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THE ACCURACY OF WIND DIRECTION FORECASTS

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This memorandum considers the accuracies of upper wind direction predictions which are attainable by each of the two prediction methods currently used in the military services. It is concluded that up to altitudes of about 40,000 feet, 24-hour forecasts of the wind direction should be accurate within ±40° at least 75 per cent of the time in winter, and at least 70 per cent of the time in summer.

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TABLE OF CONTENTS

	Page
INTRODUCTION	4
CLIMATOLOGICAL PREDICTION	4
SUBJECTIVE PREDICTION	8
DISCUSSION	9
CONCLUSIONS	15
LIST OF REFERENCES	16

THE ACCURACY OF WIND DIRECTION FORECASTS

INTRODUCTION

In the planned use of radioactive fallout as a military weapon, the ability of the user to predict wind direction is important. It seems to be a popular view that the variation of the wind at any particular time and place defies prediction. Actually, several methods of predicting the wind are available, and their likelihood of success can be estimated.

With aircraft-delivered weapons, two methods which might be considered are (1) measurement of the wind at flight altitude near the target and use of this wind to estimate the wind structure above the target, and (2) measurement of the actual winds below the aircraft, near the target. Method 1 is inadequate for bomb missions at flight altitudes in excess of 30,000 feet, for winds at these levels are not representative of the winds at lower altitudes which may determine the main fallout pattern. Method 2 is not a current operational capability, as the estimated availability date of acceptable equipment is in fiscal 1958.[1] When available, Method 2 could be the optimum for estimating fallout patterns in most military applications.

Two additional methods of wind prediction are currently available, and are applicable to either missiles or weapons. These are the climatological forecast, which is based upon the statistics of wind at the target during the applicable month or season, and the 'subjective' forecast, which is here defined as being prepared by meteorologists provided with current weather data pertinent to areas near the target. These latter two techniques typify present routine methods of the military meteorological services.

The purpose of this paper is to evaluate the accuracy attainable in operational forecasts of wind direction which are made by the climatological and subjective methods. It must be noted at the outset that the emphasis will be on the direction of winds and not their magnitudes. Any results will therefore imply capabilities as to predictions of only the directions of fallout patterns, but not the detailed structure of these patterns, since this must depend in part upon wind magnitudes and vertical wind shears.

CLIMATOLOGICAL PREDICTION

It has been shown that winds in the free air are distributed about the vector mean wind in accordance with the normal law of errors.[2*] The departure of the distribution from the circular normal was found to be within the limits of error of observed wind distributions. It is therefore possible to represent the wind distribution at any point in the free air by two parameters, the vector mean wind

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*With the restriction that the period of time involved may not include the transition between prevailing winds. In general, this requires that the period be no longer than a season.

V_r, and the standard deviation σ of the individual winds about the vector mean. Conversely, when these two parameters are known, the wind distribution can be constructed. Thus, the proportion of time f during which the wind speed V and direction φ of the wind lie between V_1 and V_2, and between φ_1 and φ_2, is:

$$f = \frac{1}{\pi\sigma^2} \int_{V_1}^{V_2} \int_{\varphi_1}^{\varphi_2} e^{-\frac{v^2}{\sigma^2}} \, V dV d\varphi, \qquad (1)$$

where v is the magnitude of the vector departure, and φ is the angular departure of the actual wind from the mean vector wind. For convenience in calculations, a quantity q (the wind 'constancy') which is uniquely determined by σ/V_r (as shown later in Fig. 5), is defined. Tabulations of f for various values of q and v and ranges of φ, are presented in Reference 3, to which the reader is referred for greater detail, if desired. For any given value of q and range of φ the summation of f over all V is denoted as f_φ; it is the frequency of winds with directions which differ from that of the mean vector wind by φ degrees or less.

Figures 1 and 2 show the geographic distributions of q at various altitudes over Eurasia, in winter and summer. Values of f_φ in percent for various values of φ (in degrees) and q are listed in Table I.

TABLE I

Climatological Frequency (f_φ) of Winds Differing by Stated Increments (φ) of Direction from that of Mean Vector Wind as a Function of Wind Constancy (q)

f_φ (percent)

q	φ (degrees)							
	20	40	60	80	100	120	140	160
10	13	25	38	49	60	71	81	90
20	15	29	42	55	65	75	84	92
30	17	33	47	60	70	79	86	93
40	20	38	53	65	75	83	89	95
50	23	43	59	71	80	86	92	96
60	27	49	66	77	85	90	94	97
70	32	55	74	84	90	94	96	98
80	41	69	84	92	95	97	98	99
90	57	85	95	99+	99+	99+	99+	99+
95	72	93	99+	99+	99+	99+	99+	99+

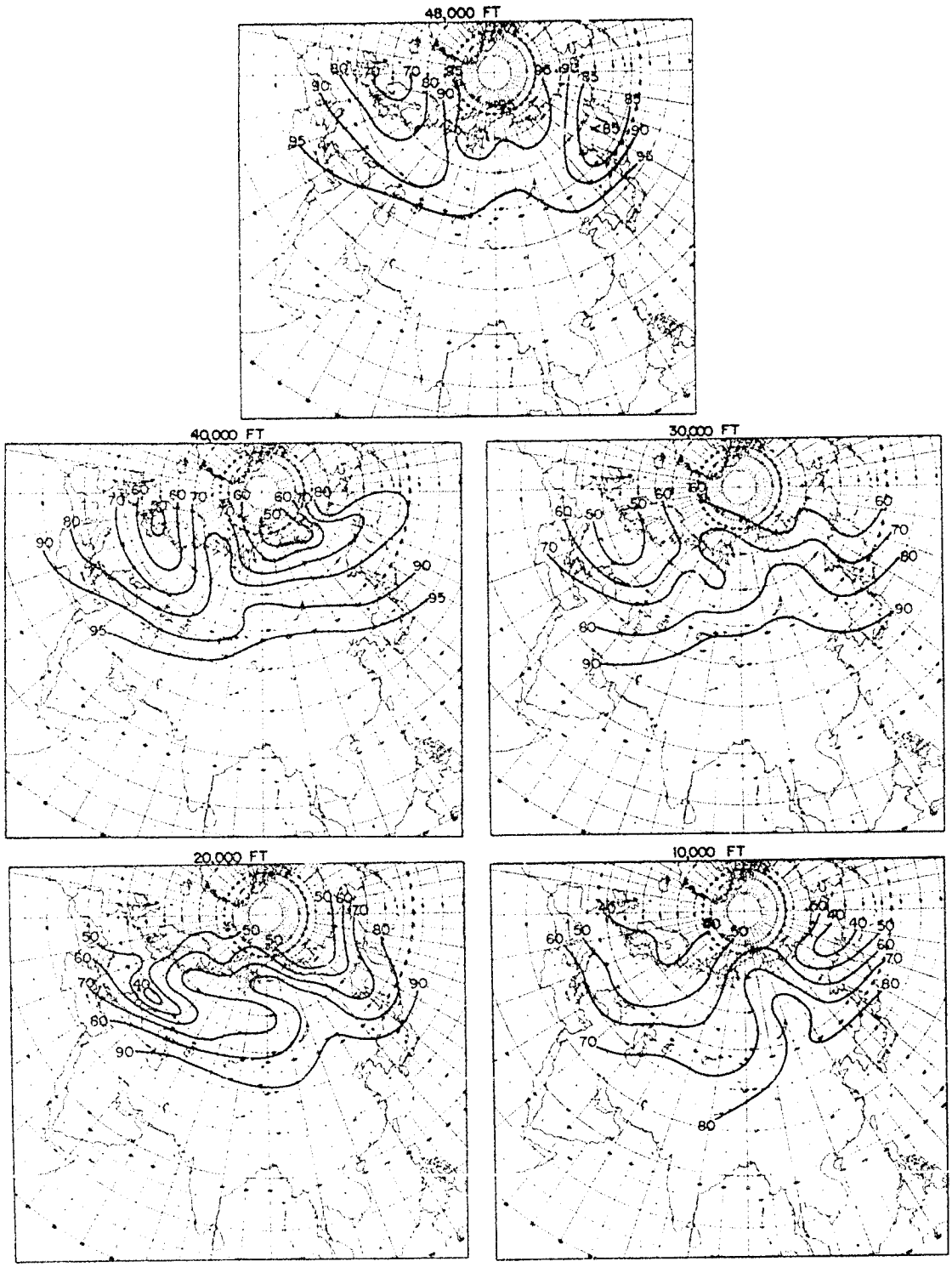

Fig. 1 -- Distribution of wind constancy (q) at various altitudes in winter

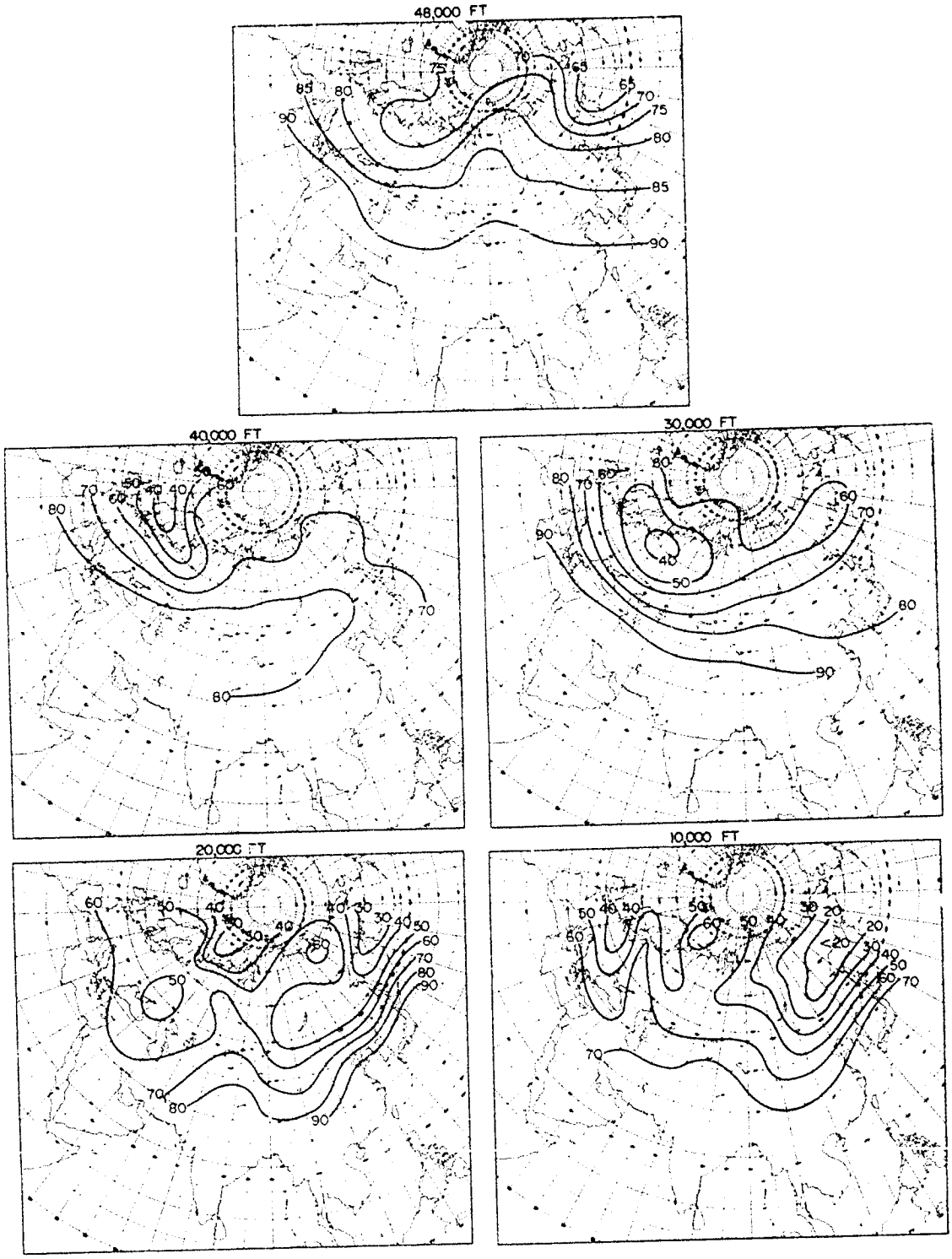

Fig. 2 -- Distribution of wind constancy (q) at various altitudes in summer

It may be determined from Fig. 1 that at 40,000 feet above Moscow (about 55°N 40°E) in winter, q is about 60. Table I shows that (when q = 60) the probability is 27 per cent that the actual wind direction will be within 20 degrees of the mean wind direction, 49 per cent that it will be within 40 degrees, etc. Similarly, if some value of φ is selected for a given operation, the minimum value of q corresponding to some desired value of f_φ may be determined from Table I, and all locations on the map which have a value of q equal to or greater than the minimum q, are suitable for use of a purely climatological prediction of the wind direction. (Note that in Figs. 1 and 2, q increases markedly with altitude.)

SUBJECTIVE PREDICTION

It is apparent from Table I and Figs. 1 and 2 that the climatological prediction will not be very reliable over much of the target area. For example, if at least 90 per cent probability is desired that the fallout pattern be within 40 degrees* of the mean vector wind direction, q must be at least 93 (from Table I). Figures 1 and 2 show that such values of q are typical only of southern Eurasia in winter at the higher altitudes. The relative unreliability of climatological forecasts in general is one reason that subjective predictions are attempted at all. The latter of course have other advantages for military operations. In its broadest sense the climatological prediction tells the probability that nature will provide some specified condition. If, for example, climatology estimates that some condition will prevail for 10 days in December, it tells nothing about which 10 days will be involved. The subjective prediction deals with specific days or hours within the month.

As previously defined, the subjective forecast is based upon current meteorological data pertinent to the target area. With present techniques, the success of subjective weather forecasts is dependent upon the quantity and quality of meteorological data available from the area of interest. During hostilities, normal data sources would be curtailed, especially in the target area. But because the weather is one of the fundamental parameters governing warfare, alternate methods of acquiring weather data from hostile areas are provided. Notable among these is the weather reconnaissance flight. It is sometimes argued that a strong enemy will actively resist every aircraft penetration of his borders. This may well be an unduly restrictive assumption, since a cardinal objective of the defender is to avoid saturation of his defenses. In any event, if aircraft delivery of weapons will be feasible at all, weather reconnaissance will be at least equally feasible. In addition, recently developed techniques involving constant-level balloon flights[5] appear to be particularly well suited to the problem of wind direction prediction. These flights should be less vulnerable to enemy interception. Also, research efforts to produce analytical methods of weather prediction for 'silent areas' are being maintained.[6] In brief, it may be said that there will probably be some basis for the use of subjective meteorological forecasts for target areas. In some respects it even appears that the data obtained under war conditions might be superior to that available in peacetime, especially for the purpose of predicting the wind direction.

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*This range of error will be used hereafter for purposes of illustration. It indicates the capability of predicting the correct quadrant of fallout; this has been indicated to be the adequate operational necessity. For example, see Reference 4, page 45.

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However one views these controversial considerations, the accuracy of subjective forecasts under normal conditions of data availability is of interest. In this connection some results of the Air Weather Service Forecast Capabilities Program should be considered. In this program military weather detachments prepared forecasts of various parameters at numerous locations in the northern hemisphere where daily observations of these parameters were routine. These forecasts were then verified, and some results are available.[7] Some of the locations for which forecasts were made and for which verifications are considered in this memorandum, are shown in Fig. 3 which also identifies the stations. In most cases, sample sizes were greater than 100.

Figure 4 shows the cumulative percentages of forecasts of wind direction which did not exceed various angular errors, averaged separately for the North American and overseas groups, as listed in Fig. 3. Note that there is little difference between the two groups; if anything, forecasts for the overseas stations were more accurate. Forecasts of wind direction were most accurate in winter at both altitudes shown. At 20,000 feet, about 80 per cent of the winter forecasts were in error by 40 degrees or less; in the summer the proportion of forecasts included in the 40-degree error range drops to about 70 per cent. Data are not available for levels other than those shown. From other considerations, however, it appears that accuracies at 30,000 feet should be about the same as those at 20,000 feet, and that the accuracies should decrease at 40,000 feet to about those at 10,000 feet. At higher levels, it is doubtful that the subjective forecasts would be significantly more accurate than climatological predictions. Note that Fig. 4 includes the results for many different types of military weather detachments. It can be presumed that accuracies would be greater at weather centrals, where techniques and communications are better.

DISCUSSION

The results shown in Fig. 4 apply to point forecasts. It is well known that the errors in forecasts of mean winds over routes are smaller than those which occur in point forecasts, and that the errors decrease with increasing length of the routes. For military applications involving fallout patterns hundreds of miles in length, the foregoing will serve to increase the probabilities that predicted wind directions are within specified angular ranges of the mean wind direction.

A rigorous evaluation of the improvement in the accuracy of route forecasts over point forecasts in the present problem of concern is impossible because of the lack of suitable data. An approximate evaluation can be made, however, because the variability in time of the mean wind over a route bears the same relationship to the variability in time of a point wind, as does the error in a route forecast to that of a point forecast. Let σ denote the variability in time of the point wind, and $\bar{\sigma}$ the variability in time of the route wind. Durst[8] has studied the ratio $\bar{\sigma}/\sigma$ over British Empire air routes, and some of his results for temperate latitudes are indicated in Table II.

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North America		Overseas	
Number	Station	Number	Station
1	Medford, Ore.	13	Larkhill, England
2	Las Vegas, Nev.	15	Paris, France
3	Rapid City, S. D.	16	Munich Riem, Germany
4	Albuquerque, N. M.	17	Wheelus AFB, Libya
5	Columbia, Mo.	18	Gibraltar
6	International Falls, Minn.	23	Haneda AFB, Japan
7	San Antonio, Tex.	24	Kadena AFB, Okinawa
8	Maxwell AFB, Ala.	25	Hazuke AFB, Japan
9	Miami, Fla.	26	Kimpo AFB, Korea
10	Selfridge AFB, Mich.	34	Thule, Greenland
11	Greensboro, N. C.	35	Keflavik, Iceland
12	Caribou, Me.	36	Komaki, Japan
28	Anchorage, Alaska		
33	Goose Bay, Labr.		

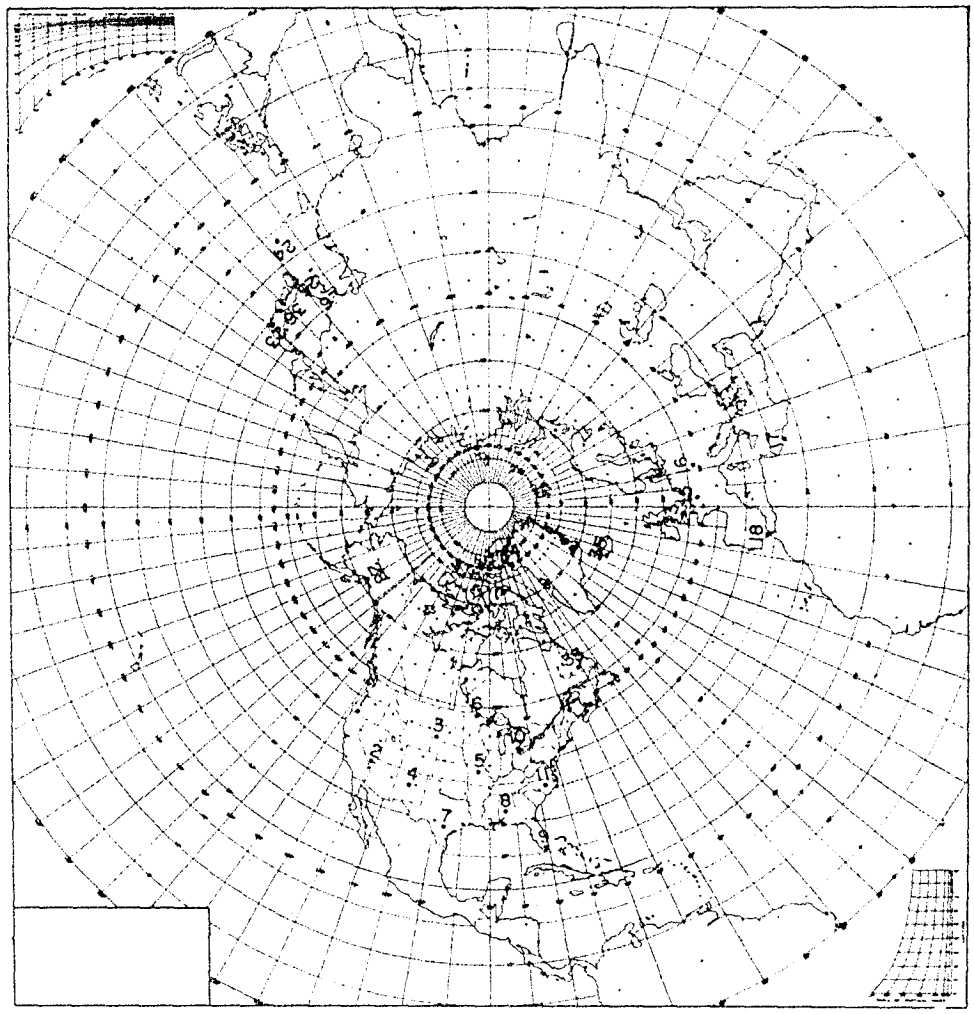

Fig. 3 -- Station Locator Chart

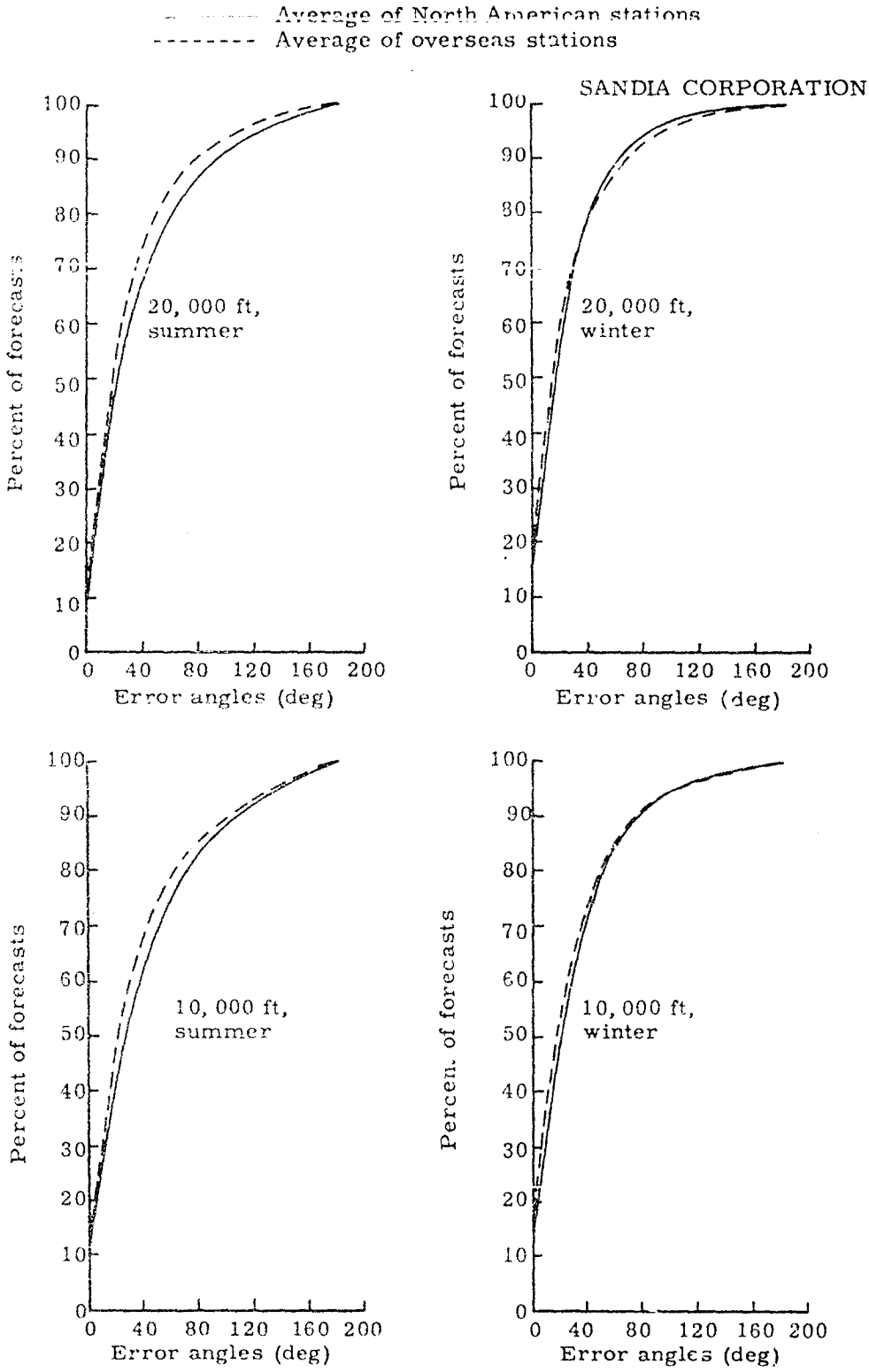

Fig. 4 -- Cumulative frequency of forecasts versus maximum errors in 24-hour subjective forecasts of wind direction

TABLE II

Values of $\bar{\sigma}/\sigma$ for Various Lengths of Route

Route Length (nautical miles)	$\bar{\sigma}/\sigma$
250	0.944
500	0.886
1000	0.737
1500	0.595
2000	0.500

Since the value of $\bar{\sigma}/\sigma$ is less than unity, the result of averaging over a route is to reduce the effective σ, and therefore the value of σ/V_r is also reduced. As shown in Fig. 5, this increases q, which is equivalent to reducing the dispersion of the wind about its mean. A numerical example follows:

> Suppose that q at some location is 70. From Fig. 5, this corresponds to a value of approximately 1.25 for σ/V_r. For a route 500 nautical miles in length, $\bar{\sigma}/V_r$ will approximate 0.886 x 1.25 = 1.11. This corresponds to a q value of about 74 (from Fig. 5). Table I shows that when q is 70, 55 per cent of the daily winds will be within 40 degrees of the mean vector wind, but that when q is 74, about 61 per cent of the daily winds are within 40 degrees of the mean. The increase, though small, is appreciable. It is larger for larger initial values of q, and for longer routes. Table III shows this dependency. It lists the probabilities f'_{40} that the directions of daily winds will be within 40 degrees of the mean vector wind, for various route lengths. The same probability for point forecasts, f_{40}, is also listed for comparison.

TABLE III

Probabilities of Mean Route Winds Being Within 40 Degrees of Route Mean Vector Wind, f'_{40}

Wind constancy, q	Probability for point forecasts, f_{40}	Route length (nautical miles)				
		250	500	1000	1500	2000
20	29	29.4	29.8	31.8	34.0	36.5
40	38	39.0	40.5	44.8	49.6	53.2
60	49	50.8	52.0	57.8	67.6	77.0
80	69	72.2	75.4	81.8	88.2	93.0

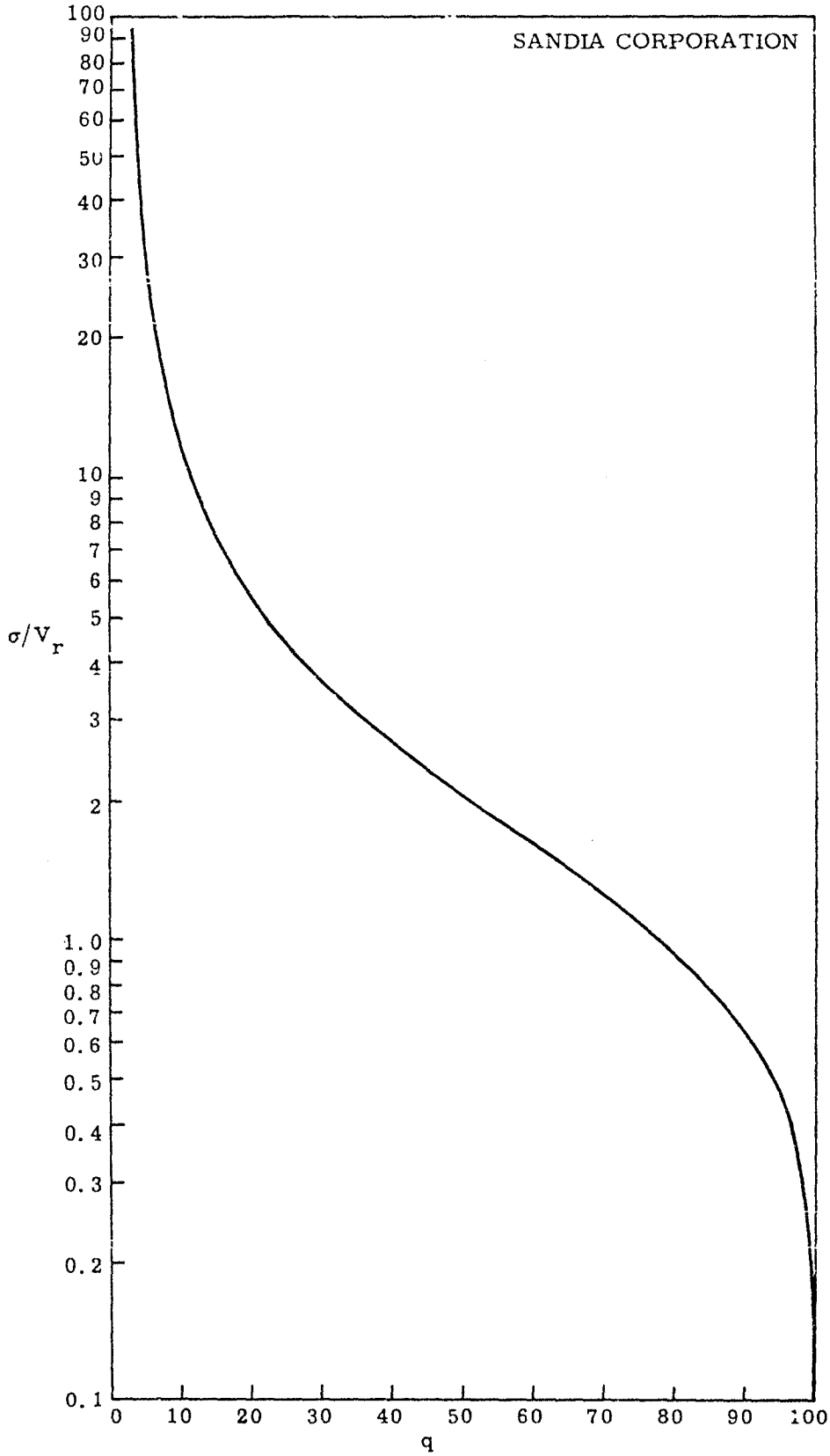

Fig. 5 -- σ/V_r versus q, where σ is the standard deviation of winds about the vector mean wind, V_r, and q is the wind 'constancy'

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The relative improvement of route forecasts over point forecasts is the difference between f'_{40} and f_{40} in Table III. Although these improvements apply specifically to the climatological prediction, the improvements for subjective prediction will be comparable, especially when the forecast wind direction is close to that of the mean vector wind. This will frequently prevail when good synoptic data are available because the mean vector wind is very nearly the modal wind. It will also prevail during conditions of poor data availability, as the forecaster must then influence his prediction by climatology.

One other bit of data may be considered. During World War II the U. S. Strategic Bombing Survey evaluated weather forecasts used by the Eighth Air Force in bombing missions over Europe.[9] In terms of equipment, personnel and refinement of operational procedures, our World War II capability of obtaining weather data from hostile areas was not as great as the present capability. This is simply the natural consequence of our recognition during and since World War II of the value of such data, and our provision of means to obtain it. Part of the findings of the USSBS are shown in Table IV which lists by seasons the frequencies of direction errors in wind forecasts at bombing altitude above targets. Under normal tactics, bombing altitudes of the Eighth Air Force were 20,000-25,000 feet (B-17 and B-24 aircraft).[10]

TABLE IV

Direction Errors in Eighth Air Force
Target Wind Forecasts

	Sample size	Percent of Forecasts with Directions Accurate to Within			
		20°	40°	60°	80°
Dec-Jan-Feb	64	78	92	95	98
Mar-Apr-May	84	75	87	95	98
Jun-Jul-Aug	148	82	92	97	97
Sep-Oct-Nov	95	70	83	95	98

The sample sizes for each season shown in Table IV were rather small and, moreover, were probably limited to cases in which visual bombing (cloud cover less than 5/10) was possible. In these respects, the data of Table IV are deficient for present purposes but they do strongly indicate that relatively accurate subjective forecasts of wind direction over enemy territory are practicable. Note that the accuracies of Table IV exceed those shown in Fig. 4. Whether this is due to sampling errors, differences in prognostic periods, or to the superiority of wartime reconnaissance data over peacetime data, cannot now be stated.

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CONCLUSIONS

1. Climatological and subjective forecasts of wind direction in the free atmosphere are most accurate in the winter season.

2. Up to altitudes of about 40,000 feet subjective 24-hour forecasts of wind direction at a point should be accurate within $\pm 40^{\circ}$ at least 75 per cent of the time in winter, and at least 70 per cent of the time in summer.

3. At greater altitudes, climatological predictions may give comparable accuracies. (It must be noted, however, that the published literature does not include the climatological summaries for high altitudes over likely target areas.)

4. The relative accuracies of wind direction predictions for fallout applications will increase with weapon yields.

B. N. CHARLES - 5123

Case No. 417.00
October 13, 1955

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