9	2.8	54.7	52.2-56.2	Norm	Above
Oct. 63	45.1	4.6	49.7	43.6-47.0	Above	Above
Nov. 63	33.8	1.8	35.6	26.4-30.4	Above	Above
Dec. 63	14.6	4.2	18.8	12.0-16.8	Above	Below
Jan. 64	0.9	13.3	14.2	5.7-11.3	Above	Above
Feb. 64	7.1	5.5	12.7	9.9-14.3	Norm	Above
Mar. 64	27.5	-5.6	21.9	20.7-26.3	Norm	Below
Apr. 64	40.9	-2.0	38.9	36.7-39.3	Norm	Norm
May 64	49.6	-2.5	47.1	47.7-50.5	Below	Above
June 64	61.3	-2.4	58.9	57.4-60.2	Norm	Norm
July 64	66.8	-2.6	64.2	63.2-66.6	Norm	Norm
Aug. 64	62.9	-3.6	59.3	61.3-64.9	Below	Below
Sept.64	57.8	-4.0	53.8	52.2-56.2	Norm	Norm
Oct. 64	56.0	-4.9	51.1	43.6-47.0	Above	Norm
Nov. 64	35.7	-2.8	32.9	26.4-30.4	Above	Norm
Dec. 64	9.6	-5.0	4.6	12.0-16.8	Below	Below

APPENDIX B. CONDITIONAL PROBABILITY HINDCASTS OF JANUARY AND FEBRUARY TEMPERATURE CATEGORIES AT SAULT STE. MARIE, MICHIGAN

Table B. 1 gives the conditional probability hindcasts for January 1955 to 1975 based on antecedent November temperature categories and the most frequent following January categories found in table 5 of section 5.1.

Table B.2. gives conditional probability hindcasts for February 1955 to 1975 based on antecedent December temperature categories and the most frequent following February categories found in table 6 of section 5.1.

Table B.l. Hindcasts of January Temperature Categories at Sault Ste. Marie, Michigan

Winter	Mean November Temperature, °F	November Category	'Table Hindcast Category	Actual January Mean Temperature, °F	Actual January Category
1955-56	29.73	Below	Normal	16.32	Normal
1956-57	33.00	Normal	Normal	8.45	Below
1957-58	34.80	Above	Above	17.10	Normal
1958-59	34.53	Normal	Normal	11.16	Below
1959-60	26.07	Below	Normal	18.23	Above
1960-61	36.27	Above	Above	10.68	Below
1961-62	34.30	Normal	Normal	10.48	Below
1962-63	34.10	Normal	Normal	8.35	Below
1963-64	38.77	Above	Above	20.55	Above
1964-65	34.97	Above	Above	11.97	Below
1965-66	32.17	Normal	Normal	10.42	Below
1966-67	30.43	Below	Normal	17.32	Normal
1967-68	29.00	Below	Normal	11.52	Below
1968-69	31.60	Normal	Normal	15.48	Normal
1969-70	32.87	Normal	Normal	9.61	Below
1970-71	32.87	Normal	Normal	9.55	Below
1971-72	31.53	Normal	Normal	13.71	Normal
1972-73	32.43	Normal	Normal	19.10	Above
1973-74	33.10	Normal	Normal	14.48	Normal
1974-75	32.82	Normal	Normal	18.35	Above

Table B.2. Hindcasts of February Temperature Categories at Sault Ste. Marie, Michigan

Winter	Mean December Temperature, °F	December Category	Table Hindcast Category	Actual February Mean Temperature, °F	Actual January Category
1955-56	17.09	Below	Below	18.31	Above
1956-57	19.84	Normal	Normal	16.82	Normal
1957-58	23.61	Normal	Normal	11.54	Below
1958-59	11.19	Below	Below	9.82	Below
1959-60	24.90	Above	Above	17.17	Normal
1960-61	16.58	Below	Below	19.18	Above
1961-62	20.77	Normal	Normal	8.39	Below
1962-63	18.55	Below	Below	6.54	Below
1963-64	16.23	Below	Below	16.71	Norm.1
1964-65	17.45	Below	Below	12.71	Below
1965-66	26.71	Above	Above	19.04	Above
1966-67	19.00	Normal	Normal	7.64	Below
1967-68	22.23	Normal	Normal	10.61	Below
1968-69	18.26	Below	Below	18.29	Above
1969-70	19.48	Normal	Normal	10.07	Below
1970-71	17.35	Below	Below	13.00	Below
1971-72	22.13	Normal	Normal	11.48	Below
1972-73	18.68	Below	Below	14.54	Normal
1973-74	19.19	Normal	Normal	9.64	Below
1974-75	24.74	Above	Above	19.18	Above

APPENDIX C. HINDCAST AND ACTUAL JANUARY TEMPERATURES FOR SAULT STE. MARIE, MICHIGAN, AND DULUTH, MINNESOTA, BY USE OF THE MARKOV CHAIN PROCESS

This appendix contains a sample of the Markov chain process for the January temperature hindcast for Duluth (table C.1) and Sault Ste. Marie (table C.2) based on November temperatures and correlation coefficients between November and January. The following terms and constants are needed to solve equation (1) (see section 5.2):

X_{t+1} = unknown January temperature to be computed

$\bar{X}_{t+1}$ = 6.1°F for Duluth and 14.1 for Sault Ste. Marie (column A)

X_t = antecedent November temperature (column C below)

$\bar{X}_t$ = 28.4°F for Duluth and 32.8°F for Sault Ste. Marie

r = 0.06 for Duluth and 0.13 for Sault Ste. Marie

S_{t+1} = 5.2°F for Duluth and 4.7°F for Sault Ste. Marie

S_t = 3.8°F for Duluth and 3.2°F for Sault Ste. Marie. From these constants r, S_{t+1}, and S_t the term $r \frac{S_t + 1}{S_t}$ of equation (1) equals 0.0828 for Duluth and 0.191 for Sault Ste. Marie and is given in column B of the tables below

t_i = random number (given in column E below).

Column D is the computation of column B times column C.

Column F is $S_{t+1}(1 - r^2)^{1/2}$.

Column G is the computation of column E times column F.

Column H is the computation of column A plus column D plus Column G and is equivalent to the hindcast temperature X_{t+1} above.

Column I is the actual January temperature.

Column J is the hindcast error or the difference between Columns H and I (absolute value).

Table C. 1. Markov Chain Process for the January Temperature Hindcast for Duluth, Minnesota, From 1960 Through 1974

Jan.	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)
1960	6.1	0.08	-9.7	-0.80	-1.08	5.17	-5.59	-0.3	10.5	10.8
1961	6.1	0.08	3.1	0.26	-0.49	5.17	-2.53	3.8	7.9	4.1
1962	6.1	0.08	0.7	0.06	1.73	5.17	8.95	15.1	3.4	11.7
1963	6.1	0.08	5.4	0.45	-1.30	5.17	-6.72	0.2	0.9	1.1
1964	6.1	0.08	7.3	0.60	0.00	5.17	0.00	6.7	16.9	10.2
1965	6.1	0.08	1.8	0.15	-0.30	5.17	-1.55	4.7	5.2	0.5
1966	6.1	0.08	-0.6	'-0.05	-1.38	5.17	-7.14	-1.1	-1.3	0.2
1967	6.1	0.08	-3.2	-0.26	-0.27	5.17	-1.40	4.4	11.2	6.8
1968	6.1	0.08	-1.8	-0.15	-0.21	5.17	-1.09	4.9	9.0	4.1
1969	6.1	0.08	0.5	0.04	0.13	5.17	0.67	6.8	7.5	0.7
1970	6.1	0.08	0.5	0.04	-0.34	5.17	-1.76	4.4	2.4	2.0
1971	6.1	0.08	-0.6	-0.05	0.01	5.17	0.06	6.1	0.5	5.6
1972	6.1	0.08	-0.3	-0.02	0.95	5.17	4.91	11.0	0.2	10.8
1973	6.1	0.08	-2.6	-0.22	-0.13	5.17	-0.67	5.2	11.6	6.4
1974	6.1	0.08	-0.6	-0.05	0.58	5.17	3.00	9.1	5.6	3.5

The SE of column J = 6.79°F.

By adding only columns A and D, one would obtain January hindcasts without the random component. Those values would have an SE = 5.2°F, equivalent to climatology.

Table C.2. Markov Chain Process for the January Temperature Hindcast for Sault Ste. Marie, Michigan, From 1907 Through 1975

Jan.	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)
1907	14.1	0.19	1.0	0.19	-1.73	4.66	-8.07	6.2	11.4	5.2
1908	14.1	0.19	-1.0	-0.19	0.81	4.66	3.78	17.7	16.2	1.5
1909	14.1	0.19	2.8	0.54	-0.16	4.66	-0.75	13.9	16.6	2.7
1910	14.1	0.19	4.0	0.76	-0.52	4.66	-2.42	12.4	15.8	3.4
1911	14.1	0.19	-2.3	-0.44	2.57	4.66	11.98	25.6	14.1	11.5
1912	14.1	0.19	-4.0	-0.76	-0.45	4.66	-2.10	11.2	00.2	11.0
1913	14.1	0.19	0.2	0.04	-0.93	4.66	-4.34	9.8	17.7	7.9
1914	14.1	0.19	3.8	0.73	1.99	4.66	9.28	24.1	17.3	6.8
1915	14.1'	0.19	-1.3	-0.25	1.11	4.66	5.18	19.0	14.6	4.4
1916	14.1	0.19	2.5	0.47	0.34	4.66	1.58	16.2	17.0	1.2
1917	14.1	0.19	-0.9	0.17	-0.50	4.66	-2.31	12.0	10.6	1.4
1918	14.1	0.19	-1.0	-0.19	0.64	4.66	3.01	16.9	3.2	13.7
1919	14.1	0.19	4.9	0.94	-2.04	4.66	-9.51	5.5	20.4	14.9
1920	14.1	0.19	-3.0	-0.57	0.27	4.66	1.26	14.8	4.4	10.4
1921	14.1	0.19	-0.2	-0.04	-1.01	4.66	-4.71	9.4	19.8	10.4
1922	14.1	0.19	-3.3	-0.63	-0.20	4.66	-0.92	12.6	12.1	0.5
1923	14.1	0.19	2.5	0.48	-0.25	4.66	-1.17	13.4	11.2	2.2
1924	14.1	0.19	3.4	0.65	0.95	4.66	4.43	19.2	8.2	11.0
1925	14.1	0.19	-1.0	-0.19	1.93	4.66	9.00	22.9	11.4	11.5
1926	14.1	0.19	-0.4	-0.08	-1.61	4.66	-7.51	6.5	16.4	9.9
1926	14.1	0.19	-4.4	-0.84	0.65	4.66	3.03	16.3	10.7	5.6
1928	14.1	0.19	-1.4	-0.27	0.61	4.66	2.84	16.7	15.8	0.9
1929	14.1	0.19	1.8	0.34	1.29	4.66	6.01	20.5	9.6	10.9
1930	14.1	0.19	-2.4	-0.46	-0.12	4.66	-0.56	13.1	11.6	1.5
1931	14.1	0.19	3.4	0.65	1.41	4.66	6.57	21.3	18.4	2.9
1932	14.1	0.19	7.9	1.51	1.01	4.66	4.71	20.3	27.1	6.8
1933	14.1	0.19	-2.1	-0.40	-0.40	4.66	-1.85	11.9	22.6	10.7
1934	14.1	0.19	-8.7	-1.66	0.32	4.66	1.49	13.9	19.2	5.3
1935	14.1	0.19	4.8	0.92	-1.64	4.66	-7.65	7.4	11.6	4.2
1936	14.1	0.19	-1.0	-0.19	1.47	4.66	6.85	20.8	12.8	8.0
1937	14.1	0.19	-7.4	-1.41	0.96	4.66	4.48	17.2	18.2	1.0
1938	14.1	0.19	1.1	0.21	-0.67	4.66	-3.12	11.2	11.9	0.7
1939	14.1	0.19	2.7	0.52	-1.64	4.66	-7.65	7.0	16.1	9.1
1940	14.1	0.19	-0.9	-0.17	-1.12	4.66	-5.22	8.7	12.2	3.5
1941	14.1	0.19	-2.5	-0.48	0.02	4.66	0.09	13.7	14.4	0.7
1942	14.1	0.19	1.5	0.29	2.07	4.66	9.65	24.0	14.5	9.5
1943	14.1	0.19	-1.3	-0.25	-0.16	4.66	0.75	14.6	11.3	3.3
1944	14.1	0.19	-1.7	-0.32	1.69	4.66	7.88	21.7	23.7	2.0
1945	14.1	0.19	1.8	0.34	1.00	4.66	4.66	19.1	7.2	11.9
1946	14.1	0.19	-0.3	-0.06	-1.73	4.66	-8.06	6.0	15.9	9.9
1947	14.1	0.19	1.0	0.19	-1.18	4.66	-5.50	8.8	17.3	8.5
1948	14.1	0.19	-2.3	-0.44	1.92	4.66	8.95	22.6	9.6	13.0

Jan.	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)
1949	14.1	0.19	4.6	0.88	-0.33	4.66	-1.54	13.4	18.6	5.2
1950	14.1	0.19	-2.8	-0.54	-0.76	4.66	-3.54	10.0	15.4	5.4
1951	14.1	0.19	-2.8	-0.54	-2.16	4.66	-10.1	3.5	14.4	10.9
1952	14.1	0.19	-6.1	-1.16	-0.85	4.66	-3.96	9.0	17.4	8.4
1953	14.1	0.19	2.1	0.40	0.39	4.66	-1.82	16.3	18.8	2.5
1954	14.1	0.19	5.5	1.05	-0.17	4.66	-0.79	14.4	11.2	3.2
1955	14.1	0.19	3.5	0.67	-0.97	4.66	-4.52	10.2	16.8	6.6
1956	14.1	0.19	-3.1	-0.59	0.52	4.66	2.42	15.9	16.3	0.4
1957	14.1	0.19	0.2	0.04	0.05	4.66	0.23	14.4	8.4	6.0
1958	14.1	0.19	2.0	0.38	-0.54	4.66	-2.52	12.0	17.1	5.1
1959	14.1	0.19	1.7	0.32	-1.91	4.66	-8.90	5.5	11.2	5.7
1960	14.1	0.19	-6.7	-1.28	-1.28	4.66	-5.97	6.9	18.2	11.3
1961	14.1	0.19	3.5	0.67	0.12	4.66	0.56	14.0	10.7	3.3
1962	14.1	'D.19	1.5	0.29	2.11	4.66	9.84	24.2	10.4	13.8
1963	14.1	0.19	1.3	0.25	-1.74	4.66	-8.11	6.2	8.4	2.2
1964	14.1	0.19	6.0	1.15	-1.97	4.66	-9.18	6.1	20.6	14.5
1965	14.1	0.19	2.2	0.42	-0.36	4.66	-1.68	12.8	12.0	0.8
1966	14.1	0.19	-0.6	-0.12	-0.66	4.66	3.08	10.9	10.4	0.5
1967	14.1	0.19	-2.4	-0.46	-1.66	4.66	-7.74	5.9	17.3	11.4
1968	14.1	0.19	-3.8	-0.73	0.27	4.66	1.26	14.6	11.5	3.1
1969	14.1	0.19	-1.2	-0.23	1.20	4.66	5.59	19.5	15.5	4.0
1970	14.1	0.19	0.1	0.02	-0.75	4.66	-3.50	10.6	9.6	1.0
1971	14.1	0.19	0.1	0.02	0.72	4.66	3.36	17.5	9.6	7.9
1972	14.1	0.19	-1.3	-0.25	0.82	4.66	3.82	17.7	13.7	4.0
1973	14.1	0.19	0.4	-0.08	-1.05	4.66	-4.90	9.1	19.1	10.0
1974	14.1	0.19	0.3	-0.06	-0.50	4.66	-2.33	11.7	14.5	2.8
1975	14.1	0.19	0.0	0.00	1.33	4.66	6.20	20.3	18.4	1.9

The SE of column J = 7.50°F.

By adding only columns A and D, one would obtain January hindcasts **without** the random component. Those values would have an SE = 4.7°F, equivalent to climatology hindcasts.