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Wind and Weather Regimes at Great Falls, Montana

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Western Region

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A western Indian symbol for rain. It also symbolizes man's dependence on weather and environment in the West.

U. S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE

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WIND AND WEATHER REGIMES AT GREAT FALLS, MONTANA

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WESTERN REGION
TECHNICAL MEMORANDUM NO. 64

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I. ABSTRACT

This is a discussion of the surface wind at Great Falls, Montana, including its seasonal and diurnal variations, and its relation to weather patterns and temperature. Methods are presented for classifying and forecasting the significant windshifts from southwesterly directions which accompany dry weather, to northerly directions which accompany the storm patterns. A convenient parameter which measures both the surface pressure gradient and the downslope effect of southwesterly winds is the difference in altimeter settings between Helena and Great Falls, known as the H-G gradient. Changes in this parameter accompanying windshifts are forecast by the Gulf Index System. This is based upon the idea of (1) Verifying the movement of short-waves of significant amplitude across the west coast of Canada, and (2) Extrapolating and tracking the resultant pressure changes southeastward from the Gulf of Alaska into Montana. The windshift at Great Falls occurs between 6 and 24 hours after the rising pressure at Juneau reaches a value at least 3 mbs above that of the falling pressure at Great Falls. Verification data is given for 3 seasons, along with other suggestions for making wind forecasts.

II. INTRODUCTION

Great Falls, Montana, is known to be a windy location. This fact is sufficient to justify a study of surface winds, since there are many days in which the most significant part of the forecast may concern the wind. Investigation also shows that the very close relationship between wind and other weather elements in the area requires a thorough understanding of surface winds in order to forecast other weather elements.

Great Falls lies within the 400-mile wide strip along the east side of the Rocky Mountains which contains most of the documented windy locations on the North American continent having mean annual wind speeds in excess of 13 miles per hour. The general climate of the windy areas is significantly different from both the mountain valleys to the west, and stations further removed from the eastern slopes of the mountains. The chief disparities are in the strong up and down slope motions affecting cloudiness and precipitation, as well as the contrasting diurnal wind patterns which have a dominating effect upon temperature.

For the Great Falls area considerable information concerning these differing wind regimes has accrued from a variety of studies, mostly unpublished, dating back to 1950. This paper is an attempt to organize all of this material in descriptive form into a single reference for the use of both briefer and forecaster. Many Great Falls wind characteristics may be applied in a general way to other windy locations along the east slopes of the mountains. Brief mention of basic principles of meteorology is felt necessary on occasion in order to facilitate explanation of local peculiarities.

III. LOCATION

Reference to the area map, Figure 1, shows the location of Great Falls on the Missouri River, about 70 miles east of and 4,000 feet lower than the Continental Divide. The topography is complicated by the Belt Mountains which roughly form a quarter circle 30 to 40 miles to the east and south, but which are loosely joined in the southwest to the main range of the Rockies. It may be noted that the Missouri River Valley is oriented southwest-northeast through Great Falls, and that there are four mountain passes which facilitate movement of air across the Divide, some 60 miles southwest of Great Falls. These geographical features are believed responsible for the preference of low level atmospheric flow along the combined mountain pass and river valley route. Such motions further suggest that the southwest and northeast quadrants, respectively, would then contain the primary downslope and upslope directions through the Great Falls area. Northerly directions are somewhat upslope and southeasterly directions downslope only with respect to presence of the Belt Mountains.

IV. WIND REGIMES

Published climatological reports (1) for Great Falls suggest that the two most notable features of the wind are its prevailing southwesterly direction and its mean yearly speed of approximately 14 miles per hour. This value is almost double the 7-8 mph mean speed for stations located in nearby mountain valleys.

To describe the prevailing wind at Great Falls as being from the southwest is an understatement. The 16-direction climatology compass restricts this term only to those winds between 213.75 and 236.25 degrees. The Great Falls wind direction falls within this narrow range 28 percent of the total hourly observations throughout the year in preference to all other 15 possible directions. On a larger quadrant basis, beginning at 190 degrees and continuing through 260 degrees, the term southwesterly winds, as used in this paper, constitutes about 51 percent of the yearly observations. Clearly, they dominate each month of the year, yet there is a seasonal rhythm in their frequency which significantly divides the year into two wind regimes of equal length but differing characteristics.

The fall-winter regime roughly begins about the time of the autumnal equinox and ends near the time of the spring equinox. The transition is gradual and varies from year to year, but it signifies the change between the warm season slack pressure patterns and the more dominant cold season systems in which low pressure in the Gulf of Alaska assumes a controlling influence upon Montana's weather east of the Divide.

Figure 2 illustrates how the frequency of southwesterly winds increases from a mean value of 45 percent of all observations in September to a maximum of 72 percent in December, followed by a decrease to 43 percent in April. The mean speed also changes from about 12 mph in September to 18 mph in December and back to 14 mph in April. During the six-month autumn-winter regime, it is normal for the surface wind at Great Falls to remain almost constantly in the southwesterly quadrant during the time between storms.

A survey of three autumn-winter seasons of the years 1965-1968 showed a total of 140 periods of continuous southwesterly winds, of which 43 percent were of 2 to 6 days duration, and the longest was 11 days. Only one out of four was less than 12 hours in length. The beginning of a period of southwesterly winds was defined by the occurrence of at least three consecutive hourly observations of winds from the directions of 190 through 260 degrees and of 5 knots or more. The end of the period was signified by at least three consecutive hours of observations of wind directions outside of the southwest quadrant.

The spring-summer wind regime is characterized by weak pressure patterns and generally poorer correlation of weather events with wind direction. At that time, the low pressure in the Gulf of Alaska is not so easily identified with dry weather east of the Continental Divide. There are more erratic changes in both wind speed and direction due to the presence of convective cells in the area. The diurnal pattern shows a greater tendency for wind speeds to increase during the warm part of the day and decrease sharply near sunset. Southwesterly winds still dominate over other directions, but their mean frequency averages only 40 percent and the mean speed of all winds decreases to 11 mph during July and August. Midsummer is therefore the least windy for Great Falls, but even so, the mean speed of these calmest months is much higher than for the windiest months of nearby mountain valley stations.

V. CLOUDS AND PRECIPITATION VERSUS WIND DIRECTION

Wind directions between 170 and 260 degrees are strongly downslope and well correlated with dry weather in the Great Falls area. A summary of 7 years of autumn-winter data indicates only a three percent likelihood of even a trace of precipitation, and only 15 percent probability of ceilings less than 9,500 feet when surface winds are southwest through south. It is interesting to note that December, with a southwesterly wind 70 percent of the time (see Figure 2) is not only the windiest month, but also the driest, with only four percent of the yearly moisture (Figure 3). The entire autumn-winter regime receives less than a third of the yearly precipitation and is also the period of maximum frequency of southwesterly winds.

One early study (2) claims upslope circulation is responsible for 63 percent of the precipitation and poor visibility in the Great Falls area. Although delineation between upslope and downslope wind directions is not precise, the most effective upslope directions lie between 60 and 300 degrees, and can be broken down into two subgroups (see Figure 4). Upriver or northeasterly winds between 10 and 60 degrees account for only nine percent of yearly observations, but 45 percent of this time is associated with precipitation and 68 percent with ceilings below 9,500 feet. Northeasterly winds are usually less than 10 knots but are nearly always observed during sustained periods of gentle precipitation when the airmass experiences a slow upglide motion over a considerable distance. Heaviest precipitation of the year occurs during May and June when the upslope flow of moisture is over the long trajectory from the Gulf of Mexico by way of the Missouri-Mississippi Valley routes.

The other subgroup of upslope winds lies within the range of 300 through 10 degrees, and constitutes 13 percent of the yearly observations. These northerly and northwesterly winds are most often related to precipitation of rather short duration which occurs with the passage of weather-producing cold fronts of either Arctic or Pacific origin. Winds from these directions indicate a 50 percent probability of precipitation and a 75 percent probability of ceilings below 9,500 feet.

Low cloud cover bears much the same correlation with wind direction as does precipitation. Approximately 80 percent of cloud ceilings less than 2,000 feet above the Great Falls Airport are recorded when surface winds are in the NW-NE directions between 300 and 60 degrees. In contrast, there is less than a 10-percent probability of obtaining a ceiling below 2,000 feet when the wind direction is between 190 and 260 degrees.

VI. METEOROLOGICAL FACTORS

Over most of the Northern Hemisphere, the combined effect of pressure gradient, rotation of the earth, and terrain friction, is such that the surface wind is directed toward lower pressure at an angle across isobars of about 30 degrees. In the case of southwesterly winds in the Great Falls area, this normal pattern is considerably altered by the increased frictional drag of the terrain, as well as the channeling effect of the geographical features previously described. The result is a direction of flow which seeks a cross-isobar angle of 60 to 90 degrees. For the typical southwest wind, surface isobars are more or less parallel to the Continental Divide, thus directing the pressure gradient across the mountains from southwest toward northeast. This, then, becomes the primary requirement for the southwest wind.

The secondary requirements concern the presence of an extensive component of westerly flow aloft and the mechanical coupling of this flow to the surface. The extent to which the upper flow is able to influence the movement of air near the ground is largely dependent upon the degree of instability in the layers of air between the surface and the faster current above. Coupling is most easily achieved when a dry adiabatic lapse rate prevails through the friction layer. Other complicating factors affecting turbulent exchange are considered to be beyond the scope of this paper. An appreciation of these complications may be gained from a recent work by P. J. Rijkoort (3), which compares the many theories dealing with the increase in wind speed through the lowest layers of the atmosphere.

The Rocky Mountains in Montana are so situated that an upper airflow from 240 degrees would be at right angles to the Continental Divide, and theoretically, most effective for the development of lee troughs and the pressure distribution most favorable for southwesterly winds along the eastern slopes.

A survey of southwest wind situations show that the accompanying 850-mb flow is generally between 220 and 260 degrees while the 700-mb wind averages between 260 and 300 degrees. This veering of direction with increasing altitude is consistent with other observations indicating that warm advection aloft is an important cause of the moderating influence of the typical southwesterly chinook winds. Classical chinook theory claims that the warmth of these winds is due to the release of heat of condensation on the windward side plus the heat of compression on the lee slope as the airmass is forced over the mountains. Observations of conditions in the Great Falls area shows better agreement with Willett's statement (4) that the primary source of chinook warmth is due to the high potential temperature of the upper air current compared to the cold airmass being displaced.

It is important to make a distinction between warm and cold advection aloft when making a forecast because of the differing characteristics of the resulting surface winds. A cold airmass moving over warm terrain undergoes rapid modification which increases instability in the lowest layers and produces the bora type of turbulent fall-wind. In contrast with the chinook which affects only the eastern slopes of the mountains, the bora type scours out the valleys as well. It is not so often noticed during winter as in the early part of the spring-summer regime after a trough moves through and terminates an extended period of heat and thunderstorms. The wind exhibits its greatest violence during the first day after the trough because the land is then so much warmer than the invading airmass. The effect diminishes rapidly the second day as the land cools and cold advection aloft decreases. The cold advection type surface wind also has a greater tendency to decrease at night.

VII. PRESSURE PATTERNS

Most of the surface pressure patterns which accompany southwesterly winds at Great Falls may be classified under three basic types:

(a) Basin High Type. Surface high pressure is centered primarily over Idaho but may cover a portion of eastern Washington, Oregon, northern Nevada, or Utah. Sometimes there is no closed high but a pressure ridge is oriented northwest-southeast along the western Montana border. A prominent low center is located in the Gulf of Alaska with extrusions of the trough down the eastern side of the Rocky Mountains through Canada and Montana. An example of this type is shown by the surface map for 0800 MST, December 18, 1965 (Figure 6). Figure 5 shows the accompanying 700-mb map for 0500 MST of the same date. This was the second day of the 5-day life cycle of this particular case and clearly indicates the presence of warm advection aloft. The 700-mb wind speeds through this period averaged about 40 knots, with a direction varying between 270 and 320 degrees.

The Basin High type is the most stable pattern for maintenance of a steady, warm southwesterly wind at Great Falls over an extended period. The life cycle of a typical Basin High generally lasts at least three days, and occasionally up to 10 days. It is most frequent during the November-January period. The case shown here had sustained southwesterly winds between 20 and 40 knots both night and day, and temperatures in the 30s and 40s.

(b) Frontal Type. This pattern resembles the Basin High type in general appearance of the surface and upper-air maps but has the additional requirement that there be a series of upper short waves or surface lows moving eastward across the Pacific coast toward Montana. A closed surface high may not be present over Idaho, but the required pressure gradient is maintained across the Continental Divide west of Great Falls as long as the centers of lower pressure are moving eastward along a latitude which is near or north of Great Falls. Pressures will then fall faster in the lee trough than they will along the western ridge. If a closed surface low forms over southern Alberta, the gradient is intensified and results in very strong winds.

Figure 8 for 2000 MST, January 13, 1966, illustrates a representative case of this type. Conditions at 700 mb are shown in Figure 7. This was near the end of an eight-day windy period with southwesterly winds between 15 and 30 knots most of the time. The last of three Pacific disturbances crossed the coast early on the afternoon of the 13th and reached the Great Falls area at 0800 MST on the 14th. The surface winds finally decreased to less than 10 knots that evening and then shifted to northwest about midnight with a 12-hour snowstorm. Throughout the eight-day windy period, the 700-mb wind at Great Falls ranged between 220 and 320 degrees, reaching speeds up to 70 knots.

The Frontal Type generally provides the highest wind speeds and the greatest fluctuations of conditions. The most notable examples of so-called "hot" Chinook winds reaching speeds of 50 knots and temperatures of 35 - 50 degrees are produced by this type.

(c) Klondike Chinook Type. The name has local significance because the resulting wind possesses a high chill factor even though temperatures may be undergoing some moderation following a severe cold outbreak from Canada. The first indication is the tendency for the high pressure over southern Canada to split along the Continental Divide into two separate cells. The main body of the cold airmass is contained in the larger cell and drifts east-southeastward toward the Dakotas. The western portion is a small closed high in the vicinity of Prince George which represents modification of the original cold airmass by mixing with maritime sources. A weak surface trough forms between the two high cells, and extends southeastward along the east side of the Divide through Alberta and Montana. As the western cell builds southward into Washington, a weak southwest wind begins in the Great Falls-Cut Bank area as soon as the first closed isobar crosses the northern border of Washington. This results in a very cold wind, with initial temperatures often well below zero degrees Fahrenheit and requiring 24 to 48 hours before warming to the melting point. In contrast to the warm Chinook which rapidly removes large quantities of snow overnight, the Klondike Chinook is capable of generating a ground blizzard of serious proportions if it follows a fresh snowfall.

Figures 9 and 10 show the 700-mb and surface charts corresponding to an example of the Klondike Chinook type which began early on the morning of January 16, 1966. This was a mild case with initial temperatures near 10 degrees Fahrenheit and requiring 24 hours for warming to above 32 degrees. It may be noted that the 700-mb flow over Great Falls was north 15 knots at the time southwest winds were first observed on the surface, and remained northerly for another 24 hours before backing to west. This illustrates a fundamental distinction between the Kondike Type, wherein the southwest wind develops from the surface upward, and the two preceding types in which there is a much more extensive westerly component aloft prior to the appearance of the southwest wind at the surface.

VIII. THE HELENA-GREAT FALLS GRADIENT

The starting point in designing a forecast system for southwesterly winds at Great Falls was the search for a convenient measure of the surface pressure gradient between the lee trough near Great Falls and the pressure ridge located near or west of the Continental Divide. Southwest wind speeds at Great Falls airport were plotted against the corresponding differences in altimeter settings between two points located across the area. The trial pairs were various combinations of pressure measurements made at Great Falls, Missoula, Helena, Cut Bank, Havre, and Kalispell.

The most effective and convenient pressure parameter was finally determined to be the difference obtained by subtracting the Great Falls altimeter setting from the Helena altimeter setting and expressing the difference in whole numbers. For example, with altimeter settings of 30.00 and 29.90 at Helena and Great Falls, respectively, a difference of plus 10, hereafter referred to as the H-G gradient, was correlated with a southwest wind of 12 knots, as shown in Figure 11, line B (a). The correlation between pressure gradient and wind speed was determined by plotting the simultaneously observed values of both variables from representative wind situations and smoothing the resulting curve.

In 1952 when the H-G gradient was first used, the Great Falls anemometer was located on top of the control tower at an elevation of 75 feet above ground. In 1959, the wind equipment was moved to a location near the runways and at a lower elevation of 23 feet above the ground. Figure 11 shows the relation between the H-G gradient and the southwest windspeed in knots as measured at both these locations. The inference from this graph is that windspeeds as reported from the runway location average about six knots less than those reported from the tower exposure. The lines are discontinued at points A and B because normally the wind shifts out of the southwest when the H-G gradient decreases to a value less than five without the windspeed necessarily becoming zero.

During periods of southwesterly surface winds, the increase in windspeed with altitude is not as consistent as might be expected. There is usually a rapid increase from the surface to about 5,000 feet above sea level (1,500 feet above the Great Falls airport), then a slight decrease in speeds through the 7,000 to 8,000 foot levels, followed by a gradual increase to speeds which soon exceed the lower maximum. A typical example of upper wind directions and speeds in October: Surface 200° 11 knots, 4 thousand 210° 17 knots, 5 thousand 220° 25 knots, 6 thousand 240° 19 knots, 7 thousand 250° 18 knots, 8 thousand 250° 22 knots, 9 thousand 260° 30 knots, 10 thousand 260° 37 knots, 15 thousand 260° 38 knots, 25 thousand 260° 39 knots.

A modest computer project was carried out in early 1969 for the purpose of establishing the quantitative distribution pattern of H-G values and precipitation occurrences. A trial deck of 1964 hourly data cards was obtained for Helena and Great Falls and a small computer at Great Falls was programed to obtain the desired information. Difficulties arose because the standard method of punching hourly observation cards does not include either the traces of precipitation or the special observations indicating the occurrence of precipitation between the hourly observations. For these and other reasons, results were not satisfactory, but they did show the total range of H-G values to be from negative 25 to positive 25, and confirmed the idea that the probability of precipitation increases with negative values of H-G gradient. The data gave the probability of precipitation occurring on the hour as about 4 percent when the H-G value is 5, and increasing to over 50 percent with H-G values decreasing to minus 10.

More detailed and reliable results were obtained by saving hourly teletype reports of surface observations for a two-year period beginning in 1968 and performing a hand correlation between hourly H-G values and the occurrence of both trace and measurable precipitation between hourly observations. The October-March periods for the two years 1968-1969 and 1969-1970 yielded the following probabilities:

H-G GRADIENT	TRACE ONLY	MEASURABLE ONLY	ANY PCPN
7	1%	1-	1
5	3	1	4
2	9	3	12
0	15	6	21
-2	25	9	34
-5	40	14	54
-7	50	18	68
-10	60	24	84

It will be noted that the probability of receiving either a trace or measurable precipitation is the sum of the separate probabilities of each because they are defined here as being mutually exclusive. Figure 12 shows the frequency distribution of all hourly H-G gradient values for the two years of data. It will be noted that a difference of 5 is most often observed, and this is unfortunate because it represents the fringe area between precipitation and no precipitation. Figure 13 illustrates the increase in probability of precipitation as the H-G gradient decreases below 5. It is recognized that the limited periods of data do not provide sufficient range of cases to precisely establish the relationship for H-G values greater than 10 and less than negative 10. A few very exceptional cases of precipitation are known to have occurred with fairly strong southwesterly surface winds and large positive H-G gradients. Investigation has shown that almost all of these have been accompanied by very strong advection of warm moist air aloft. This process is briefly described by Oliver (5), and is variously referred to as overrunning, or a trowal (trough of warm air aloft), or simply warm advection. It is not difficult to recognize but generally produces only cloudiness in the Great Falls when accompanied by southwesterly surface winds.

It should be emphasized that the H-G gradient is a nearly instantaneous measure of the surface pressure gradient to which the southwest wind is responsive. As such, it often specifies the current conditions of pressure, up or downslope motion, and precipitation probability, in a manner which is usually more conservative and useful than the existing wind. Wild fluctuations in the wind are common while rapid or erratic changes in the H-G gradient are generally limited to frontal passages of some significance. With an approaching system, the normal rate of change is about 1 unit per hour. A steady decreasing trend not only indicates decreasing southwesterly winds, but is eventually accompanied by a windshift if the H-G gradient reaches a value less than 5. Although this value of the shift point is substantiated by statistical summaries as well as observations, there is, at times, considerable variation because of strong winds aloft, convective cells in the area, or rapidly changing conditions during the passage of a cold front. The presence of a front between Helena and Great Falls can temporarily induce a misleading value in the H-G gradient, but this effect is minimized by the choosing of two points which are close together. In case the observed wind is much different from that which the H-G gradient and upper flow would indicate, one may assume an unbalanced situation exists which will soon be adjusted.

A survey of diurnal fluctuations of the H-G gradient has determined an average decrease of 3 units between the maximum value occurring during the morning hours, 0500-0800, and the minimum value about 1500-1800 MST. This is consistent with the normal occurrence of minimum and maximum temperatures which, of course, influence diurnal pressure fluctuations.

IX. DRAINAGE AND OTHER DIURNAL EFFECTS

Both observational and statistical evidence suggests the presence of a weak diurnal air movement along the Missouri River Valley. The local effects here referred to are the mountain-valley and slope winds which are produced by a combination of: (1) Differential heating by day of a column of air over the valley or plains as compared with an equal column over the mountains, and (2) gravitational downslope motion of air which is cooled at night by contact with the ground surface. At Great Falls, the strength of these drainage and up-valley winds is estimated at less than 5 knots. Therefore, they are easily masked by strong pressure gradients, and by the coupling of the surface wind with upper-air winds.

The best statistical evidence of up-valley and drainage winds in the Great Falls area is found in the summaries of winds observed at Malmstrom Air Force Base just east of Great Falls, for the period 1943-1967 (6). Figure 14 shows the percentage frequency of southwesterly (SSW+SW+WSW) winds for each hour as compared to the percentage frequency for the northeasterly group (NNE+NE+ENE). Since local effects are strongest in July and weakest in January, these months were used as a comparison. It will be noted that January shows a very slight preference for northeasterly winds at 1500-1700 MST, and southwesterly directions between 0700 and 1000 MST. In contrast, the July tabulation indicates a strong southwesterly drainage at 0400-0700 and a maximum of northeasterly directions about 1800-2100 MST. For July winds less than 10 knots, the most favored direction for each hour and the percentage frequency of occurrence for these directions were:

HOUR	00	01	02	03	04	05	06	07	08	09
DIRECTION	S	S	S	SSW	SW	WSW	W	W	W	W
% OCCURRENCE	11.6	10.3	11.8	11.4	12.7	10.8	10.1	12.2	12.5	12.9

HOUR	10	11	12	13	14	15	16	17	18	19	20
DIRECTION	W	W	W	W	NW	N	N	N	ENE	NE	N
% OCCURRENCE	11.4	11.4	8.0	7.8	6.7	6.9	6.0	6.0	5.6	6.9	6.6

HOUR	21	22	23
DIRECTION	N	S	S
% OCCURRENCE	5.6	8.0	8.6

The diurnal and seasonal pattern of drainage and up-valley winds is consistent with the diurnal fluctuations of the H-G gradient and seasonal changes in the large-scale pressure gradients.

During the autumn-winter months when the southwesterly wind is so dominant, the local effects are generally too weak to alter the wind direction, but there is often a detectable decrease in speeds during the late afternoon or early evening with the effect being quickly dissipated soon after dark. Part of the decrease is due to the normal decoupling from the upper air when the land begins to cool, but the increase after dark must be attributed to the diurnal reversal. The net effect is to cause the minimum temperature for the night to occur in early evening before the increase in wind speed.

Most of the time, local wind effects at Great Falls are of little consequence, but there are times when a knowledge of their behavior may be useful. These are: (1) When a quasi-stationary Arctic front under stagnant pressure gradients is drifting in and out of Great Falls with temperature changes of as much as 20 degrees, the movement of the front may be affected by the drainage and up-valley winds. (2) When fog patches have developed along the river in the vicinity of the airport, they may drift across the airport or away from the airport by action of the drainage wind. (3) When the forecaster mistakes the northeast up-valley wind for the onset of a more significant upslope wind leading to stratus or fog.

X. LEE TROUGH AND STANDING WAVES

There have been many detailed studies of the phenomena of lee trough development and standing waves in various mountain regions of the world. Some of these findings are applicable to the Great Falls area, but there is little evidence of extensive wave development such as has been documented in the Sierra Nevada Mountains. Sailplane pilots have, in fact, complained of the lack of sustained wave action. The uneven character of the mountains suggests a complex pattern of many wave-trains as well as interaction between these wave-trains. A few pilot reports have indicated wave lengths of the order of 10 miles or less. This would agree with frequent visual observations of wave clouds showing several waves of small amplitude comprising an individual wave-train.

Over the years, there have been sufficient pilot reports and weather related aircraft accidents between Helena and Great Falls to infer that this is a general area of turbulence which can be classed as severe more often than is considered normal with most mountain segments of the airways. The critical periods are associated with frontal passages and high winds; but the effect of these meteorological factors is insufficiently known to always permit discrimination between safe and hazardous conditions. Indeed, some of the periods with highest wind speeds (in excess of 50 knots) have been accompanied by pilot reports of smooth flight conditions. One possibility is that the extreme turbulence is caused when a slight change of airflow creates additive phase relationships between wave-trains.

Under certain conditions of strong southwest winds, there is a phenomenon which sometime ago was commonly referred to as "pumping" of the barometer. With great irregularity, there are intervals of a few minutes during which the pressure falls very rapidly and the wind speed increases markedly, followed by similar intervals of rapidly rising pressure and greatly reduced wind speeds. This is not to be confused with ordinary gustiness because attendant pressure changes are of greater magnitude and lulls are so extended as to sometimes confuse the observer into concluding that a significant change had taken place, such as a frontal passage. A possible explanation is that minor changes in the upper flow cause the wave-train to become unstable from time to time so that individual waves "wash" downstream toward Great Falls. The approach of a particular wave would then account for the rapid fall of pressure and immediate increase in windspeed, followed by reverse action as the "meso-ridge" moved over the station. The action ends when the wave-train is reestablished in a stationary attitude.

XI. WINDSHIFT CHARACTERISTICS

It has been shown that wind directions may be correlated with upslope consequences such as precipitation, cool temperatures, etc. However, it is obvious that some direction changes are caused by drainage or other temporary local effects which are not likely to be related to significant weather events. The characteristics which accompany windshifts are so variable that it is difficult to establish objective criteria which are applicable to all cases of wind behavior and able to distinguish between significant and nonsignificant changes in direction.

For instance, the previously described daytime process of coupling the surface wind to the flow aloft is sometimes capable of inducing an observed windshift to the northwest if the flow aloft is also northwesterly. The forecaster needs to recognize this as being an insignificant windshift which will not be followed by increasing cloudiness and other upslope phenomena. An example for October 29, 1970, shows one of four successive days on which the wind shifted from southwest to northwest about noon, when the daytime heating established a dry adiabatic lapse rate from the surface upward into the layers where the flow remained northwesterly. Decoupling occurred about 1800M, after which the surface gradient kept the wind in the southwest through the night.

HOUR	TEMPERATURE	H-G GRADIENT	WIND
0600	32	8	240-9 kts
0800	34	9	230-11
0900	39	10	230-17
1000	46	9	240-15
1100	50	9	240-14
1200	57	8	290-12
1300	60	7	330-14
1400	60	7	330-13
1500	59	5	330-10
1600	59	5	330-10
1700	55	5	330-06
1800	50	6	230-08
1900	46	6	240-08
2100	40	5	240-08

The winds aloft below 10,000 ft. for both morning and afternoon soundings for the same day were:

HEIGHT	0500MST	1700MST
9000	330 deg 20 kts	330-27
8000	320-20	310-18
7000	310-18	310-12
6000	290-14	320-11
5000	270-14	320-12
4000	230-10	320-10

Federal Meteorological Handbook No. 1 (formerly Circular N) defines a windshift as a clockwise shifting of gusty winds accompanied by some cold front phenomena such as rapid pressure rise, rapid drop in temperature or dewpoint, beginning of rain or snow showers. This definition is necessarily subjective because of the great variability of combinations, the order of occurrence of the phenomena, and the time lapse between windshift and phenomena.

Much of the variation in windshift characteristics is due to the strength and type of cold front which accompanies the shift. Average Pacific cold fronts which are oriented north-south and approach Montana from due west do not usually cause a windshift at Great Falls because the accompanying westerly or southwesterly flow is strongly downslope.

Pacific cold fronts which move into Montana from the northwest or north (Pacific Northerns) and are oriented more southwest-northeast and have upper-air support, are likely to shift the wind from southwest to northwest within 1 to 3 hours after the frontal passage at Great Falls. More complex cold systems of either Pacific or Continental origin which approach Montana from the north are often observed to shift the wind in two stages. The first shift is from the southwest to northwest and is presumed to be the time of frontal passage, even though not necessarily accompanied immediately by precipitation or cloud cover. A second shift then occurs from northwest to northeast a few hours later accompanied by secondary cold front characteristics, and is more likely to signal the onset of rapidly deteriorating weather conditions.

A detailed survey of all windshifts was made for three autumn-winter seasons at Great Falls. Seventy percent of these shifts were from the southwest to the northwest quadrant within the first 3 hours, with some later shifting into the northeast or east. The other 30 percent made the entire shift from southwest to northeast in the first 3 hours. The windspeed was 10 knots or less in 44 percent of the cases. Of the remaining 56 percent which showed speeds over 10 knots, about half exceeded 20 knots.

Correlation of temperature change with windshift was not useful because there was no objective way of correcting for either the diurnal change or the temporary rise in temperature due to mixing in the lower layers. An abrupt pressure rise might be construed as a most significant element of windshifts, because most precipitation at Great Falls occurs with rising pressure. However, this survey showed that one-fourth of the shifts were accompanied by either a zero net change, or a fall in altimeter setting during the first 3 hours. Another 44 percent of the cases showed a rise in altimeter setting of less than 0.10 inches during the same period. Virtually all windshifts which resulted in some instrument flight conditions and measurable precipitation during the first 3 hours were accompanied by a rise in pressure, but another group constituting half as many shifts were also accompanied by a pressure rise but with neither precipitation or significant lowering of clouds.

Ceilings below 7,000 feet during at least 6 or more of the first 12 hours followed 42 percent of the windshifts. Forty percent of the shifts had ceilings below 3,000 feet continuing into the period 12 to 18 hours after the shift, while 30 percent had some ceilings below 1,000 feet during the first 6 hours after windshift.

Concerning precipitation, 44 percent of the windshifts were accompanied by no precipitation during the first 12 hours whereas 20 percent had only a trace. Another 36 percent had measurable during the same period and nearly all of these had some form of precipitation during the first 3 hours after shift. These figures agree with other summaries showing precipitation probabilities of 3 to 4 percent with southwesterly winds compared with 50 percent or more with directions of NW, N, and NE.

After considering the great variability of conditions accompanying both significant and nonsignificant windshifts, it was decided that a flexible system of rating shifts on a point basis would be more feasible than attempting a rigid set of criteria to determine the separation between the two groups. Each shift was rated according to a scheduled number of points determined by the amount of change in pressure, wind speed, cloudiness, precipitation, and length of time the wind remained "shifted". The most significant shifts were allowed a maximum possible rating of 25 points, while all those with less than 7 points were considered insignificant for both verification and desirability of being forecast. For convenience, shifts rating 7 - 8 points were considered poor, 9 - 11 fair, 12 - 15 good, and over 16 excellent. The rating system follows:

	1 Pt.	2 Pts.	3 Pts.	4 Pts.	5 Pts.
Windspeed, 1st 3 hrs	10-19	ovr 20	--	--	--
Net alt. rise 1st 3 hrs	.01-.04	.05-.09	.10-.14	.15-.19	ovr .20
Lowest cig. 1st 6 hrs	70-94	50-65	30-49	10-29	00-09
Cigs. 00-65, 1st 12 hrs	1-2	3-6	ovr 7	--	--
Shift duration, hrs	6-11	12-17	18-23	24-48	ovr 48
Precip. 1st 12 hrs	--	trace	.01	.02-.09	ovr .09

The entire purpose of this complicated rating system was to objectively determine for verification purposes which windshifts should be forecast. Some compromise was still necessary in selection of the cutoff point after considering the lack of significant weather following many apparently vigorous windshifts compared with the eventual stronger effects following some shifts which initially seemed weaker. The 7-point cutoff was finally chosen in the belief that most of these shifts were caused by diurnal effects or by situations which would not result in significant weather events.

A typical example of an apparently insignificant windshift occurred January 30, 1967, when the wind shifted from 260 degrees 18 knots at 1600 MST to 50 degrees 11 knots at 1700 MST. This was probably not due to thermal effect but was a definite shift which ended a 4-day period of southwesterly winds occasionally gusting to 30 knots. Although termination of strong southwesterly winds may have been significant to some interests, there was no precipitation or change in cloud condition, with skies remaining clear all afternoon and night for a period of 15 hours following the shift. The rating system gave 1 point for wind exceeding 10 knots during the first 3 hours after windshift, 2 points for an altimeter setting rise of 0.06 inch in the same period, and 3 points for the 23 hour time in which the wind remained "shifted". This made a total of 6 points for a windshift whose only significance was the ending of the southwest winds. The difference between 6 and 7 points is admittedly thin, but so is the measurable difference between many windshifts.

XII. FORECASTING WINDSHIFTS AND NEGATIVE H-G GRADIENTS

If high H-G gradients and southwesterly winds are associated with dry windy conditions at Great Falls, then it is evident that foretelling negative H-G gradients and northerly winds would be vital to the forecast of precipitation and poor weather. Numerous meteorologists (7) (8) have observed the pattern of good weather which usually prevails over Montana, east of the Continental Divide, whenever a surface low pressure area exists within the Gulf of Alaska, generally, between Juneau and Annette. This is because the location of the low in the Gulf requires positioning of the long-wave pattern in such a manner as to maintain a westerly or southwesterly flow of mild maritime air over regions east of the Divide. For Great Falls, this implies the pressure gradient favoring a southwesterly wind and strong downslope motion.

Whenever a short-wave trough moves through the Gulf of Alaska, or when the upper ridge moves eastward to a position along the Canadian coast so as to shift the 700-mb wind at Annette into the northwest, a surface pressure rise line moves through the same area and is orographically guided southeastward along the east side of the Continental Divide into Montana in less than 24 hours, with resulting windshifts along most of the route. The method of forecasting this windshift into Great Falls with accompanying negative H-G gradients is then based upon, (1) the detection of a short wave of sufficient amplitude moving through the Gulf, and (2) the extrapolation of this short-wave trough southeastward into Montana.

Several years of experimentation were necessary to determine which points for pressure comparison were most effective, and what magnitude of pressure rise in the Gulf was necessary when compared with the simultaneously falling pressure at Great Falls. By trial and error it was concluded that the best single indication is when the rising pressure at Juneau reaches a value at least 3 millibars above Great Falls' pressure. Whichever of these events first occurs is referred to as a Gulf Index signal for a windshift at Great Falls about 15 hours later. These are minimum pressure comparisons for a forecast windshift. Greater pressure differences than the minimum 3 or 5 millibars simply indicate short waves of greater amplitude are on their way, and will cause more vigorous windshifts at Great Falls.

Case histories show that nearly all windshifts take place at Great Falls between 6 and 24 hours after signaling by the Gulf Index. Although the variations in lag time do not constitute a normal curve, 15 hours is generally used as a first approximation with adjustments from other considerations (See Figure 17 for average travel time of fronts and windshifts). Variations in shift time are due to the existing pressure pattern at the time of the Gulf Index signal as well as speed of movement of the short wave through Canada. The H-G gradient must decrease to a value near or less than 5, and this requires readjustments in pressure such that an existing Alberta low must be filled or an existing Basin High must weaken. To follow through on these events, use is made of additional pressure checkpoints at Boise and Whitecourt (ZU). The eventual windshift at Great Falls is practically assured by substantially falling pressure at Boise and a rise at Whitecourt to 6 millibars higher than Great Falls. Most of the details for pressure comparison at Whitecourt have been worked out by Harding (7).

The foregoing Gulf Index system applies mostly to short-wave troughs of Pacific origin, and effectively discriminates between the so-called "Pacific Northerns" which cause significant changes east of the Divide and the more frequent fronts which move into Montana from due west with resulting weather on the west slopes but little effect on the east side. For Arctic or Continental outbreaks, a somewhat different approach is used. The Arctic Index requires the pressure at Juneau to rise above the pressure at Annette, signifying filling of the Gulf low, but also requires the pressure at Whitehorse to exceed that of Great Falls. The greater the pressure difference in these comparisons, the more vigorous the outbreak. However, the Arctic Index is not so precise as the Gulf Index, and determines no particular windshift time, which may easily be 48 hours away, depending upon the pre-existing position of the front. The Arctic Index simply indicates that the Arctic or Continental front located north of Montana will move southward as long as the Arctic Index conditions are satisfied. Even with these flaws, the Arctic Index is very helpful when dealing with quasi-stationary fronts which become stalled in the area between Edmonton and Lethbridge. Most precipitation at Great Falls occurs following a Gulf Index signal but the biggest winter storms follow the simultaneous occurrence of both Gulf and Arctic Indexes.

Fundamental to the success of the Gulf Index system is the assumption that the presence of both surface and upper-air support for movement of a short-wave trough through the Gulf of Alaska is indicated by the occurrence of an Index signal. An objective refinement has been developed to help determine the upper-air support when the 700-mb wind at Annette is not available. This consists in a method of computing the mean geostrophic wind direction by use of 700-mb heights at four stations, designated by letters: Anchorage (A), ship 4YP (B), Fort Nelson (C), and Port Hardy (C). The North-South wind component is given by the heights (A+B)-(C+D), while the East-West component is supplied by (B+D)-(A+C). The resultant vector of these two components may be readily determined by use of a simple chart which thus provides the mean wind direction for the Gulf. A vector wind showing a shift from southwest to northwest or north is then confirmation of the necessary upper-air support. This method may be used for both 700-mb and 500-mb levels. The best indication of a short-wave trough moving through the Gulf is indicated by NMC guidance, a Gulf Index signal and northwesterly 700-mb flow at Annette.

For convenience under operational conditions, a continuous time graph of 3-hourly sea-level pressures has been maintained for the autumn-winter seasons beginning in 1962. The pressures entered on this graph include

Great Falls, Juneau, Annette, Whitehorse, Whitecourt, and Boise. The latter is included to give a measure of the Basin high, and therefore indicates a wider breadth of gradient across the Continental Divide. Since a strong Basin high is a necessary ingredient in one type of persistent southwest wind, the high must weaken if "Pacific Northerns" or Arctic outbreaks are to be effective in causing upslope weather conditions in Great Falls.

Figure 15 shows data for a 6-day period, November 18 - 23, 1967, illustrating effectiveness of the Gulf Index in forecasting windshifts. This data was taken directly from the original time-pressure graph in use at the Great Falls Forecast Office, but for simplicity, the lines representing pressures at Whitecourt, Whitehorse, Annette, and Boise were omitted. During the period November 16 - 24, 1967, there were 5 Gulf Index signals which correctly forecast the 5 windshifts associated with 5 different Pacific cold fronts which moved into Montana from the northwest. To conserve space, the first and last of these are not shown in Figure 15, but some of the characteristics of all 5 are summarized as follows:

INDEX TIME	HRS TO SHIFT	SHIFT RATING POINTS	PRESSURE RISE 3-HR	3RD HOUR WIND	PCPN 1ST 12 HOURS	LOWEST CIG. 1ST 6 HOURS
16th,11M	18	7	.10	0610	0	Unlimited
18th,04M	14	17	.13	3315G	T.	2000 ft
19th,22M	15	18	.06	3625G	.01	900 ft
22th,04M	14	17	.12	3615	.01	500 ft
24th,05M	9	19	.40	0312	.02	400 ft

The first of these shifts illustrates the type whose significance may be debatable from the lack of precipitation but important because it signified an end to the 72-hour period of considerable wind and resulted in lowering the minimum temperature 14 degrees below that of the previous night. The last 4 shifts were quite significant because they all resulted in several hours of instrument flight conditions due to low ceilings or visibilities in snow. The weather was not particularly severe but there was, in each case, a rather complete change between the 12- to 24-hour periods of unlimited conditions and the equally substantial periods of snow and low clouds. Such marked changes are not at all uncommon in Montana. The upper graph in Figure 15 shows the change in the H-G gradient every 3 hours and its relationship to the Great Falls wind.

XIII. VERIFICATION OF WINDSHIFT FORECASTS

Three six-month periods beginning with the autumn equinox and ending with the spring equinox for the years 1965 - 1968 were chosen for verification. This constituted a total of 540 days, but only 345 of these days were considered test cases because they were officially classified in the climatological records as having prevailing southwesterly winds which, therefore, required a forecast decision as to the likelihood of a windshift in the following 24 hours.

During the test period, there were a total of 90 Gulf Index Signals which were followed within 6 - 24 hours by:

78	Significant Shifts	(Hits)
8	Nonsignificant Shifts	(Misses)
4	No Shift	(Misses)

Also during the test period, there were a total of 137 instances in which a direction change from southwest to some other quadrant met the requirements for a windshift for a period covering at least 3 consecutive hourly observations. Rating the 137 windshifts according to the point system showed the following:

RATING	NO. OF SHIFTS	SIGNIFICANT	NONSIGNIFICANT
Excellent	43	Yes	
Good	6	Yes	
Fair	13	Yes	
Poor	16	Yes	
Very Poor	43		No
TOTAL	137	94	43

Of the 94 significant windshifts, 78 were considered hits because they occurred within the 6 - 24 hours following one of the Gulf Index signals noted above. The remaining 16 significant shifts were rated misses because they were not forecast. The remaining 12 Gulf Index signals were rated misses because 4 were followed by no windshifts, and the other 8 forecast insignificant windshifts. The resulting contingency table:

	SIGNIFICANT SHIFT FORECAST	SIGNIFICANT SHIFT NOT FORECAST	TOTAL
SIGNIFICANT SHIFT OCCURRED	78	16	94
NO SIGNIFICANT SHIFT	12	239	251
TOTAL	90	255	345

This gives a PA (Post Agreement) score of 78/90, representing 86.7 percent of the Gulf Index signals as being correct. The PF (Pre-Figurance) score of 78/94 indicated 83.0 percent of the significant windshifts were correctly forecast. The percent correct score was then 317/345 or 92.0. This compares with a persistence score of 251/345 or 72.8 percent correct if the forecast decision had been to simply continue an existing southwesterly wind another 24 hours. The bias was 90/94 or .95.

Some value should be attached to the fact that all of the 43 windshifts rated excellent by the point system were correctly forecast by the Gulf Index System. These were all associated with major storm patterns. Of the 16 significant shifts which were not forecast correctly, 8 were rated good, 5 were fair and 3 were poor. It was desired that none of the 43 shifts rated very poor would be forecast by the Gulf Index, but in this, 20 percent were forecast.

An unsuccessful attempt was made at comparing the windshift forecast capability of the Gulf Index system with that of NMC guidance products. The chief difficulty was that guidance does not specify the time and place of prognosticated windshifts with sufficient objectivity to compare directly with indications given by the Gulf Index system. Neither can the 850-wind prog be substituted for objective verification of the surface wind prog, but this does not hinder the concurrent use of both systems in operational forecasting. They serve as a very useful check upon each other.

XIV. FORECASTING SOUTHWESTERLY SURFACE WINDSPEEDS

With westerly winds aloft, an estimate of expected surface windspeeds may be obtained by reference to Figure 16. This chart was obtained by plotting simultaneously observed values of the H-G gradient, the southwesterly surface windspeed and the 700-mb windspeed twice a day (10). Forecast values of the H-G gradient and the 700-mb wind may be used. However, the graph represents only average lapse rate conditions, since no attempt was made to separate the development data into coupled and uncoupled conditions between surface and upper air. The user is also reminded that conditions as represented on the lower end of this graph are often unrealistic because of the tendency of the wind to shift out of the southwest quadrant whenever the H-G gradient decreases to less than 5.

Erratic fluctuations in windspeeds often occur and it is not likely that any objective forecast scheme will account for all of these changes without having more extensive observational data to inject into the forecast system. The most serious problem is forecasting the sudden increase in windspeeds which may result in damage to property. The following guidelines have been found helpful:

(1) Constant vigilance should be maintained for signs of increasing winds between 850 and 700 mb at the same time that conditions are likely to become favorable for coupling the surface wind to the upper air. NMC guidance material is useful for the former but the forecaster must anticipate the latter.

(2) Existing winds over 30 knots at 850 mb should always be considered a potential strong surface wind situation unless coupling to the surface is unlikely.

(3) Coupling of the surface wind with the upper airflow is practically assured whenever the surface temperature exceeds the 850-mb temperature by 2 or 3 degrees. Normally this can be expected between 1100 and 1800M on most warm days, but there is great variation in the coupling process during night and early morning hours.

Strong surface inversions which develop after cold outbreaks are often difficult to break through, and there is a tendency for lower windspeeds under Klondike Chinook conditions than would otherwise be expected.

(4) Coupling is almost automatic with cold advection following a surface trough or cold front when the ground surface is initially quite warm with respect to the air aloft.

(5) Increasing southwest windspeeds are often indicated by falling pressures along the east side of the Divide from Great Falls northward, and by increasing southwest winds at Calgary and Lethbridge.

(6) The hour-by-hour changing trend of the H-G gradient may be projected ahead for short periods of 6 - 12 hours, using an average change of 1 unit per hour. NMC progs of surface pressure patterns which resemble the Basin High, Frontal, or Klondike types should be considered along with the expected movements of troughs and fronts.

(7) Most winds over 20 knots are gusty. The 5,000 foot or 850-mb speed is a good approximation to the peak gusts, or else use 50% more than the steady windspeed being forecast.

(8) Considerable variation in speeds may normally be expected when the 700-mb wind exceeds 40 knots. Sudden changes occur at the time of frontal passages. The strongest winds are likely to precede Pacific fronts but the most rapid decrease is most often following a northern front.

(9) An estimate of the northeasterly windspeed to be forecast following the passage of a Pacific Northern cold front may be obtained from speeds reported north of the front. Figure 17 shows average 3-hourly positions of such fronts based upon 3 years of movements of fronts and windshift lines past each of the Montana and Canadian station south of Edmonton. This chart has been in use at the Great Falls Forecast Office since 1954.

XV. CONCLUSIONS

This paper represents the consolidation of over 20 years of intermittent studies and attempts to understand and forecast the wind at Great Falls. Although substantial progress has been made with respect to some of the more common wind patterns, there are less frequent types which are still quite difficult to deal with. Probably the best understood situations occur during autumn months when the pressure patterns might be considered normal and before the Arctic front takes up a quasi-stationary residence in southern Canada.

The Gulf Index system of forecasting windshifts is most effective when dealing with weather patterns in which the path of isallobaric centers is through the Gulf of Alaska and southeastward into Montana. Fortunately, this pattern is so frequent and so repetitive that, once established, there must be good reason for expecting a change into some other pattern to which the system is not responsive. Such major changes are often indicated by the 72-hour NMC progs. The system is least effective when the long-wave trough remains along the Pacific coast in such a position that isallobaric centers move into Montana from the southwest. An example of this is a front oriented SW-NE, near or parallel to a Boise-Butte line, and there is wave action along the front. The trough along the west coast may be expected to persist for an extended period during which the Gulf Index will be practically useless.

Other weather situations to which the Gulf Index is unresponsive include both upper fronts and warm advection which causes strong vertical motion over a large area. These types are of short duration with generally less serious consequences.

For a number of reasons, the Gulf Index system is little used during the summer months. At that time, the thermal trough to the southwest assumes a frequently dominating role in weather events. Conditions in the Gulf have less control over weather east of the Divide and pressure gradients are much weaker. Thunderstorms account for a large share of the rainfall and the Index system has little to offer in forecasting these. No attempt has been made in this paper to deal with erratic wind conditions associated with thunderstorms.

XVI. ACKNOWLEDGMENTS

My thanks to the many members of the Great Falls forecasting staff, both past and present, who have offered their encouragements and suggestions. Many of the ideas concerning pressure comparisons between Great Falls and the northern stations were originally suggested by Warren Harding. Harry Elser and Arthur Jacobson played a part in developing the chart of northern frontal movements. Arthur Rozett and Roy Anderson were partly responsible for the method of computing the mean upper wind from 700-mb heights. Earl Robinson, Lew Harney, and William Grimes made useful corrections in the text. Harold Ward worked with the computer. John Hamilton and Robert Guern kept the project alive.

XVII. REFERENCES

1. Climatology of the United States No. 82-24, Summary of Hourly Observations, Great Falls, Montana, 1963. U. S. Weather Bureau.

2. L. L. Kolb and M. M. Goodmanson, Journal of Meteorology, Dec. 1944, page 99.

3. Rijkoort, P. J., The Increase of Mean Wind Speed with Height in the Surface Friction Layer, Netherlands Meteorological Institute, 1968.

4. Willett, Hurd C., Descriptive Meteorology, 1944, page 274.

5. Oliver, Vincent J. and Mildred B., Forecasting the Weather With the Aid of Upper-Air Data, Handbook of Meteorology, 1945, page 820.

6. Revised Uniform Summaries of Surface Observations for Malmstrom AFB, Air Weather Service, Asheville, North Carolina, 1968.

7. Harding, Warren G., The Gulf of Alaska Low and Its Relationship to Weather in Montana and Northern Idaho, Manuscript, U. S. Weather Bureau, Great Falls, Montana, 1965.

8. Namias, J., General Aspects of Extended-Range Forecasting, Compendium of Meteorology, 1951, page 810.

9. Price, Warren B., Preliminary Report of Wind Project, Manuscript, U. S. Weather Service, Great Falls, Montana, 1953.

10. Price, Warren B., Terminal Forecasting Reference Manual, Great Falls, Montana, U. S. Weather Bureau, 1959.

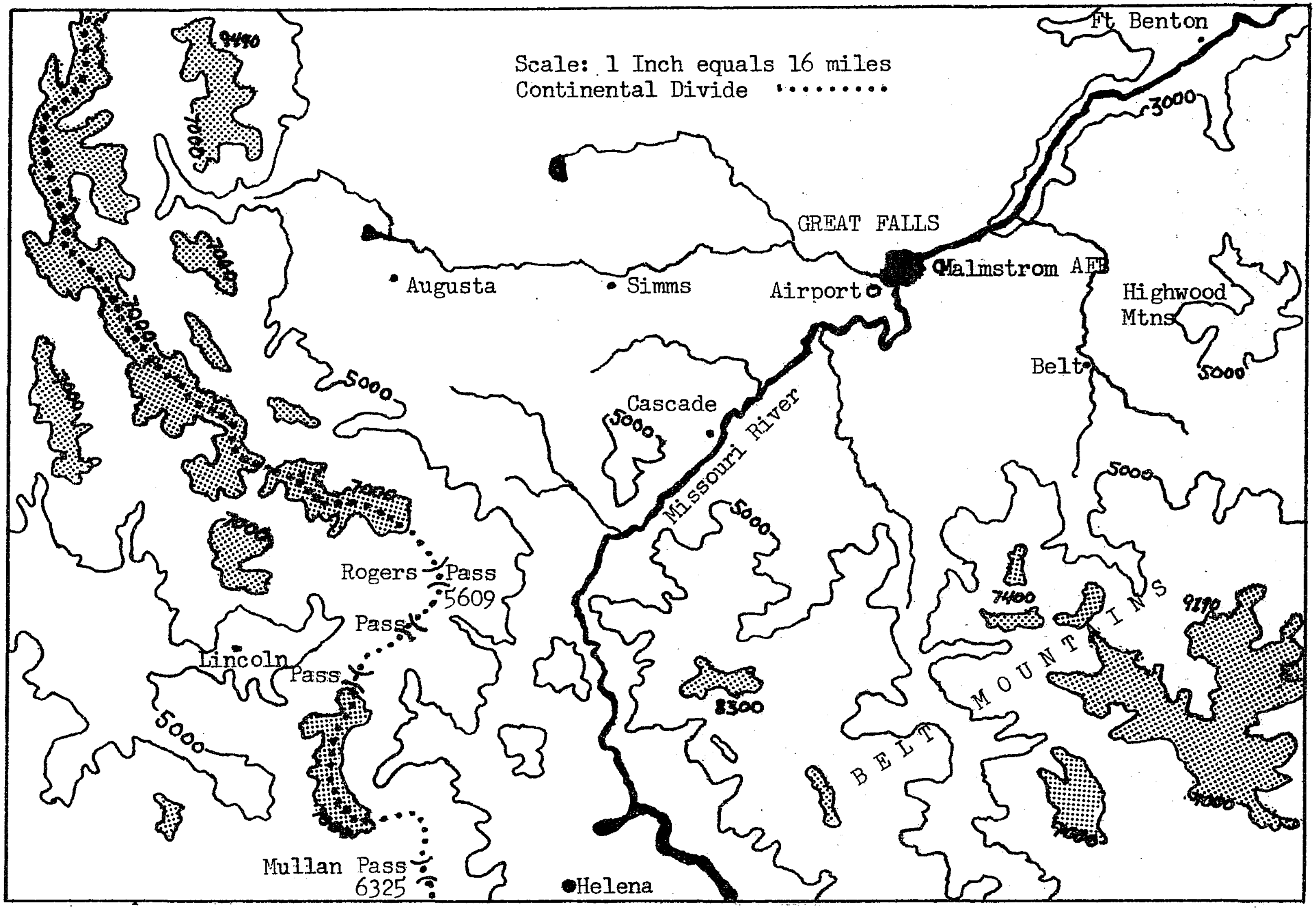


FIG. I GREAT FALLS AREA MAP

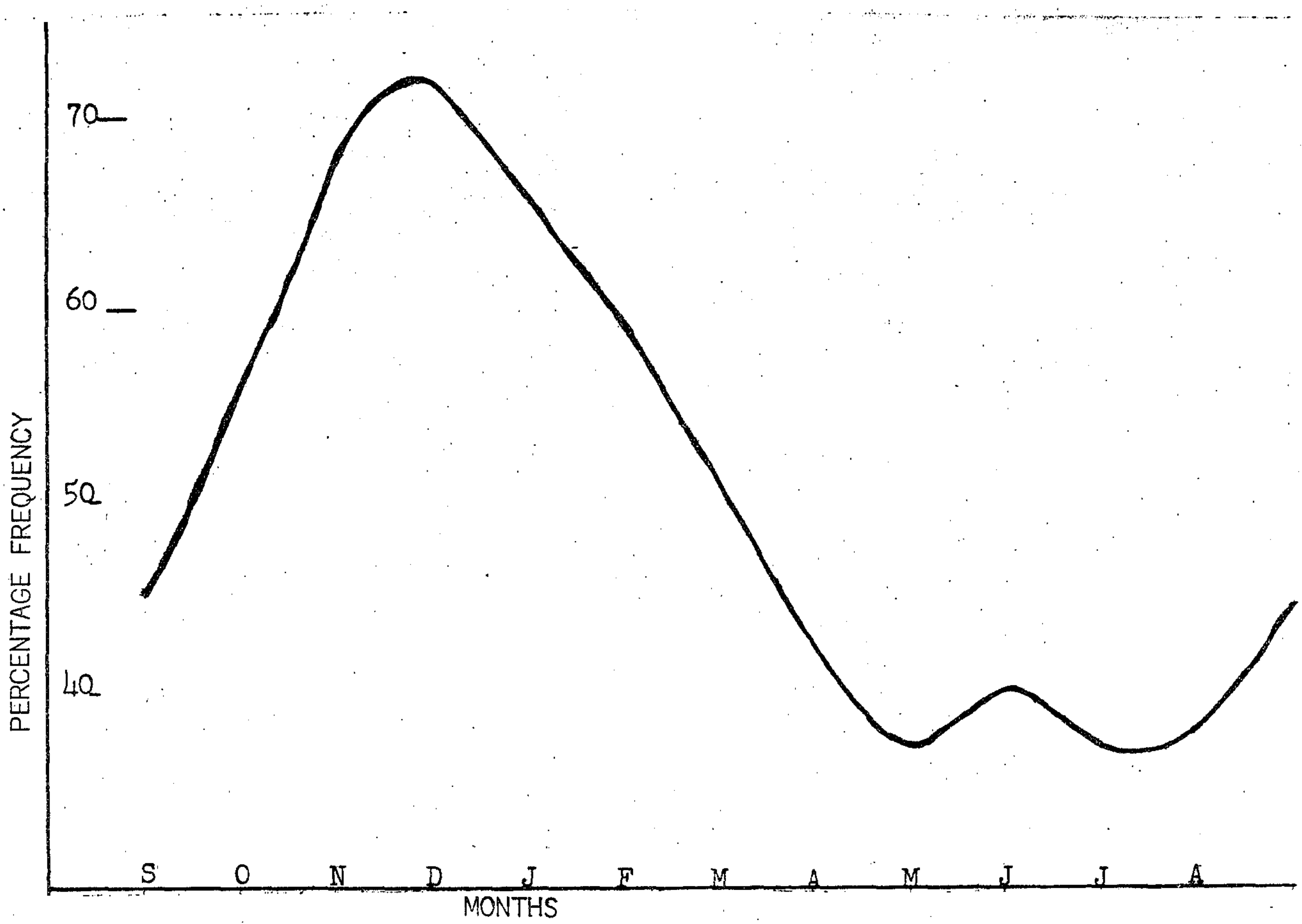


FIG. 2 MONTHLY FREQUENCY OF SOUTHWESTERLY WINDS

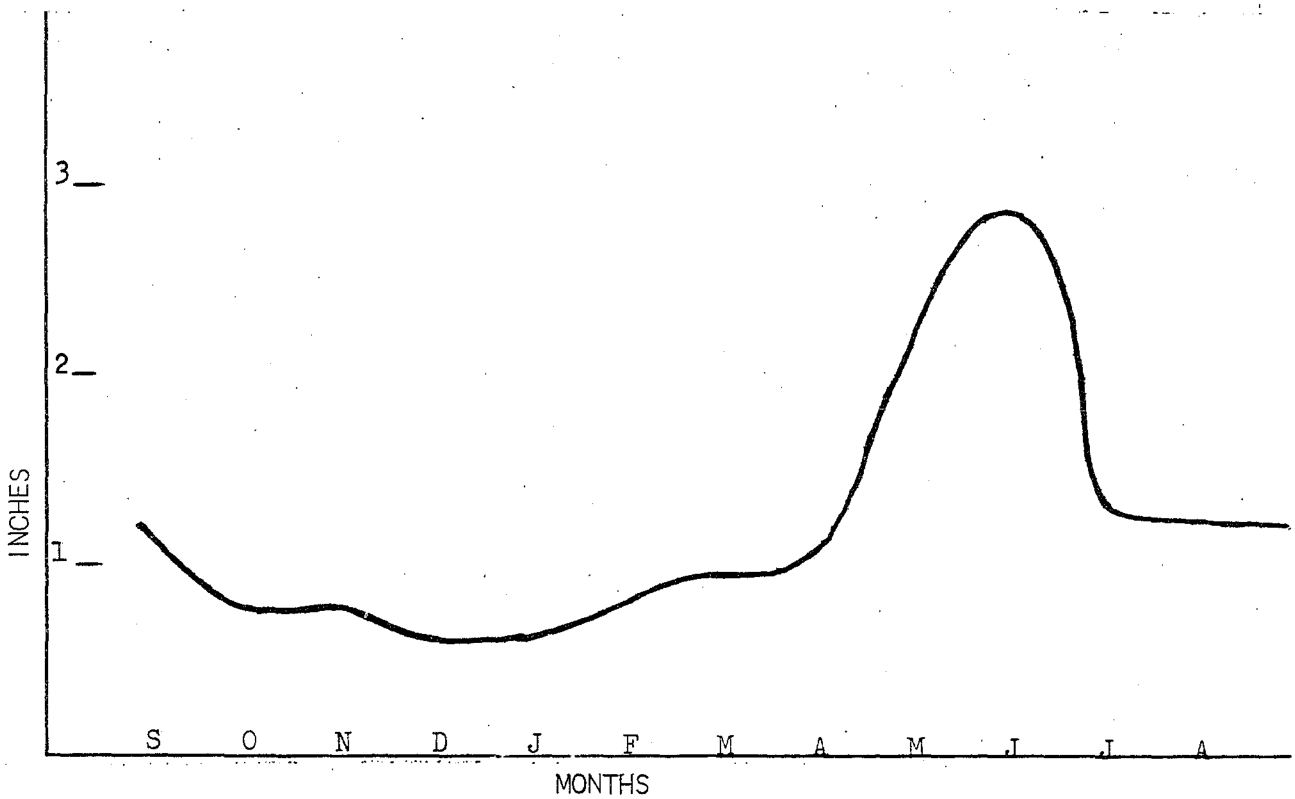
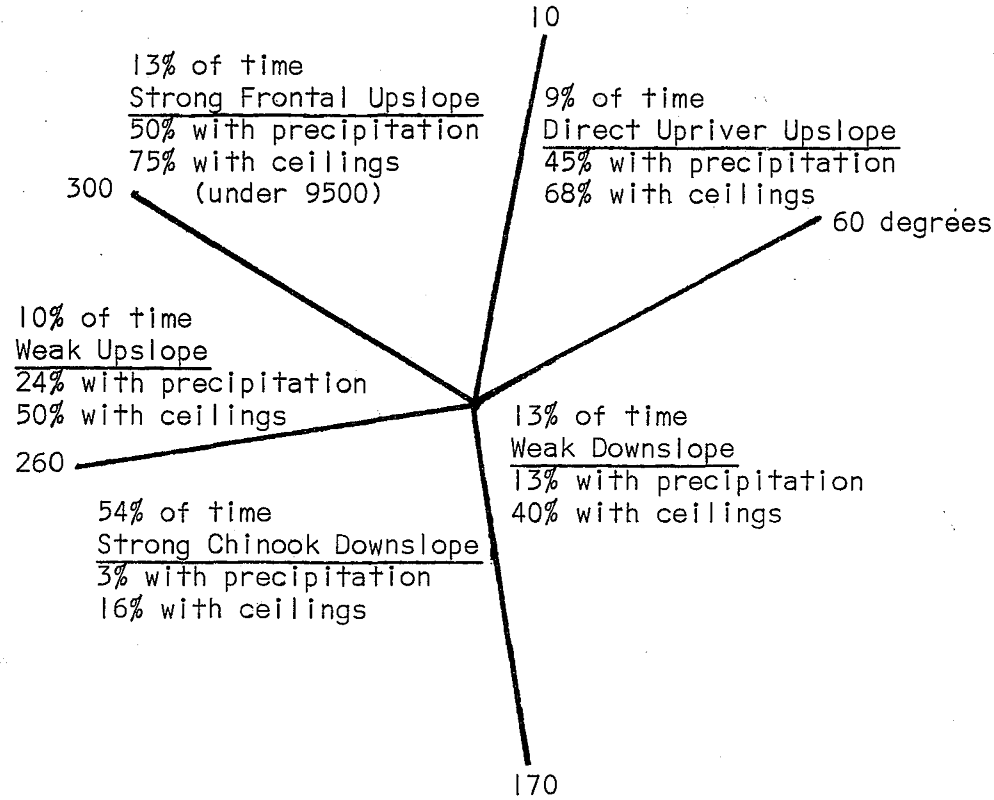


FIG. 3 MONTHLY PRECIPITATION GREAT FALLS, MONTANA



		PERCENTAGE WITH	
MEAN FREQUENCY	DIRECTION	TRACE OR MORE	CEILINGS <9500 FT.
4.4%	WNW	31.4	55.6
5.5	W	16.0	33.4
13.8	WSW	6.3	19.6
28.1	SW	2.5	8.8
9.3	SSW	1.4	13.0
2.8	S	2.8	20.8
1.3	SSE	5.7	29.0
1.9	SE	12.8	34.8
2.7	ESE	11.5	35.0
3.2	E	14.3	46.2
3.4	ENE	20.1	49.4
5.9	NE	39.1	62.1
2.8	NNE	52.0	73.4
4.6	N	53.8	74.4
4.1	NNW	58.3	78.8
4.3	NW	50.0	76.0

(Based upon 7 years' data, October-March, Inclusive, 1957-1963)

FIG. 4 WIND DIRECTION VERSUS CEILINGS AND PRECIPITATION

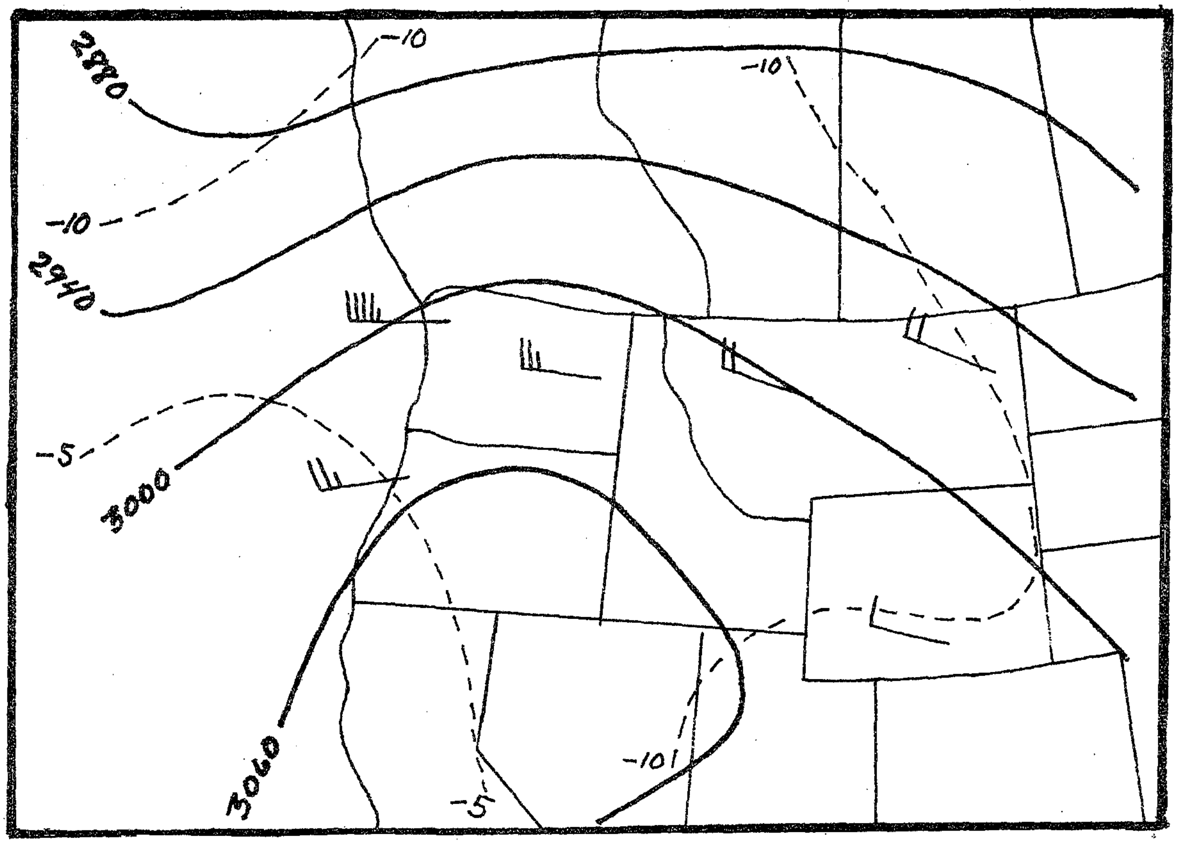


FIG. 5 BASIN HIGH TYPE 700 MB. MAP
05M Dec. 18, 1965

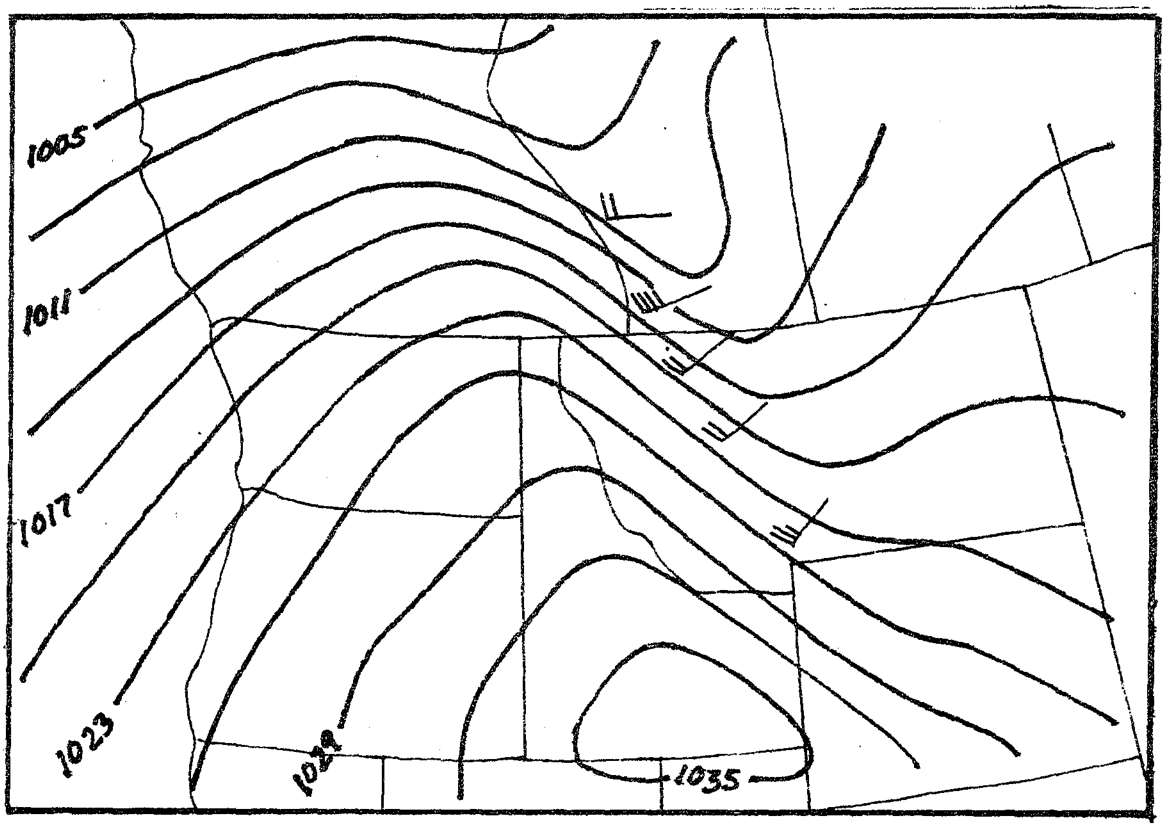


FIG. 6 BASIN HIGH TYPE SURFACE MAP
08M Dec. 18, 1965

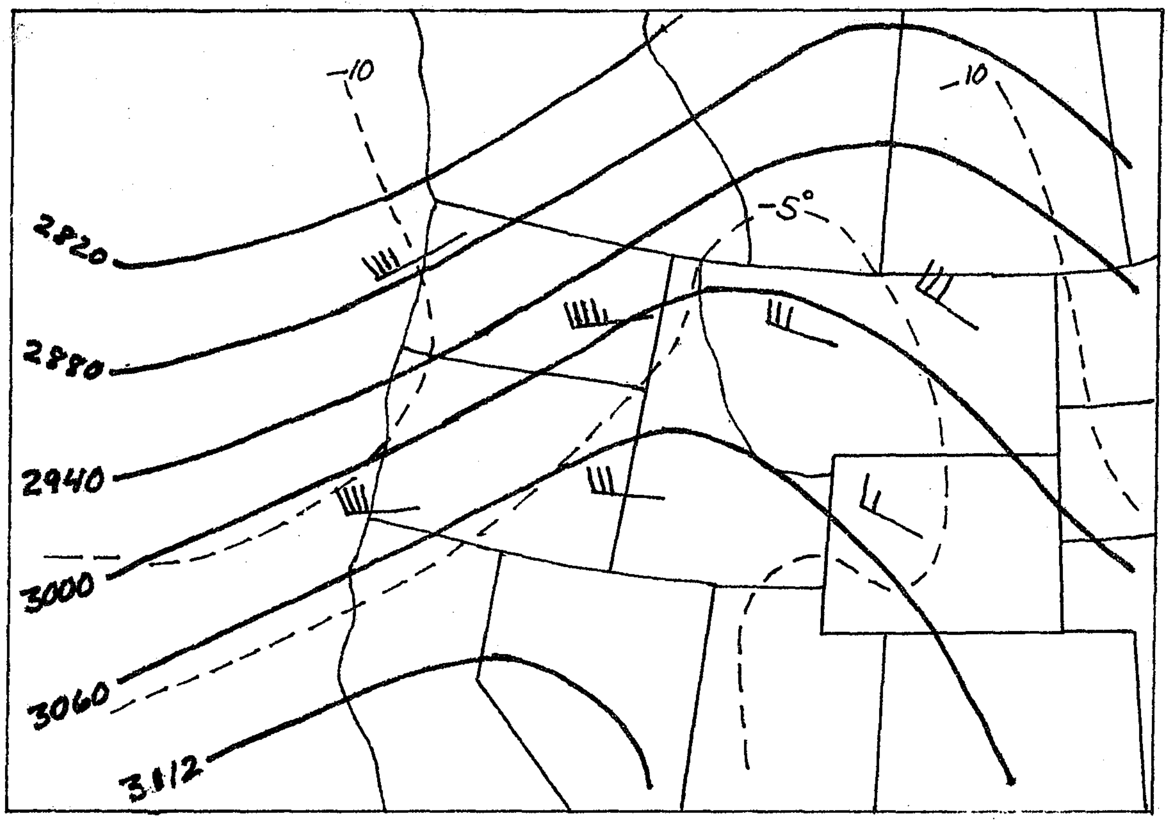


FIG 7 FRONTAL TYPE 700 MB. MAP
17M Jan. 13, 1966

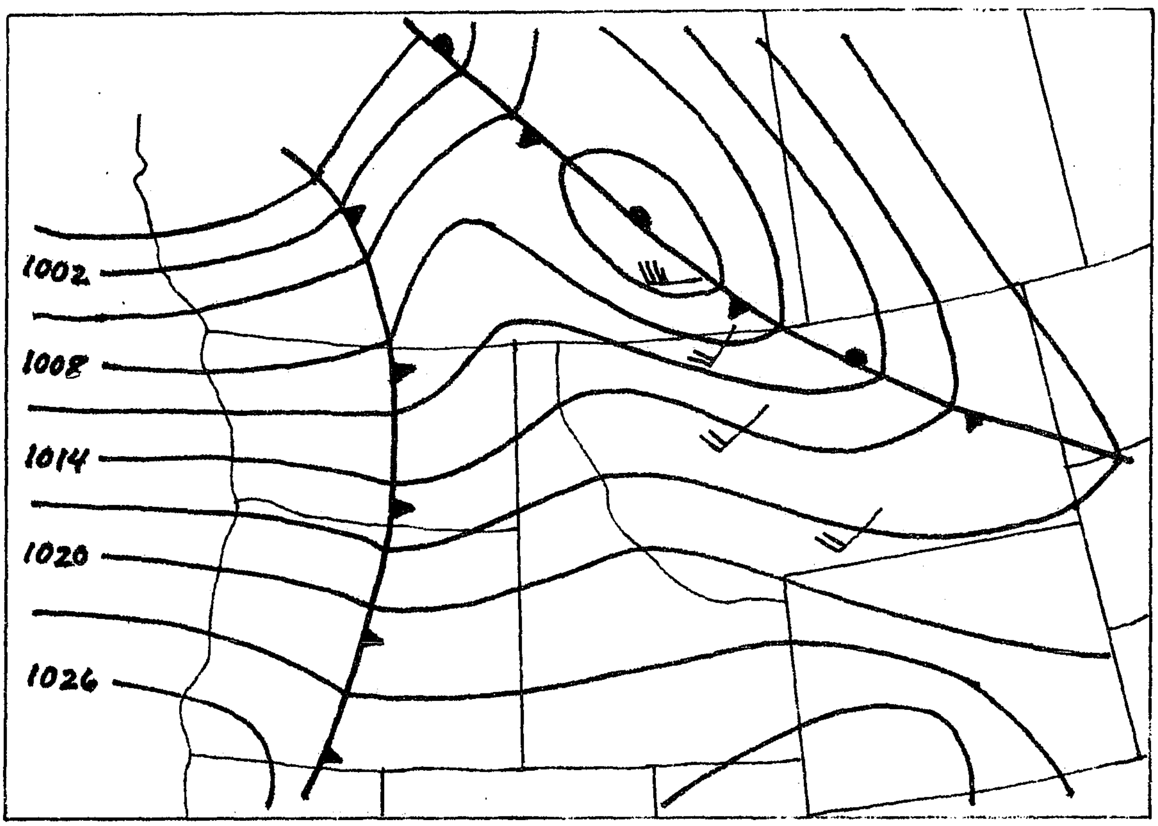


FIG. 8 FRONTAL TYPE SURFACE MAP
20M Jan. 13, 1966

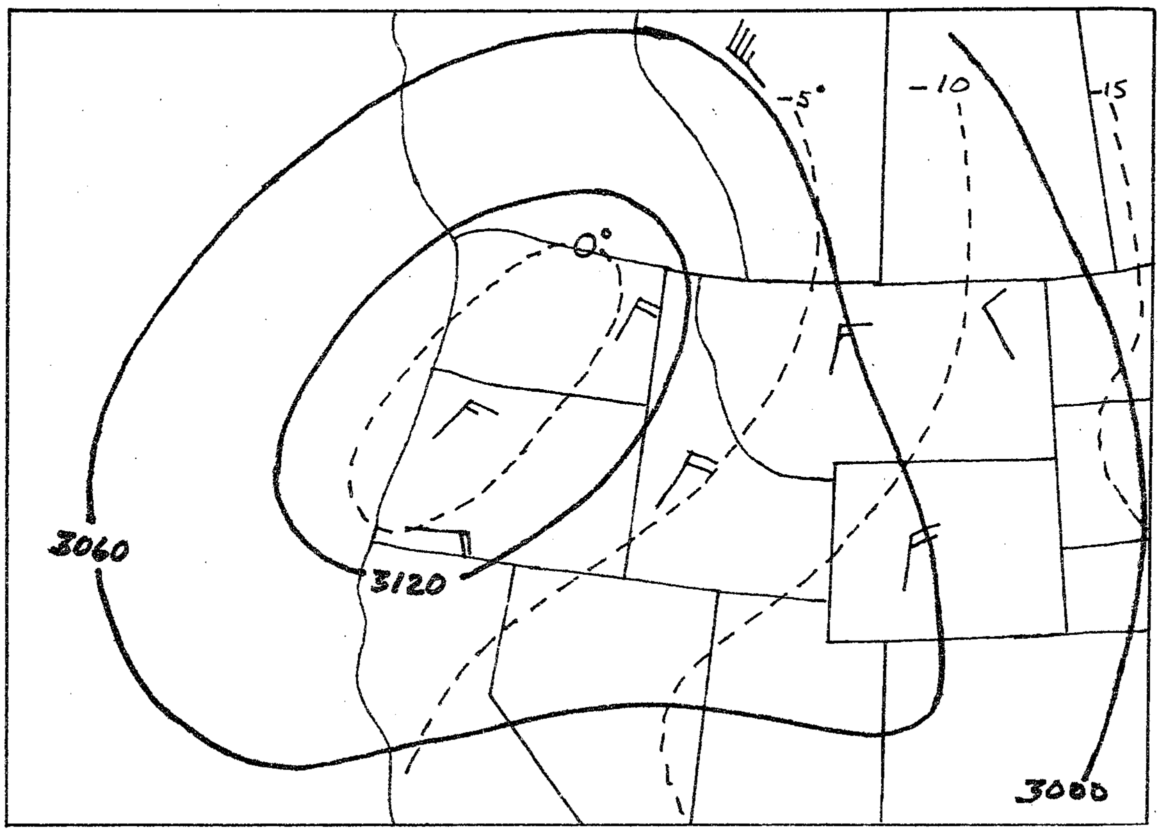


FIG. 9 KLONDIKE CHINOOK TYPE 700 MB. MAP
17M Jan. 16, 1966

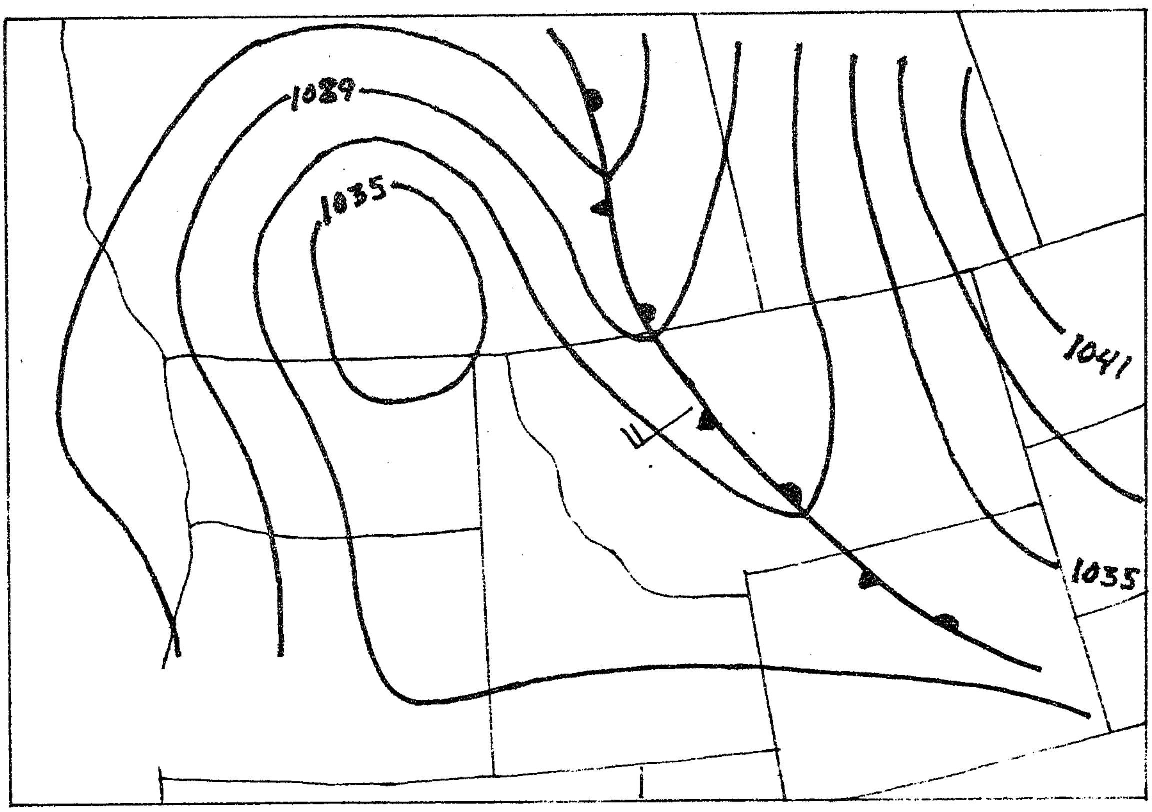


FIG. 10 KLONDIKE CHINOOK TYPE SURFACE MAP
14M Jan. 16, 1966

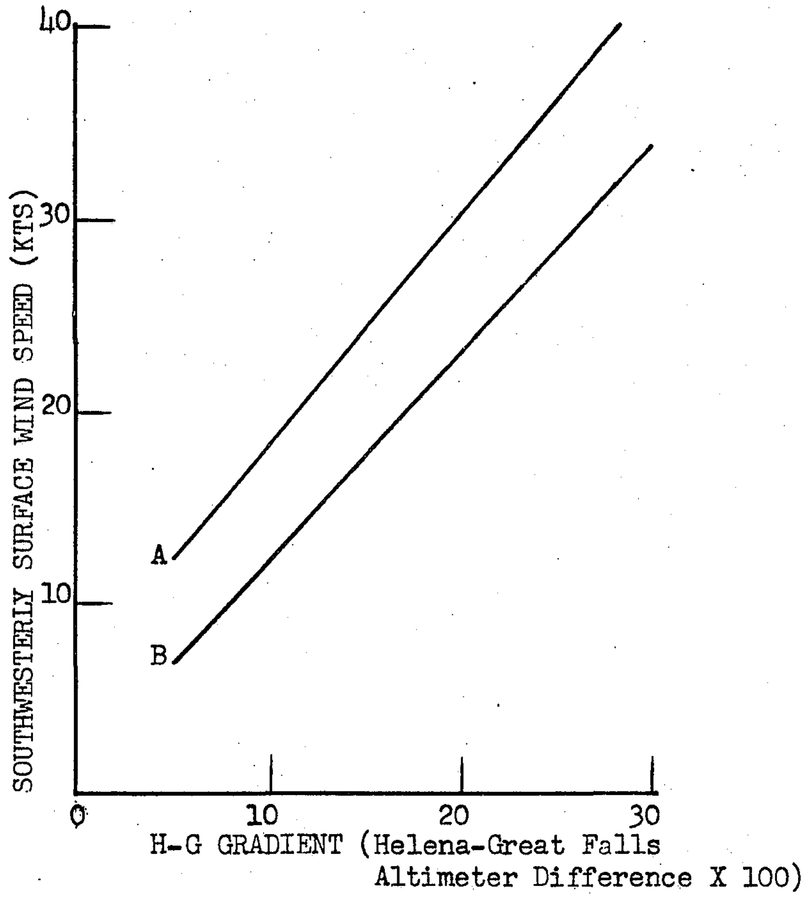


FIG. 11. H-G GRADIENT VS SURFACE WIND SPEED

Graph A: Tower located equipment before 1959
Graph B: Runway located equipment after 1959

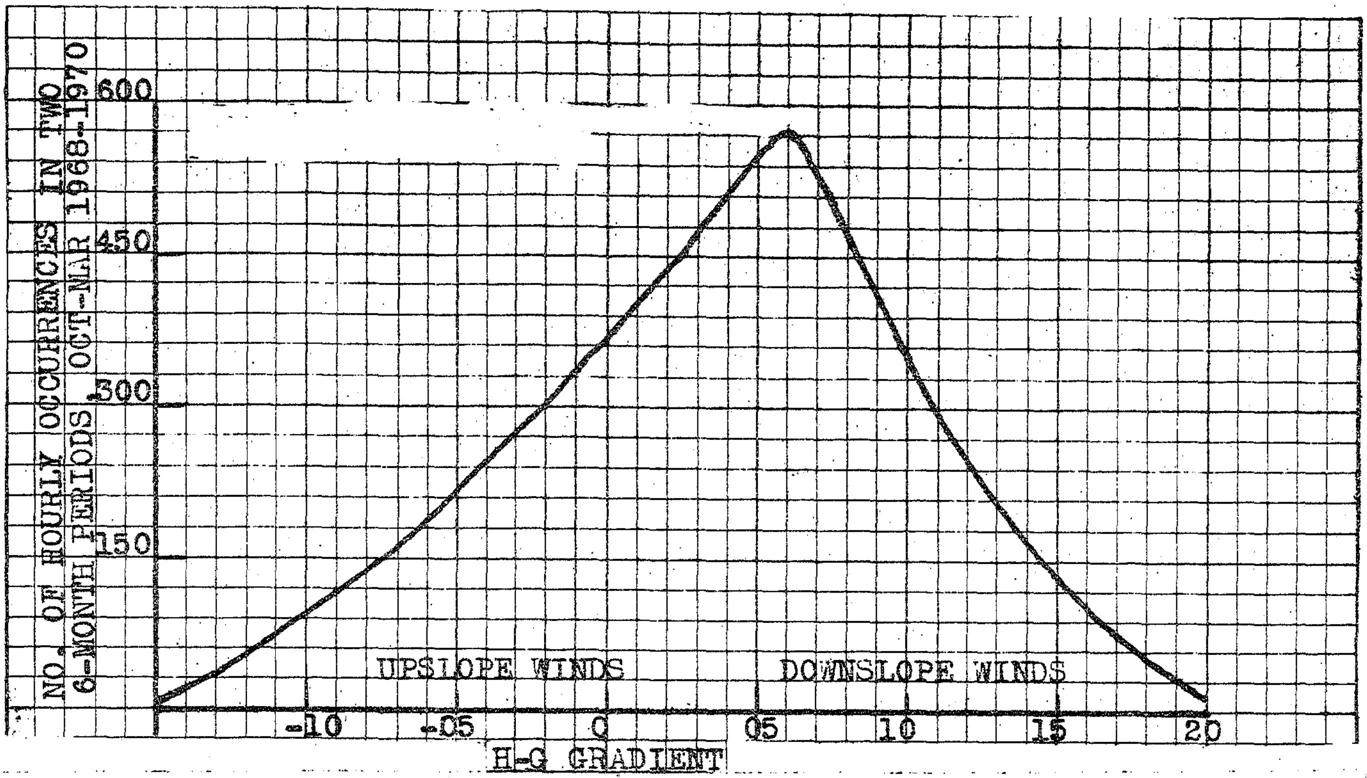


FIG. 12 DISTRIBUTION OF HOURLY H-G GRADIENT VALUES

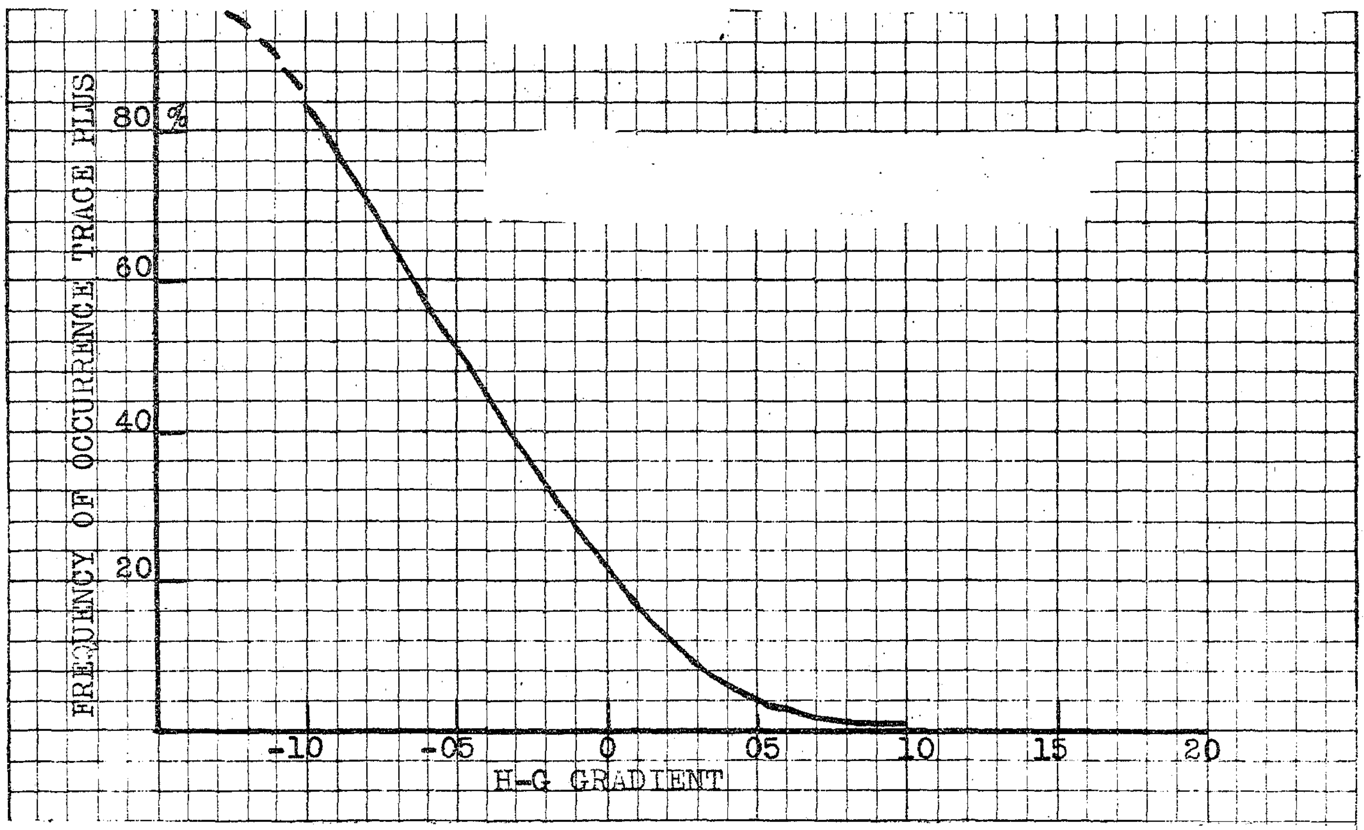


FIG. 13 FREQUENCY OF OCCURRENCE (PROBABILITY) OF TRACE OR MORE PRECIPITATION VS H-G GRADIENT

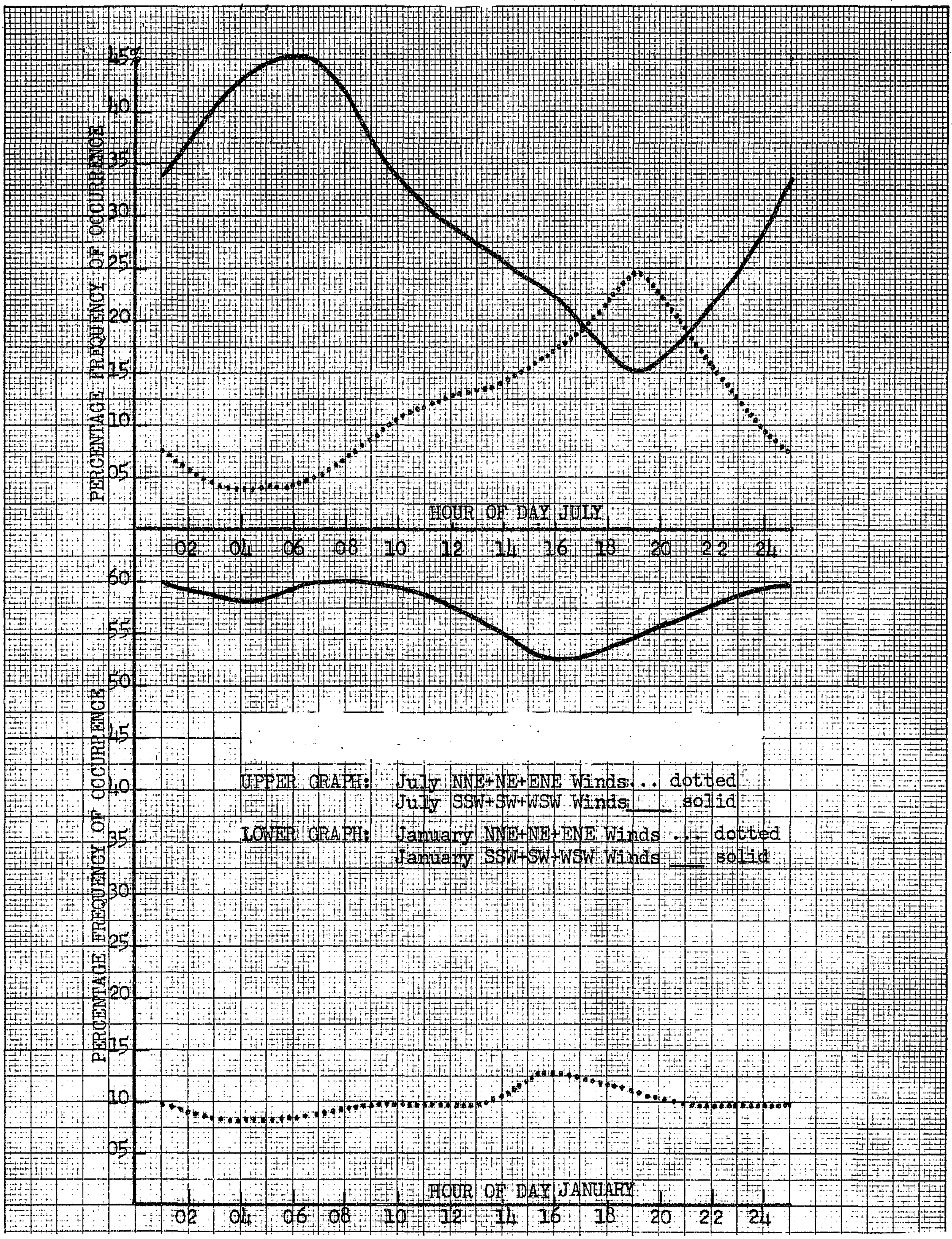


FIG. 14 HOURLY FREQUENCY OF NORTHEASTERLY VS. SOUTH-WESTERLY WINDS FOR JULY AND JANUARY

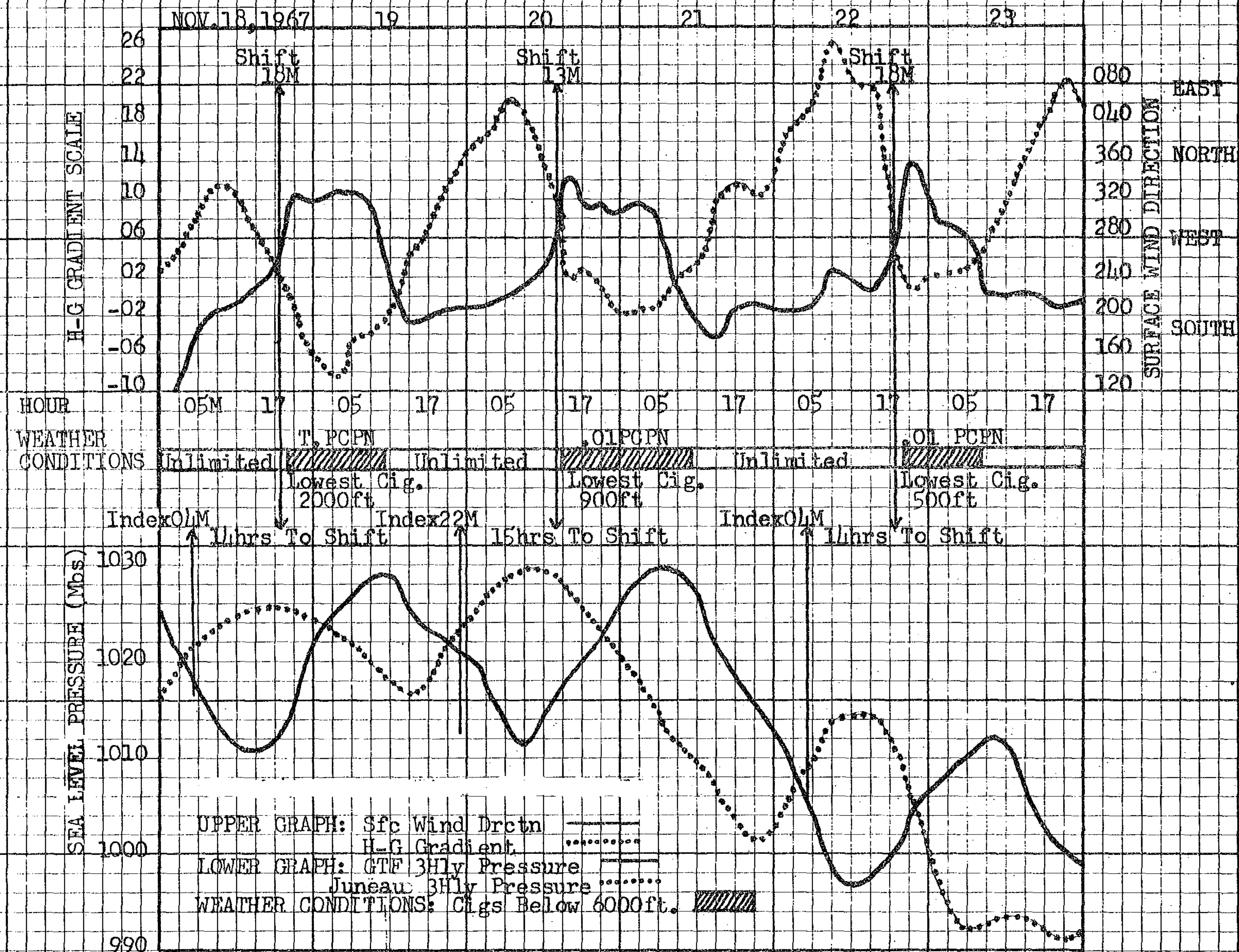


FIG. 15 ILLUSTRATION OF GULF INDEX

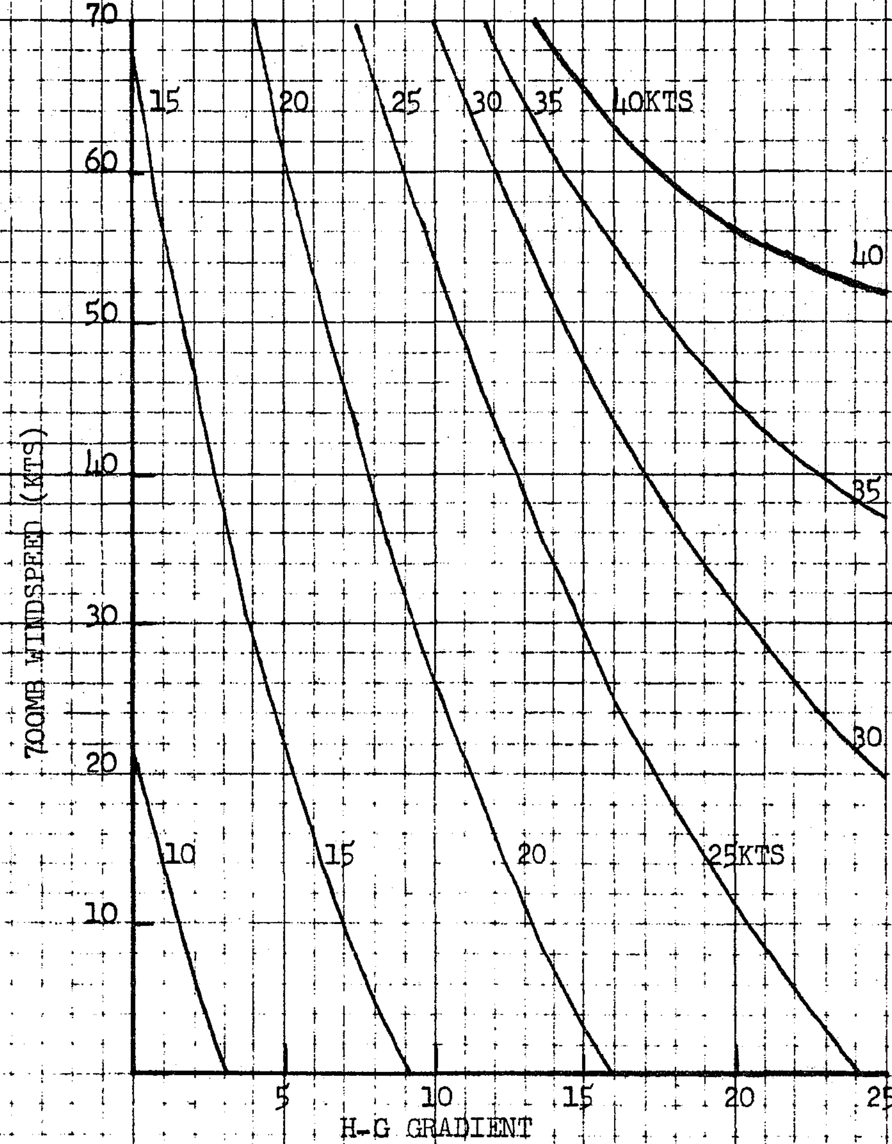


FIG. 16. SOUTHWESTERLY SURFACE WINDSPEED (CURVED LINES) AS A FUNCTION OF 700MB WINDSPEED AND H-G GRADIENT

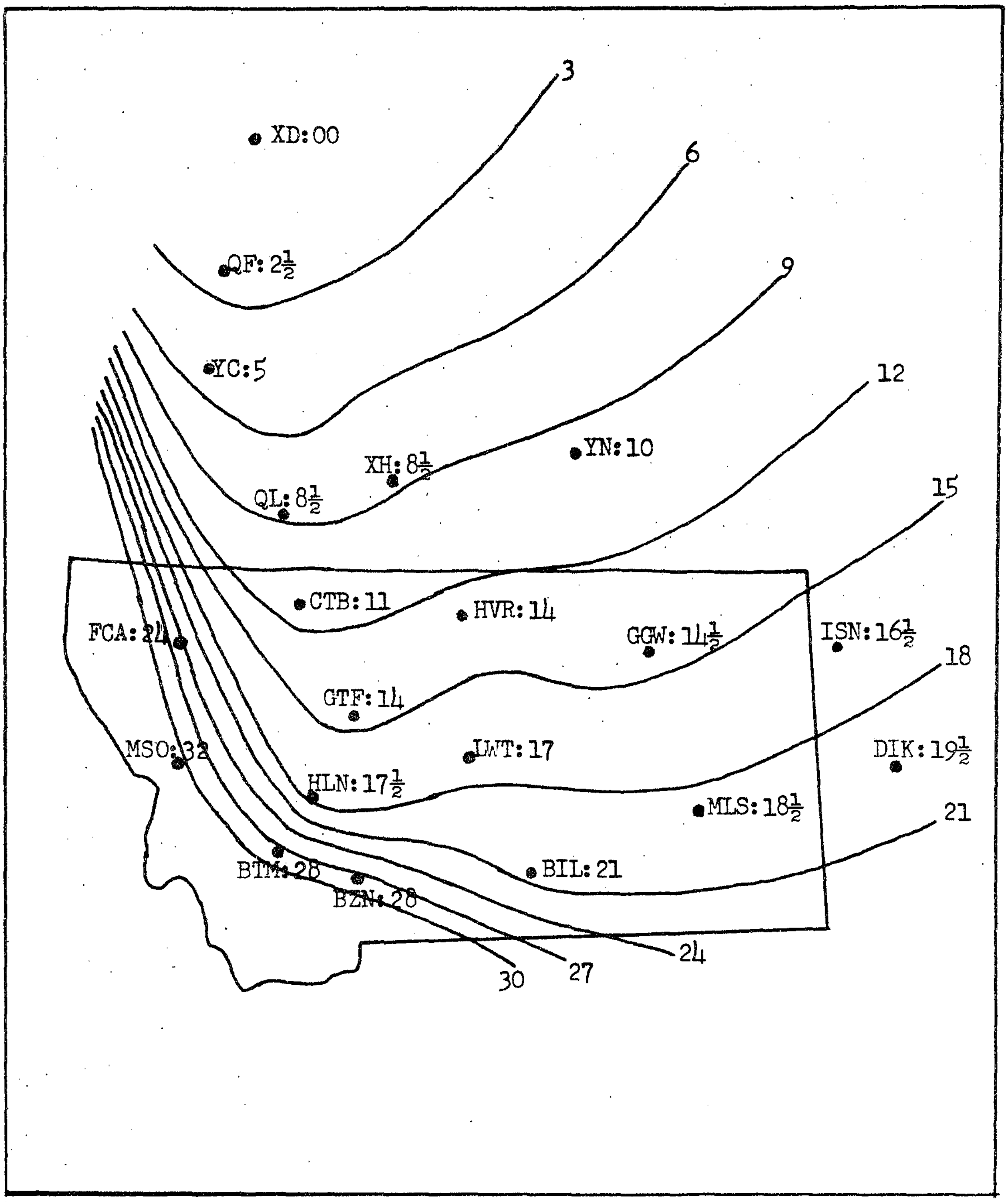


FIG. 17 MEAN 3-HOURLY FRONTAL POSITIONS AND ELAPSED TIME FROM EDMONTON

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