Determining snowpack accumulation at snow course sites in southwestern Montana using climatic station data and meteorological parameters--an assessment
by W Bruce Tremper

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Science
Montana State University
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Abstract:
This study tests the feasibility of adequately estimating snowpack water equivalent at snow course sites in southwest Montana using meteorological parameters along with precipitation and temperature data from local climate stations in an inexpensive statistical model. The model was developed using a sample period of 200 days. Meteorological and climate station parameters were entered as independent variables in a statistical stepwise multiple regression equation. Daily snowfall at snow courses and SNOTEL sites were used as dependent variables. The equations generated were then run with data from a 17 year period to estimate monthly snow accumulation at nearby monthly snow course sites. These estimated values were then compared to actual monthly totals to determine the success of the model. Using this methodology, the results show that estimates of monthly snow accumulation correlate with actual values with correlation coefficients of 0.90 and above for six of the twelve snow course sites tested (highest, 0.98) and 0.84 and above for 11 of the 12 sites.

This technique could augment snow course measurements or, in some cases, replace snow courses. This method can easily be used in other locations to. estimate mountain snowpack in a cost effective manner as long as the area in question has representative records of daily mountain snowfall and corresponding local climate station records.

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MONTANA STATE UNIVERSITY
Bozeman, Montana

March 1984

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

20 March 1984 — Date

Stephan G. Custer — Chairperson, Graduate Committee

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Stephan G. Custer — Head, Major Department

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ACKNOWLEDGMENTS

I wish to thank Robert Yaw and especially Paul Dawson (study advisor) for their inspiration, suggestions and endless hours spent in consultation with meteorological problems. Special thanks to Georgia Ziemba for her invaluable help with statistical and computer problems. I wish to give my deepest thanks to Dr. Stephan Custer (thesis advisor) for his very thorough editing of the text, his direction and inspiration. Also, Dr. John Montagne and the late Dr. Donald Smith gave many helpful suggestions and most of all, inspiration. My appreciation to Dr. Robert Brown who provided additional computer time and Bob Motch and Chris Groff for their very valuable computer advice and services. I especially want to thank Phil Farnes, Soil Conservation Service, Snow Survey for his cooperation and helpful advice.

This research was supported by a grant from the office of Water Research and Technology, authorized under the Water Resource and Development Act of 1978, P. L. 95-467. The grant was awarded by the Montana Water Resources Research Center. I wish to thank them; without their financial support, this study would not have been possible.

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ABSTRACT

This study tests the feasibility of adequately estimating snowpack water equivalent at snow course sites in southwest Montana using meteorological parameters along with precipitation and temperature data from local climate stations in an inexpensive statistical model. The model was developed using a sample period of 200 days. Meteorological and climate station parameters were entered as independent variables in a statistical stepwise multiple regression equation. Daily snowfall at snow courses and SNOTEL sites were used as dependent variables. The equations generated were then run with data from a 17 year period to estimate monthly snow accumulation at nearby monthly snow course sites. These estimated values were then compared to actual monthly totals to determine the success of the model. Using this methodology, the results show that estimates of monthly snow accumulation correlate with actual values with correlation coefficients of 0.90 and above for six of the twelve snow course sites tested (highest, 0.98) and 0.84 and above for 11 of the 12 sites.

This technique could augment snow course measurements or, in some cases, replace snow courses. This method can easily be used in other locations to estimate mountain snowpack in a cost effective manner as long as the area in question has representative records of daily mountain snowfall and corresponding local climate station records.

FORWARD

The General Problem

Knowledge of the amount of accumulated snow (snowpack) in the mountains influences our lives in many ways. The fresh water produced from melting mountain snow is a valuable resource used for agricultural irrigation, municipal water supplies and for wildlife and fish habitat. Data on daily and seasonal accumulation of snowfall as well as snowpack depths are used in wildlife biology, forestry, winter recreation and avalanche forecasting. Also, information on projected streamflow amounts and the timing of the melt water release is important in flood and drought forecasting, waterway design and water supply forecasts for irrigation. Elliot (1977) estimates the monetary worth of accurate water supply forecasts for irrigated agricultural lands of the western U.S. to be $22 million per year. Snow is also a geologic material. Knowledge of snowpack accumulation amounts are important to geologic disiplines such as geomorphology, glaciology and hydrology. Ice --metamorphosed snow-- affects much of the earth's surface through geomorphic processes such as physical weathering of rocks, erosion from meltwater and glaciation. In short, knowledge of mountain snowpack amount is very important in planning and protection of life and property as well as geologic research and application.

Currently, the Soil Conservation Service Snow Survey has the responsibility of monitoring the mountain snowpack amount and

forecasting runoff. They do this through direct sampling by technicians or remote telemetry instruments installed on-site (U.S.D.A. Soil Conservation Service, 1970). These methods have two disadvantages: first, since snow in the mountains rarely exists in a uniform thickness, measuring snowpack in only one location often misrepresents the basin in question (Lettenmaier, 1978; Goodison, 1981). The second disadvantage is the cost involved due to the expense of personnel, measuring equipment and telemetry apparatus.

In recent years, two alternative methods of estimating mountain snowpack amount have been developed which are either less expensive or do not depend on point source measurements. The first method involves using temperature and precipitation measurements routinely collected at local cooperative climate stations affiliated with the National Weather Service and extrapolation of that data to estimate the snowpack amount in the mountains (Tangborn, 1980, 1977, and Tangborn and Rasmussen, 1977, 1976). Although this method is very economical, it suffers from lack of accuracy in areas such as Montana because of the complexity of the weather and terrain and the scarcity of climate stations representative of mountain weather. The second method utilizes one of several computer models which consider the interaction of important meteorological variables with local and regional terrain features (orographic precipitation) thereby estimating mountain precipitation (Rhea, 1978; Colton, 1976; Young, 1974). This method has proven successful in many mountainous areas, however, it involves the expense of digitizing large areas of terrain in a fine mesh grid (as small as 2.5 kilometers) computer software purchase, computer

rental or design of a similarly sophisticated computer program. Also, these models often fail in estimating precipitation from some storm types especially in complex terrain (Armstrong and Williams, 1981).

Research Contribution to the Problem

The objective of this study was to test the feasibility of using precipitation and temperature data at local climate stations as well as a simplified set of meteorological parameters to adequetely estimate monthly snowfall water equivalent totals at snow course sites in southwestern Montana in an inexpensive manner. Specifically, this technique utilizes temperature and precipitation data from local climate stations as well as a simplified set of derived meteorological parameters as input to an inexpensive statistical model which estimates mountain snowpack amount at snow course sites. This method costs less because existing agencies routinely provide climate station and meteorological data. Because of the simplicity of the procedure a user can easily adapt it to an area of interest without prohibitive time and expense.

CHAPTER 1

INTRODUCTION

Background

Precipitation in the mountains originates from two general meteorologic processes, dynamic and orographic (Berry, 1981). Dynamic processes include regional-scale atmospheric motions such as fronts, low pressure systems and atmospheric instability. Orographic precipitation, on the other hand, occurs as saturated air rises, cools and thus precipitates in response to crossing a topographic barrier such as a mountain range. In other words, dynamic processes are governed by forces contained within the atmosphere while orographic processes occur due to the interaction between topography and the atmosphere. While both dynamic and orographic processes are important, between two and one hundred times more precipitation in the mountains falls from orographic sources than dynamic ones (Berry, 1981). Because of the importance of orographic precipitation in the mountains, the amount of local relief is the dominant factor controlling the amount of precipitation that falls on the area in question. Since most orographic precipitation falls within 15 kilometers of a topographic barrier (Berry, 1981), local relief is defined here as the amount of topographic rise within a radius of about 15 kilometers from the area of interest. Topographic features influence mountain snow amount distribution in a variety of ways.

Generally, the snowpack depth increases with elevation, because of two factors. First, orographic precipitation occurs more often at higher elevations because air rising in response to crossing a topographic barrier, cools by adiabatic expansion and thus has a greater chance of being saturated, and second, because of cooler air at higher elevations, less melting occurs (Berry, 1981). Slope aspect is also important in the distribution of precipitation because solar radiation melts more snow on south-facing slopes than north-facing ones, and more important, the prevailing winds in the study area scour the windward west sides of mountains and ridges and deposit the snow on the downwind sides. McPartland and others, (1971), Alford (1979) and Tabler (1975) point out the importance of redistribution of snow by wind in Montana and Wyoming. For reasons outlined above, the location of those station with respect to local relief, aspect and topography is critically important when estimating mountain precipitation based on climate stations or snow courses.

Specifically, in this study, Figure 1 shows the location of the snow courses and climate stations used in this study in relation to the local topography, Figure 2 shows the distribution by elevation. Notice that climate stations are located at lower elevations, in easily accessible areas. However, snow courses usually are located at higher elevations in areas more representative of mountain snowpack amount. In the study area, several climate stations exist at elevations equivalent to the lower elevation snow courses and in areas with similar local relief. Therefore, one would expect that these climate stations would correlate well with the amount and timing of

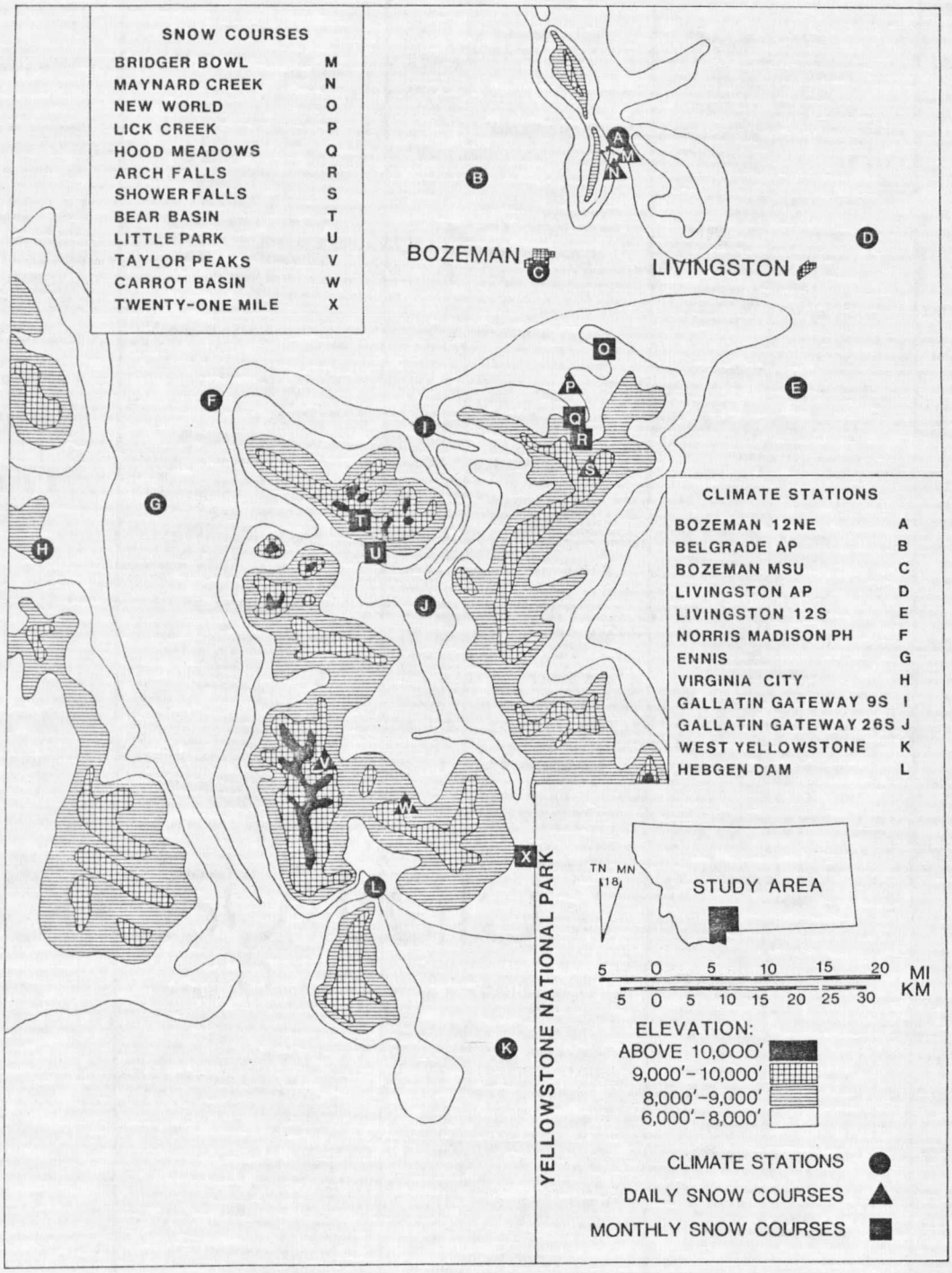


Figure 1. Map of the study area showing topography and locations of the climate stations and snow courses.

ELEVATION

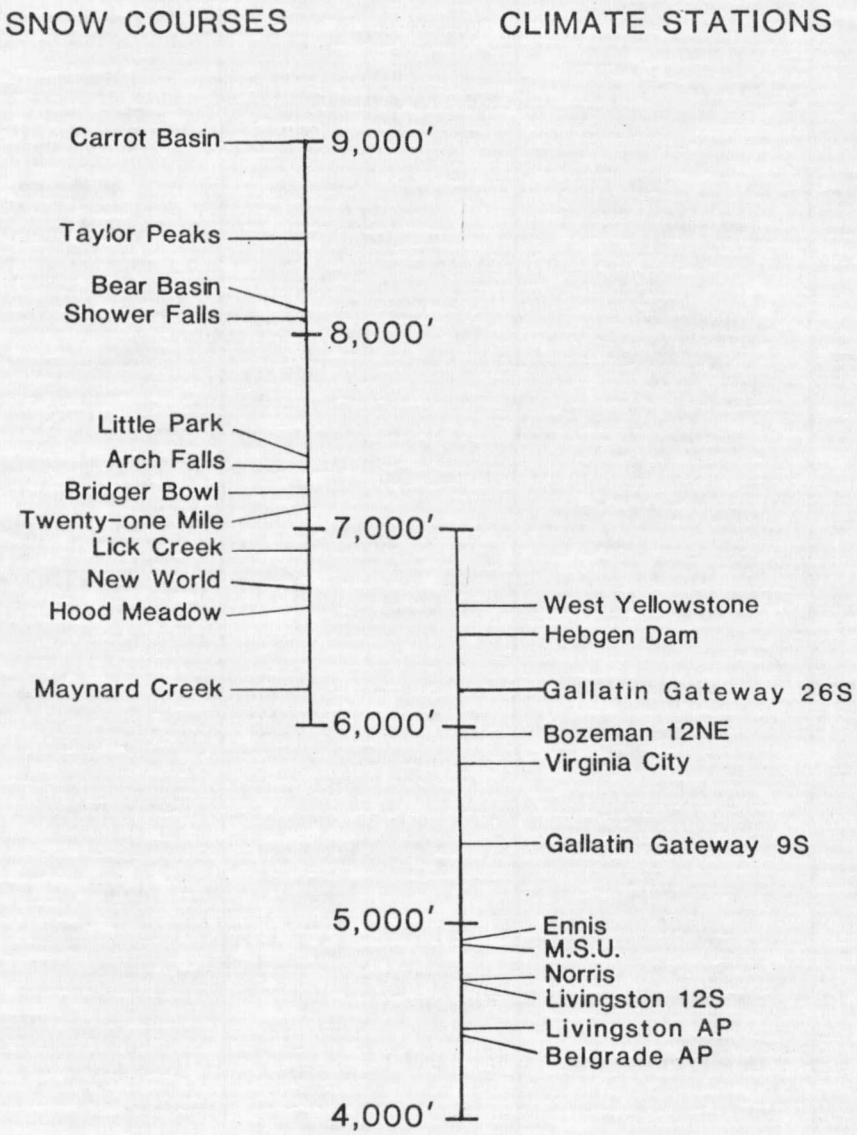


Figure 2. The distribution of snow courses and climate stations by elevation.

precipitation at snow course sites located in areas of similar aspect, elevation and local relief.

Related Research

There are two basic approaches used to determine snow amounts in the mountains. The first, is a statistical/empirical approach relating mountain snow amounts to accumulated precipitation amounts at local climate stations and snow courses located within the mountains. For example, the Soil Conservation Service Snow Survey uses mountain snow course readings as indicators of mountain snowpack amount (U.S.D.A. Soil Conservation Service, 1970). Tangborn (1977; 1980) and Tangborn and Rasmussen (1976; 1977) used precipitation and temperature data from local representative climate stations to estimate mountain snowpack amount. This method works successfully on the west coast of the U.S. where weather patterns are more predictable and less complex. However, the accuracy of this approach diminishes when applied to continental climates characterized by complex and fickle weather such as found in the mountains of southwest Montana. For example, Tangborn (1980) found that estimates of seasonal accumulated snowpack using this method accounted for only 53 percent of the variance between seasonal runoff amounts originating from snowmelt in the South Fork of the Flathead river of western Montana.

A second approach when determining mountain snow amounts is computer modeling of orographic precipitation. Researchers such as Rhea (1978), Colton (1976) and Young (1974) have developed sophisticated computer models which estimate mountain precipitation at

points on a fine mesh grid (as small as 2.5 km) of digitized elevations. For example, Rhea's model is being used successfully by the Colorado Avalanche Warning Center to forecast daily snowfall for the mountains of western Colorado. The model accounts for such factors as interception of moisture by upstream topographic barriers, sublimation of snowflakes as they fall through unsaturated air, snowflake trajectories from the time of crystallization to impacting the ground, retardation or enhancement of vertical motion due to atmospheric stability and accounting for precipitation from dynamic storm processes. Because of the sophistication of these models, they have the disadvantage of the expense involved in digitizing large areas of terrain, purchasing the computer software, or designing a similarly sophisticated computer program. Also, these models often fail in estimating precipitation from some types of storms especially in complex terrain (Armstrong and Williams, 1981).

Purpose of the Study

This study attempts to combine these two approaches into an inexpensive methodology in order to estimate mountain snowpack amount at snow course sites. The first approach is that used by Tangborn, i.e. using precipitation and temperature at climate stations to estimate mountain precipitation and snowmelt. Because the National Weather Service routinely collects and publishes climate station data, this method costs little. The second approach involves modeling of both orographic and dynamic precipitation, however, this study differs in that it uses a simplified set of weather parameters combined in an

inexpensive statistical model. This study explores the feasibility of using weather parameters as well as precipitation and temperature data from local representative climate stations to adequatly estimate monthly snow water equivalent totals at mountain snow courses in an inexpensive manner.

This study addresses only the snow accumulation period of winter and does not attempt to model runoff from melting snowpack. Therefore, this study covers the period of time from October through April--the usual snow accumulation period in the study area (Figure 3).

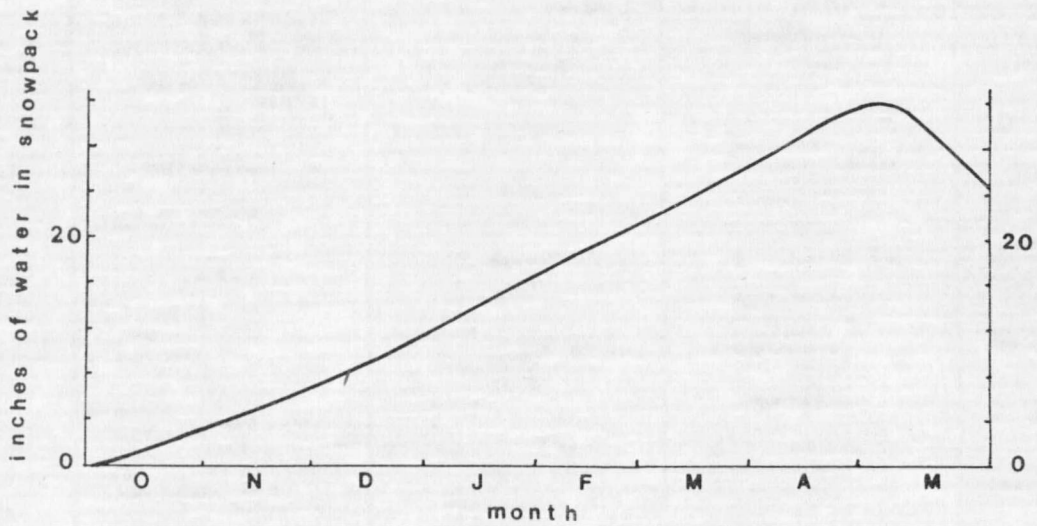


Figure 3. Plot of 1963-1977 average snowpack water equivalent accumulation through the season for Shower Falls snow course--a typical snow course in the study area (USDA Soil Conservation Service, 1983).

CHAPTER 2

EXPERIMENTAL DESIGN

Overview

This study uses 54 weather and climate parameters to predict daily and monthly accumulation of snow at snow course sites in southwest Montana. This section briefly summarizes how this was accomplished. First, it is important that the reader keep in mind that two kinds of snow courses exist. The first provides daily snowfall values. The second provides monthly totals of accumulated snow. Daily snowfall must first be predicted using daily meteorologic and climate station parameters. Computer programs were written and executed to calculate meteorologic and climate station parameters (Appendix). Then, in order to create predictive equations, a sample of 200 days of daily meteorologic and climate station parameters were entered as independent variables in a stepwise multiple regression computer program with daily snowfall at snow course sites as the dependent variable. The program determines which parameters predict snowfall best and builds them into an equation which predicts daily snowfall.

The 200 days of daily data were taken from the months of February from 1970 through 1976. The data span seven years in order to escape misrepresentation of an odd year; the month of February was chosen

because it straddles the usual snow accumulation period of winter (October through April) and it experiences both cold winter storms and warmer spring-like ones. Since the purpose of this study is to estimate monthly snow accumulation, to test the model, daily estimates were summed to provide monthly totals of snow accumulation for a period of 17 years.

In order to estimate the snowpack at monthly snow courses, equations from one of the daily snow courses were applied. This is necessary because correlations between monthly snow accumulation totals and daily climate station and meteorological parameters is an "apples and oranges" comparision and cannot be realistically accomplished. The monthly estimates were generated as follows. Taking the monthly snow course, Little Park, as an example, the monthly snow accumulation totals were compared to the monthly sums from each of the six daily equations using 17 years of data to see which correlated best. Then, the appropriate daily equation was adjusted for the difference in average snowfall amount between the two locations. As with the daily snow courses, these estimates were then compared to the actual monthly totals to provide final correlation coefficients.

Statistical Methods

In analyzing the parameters, there were two objectives: first, to find which parameters correlate well with snowfall and second, to derive equations which predict snowfall amounts using these parameters. Stepwise multiple regression was chosen as the

appropriate statistical technique because it accomplishes both objectives and is also inexpensive and straightforward. Stepwise multiple regression was accomplished using the SPSS statistical computer package (Nie, 1975)--a commonly-used computer statistical package available on disc storage at the Montana State University computer. For readers not familiar with stepwise multiple regression, a brief summary is included below. For further information, refer to Draper and Smith (1981).

Stepwise multiple regression is a statistical technique used to develop an equation which best predicts the dependent variable (snowfall) using two or more independent variables (meteorologic and climate station parameters). The program will generate an equation of the following form:

$$Y = \sum_{i=1}^{n} a_i x_i + C$$

where: Y = the dependent variable (snowfall)
n = the total number of independent variables
i = the number assigned to one of the n independent variables
x_i = values of the independent variables (weather and climate parameters)
a_i = the non-standardized coefficient, i.e. the number of units expected change in Y with a unit change in x
C = a constant term

When generating the equation, the program will first enter the most statistically significant parameter identified using the F-test, i.e. the parameter added first to the predictive equation has the least chance of having no correlation with snowfall. Then, the program will enter the second most significant parameter and so on until the parameters added no longer meaningfully add to the total accuracy of the regression equation. Because the multiple regression program tests only for a linear fit as opposed to a curvilinear relationship such as an exponential pattern, each parameter was analyzed to see if it estimates snowfall in a linear relationship. This was done by plotting each parameter against snowfall and visually examining the resulting plot pattern. None of the parameters appeared to exhibit curvilinear patterns.

Data Used

This study uses three kinds of data--snow course, climate station and weather data. Snow course data represents the measurements of snow water equivalent at twelve snow course sites located in the mountains of the study area. Climate data includes measurements of precipitation and temperature taken daily at twelve climate stations located in easily accessible areas within the study area. Meteorologic data comes from rawinsonde (weather balloon) soundings from the three closest rawinsonde stations, Great Falls Montana, Lander Wyoming, and Boise Idaho. For each kind of data, this section contains, 1) a discussion and justification of the choice of the type of data used and 2) a detailed description of the data.

Snow Course Data

This study uses snow course data as an indicator of mountain snowpack amount for the following reasons: Snow course data: 1) is the only existing data base for mountain snowpack measurements, 2) is a standard and commonly used measure of mountain snowpack amount, 3) spans a long period of record and has good quality control and 4) is routinely collected and published by the Soil Conservation Service Snow Survey making it an inexpensive source of data for this study.

In the study area, snow courses are sampled either by the U.S. Soil Conservation Service Snow Survey or by the U.S. Forest Service. For monthly snow courses, technicians visit the site as close to the first of the month as possible and use a Mt. Rose snow sampling tube to take a core of the snowpack; the weight of the core indicates the water content of the snow. For daily snow courses, a weighing scale (snow pillow) beneath the snowpack continuously weighs the snow above and records the information with an on-site strip chart which is changed once a month. For remote sites, an on-site telemetry system radios the information to a receiving station where the information is recorded (SNOTEL sites; U.S.D.A. Soil Conservation Service, 1970). The Snow Survey state office in Bozeman Montana provided both daily and monthly snow course data. Monthly data was provided on computer cards and students were hired to keypunch the daily data from copies of Snow Survey records.

Climate Station Data

Climate stations are located throughout the world and provide daily measurements of precipitation and temperature. In the United States, the stations are affiliated with the National Weather Service, are located in accessible areas and sampled daily, often by volunteer caretakers. All available stations in the vicinity of the Gallatin drainage were used which could provide reliable and continuous data for the period of time covered by the study. A total of twelve stations were used. Measurements made at these climate stations include: maximum and minimum temperature, 24-hour precipitation and 24-hour snow depth. Measurements are taken around 6:00 PM daily.

Meteorologic Data

Weather forecasts throughout the world are based primarily on data collected from rawinsondes (weather balloons). The rawinsondes are released twice daily at midnight and noon Greenwich mean time (5:00 AM and 5:00 PM mountain standard time) at predetermined locations throughout the world creating a relatively evenly-spaced network of atmospheric soundings. From this data, the National Weather Service computer generates weather maps. Thus, two sources exist for weather data--rawinsonde data and weather maps. Since all weather parameters used in this study can be calculated using either data source and also, both sources are available for sufficiently long peroids of time, a decision had to be made as to which to use. Rawinsonde data was chosen for the following reasons: First, rawinsonde data is not subject to interpretation by National Weather Service computers; by using rawinsonde data, weather parameters can

be calculated using a consistent method throughout the 17 years covered by this study. Second, calculating weather parameters from weather maps is a tedious and time consuming process while rawinsonde data can be used as input to computer programs which rapidly calculate weather parameters. Also, rawinsonde data is available on digital tapes making it easily accessible and saves the expense of key punching.

The National Oceanic and Atmospheric Administration, National Climatic Center in Asheville, North Carolina provided both weather and climate data on digital tapes. Weather data includes twice-daily upper air rawinsonde soundings from the three closest stations--Great Falls Montana, Lander Wyoming and Boise Idaho (Figure 4). Each sounding provides information from mandatory levels (850, 700 and 500 millibars (mb)) and significant levels (levels where the atmosphere exibits a significant change in conditions). Atmospheric measurements at each of these levels include: the height of the pressure level (pressure height), temperature, relative humidity, wind direction and wind velocity. The data span levels from 850 mb to 500 mb; the 850 mb level corresponds with the elevation of the Galatin Valley (about 5,000 feet). The upper boundary was chosen because most winter weather occurs below the average 500 mb height of about 18,000 feet (Hjermstad, 1970; Rhea, 1978).

Parameters Used

Recall that mountain wintertime precipitation comes primarily from two processes, dynamic and orographic. Dynamic processes include

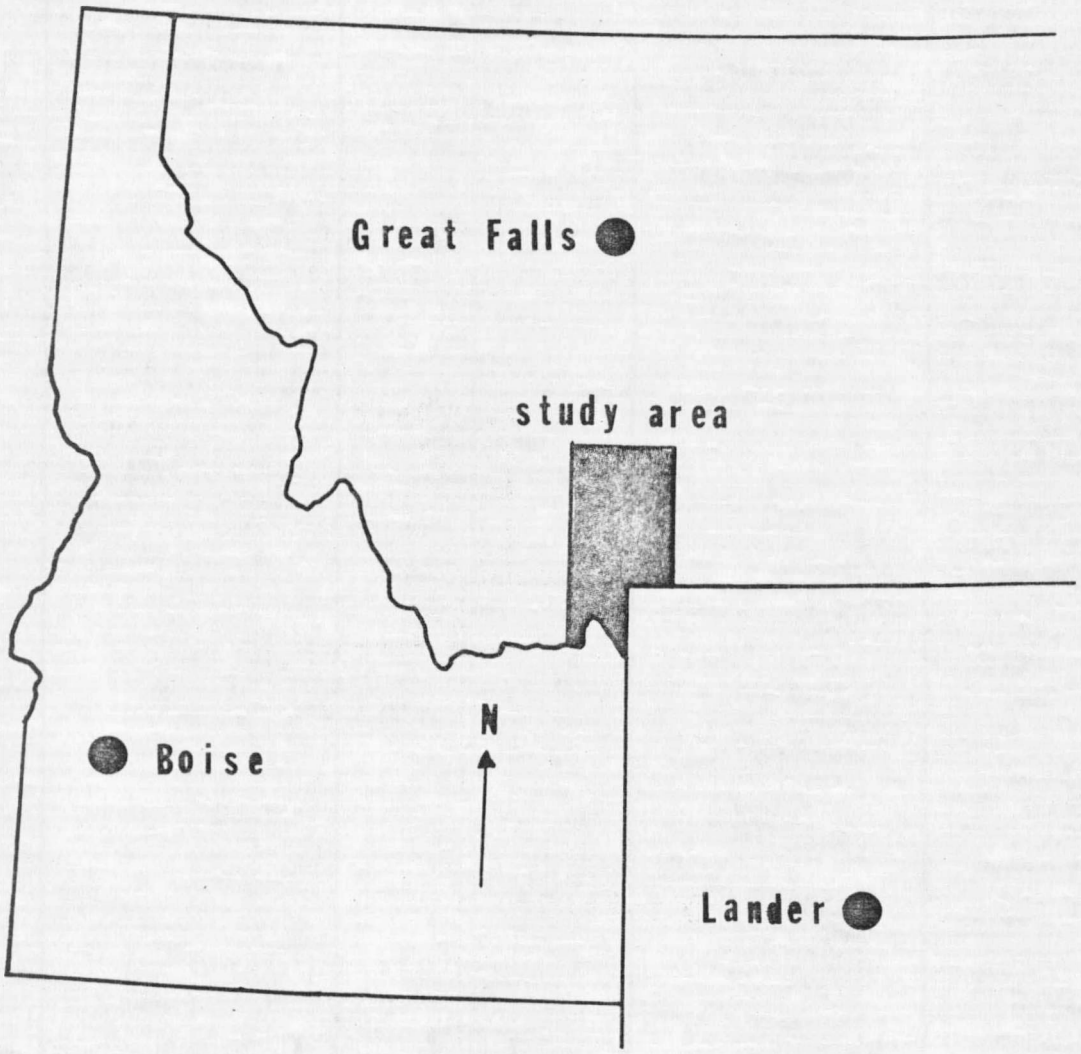


Figure 4. Map showing the location of the study area and the three closest rawinsonde stations used in the study to provide meteorological data.

four different mechanisms: First, snow can be caused by relatively warmer or colder air moving horizontally into the area (thermal advection). Second, vertical motions associated with low-pressure systems cause air to rise, cool and thus precipitate. Third, the approach of upper level air spinning counterclockwise (positive vorticity advection) causes air to rise and precipitate. Fourth, atmospheric instability causes convective precipitation. Including orographic precipitation, there are a total of five different meteorological processes which cause snowfall. This study calculates meteorological parameters which account for each of these five processes, plus some generalized parameters which are used in the calculation of other parameters.

Table 1 presents a list of parameters followed by a section containing a brief lay description of each parameter and details of the calculation of each parameter. Readers unfamiliar with the meteorolocical significance of each parameter are refered to introductory texts such as Byers (1974).

Table 1. A list of weather and climate parameters organized according to the process to which each contributes.

Meteorologic parameters:

1) Frontal activity
   - -thermal advection
   - -horizontal temperature gradient at mandatory levels

2) Low pressure systems:
   - -pressure height of mandatory levels

3) Vorticity advection:
   - -vorticity advection parameter
   - -500 mb divergence

4) Atmospheric instability:
   - -K index

5) Orographic processes:
   - -various orographic parameters (list provided in Generalized Orographic Parameters sections, p. 32)

Genaralized dynamic and orographic parameters:
- -combinations of orographic and dynamic parameters with atmospheric moisture and stability factors added.

Generalized parameters:
- -850 mb dew point spread
- -precipitable water
- -mandatory level temperature, relative humidity and wind velocity
- -mandatory level horizontal pressure height gradient

Climate parameters:
- -precipitation at climate stations
- -24-hour surface temperature change
- -snowmelt parameters

Meteorological Parameters

Thermal Advection. Thermal advection means the horizontal movement of warmer or colder air into the study area (warm or cold fronts). This parameter uses an upwind rawinsonde sounding to find if wind direction turns clockwise or counterclockwise with height indicating warm or cold advection, respectively. Thermal advection is calculated using wind vectors and a hodograph as described in Byers (1974). The method is summarized below.

Consider a layer of air with vector OA, the wind vector for the lower surface and vector OB, the wind vector for the upper surface (the 850 mb and 500 mb surfaces are the lower and upper surfaces respectively; Figure 5). In this case, the wind turns clockwise with height indicating warm advection. Vector AB is the shear component of the wind which is calculated on the computer using the law of sines. Line OC is the cross-isotherm component (isotherms will always be parallel to AB). Thermal advection can be calculated using a formula derived from Saucier (1972).

$$\text{Thermal advection} = -\frac{V f T t C}{H g} \quad \text{Deg./Time}$$

Where: V = magnitude of the shear vector (Figure 5; vector AB)
f = coriolis acceleration for the study area = 10.3×10^{-5} per second
T = average temperature of the layer in degrees Kelvin
t = time interval between rawinsonde soundings (12 hours)
C = cross isotherm component (Figure 5; vector OC)
H = thickness of the layer considered (from pressure heights)
g = acceleration of gravity

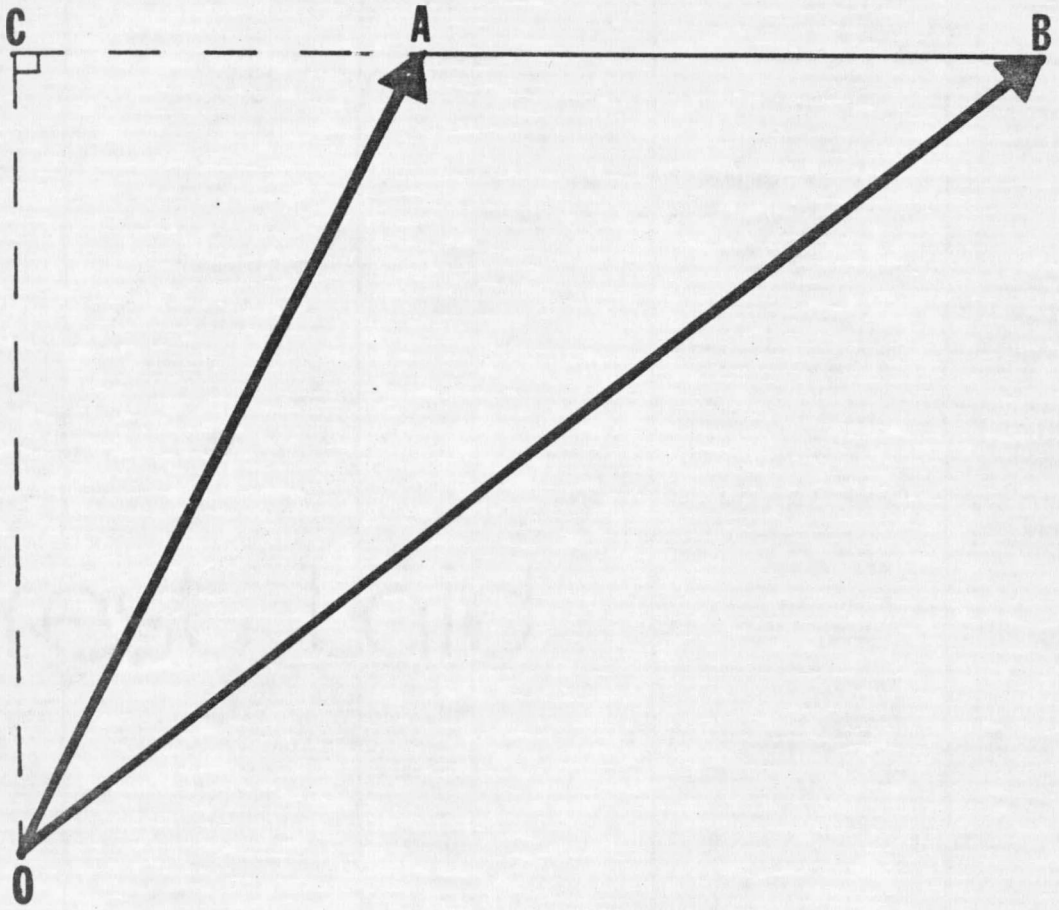


Figure 5. A diagram showing the method of calculation of thermal advection (see text for discussion).

Horizontal temperature and pressure height gradient at mandatory levels. The horizontal temperature gradient is an indicator of a front in the area bounded by the three rawinwsonde stations. The horizontal pressure height gradient is an indicator of wind velocity. In the free atmosphere (generally 700 mb or higher in this region) the balance between horizontal pressure difference and the coriolis acceleration creates geostropic winds which flow counter clockwise around a low-pressure center. At the earth's surface, winds blow toward low pressure because frictional forces with the ground overpower the effects of the coriolis acceleration. These parameters are calculated simply by taking the maximum difference between the three rawinsonde station readings. A parameter for both horizontal temperature gradient and horizontal pressure height gradient is generated for each of the three mandatory levels of 850, 700, and 500 mb.

Rawinsonde data from mandatory levels. These parameters are the raw data collected during a rawinsonde sounding which include pressure height, temperature, relative humidity, and wind velocity. Pressure height is the height of one of the mandatory pressure levels generally indicating fair or foul weather with high or low values respectively. The other parameters need no explanation. These parameters are calculated using the values from each of the three rawinsonde stations and using a weighted average based on the distance between the rawinsonde station and the study area. The following equation is used (Davis, 1973):

$$\text{Average} = \frac{\frac{V1}{D1} + \frac{V2}{D2} + \frac{V3}{D3}}{\frac{1}{D1} + \frac{1}{D2} + \frac{1}{D3}}$$

Where: V1 = the value from the Great Falls station
V2 = the value from the Lander station
V3 = the value from the Boise station
D1 = the distance from Bozeman to Great falls (230 km)
D2 = the distance from Bozeman to Lander (350 km)
D3 = the distance from Bozeman to Boise (445 km)

Vorticity advection. Vorticity is a measure of the rotation of the horizontal plane of the air. The increase of vorticity (positive vorticity advection) implies vertical atmospheric motions. Using natural coordinates, the following equation describes vorticity (Byers, 1974).

$$\text{vorticity} = \frac{dv}{dn} + \frac{V}{r} + C$$

Where: dv = change in horizontal distance over distance dn (Figure 6)
dn = distance over which velocity change is measured
V = horizontal velocity of air at a specified point
r = radius of curvature of the airstream at the point specified by V
C = constant for the coriolis acceleration @ 45 degrees latitude of 10.3×10^{-5} per second

Vorticity comes from three components: first, from the shear in the air producing a term describing the change in velocity of the air over

a specified horizontal distance (dv / dn) (Figure 7); second, from the curvature of the airstream yielding the term V/r; (Figure 8) third, from the inherent curvature of the airstream due to the rotation of the earth (coriolis acceleration).

If the wind blows from the west, vorticity is calculated in the following manner. Figure 8 shows the relative position of the three rawinsonde stations with winds represented as vectors. Thus:

$$V = \frac{v_1 + v_2}{2}$$

and

$$dv = V - v_1$$

The radius of curvature of the airstream is calculated noting that:

$$r = \frac{1}{a}$$

Notice that if V is greater than V_1, the first term is positive (counterclockwise rotation). The term r is defined to be positive only when the airstream curves counterclockwise. To calculate vorticity advection, the vorticity value from the previous sounding (12 hours before) is subtracted from the vorticity value of the present sounding yielding the change in vorticity over time (vorticity advection).

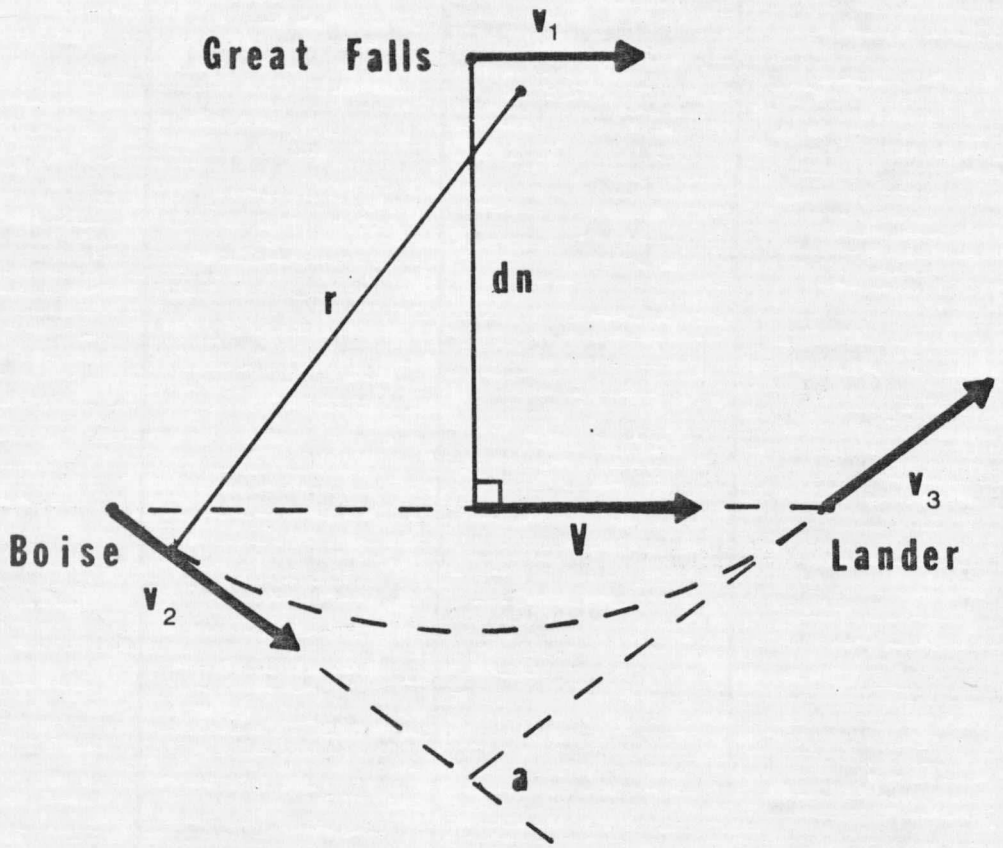


Figure 6. Shows the method of calculating vorticity for this study. See text for discussion.

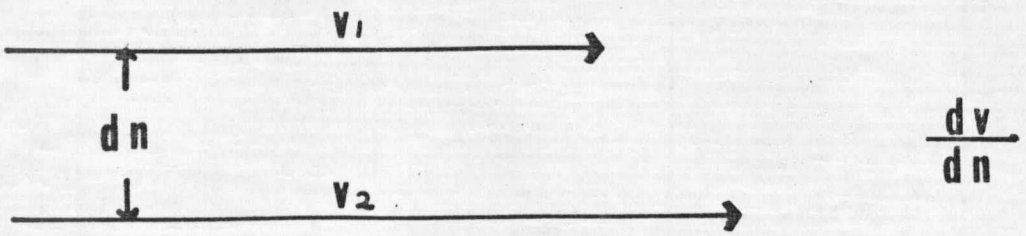


Figure 7. The shear component of vorticity.

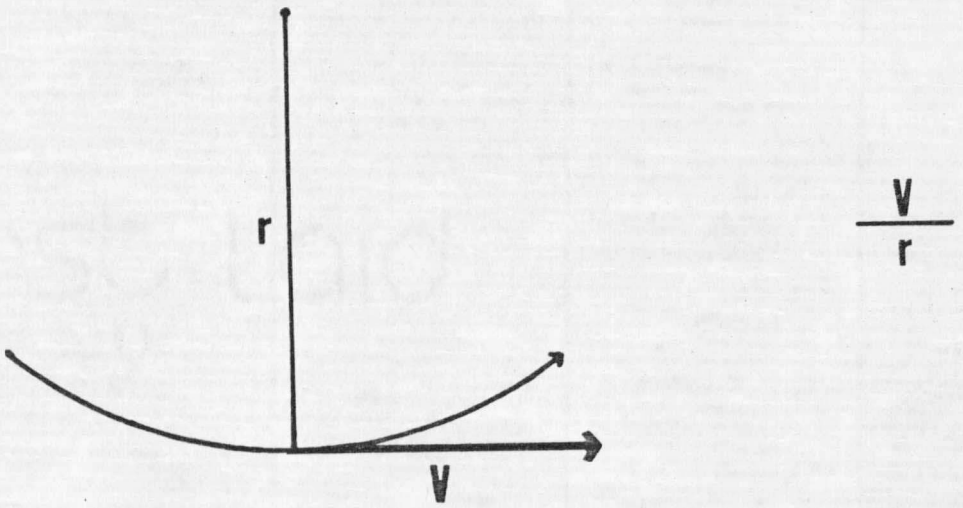


Figure 8. The curvature component of vorticity.

Divergence. Divergence refers to the horizontal spreading and diverging of the air at upper levels indicating a large scale convection caused by either low pressure or vorticity advection. Divergence is calculated using the 500 mb wind vectors for the three rawinsonde stations. The points of the wind vectors define a triangle (Figure 9) and divergence, then, is the change of the area of the triangle between each rawinsonde sounding as in the equation (Saucier, 1972).

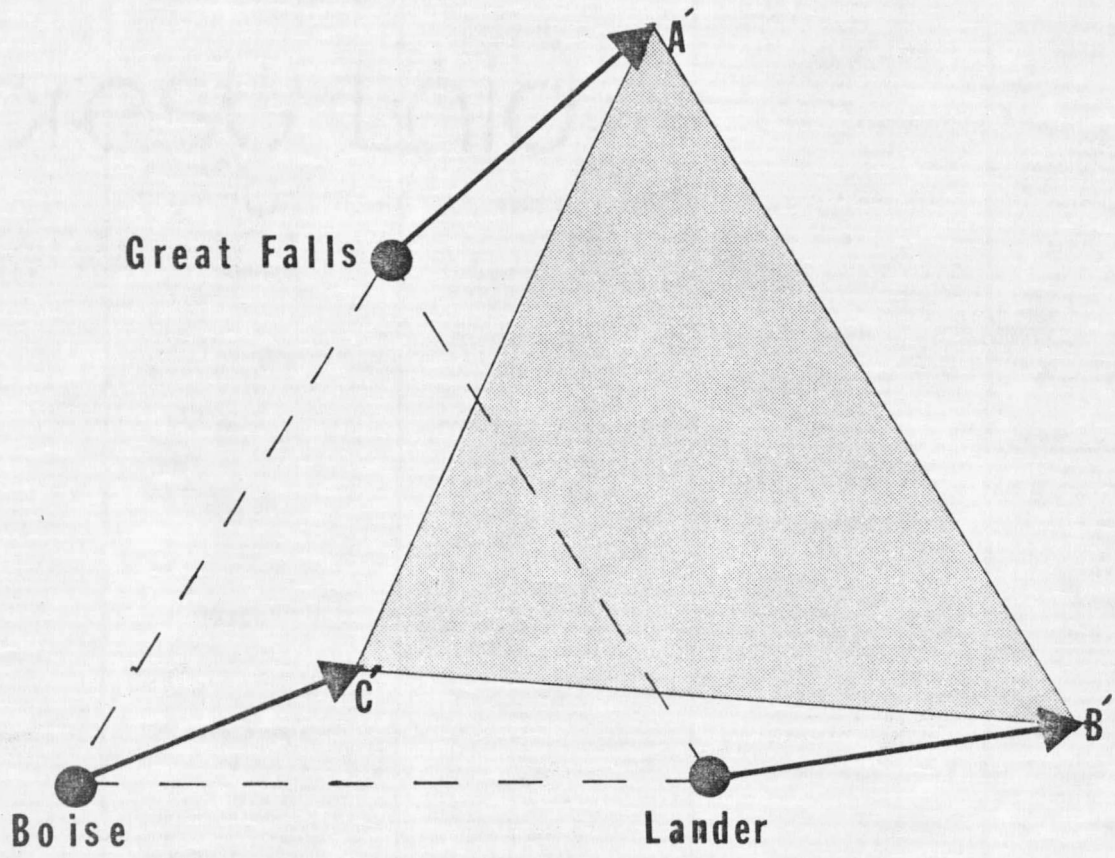


Figure 9. The method of calculation of the parameter divergence (see text for discussion).

$$\text{Divergence} = \frac{1}{A}\,\frac{\Delta A}{\Delta t}$$

Where: A = the area of the triangle
t = time interval over which area change is measured

Atmospheric instability. The atmosphere naturally becomes colder with height due to adiabatic expansion. When upper level air is colder than one would expect due to adiabatic expansion, the atmosphere is unstable because warm air rising from lower levels becomes buoyant in the colder upper layers and forms convective cells. Precipitation solely from atmospheric instability is rare in winter months but becomes more important with the approach of spring. Also, atmospheric instability enhances precipitation from dynamic and orographic processes. Therefore, this study tests atmospheric instability not only as an independent indicator of winter precipitation, but more important, it is combined with other dynamic and orographic parameters to make them more accurate indicators of precipitation. The K index is a commonly used indicator of atmospheric instability:

K index = 850 mb temperature - 500 mb temperature + 850 mb dew point - 700 mb dew point spread.

Generalized dynamic and orographic parameters. This study attempts to keep calculation simple so that the model remains simple and inexpensive. An example is the development of the orographic precipitation parameters described in this section. Wind direction

affects snowpack amounts and distribution because the angle at which the wind strikes a topographic barrier affects the atmospheric vertical velocity, thus affecting the rate of orographic precipitation. Most orographic models account for the interaction between wind direction and topography by digitizing topographic elevations and modeling the vertical velocity of the air as it crosses a topographic barrier. This study, however, does not consider the interaction between wind direction and topography because of the expense of digitizing terrain and developing or purchasing a sophisticated computer model. If this study proves successful, then future studies may have greater success by developing more sophisticated parameters.

The amount of precipitation occurring due both to dynamic and orographic processes is the sum of three components: The first is the vertical lifting of the air produced from the dynamic or orographic mechanism involved such as divergence, thermal advection and/or orographic lifting. Second, is the amount of water available for precipitation (precipitable water). Third, vertical motion can be either enhanced or retarded by the atmospheric stability. Because of this, the various dynamic and orographic lifting mechanisms are combined with precipitable water and/or atmospheric stability (K index) to make a theoretically more consistant parameter. For both dynamic and orographic processes, four parameters are created which represent various simple combinations of precipitable water, K index and one of the lifting mechanisms. In this way, four simple

parameters were created which generally indicate precipitation from dynamic processes. Four dynamic parameters are defined as follows:

Dynamic 1 = cold advection x precipitable water
Dynamic 2 = K index x precipitable water
Dynamic 3 = divergence x precipitable water
Dynamic 4 = vorticity advection x precipitable water x K index

Four orographic parameters were derived in a similar manner. The amount of orographic precipitation occurring depends on the amount of precipitable water, the thickness of the saturated layer and the amount of vertical lifting of the air (Berry 1981). The lifting mechanism occurs when horizontally moving air rises over a topographic barrier such as a mountain range. Therefore, the 700 mb horizontal wind velocity (about 10,000 feet) is used as an indicator of vertical air velocity. The 850 mb (about 5,000 feet) dew point spread (defined below) is used as an indicator of the elevation at which saturation occurs as the parcel of air is lifted. As with the dynamic parameters, the K index is added to some of these parameters to make them more accurate. Four simple combinations of the 850 mb dew point spread, precipitable water, K index and the 700 mb wind velocity are created as follows:

Orographic 1 = 700 mb wind x 1/850 mb dew point spread
Orographic 2 = 700 mb wind x precipitable water
Orographic 3 = 700 mb wind x precipitable water x K index
Orographic 4 = 700 mb wind x precipitable water x K index x 1/850 mb dew point spread

850 mb dew point spread. The difference between the temperature and the dew point is the dew point spread, indicating the degree of

saturation of the air. For example, a dew point spread of 0 means 100 percent humidity.

Precipitable water. Precipitable water is defined to be the amount of water available for precipitation. The following equations are used to calculate precipitable water (Saucier, 1972):

$$W = \frac{-1}{g} \sum_{i=1}^{n} r_i (-P_i)$$

Where: W = precipitable water in centimeters of depth
g = acceleration of gravity
P = pressure of the surface
r = mixing ratio (defined below)
i = the number representing the atmospheric surface being considered
n = the largest number of surfaces considered
P_i = the change in pressure between P_i and P_i-1

Mixing ratio is a dimensionless number defined to be the ratio of water vapor to the mass of the dry air with which the water is mixed. The commonly-used equation is:

$$r = \frac{0.622\ e}{P - e} \qquad \text{(Byers, 1974)}$$

Where: r = mixing ratio
P = atmospheric pressure in millibars
e = vapor pressure in millibars (defined below)

To obtain vapor pressure from the saturation vapor pressure:

$$e = e_s \ (RH / 100) \qquad \text{(Byers, 1974)}$$

Where: e_s = saturation vapor pressure (defined below)
RH = relative humidity in percent

The saturation vapor pressure is calculated:

$$e_s = 6.11 \times 10^{aT/[T + b]} \qquad \text{(Saucier, 1972)}$$

Where: T = temperature in degrees centigrade
a and b are constants where:
over water (above 0 deg. C) a = 7.5; b = 237.3
degrees Kelvin
over ice (below 0 deg. C) a = 9.5; b = 265.5
degrees Kelvin

Climate Parameters

Precipitation at climate stations. Precipitation is simply the 24-hour total of precipitation at climate stations. The climate measurements are taken daily at around 6:00 p.m.

24-hour surface temperature change. This parameter attempts to indicate the passage of a cold front. It consists of the negative (getting colder) change in minimum temperature value in a 24-hour period at climate stations. However, this is not an absolute indicator of a cold front passage because high values may also indicate a cold night caused by clear skies following a warm night caused by cloud cover.

Accounting for Snowmelt

This study covers only the snow accumulation period of winter (October through April) and does not attempt to estimate snowmelt during the spring melt season. However, since some fall and winter melting occurs, by accounting for this melt, the model can estimate snowpack amount more accurately. Although snowmelt is a very complex process depending on many variables, air temperature is an important indicator and can provide an estimate of snowmelt. Therefore, temperatures at climate stations are used to estimate snowmelt. A description of how this was accomplished follows.

In order to gain some understanding of how air temperature affects snowmelt, a comparison was made between snowmelt (24-hour loss of snow water equivalent) at each snow course and the maximum and minimum temperatures at each of the climate stations to see which climate station temperatures correlated best with snowmelt (Figure 10). Although these plots show a complex relationship, one can see that in general, there exists a critical maximum temperature above which melt occurs. For the plot presented, the critical temperature is around 50 degrees F. In all cases, snowmelt correlated with maximum temperature better than minimum temperatures. Also, temperatures at three climate stations correlated with snowmelt better than other climate stations: Bozeman 12 NE, Hebgen Dam and West Yellowstone. With many snow courses, an average of two climate stations correlated better than an individual climate station. Thus,

maximum temperature at one or an average of two of these climate stations was used to estimate melt (Table 2).

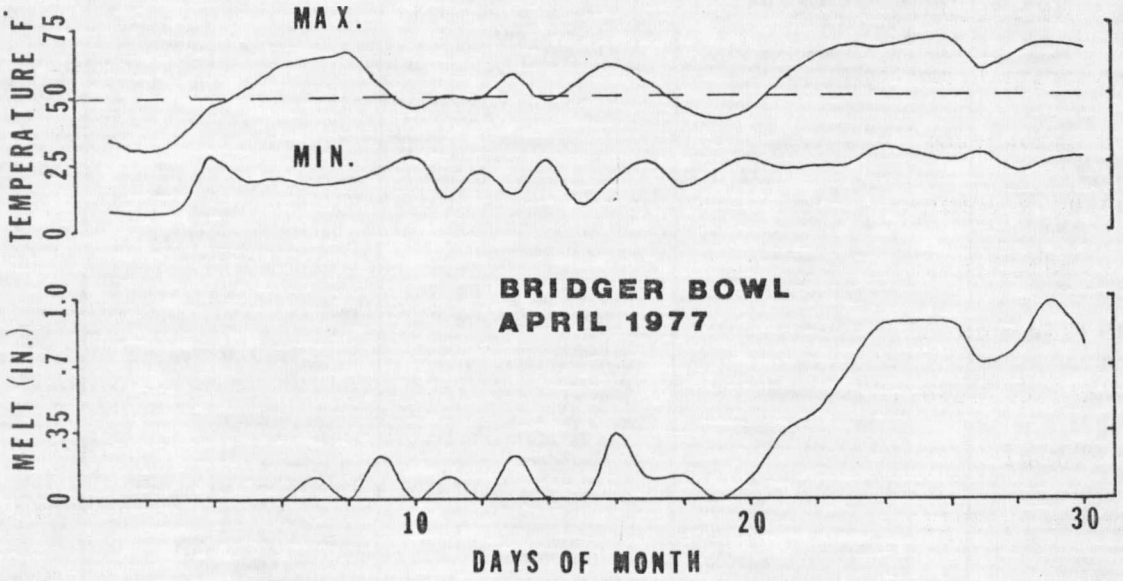


Figure 10. A plot of snowmelt (24-hour loss of snow water equivilent) at the Bridger Bowl snow course plotted against minimum and maximum temperatures at the nearby Bozeman 12 NE climate station for April, 1977. Melt seems to occur above 50 degrees Fahrenheit and correlates with maximum temperature.

In a more accurate test of critical temperature as well as determining melt rate, daily melt amount was plotted against the temperature above 50 degrees Fahrenheit (Figure 11). Notice that the X intercept (temperature where melt is zero) falls at 50 degrees, and and melt rate is 0.04 inches per degree above 50 degrees. From the empirical relationships seen in these plots, predictive melt equation were constructed based on temperature at one or an average of two

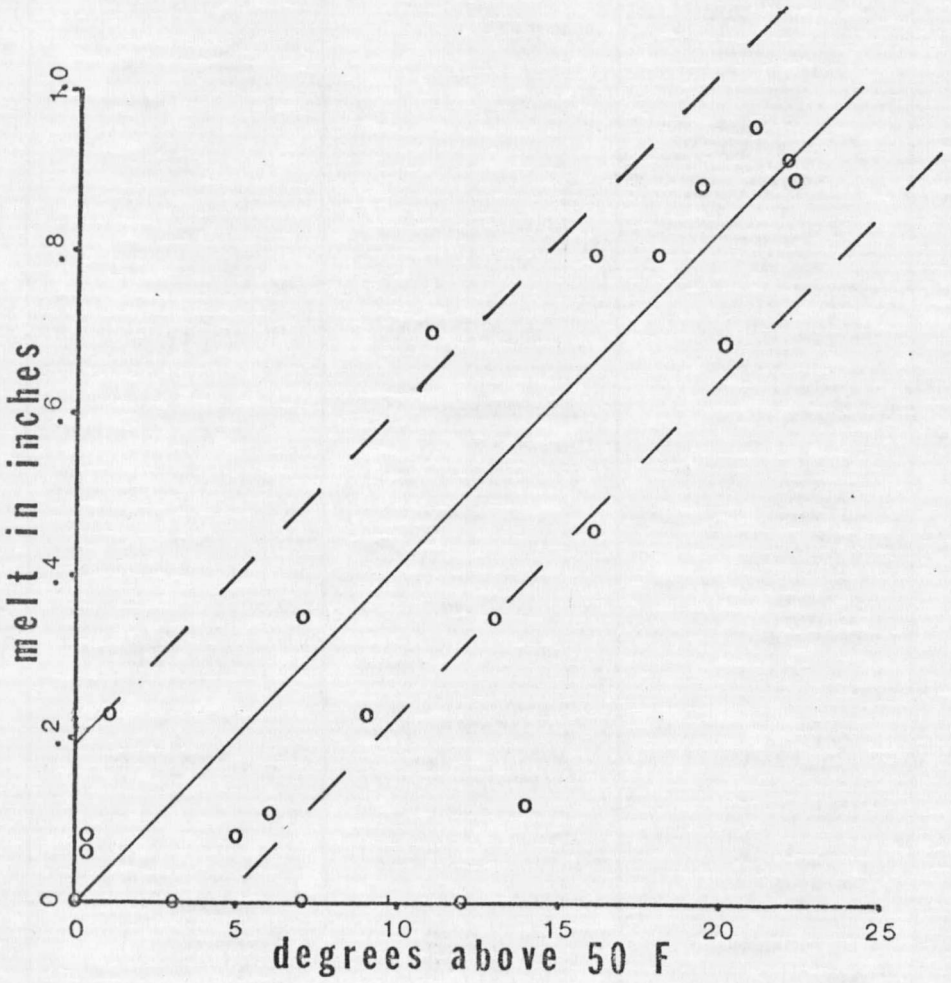


Figure 11. Plot of snowmelt (24-hour loss in snow water equivilent) at the Bridger Bowl snow course against temperature above the critical temperature of 50 degrees Fahrenheit at the Bozeman 12 NE climate station. Dashed lines are one standard deviation of melt values from the line.

climate stations. An analysis of the plots for the six daily snow courses yielded the empirical relationships shown in Table 2.

Table 2. Critical temperature, melt rate and which climate stations were used to provide temperature data for each snow course melt equation.

Snow Course	Critical Temperature	Melt rate in inches of water equivalent per degree above critical temp.	Climate stations providing temperature data.
Bridger Bowl	50	0.04	B
Maynard Creek	50	0.03	B
Shower Falls	50	0.03	H and B *
Lick Creek	45	0.05	H and B *
Carrot Basin	55	0.02	H and W *
Taylor Peaks	50	0.04	H and W *

B = Bozeman 12 NE
H = Hebgen Dam
W = West Yellowstone

* Averaged values

CHAPTER 3

RESULTS

Results are presented as follows. Table 3 shows the correlation results between estimates and actual monthly snow accumulation. In the first column, snow courses are separated into daily and monthly categories. The second column shows the correlation coefficient between monthly estimates and actual monthly totals. The third column, r^2, is the variance; this can be thought of as the amount of variance "explained" by the regression equation. The fourth column, N, is the number of cases, i.e. the number of months of data entered into the regression equation. The standard error column means that 68 percent of the time, the difference between the estimated monthly snowfall total and the actual total will be less than or equal to the standard error. The last column indicates which daily snow course equation was used as a predictor for each monthly snow course (recall that the equation developed for each daily snow course was summed to produce monthly totals).

Table 4 shows the daily equations used to generate monthly totals, the parameters used and their importance in accounting for the predictive ability of the equation. The first four columns are as above. The parameters column is the meteorological and climate station parameters used in the regression equation. The percent r^2 change column is the percent of the total explained variance accounted

Table 3. Correlation results between estimates of monthly accumulation and actual monthly snow accumulation for both daily and monthly snow courses.

Snow Course	r	r^2	N	Standard Error (inches)	Daily snow course whose equation was summed to estimate monthly snow course values.
Daily Snow Courses:					
Bridger Bowl	.94	.89	66	1.72	*
Carrot Basin	.91	.83	30	4.15	
Lick Creek	.71	.51	44	1.27	
Maynard Creek	.87	.76	54	1.50	
Shower Falls	.92	.85	43	2.56	
Taylor Peaks	.86	.74	24	0.89	
Monthly Snow Courses:					
Arch Falls	.91	.82	43	1.05	Shower Falls
Bear Basin	.97	.95	31	1.97	Shower Falls
Hood Meadows	.89	.79	24	1.47	Shower Falls
Little Park	.98	.95	29	1.40	Shower Falls
New World	.88	.76	31	2.10	Shower Falls
Twenty-One Mile	.85	.71	50	1.82	Carrot Basin

*The equation developed for each daily snow course was integrated to produce monthly totals.

r correlation coefficient
r^2 variance
N number of cases (months in the regression)

Table 4. Results of stepwise multiple regression with daily meteorologic and climate station parameters as independent variables and daily snow accumulation at snow course sites as the dependent variable. The equations constructed from these parameters and coefficients were integrated to provide monthly estimates.

SNOW COURSE	r	r^2	N	STANDARD ERROR (inches)	METEOROLOGICAL AND CLIMATIC STATION PARAMETERS	$\%r^2$ CHANGE*	COEFFICIENTS
Bridger Bowl	.81	.67	163	.16	Bozeman 12 NE	86	1.52
					Orographic	5	1.04 E-4
					Temp. change	3	-1.09 E-4
					Temp. grad. 850	3	-7.40 E-3
					Temp. 500	3	-9.80 E-3
					Constant		- .126
Maynard Creek	.59	.35	145	.14	Bozeman 12 NE	67	.564
					Spread 850	9	-9.50 E-3
					West Yellowstone	9	.460
					Temp. grad 700	8	-9.30 E-3
					Orographic 4	7	-5.50 E-5
					Constant		.130
Shower Falls	.57	.32	157	.19	Bozeman 12 NE	84	.806
					West Yellowstone	16	.586
					Constant		4.70 E-2
Lick Creek	.64	.42	135	.19	Ennis	62	5.23
					Norris	17	-3.25
					West Yellowstone	6	.679
					Dynamic 4	10	-3.33 E-4
					Divergence	5	6.28 E-3
					Constant		-1.12

Table 4 (continued)

Carrot Basin	.64	.41	122	.21	Dynamic 1	68	2.30	E-2
					Hebgen Dam	20	.440	
					West Yellowstone	6	.610	
					Orographic 1	5	-2.30	E-3
					Constant		-5.60	E-3
Taylor Peaks	.50	.26	127	.14	Hebgen	68	.330	
					Pres. grad 700	19	1.00	E-3
					West Yellowstone	13	.310	
					Constant		-5.60	

*Percent change of r^2 of the regression equation as each parameter is added.

PARAMETER DEFINITIONS:

Climate Stations:

- Bozeman 12 NE — 24-hour precipitation total
- West Yellowstone — 24-hour precipitation total
- Hebgan Dam — 24-hour precipitation total
- Ennis — 24-hour precipitation total
- Norris — 24-hour precipitation total

Weather Parameters:

- Orographic 1 — 700 mb wind speed x 1/850 mb dew point spread
- Orographic 4 — 700 mb wind speed x precipitable water x K-index x 1/850 mb dew point spread
- Dynamic 1 — cold advection x precipitable water
- Dynamic 4 — vorticity advection x precipitable water x K-index
- Temp. change — 24-hour temperature change at Bozeman 12 NE
- Temp. grad 850 — 850 mb horizontal temperature gradient
- Temp. grad 700 — 700 mb horizontal temperature gradient
- Temp. 500 — 500 mb temperature
- Spread 850 — 850 mb dew point spread
- Press grad 700 — 700 mb horizontal pressure gradient
- Divergence — 500 mb divergence

for as each parameter is added to the regression equation. The numbers can also be thought of as the percentage each parameter accounts for the total predictive ability of the regression equation. The coefficients column represents the coefficients for the associated parameters. The significance of these results will be discussed in the following chapter.

CHAPTER 4

DISCUSSION OF RESULTS

Success of the Study

The objective of this study was to test the feasibility of using precipitation and temperature data at local climate stations as well as a simplified set of meteorological parameters to adequately estimate monthly snowfall water equivalent totals at snow course sites in southwestern Montana in an inexpensive manner. Considering the objectives of the study, how well do the results support the success of this procedure? Correlation coefficients between monthly estimates and actual monthly snow accumulation totals are 0.90 and above for six of the twelve sites tested (highest, 0.98) and 0.84 and above for 11 of the 12 sites (Table 2). For example, at two snow courses, Little Park and Bear Basin, the model accounts for 95 percent of the monthly variance in snow water equivalent amounts; for six of the twelve sites tested, the model accounts for 80 percent or more of the variance and for 11 of the 12 sites it accounts for over 70 percent of the variance. Clearly, for many snow course sites, depending on the accuracy required, this methodology may represent an inexpensive alternative to snow course measurements once the predictive equations are established using snow course data.

Southwest Montana represents a challenging location to test this methodology for a number of reasons: First, weather patterns in the

study area are very complex; the study area straddles two, sometimes three, different wintertime airmasses. Second, the terrain in the study area is similarly complex. High mountain ranges abruptly border broad, flat valleys; the 16,000 square kilometer Yellowstone-Beartooth plateau stands at an elevation of 8,000 to 12,000 feet and consequently, creates much of its own weather. Third, a distance of nearly 300 kilometers separates the study area from the closest upwind rawinsonde stations of Boise Idaho and Great Falls Montana. After the storms pass these stations, they often travel over many mountain ranges before reaching the study area. Since the weather, terrain and the rawinsonde locations create disadvantages in estimating mountain weather, and since this methodology works for this area, it will almost certainly work as well in most other locations.

One is tempted to compare the success of the methodology developed in this study to the other methods such as the Tangborn method and the computer modeling method. However, neither method has been tried in southwestern Montana and a comparison would be inappropriate because of the differences in terrain and locations of climate stations and rawinsonde stations.

Important Parameters

In this section, the parameters which account for most of the predictive ability of the equations are examined. Recall that daily multiple regression equations were integrated to provide monthly estimates of snow amounts at snow course sites (Table 3). Notice that the correlation coefficients for daily estimates are much lower than

the correlation coefficients for monthly estimates (Tables 3 and 4). This is because when summing the daily estimates to produce monthly totals, the errors tend to be "smoothed over", i.e. a high estimate for one day may be balanced by a low estimate for the next day. Also note (Table 4) that each parameter accounts for varying amounts of the predictive ability of the equation according to the percentage change of r^2 of the regression equation as each parameter is added to the equation. Based on these values, a discussion of the important parameters follows.

The 24-hour precipitation total at climate stations parameters generally accounted for more predictive ability of the regression equations than meteorological parameters. For six snow courses, climate station parameters accounted for 100 percent of the estimate. At four snow courses, climate station parameters accounted for at least 76 percent of the estimate and for the remaining two snow courses, climate station parameters accounted for only 27 percent. It is not surprising that climate station parameters are better indicators than meteorological parameters considering the simplicity of the meteorological parameters and the complexity of the weather and terrain in southwest Montana. On the other hand, as the snow courses, Carrot Basin and Twenty-One Mile show, climate station data is not always a good predictor. For these snow courses, the parameter dynamic 4 accounts for 68 percent of the estimate. And for half of the snow courses used in the study, a combination of meteorological and climate parameters estimate monthly snow accumulation better than either meteorological or climate parameters alone. This shows that

neither climate station data nor meteorological parameters alone, can adequately account for snowpack amount in all locations.

Because of the importance of orographic precipitation in the mountains, two climate stations, Bozeman 12 NE and West Yellowstone represent mountain weather well because they both are located at high elevations and have a large topographic rise nearby in an upwind direction. However, notice that the Gallatin Gateway 26 climate station is located at a high elevation and in an area of high local relief but it poorly represents mountain snowpack amount (Figure 1, Table 4). This station is located in Gallatin Canyon and valley bottom locations receive precipitation primarily from dynamic systems. Any orographic precipitation reaching this station must come via wind transport from an upwind topographic barrier over 25 kilometers distant. Armstrong and Williams (1981) also found that valley bottom climate stations poorly represent orographic precipitation.

The results show the importance of testing valley climate stations as predictors of snowfall as well as climate stations located in or near the mountains. For example, at the Lick Creek snow course, notice two things: (Table 4; Figure 1): First, two lower elevation climate stations, Ennis and Norris Madison PH account for the majority of the predictive ability of the regression equation. Valley bottom climate stations with little local relief such as Ennis and Norris, receive precipitation from primarily dynamic sources because of the absence of orographic precipitation-inducing terrain. Second, notice that the two weather parameters in the equation, dynamic 4 and divergence, both reflect dynamic processes. Thus, the Lick Creek snow

course is a lower elevation snow course where dynamic processes apparently dominate. Although dynamic processes are generally less important than orographic processes in the mountains, the Lick Creek snow course shows the importance of accounting for both processes.

Cost Assessment

In this paper, the word expense appears often. What was the cost of this study? What expense could users of this technique in other locations encounter? Table 5 presents a general expense account of this study totalling $13,150. Notice most of the expense went toward salaries and computer use. Also, note that there was a one-time expense for development and testing of the model, once accomplished, there would only be a small annual expense for data entry and computer use.

However, using other techniques, future researchers could develop a similar model with even less expense. Recall that this study was divided into two parts--development of the equations and testing for success. Developing the daily equations required only 200 days of data whereas because this study chose to estimate monthly snow course accumulation, testing required 17 years of data. By far the largest expense involved testing of the model over a large time period. Future researchers might estimate daily snowfall at sites which only provide daily totals of snowfall, for example, a SNOTEL site. In this case, the model could be both developed and tested using a far smaller, yet statistically significant amount of data.

Table 5. Generalized expense account of the study.

	Amount
Salaries of research assistant, key punchers, and programmers	$ 7,360
Computer	3,000
Data*	1,680
Miscellaneous	1,110
TOTAL	$ 13,150

*Digital tape charges for 17 years of daily weather and climate data from N.O.A.A. National Climatic Center in Ashevelle, North Carolina.

With a smaller amount of data, it is even feasible to calculate the various meteorological and climate station parameters on a good hand calculator. Extrapolating further using this method, a user might erect an array of portable snow accumulation monitoring instruments in a mountainous area of interest; after perhaps only two seasons of data collection, and calibration of the model these instruments could be relocated to another area. In this way, monitoring of snow accumulation in the mountains would be very flexible and inexpensive. This approach could also complement current Soil Conservation Service snow survey efforts.

SUMMARY AND CONCLUSIONS

This study tests the feasibility of adequately estimating snowpack water equivalent at snow course sites in southwest Montana using meteorological parameters and precipitation and temperature data from local climate stations in an inexpensive statistical model. The model was developed using a sample of 200 days where meteorological and climate parameters were entered as independent variables in a statistical stepwise multiple regression equation with daily snowfall at snow course sites as the dependent variable. In order to test the model, the equations generated were integrated over a period of 17 years to estimate monthly snow accumulation at snow course sites and then compared to actual monthly totals to determine success of the model. Results show that estimates of monthly snow accumulation correlate with actual values with correlation coefficients of 0.90 and above for six of the twelve snow course sites tested (highest, 0.98) and 0.84 and above for 11 of the 12 sites.

This methodology could augment snow course measurements or, in some cases, replace snow courses. For example, the Bear Basin and Little Park monthly snow course totals can be estimated with a correlation coefficient of 0.98 using this technique. Also, this technique can easily be used in other locations to augment or replace mountain snowpack measurements as long as the area in question has fairly representative climate station data.

Future researchers may elect to estimate daily snowfall totals at snow course sites providing daily data rather than monthly data as this study has done. In this case, the model could be developed and tested using a far smaller amount of data and be able to perform calculations on a hand calculator. This technique could be combined with installing arrays of portable snow accumulation measuring instruments in the mountains of interest and after an adequate calibration time, these instruments could be relocated to another area. In this way, monitoring of snow accumulation in the mountains would be very flexible, inexpensive, and could complement current Soil Conservation Service snow survey efforts.

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APPENDIX

APPENDIX

PROGRAM LISTING

```
C     ************************************************************
C             * MAINLINE PROGRAM-- WEATHER *
C             ******************************
C
C          This program calculates a variety of meteorological
C        parameters from three upper air rawinsonde stations--
C        Great Falls, Mt., Lander, Wyoming, and Boise, Idaho.
C        The program calculates the following parameters:
C        1) It first utilizes a weighted average of the three
C        stations creating a value for the Bozeman area using the
C        distances to the stations as follows: Great Falls, 230 km.
C        Lander, 350 km. Boise, 445 km.
C        (2) Calculate the vector average wind direction for the
C        Bozeman area.
C        (3) Temperature and pressure gradient for the levels:
C        850,700,500 mbs.
C        (4) From and upwind station, it calculates K-index,
C        thermal advection and precipitable water.
C        (5) Using all three stations, it calculates vorticity,
C        vorticity advection and divergence using 500 mb. wind
C        directions and velocities.
C        (6) A variety of orographic lifting parameters.
C        (7) A variety of dynamic lifting parameters.
C        (8) Parameters based on local climate station data of
C        precipitation and temperature.
C
C     ************************************************************
C                     * USER INFORMATION *
C                     ********************
C          Input data is organized as follows:
C        Three records of morning mandatory data, i.e. data from
C        850, 700 and 500 millibar levels.  Data consists of
C        pressure height, temperature, relative humidity, wind
C        direction, wind velocity. The first record is from the
C        Great Falls station, the second from the Lander station
C        and the third from the Boise station.
C        Next, there are three records of morning significant data
C        arranged like above except that pressure is the first
C        parameter and the following are as above making six
C        parameters total per level.  There is a maximum of ten
C        levels.
C        Next, there are three records of afternoon mandatory data and
C        three records of afternoon significant data just as above.
C        Next, there is one record of climatic data.  It consists
C        of thirteen stations with each station yielding data of
C        minimum and maximum temperature, precipitation, and 24-
C        snow accumulation.  There are 14 records per day.
C
C
C
C        Record  Column  Format  Parameter
C          1       1-2     I2     Year
C          1       3-4     I2     Month
C          1       5-6     I2     Day
C          2       4-7     F4.0   850 mb pressure height
C          2       9-13    F5.1   850 mb temperature
C          2       16-18   F3.0   850 mb relative humidity
C          2       21-23   F3.0   850 mb wind velocity
C          3       26-28   F3.0   850 mb wind direction
C       The 700 mb and 500 mb data follows the same format.  The
C       700 mb data begins on column 30 and 500 mb data on column
        60. The second record is Great Falls, Record three is Boise
C       and record four is Lander.  Record five is the beginning of
```

```
C       the significant data and appears as follows:
C     Record  Column Format Parameter
C        5      3-6    F4.Ø  Pressure
C        5      1Ø-13  F4.Ø  pressure height
C        5      15-19  F5.1  temperature
C        5      22-24  F3.Ø  relative humidity
C        6      27-29  F3.Ø  wind velocity
C        6      32-34  F3.Ø  wind direction
C
C       The next significant layer begins at column 36, the next at
C       column 72 and so on with 12 significant layers total possible
C       Record five is Great Falls.  Record six is Lander and record
C       seven is Boise. Beginning with record eight is the afternoon
C       data in the same manner ending on record twelve.  Record
C       thirteen is the climate station data organized as follows:
C
C     Record Column Format Parameter
C       13     3-5   F3.Ø   maximum temperature
C       13     8-1Ø  F3.Ø   minimum temperature
C       13     12-18 F7.3   24-hour precipitation
C       13     2Ø-25 F6.2   24-hour snowfall total
C
C       The next climate station data begins on column 27, the next
C       on column 54 and so on with 13 climate stations possible
C       The climate station order is the same as their positions
C       entered in the arrays as described below.
C            The data is read into arrays as follows:
C        Array MAN(I,J,K) contains mandatory data.
C        I= station: I=1 is Great Falls; I=2 is Lander; I=3 is
C        Boise.
C        J is the level: J=1 is 85Ø mb.; J=2 is the 7ØØ mb. and
C        J=3 is the 5ØØ mb. level.
C        K is the parameter: K=1 is pressure height, K=2 is the
C        temperature, K=3 is the relative humidity, K=4 is the
C        wind direction and K=5 is the wind velocity.
C
C        Array SIG(I,J,K) contains significant data where I is the
C        the station as above and J is the level (a maximum of 1Ø
C        levels) and K is the parameter as above but the pressure
C        of that particular level is in the first position and the
C        other parameters are bumped up one position so there are
C        six parameters total.
C
C        Array CLIM(I,J) contains climatic data where I is the
C        station and J is the parameter as follows:
C        I = 1 is Belgrade Airport
C        I = 2 is Montana State University
C        I = 3 is The Forsyth ranch near Bridger (Bozeman 12 NE)
C        I = 4 is Ennis.
C        I = 5 is Gallatin Gateway 9 S.
C        I = 6 is Gallatin Gateway 27 S. (1952-1962)
C        I = 7 is Gallatin Gateway 26 S. (1967-present)
C        I = 8 is Hebgan Dam.
C        I = 9 is Livingston 12 S.
C        I = 1Ø is Livingston Airport.
C        I = 11 is Norris.
C        I = 12 is Virginia City.
C        I = 13 is West Yellowstone.
C
C        J = 1 is maximum temperature.
C        J = 2 is minimum temperature.
C        J = 3 is precipitation in inches.
C        J = 4 is 24-hour snowfall in inches.
```

```
C
C          Output of this program is organized as follows:
C
C           Record Column Format Parameter
C             1      2-3     I2    year
C             1      5-6     I2    month
C             1      8-9     I2    day
C             2      2-6     F5.Ø  85Ø mb pressure height
C             2      7-11    F5.Ø  85Ø mb temperature
C             2     12-16    F5.Ø  85Ø mb relative humidity
C             2     17-21    F5.Ø  85Ø mb wind velocity
C          The 7ØØ mb and 5ØØ mb data are as above. the 7ØØ mb data
C          begins in column 27 and the 5ØØ mb data begins in column
C          54.
C             2     62-66    F4.Ø  7ØØ mb wind direction
C             2     67-71    F4.Ø  5ØØ mb wind direction
C             3      2-5     F4.Ø  85Ø mb pressure height gradient
C             3      6-1Ø    F4.Ø  7ØØ mb pressure height gradient
C             3     11-15    F4.Ø  5ØØ mb pressure height gradient
C             3     16-2Ø    F4.Ø  85Ø mb temperature gradient
C             3     21-25    F4.Ø  7ØØ mb temperature gradient
C             3     26-3Ø    F4.Ø  5ØØ mb temperature gradient
C             3     31-35    F4.Ø  K index
C             3     36-4Ø    F4.Ø  85Ø mb dew point spread
C             3     41-48    F7.3  precipitable water
C             3     49-55    F6.2  thermal advection
C             3     56-62    F6.2  cold thermal advection
C             3     63-69    F6.2  warm thermal advection
C             3     7Ø-76    F6.2  thermal advection squared
C             4      2-7     F6.2  warm thermal advection squared
C             4      8-14    F6.2  cold thermal advection squared
C             4     15-21    F6.2  divergence
C             4     22-28    F6.2  divergence squared
C             4     29-35    F5.1  vorticity
C             4     36-41    F5.1  vorticity advection
C             4     42-47    F5.1  vorticity advection squared
C             4     48-53    F5.Ø  orographic parameter 1
C             4     54-59    F5.Ø  orographic parameter 2
C             4     6Ø-65    F5.Ø  orographic parameter 3
C             4     66-71    F5.Ø  orographic parameter 4
C             5      2-7     F6.1  dynamic parameter 1
C             5      8-14    F6.1  dynamic parameter 2
C             5     15-21    F6.1  dynamic parameter 3
C             5     22-28    F6.1  dynamic parameter 4
C             5     29-33    F4.Ø  Bozeman 12 NE 24-hour min. temp. change
C             5     34-38    F4.Ø  M.S.U. 24-hour min. temp. change
C
C          The following parameters are climate station parameters.
C             6      2-5     F4.Ø  maximum temperature
C             6      6-1Ø    F4.Ø  minimum temperature
C             6     11-18    F7.3  24-hour precipitation
C             6     19-25    F6.2  24-hour snowfall
C          There are three climate stations per record with the second
C          one beginning in column 29 and the third in column 58.
C          Again, the order of the climate stations is the same
C          as listed above.
C
C
C     ***************************************************************
C                * DIVISION OF MAINLINE PROGRAM *
C                  ****************************
C
C          * Read in data
```

```
C           * Weighted average for Bozeman area
C           * Average wind direction
C           * Temperature and pressure gradients
C           * Thermal advection, K-index, precipitable water and 850
C             millibar dew point spread.
C           * Divergence
C           * Vorticity
C           * Orographic parameters
C           * Dynamic lifting parameters
C           * Climate station parameters
C
C     ************************************************************
C                     * SUBROUTINES REQUIRED *
C                     ************************
C           * ADVECTION--calculates thermal advection
C           * WATER--calculates precipitable water
C           * STABLE--calculates K-index
C           * VORT--calculates vorticity
C     ************************************************************
C
C
C
C
C
C     ************************************************************
C                 * MODULE TO DIMENTION VARIABLES *
C                 *********************************
C
      INTEGER DAY,YEAR,MONTH
      REAL GRADSAVE(2,3,2),GRADAVE(3,2),LASTFOR,LANSPREAD,
     *LASTBZN,BZNAVE(3,5),BZN(3,5),GRAD(3,2),BZNSAVE(2,3,5),
     *D(3),MAN(3,3,5),SIG(3,12,6),DIR(3),L,PWATER,
     *LANWATER,LANADV,LANWADV,LANCADV,LANINDEX,LASTVORT,
     *GFMAN(3,5),LANMAN(3,5),BOIMAN(3,5),GFSIG(12,6),STORE(9),
     *LANSIG(12,6),BOISIG(12,6),KINDEX,LANSIN,LANCOS,LANDIR,
     *PAVE(25),PARAM(2,25),CLIM(13,4)
      LOGICAL FIRST
      DATA FIRST /.TRUE./,READCOUNT/1/
      OPEN(UNIT=105,RECL=440,STATUS='OLD')
C
C
C
C
C           Read in data.
  4   IF(READCOUNT.EQ.1)THEN
        READ(105,5,END=270)YEAR,MONTH,DAY
      END IF
      READ(105,10,END=270)(((MAN(I,J,K),K=1,5),J=1,3),I=1,3)
      READ(105,12,END=270)(((SIG(I,J,K),K=1,6),J=1,12),I=1,3)
      IF(READCOUNT.EQ.2)THEN
        READ(105,14,END=270)((CLIM(I,J),J=1,4),I=1,13)
      END IF
C
    5 FORMAT(3(I2))
   10  FORMAT(2(3(3X,F4.0,X,F5.1,3(2X,F3.0),2X)/),3(3X,F4.0,X,F5.1,
     *3(2X,F3.0),2X))
   12  FORMAT(2(12(2X,F4.0,3X,F4.0,X,F5.1,3(2X,F3.0),2X)/),12(2X,F4.0,
     *3X,F4.0,X,F5.1,3(2X,F3.0),2X))
   14  FORMAT(13(2(2X,F3.0),X,F7.3,X,F6.2,2X))
C          ************************************************************
C             * MODIFY ARRAYS AND EXTRAPOLATE MISSING VALUES *
C             ************************************************
```

```
C
C
C          In this data, significant level pressures numerically
C          ten times their actual values, so I divide by 1Ø.
C
  16   DO 18 I=1,3
         DO 17,J=1,12
         IF(SIG(I,J,1).EQ.-99.Ø)GO TO 17
           SIG(I,J,1)=SIG(I,J,1)/1Ø
  17     CONTINUE
  18   CONTINUE
C
C          The station at Lander, Wy. is above the 85Ø mb. level and
C          consequently, the 85Ø mb. mandatory data is usually
C          missing.  So here, I use data taken from the first
C          significant layer above Lander and extrapolate these
C          values to the 85Ø mb. level.  At this level, pressure
C          in millibars and height in meters is nearly numerically
C          equivilent, so I use them interchangeably.
C          Temperature lapse rate = .Ø65 degrees C / meter.
C          Relative humidity lapse rate = -1Ø% / 5Ø meters.
C          Height in meters = pressure in millibars.
C          Wind velocity and direction extrapolate directly.
C
       DO 22 I=1,3
  19     DO 2Ø K=1,5
         IF(MAN(I,1,K).NE.-99.Ø)GO TO 2Ø
         IF(SIG(I,1,1).LT.75Ø)THEN
       GO TO 22
       ELSE
C
C            Set DP = pressure difference between 85Ø mb. and the
C            pressure of the first significant layer.
         DP=85Ø-SIG(I,1,1)
C            Test for missing data in MAN and if so assign exptapolated
C            value from SIG
         IF(MAN(I,1,1).EQ.-99.Ø.AND.SIG(I,1,2).NE.-99.Ø)
     *   MAN(I,1,1)=SIG(I,1,2)-DP
         IF(MAN(I,1,2).EQ.-99.Ø.AND.SIG(I,1,3).NE.-99.Ø)
     *   MAN(I,1,2)=SIG(I,1,3)+(DP*.Ø65)
         IF(MAN(I,1,3).EQ.-99.Ø.AND.SIG(I,1,4).NE.-99.Ø)
     *   MAN(I,1,3)=SIG(I,1,4)-(.2*DP)
         IF(MAN(I,1,4).EQ.-99.Ø.AND.SIG(I,1,5).NE.-99.Ø)
     *   MAN(I,1,4)=SIG(I,1,5)
         IF(MAN(I,1,5).EQ.-99.Ø.AND.SIG(I,1,6).NE.-99.Ø)
     *   MAN(I,1,5)=SIG(I,1,6)
       END IF
C
  2Ø     CONTINUE
  22   CONTINUE
C
C          ***************************************************************
C                              * WEIGHTED AVERAGE *
C                              ********************
C
C
C
C          Here, I calculate the weighted average.  D(?)= inverse
C          of the distance from the Gallatin drainage to each of the
C          rawinsonde stations.  D(1)= Great Falls, D(2)= Lander,
C          D(3)= Boise.  It calclates a weighted average for all
C          5 parameters although the average for wind direction
C          (k=4) has no meaning in this case and I never use it.
```

```
C          The average wind direction is calculated in the
C          following section.
C
      DO 4Ø J=1,3
         DO 3Ø K=1,5
         D(1)=.ØØ4348
         D(2)=.ØØ2857
         D(3)=.ØØ2247
            DO 25 I=1,3
   25       IF(MAN(I,J,K).EQ.-99.Ø)D(I)=Ø
      IF((D(1).EQ.Ø.AND.D(2).EQ.Ø).OR.(D(1).EQ.Ø.AND.D(3).EQ.Ø)
     *.OR.(D(2).EQ.Ø.AND.D(3).EQ.Ø).OR.(D(1).EQ.Ø.AND.
     *D(2).EQ.Ø.AND.D(3).EQ.Ø))THEN
      BZN(J,K)=-99.Ø
      GO TO 3Ø
      END IF
         DIST=D(1)+D(2)+D(3)
         BZN(J,K)=(MAN(1,J,K)*D(1)+MAN(2,J,K)*D(2)+MAN(3,J,K)*D(3))
     *    /DIST
   3Ø    CONTINUE
   4Ø CONTINUE
C*****************************************************************
C                        * AVERAGE WIND DIRECTION *
C                        *************************
C
C          Average winds by separating them into X and Y components
C          and finding an average for them for 7ØØ and 5ØØ mbs.
C          First, I calculate the radian direction of the wind vector,
C          separate directions into components and find sum of
C          sine and cosine.  Add .ØØØ1 to SUMCOS so I don't divide
C          by zero.  J=2 is 7ØØmb.; J=3 is 5ØØ mb.
C                        VARIABLE DIRECTORY:
C       DIRCOUNT    -Counts the number of stations with missing data.
C       GFDIR       -radian direction converted to trig. coordinates.
C       LANDIR      -radian direction converted to trig. coordinates.
C       BOIDIR      -radian direction converted to trig. coordinates.
C       GFSIN       -Sine of the Great Falls Station.
C       LANSIN      -Sine of the Lander Station.
C       BOISIN      -Sine of the Boise Station.
C       GFCOS       -Cosine of the Great Falls station.
C       LANCOS      -Cosine of the Lander station.
C       BOICOS      -Cosine of the Boise station.
C       SUMSIN      -Sum of the sines of the stations.
C       SUMCOS      -Sum of the cosines of the stations.
C       ANGLE       -Average direction in radians in trig. coordinates.
C       DIR(J)      -Average direction in compass coordinates--DIR(2)
C                    is for 7ØØ mb. and DIR(3) is for 5ØØ mb.
C         Loop through twice to figure 7ØØ and 5ØØ mb. directions.
      DO 45 J=2,3
      DIRCOUNT=Ø
C
C          Change compass directions in array MAN to radian trig.
C          coordinates.
      GFDIR=(-(MAN(1,J,4)+9Ø))*.Ø174533
      LANDIR=(-(MAN(2,J,4)+9Ø))*.Ø174533
      BOIDIR=(-(MAN(3,J,4)+9Ø))*.Ø174533
C
C
C          Find sine and cosine of directions.
      GFSIN = SIN(GFDIR)
      LANSIN = SIN(LANDIR)
      BOISIN = SIN(BOIDIR)
      GFCOS = COS(GFDIR)
```

```
      LANCOS = COS(LANDIR)
      BOICOS = COS(BOIDIR)
C
C
C        Test for missing data.  If so, increment counter (DIRCOUNT) and
C        set sine and cosine for station to Ø so they won't contribute
C        to the sum.
      IF(MAN(1,J,4).EQ.-99.Ø)THEN
      GFSIN=Ø
      GFCOS=Ø
      DIRCOUNT=DIRCOUNT+1
      END IF
C
      IF(MAN(2,J,4).EQ.-99.Ø)THEN
      LANSIN=Ø
      LANCOS=Ø
      DIRCOUNT=DIRCOUNT+1
      END IF
C
      IF(MAN(3,J,4).EQ.-99.Ø)THEN
      BOISIN=Ø
      BOICOS=Ø
      DIRCOUNT=DIRCOUNT+1
      END IF
C          If all three directions are missing, set DIR(J) TO =99.Ø.
      IF(DIRCOUNT.EQ.3)THEN
      DIR(J)=-99.Ø
      GO TO 45
      END IF
C
C
C
C          Sum sines and cosines.
      SUMSIN = GFSIN + LANSIN + BOISIN
      SUMCOS = GFCOS + LANCOS + BOICOS
C
C          Find average direction.
      IF(SUMCOS.EQ.Ø)SUMCOS=.ØØØØ1
      ANGLE=ATAN(SUMSIN/SUMCOS)
C
C          Convert direction back to degrees again.
      AVEDIR=ANGLE*57.29577
C
C          Test signs of sumsin and sumcos to see what quadrant it
C          should be in.
      IF(SUMSIN.GT.Ø.AND.SUMCOS.LT.Ø)AVEDIR=AVEDIR+18Ø
      IF(SUMSIN.LT.Ø.AND.SUMCOS.LT.Ø)AVEDIR=AVEDIR+18Ø
C
C           Now subtract 9Ø degrees and change signs to get ANGLE
C           back into compass directions again.
      DIR(J)=-(AVEDIR-9Ø)
      IF(DIR(J).GT.36Ø)DIR(J)=DIR(J)-36Ø
      IF(DIR(J).LE.Ø)DIR(J)=DIR(J)+36Ø
   45 CONTINUE
C
C
C     ****************************************************************
C               * PRESSURE AND TEMPERATURE GRADIENTS *
C               ************************************
C
C          Here I calculate temperature and pressure gradients simply
C          using the maximum difference between the readings for the
C          three stations.  GRAD(I,J)=gradient of pressure (when J=1)
```

```
C          or gradient of temperature (when J=2) for the levels 850mb
C          (I=1), 700mb(I=2), 500mb(I=3)
  50   DO 80 J=1,3
       DO 70 K=1,2
          DO 60 I=1,3
       IF(MAN(I,J,K).EQ.-99.0)THEN
       GRAD(J,K)=-99
       GO TO 70
       END IF
 60     CONTINUE
        H=MAX(MAN(1,J,K),MAN(2,J,K),MAN(3,J,K))
        L=MIN(MAN(1,J,K),MAN(2,J,K),MAN(3,J,K))
        GRAD(J,K)=H-L
   70   CONTINUE
   80 CONTINUE
C
C
C*********************************************************************
C          * PRECIPITABLE WATER, THERMAL ADVECTION AND K-INDEX *
C          ****************************************************
C
C         First, I read the data into separate arrays--one for each
C         station:
C         GFMAN = mandatory data for Great Falls.
C         LANMAN = mandatory data for Lander.
C         BOIMAN = mandatory data for Boise.
C         GFSIG = significant level data for Great Falls.
C         LANSIG = significant level data for Lander.
C         BOISIG = significant level data for Boise.
C
C             First, I test which way the average 700 millibar winds
C         blow and use data from an upwind station or an average of two
C         upwind stations to calculate thermal advection (subroutine
C         ADVECTION), K-index and 850 mb. dew point spread (subroutine
 C        STABLE) and  precipitable water (subroutine WATER).
C         I do this by using the appropriate arrays as arguments
C         in the subroutines based on the wind direction.
C
C                          VARIABLE LIST:
C         PWATER = Precipitable water.
C         ADV    = Absolute advection.
C         CADV   = Cold advection
C         WADV   = Warm advection
C         KINDEX = K-index.
C         SPREAD= 850 millibar dew point spread.
C
C
       DO 93 J=1,3
          DO 90 K=1,5
          GFMAN(J,K)=MAN(1,J,K)
          LANMAN(J,K)=MAN(2,J,K)
          BOIMAN(J,K)=MAN(3,J,K)
   90     CONTINUE
   93  CONTINUE
C
       DO 97 J=1,12
         DO 95 K=1,6
         GFSIG(J,K)=SIG(1,J,K)
         LANSIG(J,K)=SIG(2,J,K)
         BOISIG(J,K)=SIG(3,J,K)
   95    CONTINUE
   97  CONTINUE
C
```

```
C
C
C          ================================================
C            If 700 mb. winds blow from Great Falls.
      IF(DIR(2).LE.210.AND.DIR(2).GT.150)THEN
         CALL WATER(GFSIG,GFMAN,PWATER)
         CALL ADVECTION(GFMAN,ADV,WADV,CADV)
         CALL STABLE(GFMAN,KINDEX,SPREAD)
      END IF
C
C
C          ========================================================
C            If 700 mb. winds blow from a direction between Great Falls
C            and Lander.
      IF(DIR(2).GT.210.AND.DIR(2).LE.270)THEN
C
         CALL WATER(GFSIG,GFMAN,GFWATER)
         CALL WATER(LANSIG,LANMAN,LANWATER)
         PWATER=(GFWATER+LANWATER)/2
C
         IF(GFWATER.EQ.-99.0.AND.LANWATER.NE.-99.0)PWATER=LANWATER
         IF(GFWATER.NE.-99.0.AND.LANWATER.EQ.-99.0)PWATER=GFWATER
         IF(GFWATER.EQ.-99.0.AND.LANWATER.EQ.-99.0)PWATER=-99.0
C
         CALL STABLE(GFMAN,GFINDEX,GFSPREAD)
         CALL STABLE(LANMAN,LANINDEX,LANSPREAD)
         KINDEX=(GFINDEX+LANINDEX)/2
         IF(GFINDEX.NE.-99.0.AND.LANINDEX.EQ.-99.0)KINDEX=GFINDEX
         IF(GFINDEX.EQ.-99.0.AND.LANINDEX.NE.-99.0)KINDEX=LANINDEX
         IF(GFINDEX.EQ.-99.0.AND.LANINDEX.EQ.-99.0)KINDEX=-99.0
C
         SPREAD=(GFSPREAD+LANSPREAD)/2
         IF(GFSPREAD.EQ.-99.0.AND.LANSPREAD.NE.-99.0)SPREAD=LANSPREAD
         IF(GFSPREAD.NE.-99.0.AND.LANSPREAD.EQ.-99.0)SPREAD=GFSPREAD
         IF(GFSPREAD.EQ.-99.0.AND.LANSPREAD.EQ.-99.0)SPREAD=-99.0
C
         CALL ADVECTION(GFMAN,GFADV,GFWADV,GFCADV)
         CALL ADVECTION(LANMAN,LANADV,LANWADV,LANCADV)
         ADV=(GFADV+LANADV)/2
         WADV=(GFWADV+LANWADV)/2
         CADV=(GFCADV+LANCADV)/2
         IF(GFADV.EQ.-99.0.AND.LANADV.NE.-99.0)ADV=LANADV
         IF(GFADV.NE.-99.0.AND.LANADV.EQ.-99.0)ADV=GFADV
         IF(GFADV.EQ.-99.0.AND.LANADV.EQ.-99.0)ADV=-99.0
         IF(GFCADV.EQ.-99.0.AND.LANCADV.NE.-99.0)CADV=LANCADV
         IF(GFCADV.NE.-99.0.AND.LANCADV.EQ.-99.0)CADV=GFCADV
         IF(GFCADV.EQ.-99.0.AND.LANCADV.EQ.-99.0)CADV=-99.0
         IF(GFWADV.EQ.-99.0.AND.LANWADV.NE.-99.0)WADV=LANWADV
         IF(GFWADV.NE.-99.0.AND.LANWADV.EQ.-99.0)WADV=GFWADV
         IF(GFWADV.EQ.-99.0.AND.LANWADV.EQ.-99.0)WADV=-99.0
      END IF
C
C
C
C
C
C
C          ========================================================
C            If 700 mb. winds blow from Lander.
      IF(DIR(2).GT.270.AND.DIR(2).LE.330)THEN
         CALL WATER(LANSIG,LANMAN,PWATER)
         CALL ADVECTION(LANMAN,ADV,WADV,CADV)
         CALL STABLE(LANMAN,KINDEX,SPREAD)
```

```
      END IF
C
C
C
C
C           ========================================================
C        If 700 mb. winds blow from between Lander and Boise.
      IF(DIR(2).GT.330.AND.DIR(2).LE.30)THEN
C
         CALL WATER(BOISIG,BOIMAN,BOIWATER)
         CALL WATER(LANSIG,LANMAN,LANWATER)
         PWATER=(BOIWATER+LANWATER)/2
C
         IF(BOIWATER.EQ.-99.0.AND.LANWATER.NE.-99.0)PWATER=LANWATER
         IF(BOIWATER.NE.-99.0.AND.LANWATER.EQ.-99.0)PWATER=BOIWATER
         IF(BOIWATER.EQ.-99.0.AND.LANWATER.EQ.-99.0)PWATER=-99.0
C
         CALL STABLE(BOIMAN,BOIINDEX,BOISPREAD)
         CALL STABLE(LANMAN,LANINDEX,LANSPREAD)
         KINDEX=(BOIINDEX+LANINDEX)/2
         IF(BOIINDEX.EQ.-99.0.AND.LANINDEX.NE.-99.0)KINDEX=BOIINDEX
         IF(BOIINDEX.NE.-99.0.AND.LANINDEX.EQ.-99.0)KINDEX=LANINDEX
         IF(BOIINDEX.EQ.-99.0.AND.LANINDEX.EQ.-99.0)KINDEX=-99.0
C
         SPREAD=(LANSPREAD+BOISPREAD)/2
      IF(BOISPREAD.EQ.-99.0.AND.LANSPREAD.NE.-99.0)SPREAD=LANSPREAD
      IF(BOISPREAD.NE.-99.0.AND.LANSPREAD.EQ.-99.0)SPREAD=BOISPREAD
         IF(BOISPREAD.EQ.-99.0.AND.LANSPREAD.EQ.-99.0)SPREAD=-99.0
C
C
         CALL ADVECTION(BOIMAN,BOIADV,BOIWADV,BOICADV)
         CALL ADVECTION(LANMAN,LANADV,LANWADV,LANCADV)
         ADV=(BOIADV+LANADV)/2
         WADV=(BOIWADV+LANWADV)/2
         CADV=(BOICADV+LANCADV)/2
         IF(BOIADV.EQ.-99.0.AND.LANADV.NE.-99.0)ADV=LANADV
         IF(BOIADV.NE.-99.0.AND.LANADV.EQ.-99.0)ADV=BOIADV
         IF(BOIADV.EQ.-99.0.AND.LANADV.EQ.-99.0)ADV=-99.0
        IF(BOICADV.EQ.-99.0.AND.LANCADV.NE.-99.0)CADV=LANCADV
        IF(BOICADV.NE.-99.0.AND.LANCADV.EQ.-99.0)CADV=BOICADV
        IF(BOICADV.EQ.-99.0.AND.LANCADV.EQ.-99.0)CADV=-99.0
        IF(BOIWADV.EQ.-99.0.AND.LANWADV.NE.-99.0)WADV=LANWADV
        IF(BOIWADV.NE.-99.0.AND.LANWADV.EQ.-99.0)WADV=BOIWADV
        IF(BOIWADV.EQ.-99.0.AND.LANWADV.EQ.-99.0)WADV=-99.0
      END IF
C
C
C
C
C          ========================================================
C        If 700 mb. wind blow from Boise.
      IF(DIR(2).GT.30.AND.DIR(2).LE.90)THEN
         CALL WATER(BOISIG,BOIMAN,PWATER)
         CALL ADVECTION(BOIMAN,ADV,WADV,CADV)
         CALL STABLE(BOIMAN,KINDEX,SPREAD)
      END IF
C
C
C
C          ========================================================
C        If 700 mb. winds blow from between Great Falls and Boise.
      IF(DIR(2).GT.90.AND.DIR(2).LE.150)THEN
C
```

```
      CALL WATER(GFSIG,GFMAN,GFWATER)
      CALL WATER(BOISIG,BOIMAN,BOIWATER)
      PWATER=(GFWATER+BOIWATER)/2
C
      IF(GFWATER.EQ.-99.Ø.AND.BOIWATER.NE.-99.Ø)PWATER=BOIWATER
      IF(GFWATER.NE.-99.Ø.AND.BOIWATER.EQ.-99.Ø)PWATER=GFWATER
      IF(GFWATER.EQ.-99.Ø.AND.BOIWATER.EQ.-99.Ø)PWATER=-99.Ø
C
      CALL STABLE(GFMAN,GFINDEX,GFSPREAD)
      CALL STABLE(BOIMAN,BOIINDEX,BOISPREAD)
      KINDEX=(GFINDEX+BOIINDEX)/2
      IF(GFINDEX.EQ.-99.Ø.AND.BOIINDEX.NE.-99.Ø)KINDEX=GFINDEX
      IF(GFINDEX.NE.-99.Ø.AND.BOIINDEX.EQ.-99.Ø)KINDEX=BOIINDEX
      IF(GFINDEX.EQ.-99.Ø.AND.BOIINDEX.EQ.-99.Ø)KINDEX=-99.Ø
C
      SPREAD=(BOISPREAD+GFSPREAD)/2
      IF(GFSPREAD.EQ.-99.Ø.AND.BOISPREAD.NE.-99.Ø)SPREAD=BOISPREAD
      IF(GFSPREAD.NE.-99.Ø.AND.BOISPREAD.EQ.-99.Ø)SPREAD=GFSPREAD
      IF(GFSPREAD.EQ.-99.Ø.AND.BOISPREAD.EQ.-99.Ø)SPREAD=-99.Ø
C
      CALL ADVECTION(GFMAN,GFADV,GFWADV,GFCADV)
      CALL ADVECTION(BOIMAN,BOIADV,BOIWADV,BOICADV)
      ADV=(GFADV+BOIADV)/2
      WADV=(GFWADV+BOIWADV)/2
      CADV=(GFCADV+BOICADV)/2
      IF(GFADV.EQ.-99.Ø.AND.BOIADV.NE.-99.Ø)ADV=BOIADV
      IF(GFADV.NE.-99.Ø.AND.BOIADV.EQ.-99.Ø)ADV=GFADV
      IF(GFADV.EQ.-99.Ø.AND.BOIADV.EQ.-99.Ø)ADV=-99.Ø
     IF(GFCADV.EQ.-99.Ø.AND.BOICADV.NE.-99.Ø)CADV=BOICADV
     IF(GFCADV.NE.-99.Ø.AND.BOICADV.EQ.-99.Ø)CADV=GFCADV
     IF(GFCADV.EQ.-99.Ø.AND.BOICADV.EQ.-99.Ø)CADV=-99.Ø
     IF(GFWADV.EQ.-99.Ø.AND.BOIWADV.NE.-99.Ø)WADV=BOIWADV
     IF(GFWADV.NE.-99.Ø.AND.BOIWADV.EQ.-99.Ø)WADV=GFWADV
     IF(GFWADV.EQ.-99.Ø.AND.BOIWADV.EQ.-99.Ø)WADV=-99.Ø
C
C
      END IF
      IF((SPREAD.GT.6Ø.OR.SPREAD.LT.-Ø.5).AND.(SPREAD.NE.-99.Ø))THEN
      WRITE(6,98)SPREAD
      END IF
 98   FORMAT(X,'TROUBLE SPREAD= ',E6.2)
C
C          Calculate the square of warm, cold and absolute advection.
C          I add one to the terms before multiplication so the product
C          is greater than one.
C
      SQADV=(ADV+1)*(ADV+1)
      SQWARM=(WADV+1)*(WADV+1)
      SQCOLD=(CADV+1)*(CADV+1)
      IF(ADV.EQ.-99.Ø)SQADV=-99.Ø
      IF(WADV.EQ.-99.Ø)SQWARM=-99.Ø
      IF(CADV.EQ.-99.Ø)SQCOLD=-99.Ø
C      ***************************************************************
C                     * DIVERGENCE *
C                     **************
C
C          This section calculates divergence by converting each of
C          the wind directions for each of the three stations to
C          vectors and then calculating the area of the resulting
C          triangle (see paper for futher datils).  Divergence is
C          then the percent change of area for a given time interval.
C          In this case, I use only the area of the triangle
C          (AREA) because it is proportional to divergence
```

```
C          and is thus statistically equivalent.
C
C                         VARIABLE LIST:
C
C          RADDIR#= The direction in radians of the wind vector.
C              RADDIR1= Great Falls, RADDIR2= Lander, RADDIR3= Boise.
C          X1= The X componet of the Great Falls station.
C          Y1= The Y componet of the Great Falls station.
C          X2= The X componet of the Lander station.
C          Y1= The Y componet of the Lander station.
C          X3= The X componet of the Boise station.
C          Y1= The Y componet of the Boise station.
C          AREA= The resulting area of the triangle after displacement
C          by the wind vectors.
C          SQAREA = square of the area.
C
C          Test for missing data; if so don't calculate divergence.
  99   DO 11Ø I=1,3
          DO 1ØØ K=4,5
       IF(MAN(I,3,K).EQ.-99.Ø)THEN
          SQAREA=-99.Ø
          AREA=-99.Ø
          GO TO 115
          END IF
 1ØØ    CONTINUE
  11Ø  CONTINUE
C
       X1=((COS(GFDIR))*MAN(1,3,5))+1ØØ
       Y1=((SIN(GFDIR))*MAN(1,3,5))+2ØØ
       X2=((COS(LANDIR))*MAN(2,3,5))+2ØØ
       Y2=((SIN(LANDIR))*MAN(2,3,5))
       X3=((COS(BOIDIR))*MAN(3,3,5))
       Y3=((SIN(BOIDIR))*MAN(3,3,5))
       AREA=(.5*ABS(X1*Y2-X2*Y1+X2*Y3-X3*Y2+X3*Y1-X1*Y3))*.Ø1
       SQAREA=AREA*AREA*.Ø1
C
C
C
C
C
C      ************************************************************
C                    * VORTICITY *
C                    ************
C
C           This part of the program calculates vorticity from the
C           5ØØmb wind direction and velocity.  The velocity is input in
C           knots and I convert them to meters per second.  The
C           direction is input as degrees on a compass and I must go
C           through alot of pains to convert it to to standard trig.
C           format that the computer uses.  I also convert the wind
C           from the direction the wind blows from to a vector
C           direction i.e. the direction the wind blows to.  In this
C           program, I pretend the wind is blowing out of the west
C           by rotating the wind back to that orentation each time.
C           I refer to the stations by name but this only signifies
C           the position in the triangle after rotation and may or
C           may not be their real positions or names.
C
C                         VARIABLE DIRECTORY:
C      VORTICITY=Absolute vorticity figured in units of 1Ø**5/sec.
C      RADDIR#= Wind directions of the three stations converted to
C         standard trigonometric coordinates for vectors.
C      SUMSIN= Sum of the sines of the directions.
```

```
C       SUMCOS= Sum of the cosines of the directions.
C       AVERAD= Direction of average wind vector in radians.
C       AVEDIR= Direction of average wind vector in degrees.
C       VORTADV = vorticity advection.
C       SQVORTADV = the square of vorticity advection.
C       N= Distance from the apex to the bisector of the opposite side
C           and is used for calculating the velocity change over N
C           distance.
C       S= The distance between stations.
C
C            Check for missing values; if so don't calculate vorticity.
  115 DO 13Ø I=1,3
         DO 12Ø K=4,5
         IF(MAN(I,3,K).EQ.-99.Ø.OR.DIR(3).EQ.-99.Ø)THEN
         VORTADV=-99.Ø
         SQVORTADV=-99.Ø
         LASTVORT=-99.Ø
         VORTICITY=-99.Ø
         GO TO 134
         END IF
  12Ø    CONTINUE
  13Ø    CONTINUE
C
C             Now set function parameters for vorticity.  The function
C             calculates vorticity as if wind were from the west.  Here
C             I test which way the wind is blowing and set the
C             function parameters accordingly.  It is similar to
C             rotating the wind back to the west each time.
       IF((DIR(3).GE.24Ø.AND.DIR(3).LE.3ØØ).OR.(DIR(3).GE.6Ø.AND.DIR(3)
      *.LE.12Ø))THEN
       N=473ØØØ
       S=621ØØØ
       CALL VORTSUB(VORT,MAN(1,3,4),MAN(1,3,5),MAN(2,3,4),MAN(2,3,5),
      *MAN(3,3,4),MAN(3,3,5),N,S,DIR(3))
       VORTICITY=VORT
       END IF
C
       IF(DIR(3).LE.6Ø.OR.(DIR(3).GE.18Ø.AND.DIR(3).LE.24Ø))THEN
       N=421ØØØ
       S=575ØØØ
       CALL VORTSUB(VORT,MAN(2,3,4),MAN(2,3,5),MAN(3,3,4),MAN(3,3,5),
      *MAN(1,3,4),MAN(1,3,5),N,S,DIR(3))
       VORTICITY=VORT
       END IF
C
       IF(DIR(3).GE.3ØØ.OR.(DIR(3).GE.12Ø.AND.DIR(3).LE.18Ø))THEN
       N=526ØØØ
       S=6ØØØØØ
       CALL VORTSUB(VORT,MAN(3,3,4),MAN(3,3,5),MAN(1,3,4),MAN(1,3,5),
      *MAN(2,3,4),MAN(2,3,5),N,S,DIR(3))
       VORTICITY=VORT
       END IF
C
C
C             Calculate vorticity advection.
       IF(FIRST)THEN
       VORTADV=-99.Ø
       SQVORTADV=-99.Ø
       LASTVORT=VORTICITY
       GO TO 134
       END IF
       VORTADV=VORTICITY-LASTVORT
       SQVORTADV=(VORTADV)*(VORTADV)
```

```
      IF(VORTADV.LT.Ø)SQVORTADV=-SQVORTADV
      IF(VORTICITY.EQ.-99.Ø.OR.LASTVORT.EQ.-99.Ø)THEN
      VORTADV=-99.Ø
      SQVORTADV=-99.Ø
      END IF
      LASTVORT=VORTICITY
C*****************************************************************
C              OROGRAPHIC PRECIPITATION PARAMETERS
C              **********************************
C
C               Here I calculate parameters designed to predict
C              orographic precipitation (lift#).
  134 LIFT1=BZN(2,5)*(1Ø/(SPREAD+1))
      IF(BZN(2,5).EQ.-99.OR.PWATER.EQ.-99.Ø)LIFT1=-99.Ø
      LIFT2=BZN(2,5)*PWATER
      IF(BZN(2,5).EQ.-99.OR.PWATER.EQ.-99.Ø)LIFT2=-99.Ø
      LIFT3=(BZN(2,5)*PWATER*KINDEX)/1Ø
      IF(BZN(2,5).EQ.-99.OR.PWATER.EQ.-99.Ø.OR.KINDEX.EQ.-99.Ø)LIFT3=-99
      LIFT4=(BZN(2,5)*PWATER*KINDEX*(1Ø/(SPREAD+1)))/1Ø
      IF(BZN(2,5).EQ.-99.OR.PWATER.EQ.-99.Ø.OR.KINDEX.EQ.-99.Ø)LIFT4=-99
C
C
C
C
C*****************************************************************
C               DYNAMIC LIFTING PARAMETERS
C               **************************
C           Calculate parameter DYN# which attemps to predict
C           dynamic lifting.
  135 DYN1=(ADV+1)*PWATER
      DYN2=((KINDEX+4Ø)*PWATER)/1Ø
      DYN3=(AREA*PWATER)/1Ø
      DYN4=(ABS(1Ø+VORTADV)*PWATER*(KINDEX+4Ø))/1Ø
      IF(ADV.EQ.-99.Ø.OR.PWATER.EQ.-99.Ø)DYN1=-99.Ø
      IF(KINDEX.EQ.-99.Ø.OR.PWATER.EQ.-99.Ø)DYN2=-99.Ø
      IF(AREA.EQ.-99.Ø.OR.PWATER.EQ.-99.Ø)DYN3=-99.Ø
      IF(VORTADV.EQ.-99.Ø.OR.PWATER.EQ.-99.Ø.OR.KINDEX.EQ.-99.Ø)DYN4=-99
C
C
C         ======================================
C         Change directions back to compass directions again.
      DO 14Ø I=2,3
        DIR(I)=DIR(I)+18Ø
        IF(DIR(I).GT.36Ø)DIR(I)=DIR(I)-36Ø
  14Ø CONTINUE
C
C
C           ************************************************************
C                 *AVERAGE MORNING AND AFTERNOON PARAMETERS *
C                  ************************************
C
C           This section of the program stores morning and afternoon parameters
C           into arrays so they can be averaged for the day.  Some parameters
C           are calculated from upwind stations so they are delayed for
C           12 hours by averaging the morning value with the afternoon
C           values the day before.
C
C                          VARIABLE DIRECTORY:
C           BZNSAVE (READCOUNT,I,J) = Array that stores the values for the
C                          weighted average for the Bozeman area. where:
C                          READCOUNT = 1  is for the morning data
C                          READCOUNT = 2  is for the afternoon data.
C                          I = The level (as defined before).
```

```
C                          J = The parameter (as defined before).
C          GRADSAVE(READCOUNT,I,J) = Array to store the temperature and
C                          pressure gradients.
C          PARAM(READCOUNT,#) = An array which stores the various parameters
C                          each assigned to a location designated by #.
C          BZNAVE(I,J) =   an array containing the average of morning and
C                          afternoon readings for the array BZNSAVE.
C          GRADAVE(I,J) = The average of the morning and afternoon parameters
C                          from the array GRADSAVE.
C          PARAMAVE(I,J) = The average of the two readings from the array
C                           PARAM.
C          STORE(I) =      Contains the stored values for the parameters
C                          which are measured from upwind stations.
C          LASTFOR =       The minimum temperature from the Forsyth Ranch
C                          climate station from the day before.
C          LASTBZN =       The minimum temperature from the Belgrade airport
C                          climate station from the day before.
C          FORCHANGE =     The 24-hour change in minimum temperature at
C                          Forsyth Ranch climate station (Bozeman 12 NE)
C          BZNCHANGE =     The 24-hour change in minimum temperature at
C                          Belgrade Airport climate station.
C
C
C
C
C          Store morning and afternoon parameters into various arrays
C          described above.
      DO 16Ø I=1,3
        DO 15Ø J=1,3
 15Ø    BZNSAVE(READCOUNT,I,J)=BZN(I,J)
 16Ø  CONTINUE
C
C
      DO 17Ø I=1,3
 17Ø    BZNSAVE(READCOUNT,I,5)=BZN(I,5)
C
C
      DO 19Ø I=1,3
        DO 18Ø J=1,2
 18Ø    GRADSAVE(READCOUNT,I,J)=GRAD(I,J)
 19Ø  CONTINUE
C
C
C
C
C
      PARAM(READCOUNT,1)=KINDEX
      PARAM(READCOUNT,2)=SPREAD
      PARAM(READCOUNT,3)=PWATER
      PARAM(READCOUNT,4)=ADV
      PARAM(READCOUNT,5)=WADV
      PARAM(READCOUNT,6)=CADV
      PARAM(READCOUNT,7)=SQADV
      PARAM(READCOUNT,8)=SQWARM
      PARAM(READCOUNT,9)=SQCOLD
      PARAM(READCOUNT,1Ø)=AREA
      PARAM(READCOUNT,11)=SQAREA
      PARAM(READCOUNT,12)=VORTICITY
      PARAM(READCOUNT,13)=VORTADV
      PARAM(READCOUNT,14)=SQVORTADV
      PARAM(READCOUNT,15)=LIFT1
      PARAM(READCOUNT,16)=LIFT2
      PARAM(READCOUNT,17)=LIFT3
```

```
      PARAM(READCOUNT,18)=LIFT4
      PARAM(READCOUNT,19)=DYN1
      PARAM(READCOUNT,20)=DYN2
      PARAM(READCOUNT,21)=DYN3
      PARAM(READCOUNT,22)=DYN4
      PARAM(READCOUNT,23)=MAN(1,1,4)
      PARAM(READCOUNT,24)=DIR(2)
      PARAM(READCOUNT,25)=DIR(3)
C
C        Change READCOUNT to the afternoon value (2) and return to the
C        beginning to read the afternoon readings.  If afternoon reading
C        have already been calculated and stored, go to the to averaging
C        section of the program below.
C
      IF(READCOUNT.EQ.1)THEN
      READCOUNT=2
      GO TO 4
      END IF
C
C
C
C
C           Average the morning and afternoon data and store in the various
C           arrays as defined above.
      DO 210 I=1,3
        DO 200 J=1,3
        BZNAVE(I,J)=(BZNSAVE(1,I,J)+BZNSAVE(2,I,J))/2
        IF(BZNSAVE(1,I,J).EQ.-99.AND.BZNSAVE(2,I,J).NE.-99)
     *  BZNAVE(I,J)=BZNSAVE(2,I,J)
        IF(BZNSAVE(1,I,J).NE.-99.AND.BZNSAVE(2,I,J).EQ.-99)
     *  BZNAVE(I,J)=BZNSAVE(1,I,J)
        IF(BZNSAVE(1,I,J).EQ.-99.AND.BZNSAVE(2,I,J).EQ.-99)
     *  BZNAVE(I,J)=-99
 200    CONTINUE
 210  CONTINUE
C
C
C
      DO 220 I=1,3
        BZNAVE(I,5)=(BZNSAVE(1,I,5)+BZNSAVE(2,I,5))/2
C
        IF(BZNSAVE(1,I,5).EQ.-99.AND.BZNSAVE(2,I,5).NE.-99)
     *  BZNAVE(I,5)=BZNSAVE(2,I,5)
        IF(BZNSAVE(1,I,5).NE.-99.AND.BZNSAVE(2,I,5).EQ.-99)
     *  BZNAVE(I,5)=BZNSAVE(1,I,5)
        IF(BZNSAVE(1,I,5).EQ.-99.AND.BZNSAVE(2,I,5).EQ.-99)
     *  BZNAVE(I,J)=-99
 220  CONTINUE
C
C
      DO 240 I=1,3
        DO 230 J=1,2
C
        GRADAVE(I,J)=(GRADSAVE(1,I,J)+GRADSAVE(2,I,J))/2
C
        IF(GRADSAVE(1,I,J).EQ.-99.AND.GRADSAVE(2,I,J).NE.-99)
     *  GRADAVE(I,J)=GRADSAVE(2,I,J)
        IF(GRADSAVE(1,I,J).NE.-99.AND.GRADSAVE(2,I,J).EQ.-99)
     *  GRADAVE(I,J)=GRADSAVE(1,I,J)
        IF(GRADSAVE(1,I,J).EQ.-99.AND.GRADSAVE(2,I,J).EQ.-99)
     *  GRADAVE(I,J)=-99
 230    CONTINUE
 240  CONTINUE
```

```
C
C
      DO 245 I=1,9
        PAVE(I)=(STORE(I)+PARAM(1,I))/2
        IF(STORE(I).EQ.-99.Ø.AND.PARAM(1,I).NE.-99.Ø)PAVE(I)=PARAM(1,I)
        IF(STORE(I).NE.-99.Ø.AND.PARAM(1,I).EQ.-99.Ø)PAVE(I)=STORE(I)
        IF(STORE(I).EQ.-99.Ø.AND.PARAM(1,I).EQ.-99.Ø)PAVE(I)=-99.Ø
 245  CONTINUE
      IF(FIRST)THEN
        DO 247 I=1,9
 247    PAVE(I)=-99.Ø
      END IF
C
      DO 25Ø I=1Ø,25
C
        PAVE(I)=(PARAM(1,I)+PARAM(2,I))/2
C
       IF(PARAM(1,I).EQ.-99.Ø.AND.PARAM(2,I).NE.-99.Ø)PAVE(I)=PARAM(2,I)
       IF(PARAM(1,I).NE.-99.Ø.AND.PARAM(2,I).EQ.-99.Ø)PAVE(I)=PARAM(1,I)
        IF(PARAM(1,I).EQ.-99.Ø.AND.PARAM(2,I).EQ.-99.Ø)PAVE(I)=-99.Ø
 25Ø  CONTINUE
C
C           Now store the values calculated from the upwind stations so
C           can  be averaged on the next loop of the program (tomorow).
      STORE(1)=KINDEX
      STORE(2)=SPREAD
      STORE(3)=PWATER
      STORE(4)=ADV
      STORE(5)=WADV
      STORE(6)=CADV
      STORE(7)=SQADV
      STORE(8)=SQWARM
      STORE(9)=SQCOLD
C
C       Here, I calculate a temperature change parameter. I do this
C       by taking the difference between today's minimum
C       and yesterday's minimum temperature.  The difference
C       must be more than 15 degrees in order to register other
C       than a zero.  This parameter is designed to indicate
C       the pasage of a cold front.
C
      FORCHANGE=LASTFOR-CLIM(3,2)-1Ø
      BZNCHANGE=LASTBZN-CLIM(2,2)-1Ø
      IF(FORCHANGE.LT.Ø)FORCHANGE=Ø
      IF(BZNCHANGE.LT.Ø)BZNCHANGE=Ø
      IF(FIRST)THEN
      FORCHANGE=-99
      BZNCHANGE=-99
      END IF
      IF(LASTFOR.EQ.-99.OR.CLIM(3,2).EQ.-99.Ø)FORCHANGE=-99
      IF(LASTBZN.EQ.-99.OR.CLIM(2,2).EQ.-99.Ø)CLIM(2,2)=-99
C
C
C       Now, change variable FIRST to .FALSE. so I know I have been
C       through the program at least once.
      FIRST=.FALSE.
C
C          ************************************************************
C                              * WRITE THE PARAMETERS *
C                              ************************
C
C
C
```

```
      WRITE(106,266)YEAR,MONTH,DAY
      WRITE(106,267)(BZNAVE(1,J),J=1,3),BZNAVE(1,5),
     *(BZNAVE(2,J),J=1,3),BZNAVE(2,5),(BZNAVE(3,J),J=1,3),BZNAVE(3,5),
     *PAVE(23),PAVE(24),PAVE(25),
     *(GRADAVE(I,1),I=1,3),(GRADAVE(I,2),I=1,3),(PAVE(I),I=1,22),
     *FORCHANGE,BZNCHANGE
      WRITE(106,260)((CLIM(I,J),J=1,4),I=1,13)
 260  FORMAT(4(3(2(X,F4.0),X,F7.3,X,F6.2,2X)/)2(X,F4.0),X,F7.3,X,F6.2/)
C
 266  FORMAT(3(X,I2))
 267  FORMAT(X,3(4(F5.0))3(X,F4.0)/,
     *8(X,F4.0),X,F7.3,4(X,F6.2)/,
     *4(X,F6.2),X,3(X,F5.1),4(X,F5.0)/,
     *4(X,F6.1),2(X,F4.0))
C
C        Now, store today's minimum temperatures into yesterday's
C        minimum temperatures.
      LASTFOR=CLIM(3,2)
      LASTBZN=CLIM(2,2)
C
C
C
      IF(READCOUNT.EQ.2)THEN
      READCOUNT=1
      GO TO 4
      END IF
C
 270  END
C
C
C ********************************************************************
C ********************************************************************
C                          * SUBROUTINES *
C                          ***************
C
C
C
C
C*********************************************************************
C                        * SUBROUTINE WATER *
C                        ********************
C
      SUBROUTINE WATER(SIG,MAN,H2O)
C         In this subroutine, both mandatory and significant data are used
C         to total up the precipitable water in a column of air.  First
C         mandatory levels must be inserted into the proper order within the
C         significant levels according to pressure.  I do this by putting
C         in an array called LIST.  The 850 and 500 mb. data go on the the top
C         and bottom and the 700 mb. data goes in the middle wherever it
C         belongs according to pressure.   Then the water in each layer of
C         air (now contained in the array LIST) is summed up to produce
C         total precipitable water in the collumn of air.
C
C                          VARIABLE DIRECTORY:
C         MAN(J,K) =     Mandatory data.
C         SIG(J,K) =     Significant data.
C         LIST(J,K) =    A list of mandatory and significant data in
C                        order of pressure.
C                        K = the parameter (as defined before)
C                        J = pressure level (as defined before)
C        W(I) =          contains precipitable water for each level.
C        H2O =           total precipitable water.
C        COUNT =         the count of the number of layers with missing data.
```

```
C         MARK700 =       Logical variable signaling when the 700 mb. level was
C                         inserted into array LIST.
C         FIRST =         Logical variable signaling the first time through
C                         loop which sums precipitable water.
C         ES =            Saturated vapor pressure.
C         E =             Vapor pressure.
C         LASTMIX =       Mixing ratio from the next layer below.
C         LASTHEIGHT =    Pressure height for the next layer below.
C
C
      REAL SIG(12,6),H2O,W(15),MAN(3,5),LIST(15,4),LASTMIX
      LOGICAL FIRST,MARK700
      COUNT=0
      H2O=0
      FIRST=.TRUE.
      MARK700=.FALSE.
C
C
C       Put 850 and 500 mb. data on the bottom and top respectivly.
       LIST(1,1)=850
       LIST(15,1)=500
       DO 10 K=1,3
         LIST(1,K+1)=MAN(1,K)
  10     LIST(15,K+1)=MAN(3,K)
C
C
C
C         Here, I loop through the 12 possible significant levels and in
C         the data below 700 mb. into array LIST.  Then, when the first
C         above 700 mb. is encountered, I insert the 700 mb. data.
C
       DO 40 J=2,13
C          Insert data below 700 mb.
       IF(SIG(J-1,1).GT.700)THEN
         DO 15 K=1,4
  15       LIST(J,K)=SIG(J-1,K)
       END IF
C
C
C       Test for first significant level encountered above 700 mb.  If so,
C       insert 700 mb. data into LIST and set marker (MARK700 = .TRUE).
      IF(SIG(J-1,1).LT.700.AND.SIG(J-1,1).NE.-99.0.AND..NOT.MARK700)THEN
         LIST(J,1)=700
         DO 20 K=2,4
  20       LIST(J,K)=MAN(2,K-1)
         MARK700 = .TRUE.
C
       END IF
C
C         If the 700 mb. data hasn't been inserted yet by the time the
C         13th position has come up, insert the highest significant data
C         into the 13th slot and insert the 700 mb.data into the 14th slot.
C
      IF(J.EQ.13.AND..NOT.MARK700)THEN
         DO 23 K=1,4
  23       LIST(J,K)=SIG(J-1,K)
C
         LIST(14,1)=700
         DO 27 K=2,4
  27       LIST(14,K)=MAN(2,K-1)
C
         MARK700=.TRUE.
      END IF
```

```
C
C
C          Insert data above 7ØØ mb. into LIST.
         IF(MARK7ØØ)THEN
            DO 3Ø K=1,4
   3Ø          LIST(J+1,K)=SIG(J-1,K)
         END IF
C
   4Ø  CONTINUE

C
C          Test list to make sure it is in order of declining pressure.
C          something is wrong.  Make H2O = -99.Ø and return.
        DO 45 J=1,14
          IF(LIST(J,1).NE.-99.Ø.AND.LIST(J+1,1).NE.-99.Ø.AND.(LIST(J,1)
      *   -LIST(J+1,1)).LE.Ø)THEN
          WRITE(6,43)
   43     FORMAT(X,'TROUBLE!  ARRAY LIST IS TURNED AROUND.')
          RETURN
        END IF
  45    CONTINUE
C
C          ============================================================
C          Calculate water (mixing ratio) for each layer and store in W(I)
        DO 5Ø I=1,15
          IF(LIST(I,1).EQ.-99.Ø.OR.LIST(I,3).EQ.-99.Ø.OR.LIST(I,4).EQ.
      *   -99.Ø)THEN
            W(I)=-99.Ø
            GO TO 5Ø
          END IF
          ES=1Ø**(9.286-(2322.3789/(LIST(I,3)+273)))
          E=((LIST(I,4)+.ØØØØ1)/1ØØ)*ES
          W(I)=(.622*E)/(LIST(I,1)-E)
   5Ø CONTINUE
C
C
        DO 6Ø I=1,15
C            Test for missing data; if so, increment COUNT and loop again.
C            If not, add up precipitable water.
          IF(W(I).EQ.-99.Ø.OR.LIST(I,2).EQ.-99.Ø)THEN
            COUNT=COUNT+1
            GO TO 6Ø
          END IF
C
C              Store the lowest non-missing mixing ratio and height.
          IF(FIRST)THEN
            LASTMIX=W(I)
            LASTHEIGHT=LIST(I,2)
            FIRST=.FALSE.
          GO TO 6Ø
C
C              Multiply average water in each layer by the thickness of each
C              layer and sum the layers to determine total precipitable
C              water.
          ELSE
            H2O=H2O+(((W(I)+LASTMIX)/2)*((LIST(I,2)-LASTHEIGHT)/.98))
            LASTMIX=W(I)
            LASTHEIGHT=LIST(I,2)
          END IF
   6Ø  CONTINUE
C
C
C
```

```
C           If more than 7 layers are missing, assign -99.Ø (missing) to
C           precipitable water (H2O).
      IF((W(15).EQ.-99.Ø.OR.LIST(15,2).EQ.-99.Ø).AND.COUNT.GE.7)
     *H2O=-99
      IF((W(1).EQ.-99.OR.LIST(1,2).EQ.-99).AND.COUNT.GE.7)H2O=-99.
      IF(COUNT.GE.9)H2Ø=-99
C
C       Test for unreasonable data.
      IF((H2O.NE.-99.Ø).AND.(H2O.GT.4Ø.OR.H2O.LE.Ø.1))THEN
        WRITE(6,7Ø)H2O
   7Ø   FORMAT(X,'TROUBLE!  PRECIPITABLE WATER = ', F1Ø.2)
      END IF
C
      RETURN
      END
C
C
C ********************************************************************
C                    * SUBROUTINE ADVECTION *
C                    ************************
C
C           This is a subroutine to calculate thermal advection from
C           a raob sounding based on the change of wind direction and
C           magnitude with height.  It figures thermal advection in two layers
C           It first figures thermal advection for the 85Ø to 7ØØ mb. levels,
C           then for the 7ØØ to 5ØØ mb. level.  Then it averages the values
C           the two layers.  It calculates both warm and cold advection
C           each layer and also an absolute value for each layer.
C
C                                VARIABLE DIRECTORY:
C           MAN(I,J) =      Mandatory data, where:
C                           I = Level (as defined in the main program)
C                           J = Parameter (as defined in the main program)
C           ADV =           The absolute thermal advection value.
C           COLD =          Cold advection value.
C           WARM =          Warm advection value.
C           LOW(J) =        Lower level parameters of each layer considered
C           HIGH(J) =       Upper level parameters of each layer considered
C           HALFWARM(I) = Warm advection for each layer.
C           HALFCOLD(I) = Cold advection for each layer.
C           HALDADV(I) =  The absolute value for advection for each layer
C           H =             The thickness of each layer.
C           TEMP =          Average temperature of the layer.
C           ANGLE =         The radian measure of the angle created by the
C                           difference in wind directions between the bottom
C                           and the top of each layer.
C           SHEAR =         The shear vector between the two winds.
C           TG =            Temperature gradient.
C           XISO =          The cross-isotherm component of the wind.
C           SIGN =          The sign (+ or -) of variable ANGLE.
C
C
C
C
      SUBROUTINE ADVECTION(MAN,ADV,COLD,WARM)
      INTEGER LOW(5),HIGH(5)
      REAL H,HALFADV(2),HALFCOLD(2),HALFWARM(2),MAN(3,5)
      LOGICAL SWITCH
C
C           Read lower and upper mandatory values into arrays LOW(J) AND
      DO 5 I=1,2
         SWITCH=.FALSE.
         DO 4 J=1,5
```

```
      LOW(J)=MAN(I,J)
    4 HIGH(J)=MAN(I+1,J)
C          Check for missing data and assign -99 to advections.
      IF(LOW(1).EQ.-99.Ø.OR.LOW(2).EQ.-99.Ø.OR. LOW(4).EQ.-99.Ø.OR.
     *LOW(5).EQ.-99.Ø.OR.HIGH(1).EQ.-99.Ø.OR.HIGH(2).EQ.-99.Ø.OR.
     *HIGH(4).EQ.-99.Ø.OR.HIGH(5).EQ.-99.Ø)THEN
      HALFADV(I)=-99.Ø
      HALFCOLD(I)=-99.Ø
      HALFWARM(I)=-99.Ø
      GO TO 5
      END IF
C
C          Calculate thickness of layer.
      H=HIGH(1)-LOW(1)
C
C          Calculate average temperature of the layer.
      TEMP=((LOW(2)+HIGH(2))/2)+273
C
C          Find angle change of wind as you go up.  If two points
C          staddle 36Ø degrees, I am in trouble, so in that case, I
C          will add 36Ø degrees to those between Ø and 9Ø, then
C          subtract to find the difference.
      IF((LOW(4).GT.27Ø.OR.HIGH(4).GT.27Ø).AND.(LOW(4).LT.9Ø.OR.
     *HIGH(4).LT.9Ø))THEN
      IF(LOW(4).LT.9Ø)LOW(4)=LOW(4)+36Ø
      IF(HIGH(4).LT.9Ø)HIGH(4)=HIGH(4)+36Ø
      END IF
      IANGLE=ABS(HIGH(4)-LOW(4))
      IF(IANGLE.GT.18Ø)THEN
        IANGLE=36Ø-IANGLE
        SWITCH=.TRUE.
      END IF
      ANGLE=IANGLE*.Ø174533
C
C          Calculate the shear vector using the law of cosines.
      SHEAR=SQRT(LOW(5)**2+HIGH(5)**2-(2*LOW(5)*HIGH(5)*COS(ANGLE)))
C
C          Calculate thermal gradient which is (shear/thickness)*
C          (coriolis parameter*average temperature)/acceleration
C          of gravity.
      TG=(SHEAR*.ØØØ1Ø3*TEMP)/(H*9.8)
C
C          Calculate the cross isotherm component of winds which is
C          derived from the law of sines.
      IF(SHEAR.EQ.Ø)SHEAR=SHEAR+.ØØØØØ1
      XISO=(LOW(5)*HIGH(5)*(SIN(ANGLE)))/SHEAR
C
C          Calculate the thermal advection in degrees per hour.
C          (36ØØ seconds in one hour).
      HALFADV(I)=TG*XISO*36ØØ
C
C          Determine whether advection is warm or cold.  If winds back
C        with height, there is cold advection; warm, veer.
      SIGN=HIGH(4)-LOW(4)
      IF(SWITCH)SIGN=-SIGN
      IF(SIGN.GT.Ø)THEN
        HALFWARM(I)=HALFADV(I)
        HALFCOLD(I)=Ø
      END IF
      IF(SIGN.LE.Ø)THEN
        HALFWARM(I)=Ø
        HALFCOLD(I)=HALFADV(I)
      END IF
```

```
    5  CONTINUE
C
C           Average low advection and high advection.
      ADV=(HALFADV(1)+HALFADV(2))/2
      COLD=(HALFCOLD(1)+HALFCOLD(2))/2
      WARM=(HALFWARM(1)+HALFWARM(2))/2
      IF(HALFADV(1).EQ.-99.Ø.OR.HALFADV(2).EQ.-99.Ø)ADV=-99.Ø
      IF(HALFCOLD(1).EQ.-99.Ø.OR.HALFCOLD(2).EQ.-99.Ø)COLD=-99.Ø
      IF(HALFWARM(1).EQ.-99.Ø.OR.HALFWARM(2).EQ.-99.Ø)WARM=-99.Ø
C
C
C        Test for unreasonable values.
      IF((ADV.LT.Ø.OR.ADV.GT.1Ø).AND.(ADV.NE.-99.Ø))THEN
      WRITE(6,7)ADV
    7 FORMAT(X,'TROUBLE!  ADVECTION = ', F1Ø.3)
      END IF
   1Ø RETURN
      END
C
C
C
C
C
C*********************************************************************
C             * SUBROUTINE TO CALCULATE K-INDEX *
C             ***********************************
C
C
C
      SUBROUTINE STABLE(MAN,KINDEX,SPREAD)
C
C        This subroutine calculates K-index which is:
C        85Ø mb. temperature - 5ØØ mb. temperature + 85Ø mb. dew
C        point - 7ØØ mb. dew point spread.
C
C                     VARIABLE LIST:
C       TEMP8 = 85Ø mb. temperature.
C       TEMP7 = 7ØØ mb. temperature.
C       TEMP5 = 5ØØ mb. temperature.
C       RH8 = 85Ø mb. relative humidity.
C       RH7 = 7ØØ mb. relative humidity.
C       KINDEX = K-index.
C       SPREAD = 85Ø mb. dew point spread.
C       ES8 = Saturation vapor pressure at 85Ø mb.
C       ES7 = Saturation vapor pressure at 7ØØ mb.
C
C
      REAL MAN(3,5),KINDEX
C
      IF(MAN(3,2).EQ.-99.Ø.OR.MAN(2,3).EQ.-99.Ø.OR.MAN(2,2).EQ.-99.Ø
     *.OR.MAN(1,3).EQ.-99.Ø.OR.MAN(1,2).EQ.-99.Ø)THEN
      KINDEX=-99.Ø
      SPREAD=-99
      GO TO 3Ø
      END IF
C
C
C       Put array variables into variables.
        TEMP7=MAN(2,2)
        TEMP5=MAN(3,2)
        RH7=MAN(2,3)
        TEMP8=MAN(1,2)
        RH8=MAN(1,3)
```

```
C
C
C      Calculate saturation vapor pressure at 85Ø and 7ØØ mb.
       ES8=1Ø**((9.286-(2322.3789/(TEMP8+273))))
       ES7=1Ø**((9.286-(2322.3789/(TEMP7+273))))
C
C          Calculate dew points.
       DP8=(2322.3789/(9.286-ALOG1Ø((RH8/1ØØ)*ES8)))-273
       DP7=(2322.3789/(9.286-ALOG1Ø((RH7/1ØØ)*ES7)))-273
C
C          Calculate K-index.
       KINDEX=TEMP8-TEMP5+DP8-(TEMP7-DP7)
C
C
       SPREAD=TEMP8-DP8
C
C
C              Test for unreasonable values.
       IF((KINDEX.GT.1ØØ.OR.KINDEX.LT.-1ØØ).AND.(KINDEX.NE.-99.Ø))THEN
          WRITE(6,1Ø)KINDEX
 1Ø       FORMAT(X,'TROUBLE!  KINDEX = ', F1Ø.2)
       END IF
C
       IF((SPREAD.GT.6Ø.OR.SPREAD.LT.-Ø.5).AND.(SPREAD.NE.-99.Ø))THEN
          WRITE(6,2Ø)SPREAD,TEMP8,RH8
 2Ø       FORMAT(X,'TROUBLE! SPREAD = ',F1Ø.2/9X,'TEMP8 = ',F1Ø.2/
     *    9X,'RH8 = ', F1Ø.2)
       END IF
C
  3Ø   RETURN
       END
C
C
C      ****************************************************************
C                  * SUBROUTINE VORTICITY *
C                  ********************************
C
C
C           This subroutine calculates relative vorticity values based
C           on the direction and magnitude of the 5ØØ mb wind vectors
C           for the three rawinsonde stations as described in the main
C           program.  Recall that the main program "rotates" the winds
C           to the west to simplify calculations.  Therefore, I refer
C           to the stations by name as if the wind is comming from the
C           west.
C
C                  **********************
C                  * VARIABLE DIRECTORY *
C                  **********************
C     DIR= the average vector direction the wind blows.
C     DIR(J) = The direction the wind blows from in compass directions.
C     CHANGE= Direction change between Lander and Boise.  Positive
C       means counterclockwise.
C     V#= Velocities at stations in meters per second.
C     AVEV= Average wind velocity of Lander and Boise.
C     ADIR= Average wind direction of Lander and Boise in compass direction
C     DCHANGE= Absolute value of wind direction change between the
C        Lander/Boise average and Great Falls.
C     DV= The wind velocity change between the Lander/Boise average
C        and Great Falls.
C     THEDA= conversion of CHANGE to radians.
C     R= The radius of curvature of the wind streamline.  Positive
C        means counterclockwise.
```

```
C     VORT= Absolute vorticity multiplied by 10**5.
C
      SUBROUTINE VORTSUB(VORT,DIR1,VEL1,DIR2,VEL2,DIR3,VEL3,N,S,DIR)
      INTEGER N,S
      REAL VORT,DIR1,VEL1,DIR2,VEL2,DIR3,VEL3,DIR
C
C         Test individual winds to see if they straddle 360 degrees
C         If so, add 360 degrees to the ones between 0 and 90 degrees
C         and subtract to get change in diretction.
      IF((DIR1.GT.270.OR.DIR2.GT.270.OR.DIR3.GT.270).AND.
     *(DIR1.LT.90.OR.DIR2.LT.90.OR.DIR3.LT.90))THEN
      IF(DIR1.LT.90)DIR1=DIR1+360
      IF(DIR2.LT.90)DIR2=DIR2+360
      IF(DIR3.LT.90)DIR3=DIR3+360
      END IF
      CHANGE=DIR3-DIR2
C
C           Change knots to meters per second.
      V1=VEL1*.514
      V2=VEL2*.514
      V3=VEL3*.514
C
C           Average velocities at Lander and Boise.
      AVEV=(V3+V2)/2
C
C           Here, I calculate the change in velocity between Great
C           Falls and the average velocity calculated above, but I use
C           only the component parallel to the streamline flow.
      ADIR=(DIR2+DIR3)/2
      DCHANGE=ABS(ADIR-DIR1)*.0174533
      DV=AVEV-((COS(DCHANGE))*V1)
C
C           In this method, if the wind blows from the west,
C           counterclockwise flow is positive, but if the wind blows
C           from the east in counterclockwise flow I must change the
C           signs on CHANGE and DV to get them to come out positive.
C           So, I test for east flow and also for flow from the other
C           two quadrants which correspond to east flow after rotation.
C
      IF((DIR.GT.0.AND.DIR.LT.60).OR.(DIR.GT.120.AND.DIR.LT.180)
     *.OR.(DIR.GT.240.AND.DIR.LT.300))THEN
      CHANGE=-CHANGE
      DV=-DV
      END IF
C
C           Change degrees to radians.
      THEDA=.0174533*CHANGE
C
C           Calculate the radius of curvature of the streamline.
      IF(THEDA.EQ.0)THEDA=THEDA+.00001
      R=S/THEDA
C
C           And (finally) calculate vorticity. Here, I multiply by
C           10**5 to get a workable number and I add 10.3 which is the
C           vorticity caused by the rotation of the earth at 45
C           degrees latitude.
      VORT=(((DV/N)+(AVEV/R))*100000)+10.3
C         Test for unreasonable values.
      IF((VORT.GT.20.OR.VORT.LE.2).AND.(VORT.NE.-99.0))THEN
         WRITE(6,10)VORT,DIR
   10    FORMAT(X,'TROUBLE!  VORTICITY =',F10.2/9X,'DIRECTION = ',F10.2)
      END IF
      RETURN

      END
```

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