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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AND METEOROLOGICAL PARAMETERS—AN ASSESSMENT

by

W. Bruce Tremper

A thesis submitted in partial fulfillment
of the requirements for the degree
of
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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.

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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 disciplines—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 adequately 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.
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 adequately 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" comparison 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 periods 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 exhibits 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 meteorological significance of each parameter are referred 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)

   Generalized 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 = \( 10.3 \times 10^{-5} \) 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 rawinsonde 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 geostrophic 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):
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: \(dv = \text{change in horizontal distance over distance } dn\) (Figure 6)  
\(dn = \text{distance over which velocity change is measured}\)  
\(V = \text{horizontal velocity of air at a specified point}\)  
\(r = \text{radius of curvature of the airstream at the point specified by } V\)  
\(C = \text{constant for the coriolis acceleration \(\theta 45\) degrees latitude of } 10.3 \times 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:

\[
\begin{align*}
V &= \frac{v_1 + v_2}{2} \\
dv &= V - v_1
\end{align*}
\]

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:

\[
\text{K index} = 850 \text{ mb temperature} - 500 \text{ mb temperature} + 850 \text{ mb dew point} - 700 \text{ mb dew point spread.}
\]

**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 consistent 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 \times precipitable water
Dynamic 2 = K \text{ index} \times precipitable water
Dynamic 3 = divergence \times precipitable water
Dynamic 4 = vorticity advection \times precipitable water \times K \text{ 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 \text{ mb wind} \times \frac{1}{850} \text{ mb dew point spread}
Orographic 2 = 700 \text{ mb wind} \times \text{ precipitable water}
Orographic 3 = 700 \text{ mb wind} \times \text{ precipitable water} \times K \text{ index}
Orographic 4 = 700 \text{ mb wind} \times \text{ precipitable water} \times K \text{ index} \times \frac{1}{850} \text{ mb dew point spread}

850 \text{ 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):

\[
W = \sum_{i=1}^{n} g \frac{r}{(-P_i)}
\]

Where:
- \(W\) = precipitable water in centimeters of depth
- \(g\) = acceleration of gravity
- \(P_i\) = 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
- \(P_i = P_{i-1}\)

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:

\[
r = \frac{0.622 e}{P - e}
\]

(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:

\[ e = e_s \left( \frac{R_H}{100} \right) \]  

(Byers, 1974)

Where: 
- \( e_s \) = saturation vapor pressure (defined below) 
- \( R_H \) = relative humidity in percent

The saturation vapor pressure is calculated:

\[ e_s = \frac{aT}{T + b} \]  

(\( a = 6.11 \times 10^{	ext{aT}/[T + b]} \))  

(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 equivalent) 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 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 equivalent) 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.

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.

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

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.

<table>
<thead>
<tr>
<th>Snow Course</th>
<th>r</th>
<th>$r^2$</th>
<th>N</th>
<th>Standard Error (inches)</th>
<th>Daily snow course whose equation was summed to estimate monthly snow course values.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td><strong>Daily Snow Courses:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bridger Bowl</td>
<td>.94</td>
<td>.89</td>
<td>66</td>
<td>1.72</td>
<td></td>
</tr>
<tr>
<td>Carrot Basin</td>
<td>.91</td>
<td>.83</td>
<td>30</td>
<td>4.15</td>
<td></td>
</tr>
<tr>
<td>Lick Creek</td>
<td>.71</td>
<td>.51</td>
<td>44</td>
<td>1.27</td>
<td></td>
</tr>
<tr>
<td>Maynard Creek</td>
<td>.87</td>
<td>.76</td>
<td>54</td>
<td>1.50</td>
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<tr>
<td>Shower Falls</td>
<td>.92</td>
<td>.85</td>
<td>43</td>
<td>2.56</td>
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<tr>
<td>Taylor Peaks</td>
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<td>.74</td>
<td>24</td>
<td>0.89</td>
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<tr>
<td><strong>Monthly Snow Courses:</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td>.82</td>
<td>43</td>
<td>1.05</td>
<td>Shower Falls</td>
</tr>
<tr>
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<td>.95</td>
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<td>1.97</td>
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<td>.95</td>
<td>29</td>
<td>1.40</td>
<td>Shower Falls</td>
</tr>
<tr>
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<td>.88</td>
<td>.76</td>
<td>31</td>
<td>2.10</td>
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<tr>
<td>Twenty-One Mile</td>
<td>.85</td>
<td>.71</td>
<td>50</td>
<td>1.82</td>
<td>Carrot Basin</td>
</tr>
</tbody>
</table>

*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.

<table>
<thead>
<tr>
<th>SNOW COURSE</th>
<th>r</th>
<th>r²</th>
<th>N</th>
<th>STANDARD ERROR (inches)</th>
<th>METEOROLOGICAL AND CLIMATIC STATION PARAMETERS</th>
<th>%r²</th>
<th>COEFFICIENTS</th>
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</thead>
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<tr>
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<td></td>
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<td>Bozeman 12 NE</td>
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</tr>
<tr>
<td>Bridger Bowl</td>
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<td>163</td>
<td>.16</td>
<td></td>
<td>86</td>
<td>1.52 E-4</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Orographic</td>
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<td>1.04 E-4</td>
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<tr>
<td></td>
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<td>Temp. change</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>Temp. grad. 850</td>
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<td>Temp. 500</td>
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Table 4 (continued)

<table>
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<tr>
<th>Climate Stations</th>
<th>Weather Parameters</th>
<th>r²</th>
<th>1/r²</th>
<th>24-hour Temperature Change at Bozeman 12 NE</th>
<th>Climate Stations</th>
<th>Weather Parameters</th>
<th>r²</th>
<th>1/r²</th>
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<tbody>
<tr>
<td>Carrot Basin</td>
<td>Dynamic 1</td>
<td>2.1</td>
<td>68</td>
<td>2.30 E-2</td>
<td>Hebgen Dam</td>
<td>Dynamic 1</td>
<td>20</td>
<td>440</td>
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<td>West Yellowstone</td>
<td>Dynamic 4</td>
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<td>610</td>
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<td></td>
<td>Constant</td>
<td></td>
<td></td>
<td>-5.60 E-3</td>
</tr>
<tr>
<td>Taylor Peaks</td>
<td></td>
<td>.14</td>
<td></td>
<td></td>
<td>Hebgen</td>
<td></td>
<td>68</td>
<td>.330</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pres. grad 700</td>
<td></td>
<td>19</td>
<td>1.00 E-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>West Yellowstone</td>
<td></td>
<td>13</td>
<td>.310</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Constant</td>
<td></td>
<td></td>
<td>-5.60</td>
</tr>
</tbody>
</table>

*Percent change of r² of the regression equation as each parameter is added.

PARAMETER DEFINITIONS:

- **Climate Stations:**
  - Bozeman 12 NE
  - West Yellowstone
  - Hebegen Dam
  - Ennis
  - Norris

- **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.

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salaries of research assistant, key punchers, and programmers</td>
<td>$7,360</td>
</tr>
<tr>
<td>Computer</td>
<td>$3,000</td>
</tr>
<tr>
<td>Data*</td>
<td>$1,680</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>$1,110</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$13,150</strong></td>
</tr>
</tbody>
</table>

*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.
REFERENCES CITED


APPENDIX

PROGRAM LISTING
This program calculates a variety of meteorological parameters from three upper air rawinsonde stations—Great Falls, Mt., Lander, Wyoming, and Boise, Idaho. The program calculates the following parameters:

1) It first utilizes a weighted average of the three stations creating a value for the Bozeman area using the distances to the stations as follows: Great Falls, 230 km. Lander, 350 km. Boise, 445 km.

2) Calculate the vector average wind direction for the Bozeman area.

3) Temperature and pressure gradient for the levels: 850, 700, 500 mbs.

4) From and upwind station, it calculates k-index, thermal advection and precipitable water.

5) Using all three stations, it calculates vorticity, vorticity advection and divergence using 500 mb. wind directions and velocities.

6) A variety of orographic lifting parameters.

7) A variety of dynamic lifting parameters.

8) Parameters based on local climate station data of precipitation and temperature.

Input data is organized as follows:

Three records of morning mandatory data, i.e. data from 850, 700 and 500 millibar levels. Data consists of pressure height, temperature, relative humidity, wind direction, wind velocity. The first record is from the Great Falls station, the second from the Lander station and the third from the Boise station.

Next, there are three records of morning significant data arranged like above except that pressure is the first parameter and the following are as above making six parameters total per level. There is a maximum of ten levels.

Next, there are three records of afternoon mandatory data and three records of afternoon significant data just as above.

Next, there is one record of climatic data. It consists of thirteen stations with each station yielding data of minimum and maximum temperature, precipitation, and 24-snow accumulation. There are 14 records per day.

<table>
<thead>
<tr>
<th>Record</th>
<th>Column</th>
<th>Format</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-2</td>
<td>I2</td>
<td>Year</td>
</tr>
<tr>
<td>1</td>
<td>3-4</td>
<td>I2</td>
<td>Month</td>
</tr>
<tr>
<td>1</td>
<td>5-6</td>
<td>I2</td>
<td>Day</td>
</tr>
<tr>
<td>2</td>
<td>4-7</td>
<td>F4.Ø</td>
<td>850 mb pressure height</td>
</tr>
<tr>
<td>2</td>
<td>9-13</td>
<td>F5.1</td>
<td>850 mb temperature</td>
</tr>
<tr>
<td>2</td>
<td>16-18</td>
<td>F3.Ø</td>
<td>850 mb relative humidity</td>
</tr>
<tr>
<td>2</td>
<td>21-23</td>
<td>F3.Ø</td>
<td>850 mb wind velocity</td>
</tr>
<tr>
<td>3</td>
<td>26-28</td>
<td>F3.Ø</td>
<td>850 mb wind direction</td>
</tr>
</tbody>
</table>

The 700 mb and 500 mb data follows the same format. The 700 mb data begins on column 39 and 500 mb data on column 69. The second record is Great Falls, Record three is Boise and record four is Lander. Record five is the beginning of
the significant data and appears as follows:

Record Column Format Parameter
5 3-6 F4.0 Pressure
5 10-13 F4.0 pressure height
5 15-19 F5.1 temperature
5 22-24 F3.0 relative humidity
6 27-29 F3.0 wind velocity
6 32-34 F3.0 wind direction

The next significant layer begins at column 36, the next at column 72 and so on with 12 significant layers total possible. Record five is Great Falls. Record six is Lander and record seven is Boise. Beginning with record eight is the afternoon data in the same manner ending on record twelve. Record thirteen is the climate station data organized as follows:

Record Column Format Parameter
13 3-5 F3.0 maximum temperature
13 8-10 F3.0 minimum temperature
13 12-18 F7.3 24-hour precipitation
13 20-25 F6.2 24-hour snowfall total

The next climate station data begins on column 27, the next on column 54 and so on with 13 climate stations possible. The climate station order is the same as their positions entered in the arrays as described below.

The data is read into arrays as follows:

Array MAN(I,J,K) contains mandatory data.
I=station: I=1 is Great Falls; I=2 is Lander; I=3 is Boise.
J is the level: J=1 is 850 mb.; J=2 is the 700 mb. and J=3 is the 500 mb. level.
K is the parameter: K=1 is pressure height, K=2 is the temperature, K=3 is the relative humidity, K=4 is the wind direction and K=5 is the wind velocity.

Array SIG(I,J,K) contains significant data where I is the station as above and J is the level (a maximum of 10 levels) and K is the parameter as above but the pressure of that particular level is in the first position and the other parameters are bumped up one position so there are six parameters total.

Array CLIM(I,J) contains climatic data where I is the station and J is the parameter as follows:
I 1 is Belgrade Airport
I 2 is Montana State University
I 3 is The Forsyth ranch near Bridger (Bozeman 12 NE)
I 4 is Ennis.
I 5 is Gallatin Gateway 9 S.
I 6 is Gallatin Gateway 27 S. (1952-1962)
I 7 is Gallatin Gateway 26 S. (1967-present)
I 8 is Hebgen Dam.
I 9 is Livingston 12 S.
I 10 is Livingston Airport.
I 11 is Norris.
I 12 is Virginia City.
I 13 is West Yellowstone.

J=1 is maximum temperature.
J=2 is minimum temperature.
J=3 is precipitation in inches.
J=4 is 24-hour snowfall in inches.
Output of this program is organized as follows:

<table>
<thead>
<tr>
<th>Record Column</th>
<th>Format</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2-3</td>
<td>I2 year</td>
</tr>
<tr>
<td>1</td>
<td>5-6</td>
<td>I2 month</td>
</tr>
<tr>
<td>1</td>
<td>8-9</td>
<td>I2 day</td>
</tr>
<tr>
<td>2</td>
<td>2-6</td>
<td>F5.0 850 mb pressure height</td>
</tr>
<tr>
<td>2</td>
<td>7-11</td>
<td>F5.0 850 mb temperature</td>
</tr>
<tr>
<td>2</td>
<td>12-16</td>
<td>F5.0 850 mb relative humidity</td>
</tr>
<tr>
<td>2</td>
<td>17-21</td>
<td>F5.0 850 mb wind velocity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The 700 mb and 500 mb data are as above. The 700 mb data begins in column 27 and the 500 mb data begins in column 54.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Record Column</th>
<th>Format</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>62-66</td>
<td>F4.0 700 mb wind direction</td>
</tr>
<tr>
<td>2</td>
<td>67-71</td>
<td>F4.0 500 mb wind direction</td>
</tr>
<tr>
<td>3</td>
<td>2-5</td>
<td>F4.0 850 mb pressure height gradient</td>
</tr>
<tr>
<td>3</td>
<td>6-10</td>
<td>F4.0 700 mb pressure height gradient</td>
</tr>
<tr>
<td>3</td>
<td>11-15</td>
<td>F4.0 500 mb pressure height gradient</td>
</tr>
<tr>
<td>3</td>
<td>16-20</td>
<td>F4.0 850 mb temperature gradient</td>
</tr>
<tr>
<td>3</td>
<td>21-25</td>
<td>F4.0 700 mb temperature gradient</td>
</tr>
<tr>
<td>3</td>
<td>26-30</td>
<td>F4.0 500 mb temperature gradient</td>
</tr>
<tr>
<td>3</td>
<td>31-35</td>
<td>F4.0 K index</td>
</tr>
<tr>
<td>3</td>
<td>36-40</td>
<td>F4.0 850 mb dew point spread</td>
</tr>
<tr>
<td>3</td>
<td>41-48</td>
<td>F7.3 precipitable water</td>
</tr>
<tr>
<td>3</td>
<td>49-55</td>
<td>F6.2 thermal advection</td>
</tr>
<tr>
<td>3</td>
<td>56-62</td>
<td>F6.2 cold thermal advection</td>
</tr>
<tr>
<td>3</td>
<td>63-69</td>
<td>F6.2 warm thermal advection</td>
</tr>
<tr>
<td>3</td>
<td>70-76</td>
<td>F6.2 thermal advection squared</td>
</tr>
<tr>
<td>3</td>
<td>77-82</td>
<td>F6.2 warm thermal advection squared</td>
</tr>
<tr>
<td>3</td>
<td>8-14</td>
<td>F6.2 cold thermal advection squared</td>
</tr>
<tr>
<td>4</td>
<td>15-21</td>
<td>F6.2 divergence</td>
</tr>
<tr>
<td>4</td>
<td>22-28</td>
<td>F6.2 divergence squared</td>
</tr>
<tr>
<td>4</td>
<td>29-35</td>
<td>F5.1 vorticity</td>
</tr>
<tr>
<td>4</td>
<td>36-41</td>
<td>F5.1 vorticity advection</td>
</tr>
<tr>
<td>4</td>
<td>42-47</td>
<td>F5.1 vorticity advection squared</td>
</tr>
<tr>
<td>4</td>
<td>48-53</td>
<td>F5.0 orographic parameter 1</td>
</tr>
<tr>
<td>4</td>
<td>54-59</td>
<td>F5.0 orographic parameter 2</td>
</tr>
<tr>
<td>4</td>
<td>60-65</td>
<td>F5.0 orographic parameter 3</td>
</tr>
<tr>
<td>4</td>
<td>66-71</td>
<td>F5.0 orographic parameter 4</td>
</tr>
<tr>
<td>5</td>
<td>2-7</td>
<td>F6.1 dynamic parameter 1</td>
</tr>
<tr>
<td>5</td>
<td>8-14</td>
<td>F6.1 dynamic parameter 2</td>
</tr>
<tr>
<td>5</td>
<td>15-21</td>
<td>F6.1 dynamic parameter 3</td>
</tr>
<tr>
<td>5</td>
<td>22-28</td>
<td>F6.1 dynamic parameter 4</td>
</tr>
<tr>
<td>5</td>
<td>29-33</td>
<td>F4.0 Bozeman 12 NE 24-hour min. temp. change</td>
</tr>
<tr>
<td>5</td>
<td>34-38</td>
<td>F4.0 M.S.U. 24-hour min. temp. change</td>
</tr>
</tbody>
</table>

The following parameters are climate station parameters.

<table>
<thead>
<tr>
<th>Record Column</th>
<th>Format</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2-5</td>
<td>F4.0 maximum temperature</td>
</tr>
<tr>
<td>6</td>
<td>6-10</td>
<td>F4.0 minimum temperature</td>
</tr>
<tr>
<td>6</td>
<td>11-18</td>
<td>F7.3 24-hour precipitation</td>
</tr>
<tr>
<td>6</td>
<td>19-25</td>
<td>F6.2 24-hour snowfall</td>
</tr>
</tbody>
</table>

There are three climate stations per record with the second one beginning in column 29 and the third in column 58. Again, the order of the climate stations is the same as listed above.

***************************************************************************************************************
* DIVISION OF MAINLINE PROGRAM *
***************************************************************************************************************

* Read in data
* Weighted average for Bozeman area
* Average wind direction
* Temperature and pressure gradients
* Thermal advection, K-index, precipitable water and 850 millibar dew point spread.
* Divergence
* Vorticity
* Orographic parameters
* Dynamic lifting parameters
* Climate station parameters

***************************************************************
* SUBROUTINES REQUIRED *
***************************************************************
* ADVECTION--calculates thermal advection
* WATER--calculates precipitable water
* STABLE--calculates K-index
* VORT--calculates vorticity

***************************************************************
* MODULE TO DIMENTION VARIABLES *
***************************************************************

INTEGER DAY,YEAR,MONTH
REAL GRADS(2,3,2),GRADSAVE(3,2),LASTFOR,LANSPREAD,
*LASTBZN,BZSAVE(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,LANADV,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./,REACOUNT/1/
OPEN(UNIT=105,RECL=440,STATUS='OLD')

Read In data.
4 IF(REACOUNT.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(REACOUNT.EQ.2)THEN
  READ(105,14,END=270)((CLIM(I,J),J=1,4),I=1,13)
END IF
C
C
C
5 FORMAT(3(I2))
10 FORMAT(2(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,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(2X,F3.0),X,F7.3,X,F5.2,2X))

***************************************************************
* MODIFY ARRAYS AND EXTRAPOLATE MISSING VALUES *
***************************************************************
In this data, significant level pressures numerically ten times their actual values, so I divide by 10.

The station at Lander, Wyo. is above the 850 mb. level and consequently, the 850 mb. mandatory data is usually missing. So here, I use data taken from the first significant layer above Lander and extrapolate these values to the 850 mb. level. At this level, pressure in millibars and height in meters is nearly numerically equivalent, so I use them interchangeably.

Temperature lapse rate = 0.065 degrees C/meter.
Relative humidity lapse rate = -10% / 50 meters.
Height in meters = pressure in millibars.
Wind velocity and direction extrapolate directly.

Here, I calculate the weighted average. \( D(?) \) = inverse of the distance from the Gallatin drainage to each of the rawinsonde stations. \( D(1) \) = Great Falls, \( D(2) \) = Lander, \( D(3) \) = Boise. It calculates a weighted average for all 5 parameters although the average for wind direction \((k=4)\) has no meaning in this case and I never use it.
The average wind direction is calculated in the following section.

```
C  The average wind direction is calculated in the following section.

DO 40 J=1,3
  DO 30 K=1,5
    D(1)=.004348
    D(2)=.002857
    D(3)=.002247
  DO 25 I=1,3
    25      IF(MAN(I,J,K).EQ.-99.9)D(I)=0
    IF(D(1).EQ.0.AND.D(2).EQ.0).OR.(D(1).EQ.0.AND.D(3).EQ.0)
      *D(2).EQ.0.AND.D(3).EQ.0)THEN
      BZN(J,K)=-99.9
      GO TO 30
    END IF
    DIST=D(1)+D(2)+D(3)
    BZN(J,K)=(MAN(I,J,K)*D(1)+MAN(2,J,K)*D(2)+MAN(3,J,K)*D(3))
  /DIST
  30 CONTINUE
40 CONTINUE
```

**AVGAWIND**

Average winds by separating them into X and Y components and finding an average for them for 700 and 500 mbs.
First, I calculate the radian direction of the wind vector, separate directions into components and find sum of sine and cosine. Add .0001 to SUMCOS so I don't divide by zero. J=2 is 700mb.; J=3 is 500 mb.

**VARIABLE DIRECTORY:**

- **DIRCOUNT** - Counts the number of stations with missing data.
- **GFDIR** - Radian direction converted to trig. coordinates.
- **LANDIR** - Radian direction converted to trig. coordinates.
- **BOIDIR** - Radian direction converted to trig. coordinates.
- **GFSIN** - Sine of the Great Falls Station.
- **LANSIN** - Sine of the Lander Station.
- **BOISIN** - Sine of the Boise Station.
- **GFCOS** - Cosine of the Great Falls station.
- **LANCOS** - Cosine of the Lander station.
- **BOICOS** - Cosine of the Boise station.
- **SUMSIN** - Sum of the sines of the stations.
- **SUMCOS** - Sum of the cosines of the stations.
- **ANGLE** - Average direction in radians in trig. coordinates.
- **DIR(J)** - Average direction in compass coordinates -- DIR(2)

Loop through twice to figure 700 and 500 mb. directions.

```
    DO 45 J=2,3
    DIRCOUNT=0
    Change compass directions in array MAN to radian trig.
    coordinates.
    GFDIR=(-(MAN(1,J,4)+90))*.0174533
    LANDIR=(-(MAN(2,J,4)+90))*.0174533
    BOIDIR=(-(MAN(3,J,4)+90))*.0174533
    Find sine and cosine of directions.
    GFSIN = SIN(GFDIR)
    LANSIN = SIN(LANDIR)
    BOISIN = SIN(BOIDIR)
    GFCOS = COS(GFDIR)
```
LANCOS = \cos\text{(LANDIR)}  
BOICOS = \cos\text{(BOIDIR)}

Test for missing data. If so, increment counter (DIRCOUNT) and set sine and cosine for station to 0 so they won't contribute to the sum.

\begin{align*}
\text{IF} (\text{MAN}(1,J,4) \text{.EQ.} -99.0) & \text{THEN} \\
\text{GFSIN} & = 0 \\
\text{GFCOS} & = 0 \\
\text{DIRCOUNT} & = \text{DIRCOUNT} + 1 \\
\text{END IF}
\end{align*}

\begin{align*}
\text{IF} (\text{MAN}(2,J,4) \text{.EQ.} -99.0) & \text{THEN} \\
\text{LANSIN} & = 0 \\
\text{LANCOS} & = 0 \\
\text{DIRCOUNT} & = \text{DIRCOUNT} + 1 \\
\text{END IF}
\end{align*}

\begin{align*}
\text{IF} (\text{MAN}(3,J,4) \text{.EQ.} -99.0) & \text{THEN} \\
\text{BOISIN} & = 0 \\
\text{BOICOS} & = 0 \\
\text{DIRCOUNT} & = \text{DIRCOUNT} + 1 \\
\text{END IF}
\end{align*}

If all three directions are missing, set DIR(J) TO =99.0.

\begin{align*}
\text{IF}(\text{DIRCOUNT} \text{.EQ.} 3) & \text{THEN} \\
\text{DIR(J)} & = 99.0 \\
\text{GO TO} 45 \\
\text{END IF}
\end{align*}

\begin{align*}
\text{Sum sines and cosines.} \\
\text{SUMSIN} & = \text{GFSIN} + \text{LANSIN} + \text{BOISIN} \\
\text{SUMCOS} & = \text{GFCOS} + \text{LANCOS} + \text{BOICOS}
\end{align*}

Find average direction.

\begin{align*}
\text{IF}(\text{SUMCOS} \text{.EQ.} 0) & \text{SUMCOS} = .00001 \\
\text{ANGLE} & = \text{ATAN}(\text{SUMSIN}/\text{SUMCOS})
\end{align*}

Convert direction back to degrees again.

\begin{align*}
\text{AVEDIR} & = \text{ANGLE} \times 57.29577
\end{align*}

Test signs of sumsin and sumcos to see what quadrant it should be in.

\begin{align*}
\text{IF}(\text{SUMSIN} \text{.GT.} 0 \text{.AND. SUMCOS} \text{.LT.} 0) & \text{AVEDIR} = \text{AVEDIR} + 180 \\
\text{IF}(\text{SUMSIN} \text{.LT.} 0 \text{.AND. SUMCOS} \text{.LT.} 0) & \text{AVEDIR} = \text{AVEDIR} + 180 \\
\end{align*}

Now subtract 90 degrees and change signs to get ANGLE back into compass directions again.

\begin{align*}
\text{DIR(J)} & = (\text{AVEDIR} - 90) \\
\text{IF}(\text{DIR(J)} \text{.GT.} 360) & \text{DIR(J)} = \text{DIR(J)} - 360 \\
\text{IF}(\text{DIR(J)} \text{.LE.} 0) & \text{DIR(J)} = \text{DIR(J)} + 360 \\
\text{45 CONTINUE}
\end{align*}

* PRESSURE AND TEMPERATURE GRADIENTS *

Here I calculate temperature and pressure gradients simply using the maximum difference between the readings for the three stations. \text{GRAD}(I,J) = \text{gradient of pressure (when } J = 1)
First, I read the data into separate arrays—one for each station:

- GFMAN = mandatory data for Great Falls.
- LANMAN = mandatory data for Lander.
- BOIMAN = mandatory data for Boise.
- GFSIG = significant level data for Great Falls.
- LANSIG = significant level data for Lander.
- BOISIG = significant level data for Boise.

I then test which way the average 700 millibar winds blow and use data from an upwind station or an average of two upwind stations to calculate thermal advection (subroutine ADVDEG), K-Index and 850 mb dew point spread (subroutine STABLE) and precipitable water (subroutine WATER). I do this by using the appropriate arrays as arguments in the subroutines based on the wind direction.

VARIABLE LIST:

- PWATER = Precipitable water.
- ADV = Absolute advection.
- CADV = Cold advection.
- WADV = Warm advection.
- KINDEX = K-Index.
- SPREAD = 850 mb dew point spread.
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

If 700 mb. winds blow from a direction between Great Falls and Lander.

IF(DIR(2).GT.210.AND.DIR(2).LE.270)THEN
CALL WATER(GFSIG,GFMAN,GFWATER)
CALL WATER(LANSIG,LANMAN,LANWATER)
PWATER=(GFWATER+LANWATER)/2

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

CALL STABLE(GFMAN,GINDEX,GFSPREAD)
CALL STABLE(LANMAN,LANINDEX,LANSPREAD)
KINDEX=(GINDEX+LANINDEX)/2
IF(GINDEX.NE.-99.0.AND.LANINDEX.EQ.-99.0)KINDEX=GINDEX
IF(GINDEX.EQ.-99.0.AND.LANINDEX.NE.-99.0)KINDEX=LANINDEX
IF(GINDEX.EQ.-99.0.AND.LANINDEX.EQ.-99.0)KINDEX=-99.0

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

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

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)
If 700 mb. winds blow from between Lander and Boise.
IF(DIR(2).GT.330.AND.DIR(2).LE.30)THEN
CALL WATER(BOISIG,BOIMAN,BOIWATER)
CALL WATER(LANSIG,LANMAN,LANWATER)
P\_WATER=(BOIWATER+LANWATER)/2
IF(BOIWATER.EQ.-99.0.AND.LANWATER.NE.-99.0)P\_WATER=LANWATER
IF(BOIWATER.NE.-99.0.AND.LANWATER.EQ.-99.0)P\_WATER=BOIWATER
IF(BOIWATER.EQ.-99.0.AND.LANWATER.EQ.-99.0)P\_WATER=-99.0
CALL STABLE(BOIMAN,BOINDEX,BOISPREAD)
CALL STABLE(LANMAN,LANINDEX,LANSPREAD)
K\_INDEX=(BOINDEX+LANINDEX)/2
IF(BOINDEX.EQ.-99.0.AND.LANINDEX.NE.-99.0)K\_INDEX=BOINDEX
IF(BOINDEX.NE.-99.0.AND.LANINDEX.EQ.-99.0)K\_INDEX=LANINDEX
IF(BOINDEX.EQ.-99.0.AND.LANINDEX.EQ.-99.0)K\_INDEX=-99.0
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
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

If 700 mb. winds blow from Great Falls and Boise. 
IF(DIR(2).GT.90.AND.DIR(2).LE.150)THEN
CALL WATER(BOISIG,BOIMAN,P\_WATER)
CALL ADVECTION(BOIMAN,ADV\_WADV,CADV)
CALL STABLE(BOIMAN,K\_INDEX,SPREAD)
END IF

If 700 mb. winds blow from between Great Falls and Boise. 
IF(DIR(2).GT.90.AND.DIR(2).LE.150)THEN
CALL WATER(GFSIG,GFMAN,GFWATER)
CALL WATER(BOISIG,BOIMAN,BOIWARD)
PWARD=(GFWATER+BOIWARD)/2
C
IF(GFWATER.EQ.-99.0.AND.BOIWARD.NE.-99.0)PWARD=BOIWARD
IF(GFWATER.NE.-99.0.AND.BOIWARD.EQ.-99.0)PWARD=GFWATER
IF(GFWATER.EQ.-99.0.AND.BOIWARD.EQ.-99.0)PWARD=-99.0
C
CALL STABLE(GFMAN,GFINDEX,GFSpread)
CALL STABLE(BOIMAN,BOIINDEX,BOISPREAD)
KINDEX=(GFINDEX+BOIINDEX)/2
IF(GFINDEX.EQ.-99.0.AND.BOIINDEX.NE.-99.0)KINDEX=GFINDEX
IF(GFINDEX.NE.-99.0.AND.BOIINDEX.EQ.-99.0)KINDEX=BOIINDEX
IF(GFINDEX.EQ.-99.0.AND.BOIINDEX.EQ.-99.0)KINDEX=-99.0
C
SPREAD=(BOISPREAD+GFSpread)/2
IF(GFSpread.EQ.-99.0.AND.BOISPREAD.NE.-99.0)SPREAD=BOISPREAD
IF(GFSpread.NE.-99.0.AND.BOISPREAD.EQ.-99.0)SPREAD=GFSpread
IF(GFSpread.EQ.-99.0.AND.BOISPREAD.EQ.-99.0)SPREAD=-99.0
C
CALL ADVECTATION(GFMAN,GFADV,GFWADV,GFCADV)
CALL ADVECTATION(BOIMAN,BOIADV,BOIWADV,BOICADV)
ADV=(GFADV+BOIADV)/2
WADV=(GFWADV+BOIWADV)/2
CADV=(GFCADV+BOICADV)/2
IF(GFADV.EQ.-99.0.AND.BOIADV.NE.-99.0)ADV=BOIADV
IF(GFADV.NE.-99.0.AND.BOIADV.EQ.-99.0)ADV=GFADV
IF(GFADV.EQ.-99.0.AND.BOIADV.EQ.-99.0)ADV=-99.0
IF(GFCADV.EQ.-99.0.AND.BOICADV.NE.-99.0)CADV=BOICADV
IF(GFCADV.NE.-99.0.AND.BOICADV.EQ.-99.0)CADV=GFCADV
IF(GFCADV.EQ.-99.0.AND.BOICADV.EQ.-99.0)CADV=-99.0
IF(GFWADV.EQ.-99.0.AND.BOIWADV.NE.-99.0)WADV=BOIWADV
IF(GFWADV.NE.-99.0.AND.BOIWADV.EQ.-99.0)WADV=GFWADV
IF(GFWADV.EQ.-99.0.AND.BOIWADV.EQ.-99.0)WADV=-99.0
C
END IF
IF(SPREAD.GT.60.OR.SPREAD.LT.-0.5).AND.(SPREAD.NE.-99.0))THEN
WRITE(6,98)SPREAD
END IF
98 FORMAT(X,'TROUBLE SPREAD= ',E6.2)

Calculate the square of warm, cold and absolute advection.
I add one to the terms before multiplication so the product
is greater than one.

SQADV=(ADV+1)*(ADV+1)
SQWARM=(WADV+1)*(WADV+1)
SOCOLD=(CADV+1)*(CADV+1)
IF(ADV.EQ.-99.0)SQADV=-99.0
IF(WADV.EQ.-99.0)SQWARM=-99.0
IF(CADV.EQ.-99.0)SOCOLD=-99.0

******************************************************************************

* DIVERGENCE *
******************************************************************************

This section calculates divergence by converting each of
the wind directions for each of the three stations to
vectors and then calculating the area of the resulting
triangle (see paper for futher details). Divergence is
then the percent change of area for a given time interval.
In this case, I use only the area of the triangle
(AREA) because it is proportional to divergence.
and is thus statistically equivalent.

VARIABLE LIST:

RADDIR# = The direction in radians of the wind vector.
RADDIR1 = Great Falls, RADDIR2 = Lander, RADDIR3 = Boise.
X1 = The X component of the Great Falls station.
Y1 = The Y component of the Great Falls station.
X2 = The X component of the Lander station.
Y2 = The Y component of the Lander station.
X3 = The X component of the Boise station.
Y3 = The Y component of the Boise station.
AREA = The resulting area of the triangle after displacement
by the wind vectors.
SQUARE = square of the area.

Test for missing data; if so don't calculate divergence.

99 DO 110 I=1,3
   DO 100 K=4,5
      IF(MAN(1,3,K).EQ.-99.0)THEN
         SQUARE=-99.0
         AREA=-99.0
         GO TO 115
      END IF
   100 CONTINUE
110 CONTINUE

X1=((COS(GFDIR))*MAN(1,3,5))+100
Y1=((SIN(GFDIR))*MAN(1,3,5))+200
X2=((COS(LANDIR))*MAN(2,3,5))+200
Y2=((SIN(LANDIR))*MAN(2,3,5))
X3=((COS(BOIDIR))*MAN(3,3,5))
Y3=((SIN(BOIDIR))*MAN(3,3,5))
AREA=1.5*ABS(X1*Y2-X2*Y1+X2*Y3-X3*Y2+X3*Y1-X1*Y3))*.01
SQUARE=AREA*AREA*.01

**************************

* VORTICITY *

**************************

This part of the program calculates vorticity from the 500mb wind direction and velocity. The velocity is input in
knots and I convert them to meters per second. The
direction is input as degrees on a compass and I must go
through a lot of pains to convert it to the standard trig
format that the computer uses. I also convert the wind
direction the wind blows from to a vector
direction i.e. the direction the wind blows to. In this
program, I pretend the wind is blowing out of the west
by rotating the wind back to that orientation each time.
I refer to the stations by name but this only signifies
the position in the triangle after rotation and may or
may not be their real positions or names.

VARIABLE DIRECTORY:

VORTICITY=Absolute vorticity figured in units of 10**5/sec.
RADDIR# = Wind directions of the three stations converted to
standard trigonometric coordinates for vectors.
SUMSIN = Sum of the sines of the directions.
SUMCOS = Sum of the cosines of the directions.
AVERAD = Average wind vector in radians.
AVEDIR = Direction of average wind vector in degrees.
VORTADV = Vorticity advection.
SQVORTADV = The square of vorticity advection.
N = Distance from the apex to the bisector of the opposite side and is used for calculating the velocity change over N distance.
S = The distance between stations.

Check for missing values; if so don't calculate vorticity.

115 DO 130 J = 1, 3
    DO 120 K = 4, 5
      IF (MAN(1, 3, K) .EQ. -99.0 .OR. DIR(3) .EQ. -99.0) THEN
        VORTADV = -99.0
        SQVORTADV = -99.0
        VORTICITY = -99.0
        LASTVORT = -99.0
        GO TO 134
      END IF
    120 CONTINUE
  130 CONTINUE

Now set function parameters for vorticity. The function calculates vorticity as if wind were from the west. Here I test which way the wind is blowing and set the function parameters accordingly. It is similar to rotating the wind back to the west each time.

IF (DIR(3) .GE. 240 .AND. DIR(3) .LE. 360) .OR. (DIR(3) .GE. 60 .AND. DIR(3) .LE. 120) THEN
  N = 473000
  S = 621000
  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

IF (DIR(3) .LE. 60 .OR. (DIR(3) .GE. 180 .AND. DIR(3) .LE. 240)) THEN
  N = 421000
  S = 575000
  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

IF (DIR(3) .GE. 300 .OR. (DIR(3) .GE. 120 .AND. DIR(3) .LE. 180)) THEN
  N = 526000
  S = 680000
  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

Calculate vorticity advection.

IF (FIRST) THEN
  VORTADV = -99.0
  SQVORTADV = -99.0
  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
Here I calculate parameters designed to predict
orographic precipitation (lifts).

134 LIFT1=BNZ(2,5)*(10/(SPREAD+1))
IF(BZN(2,5).EQ.-99.0.OR.PWATER.EQ.-99.0)LIFT1=-99.0
LIFT2=BNZ(2,5)*PWATER
IF(BZN(2,5).EQ.-99.0.OR.PWATER.EQ.-99.0)LIFT2=-99.0
LIFT3=(BNZ(2,5)*PWATER*KINDEX)/10
IF(BZN(2,5).EQ.-99.0.OR.PWATER.EQ.-99.0.OR.KINDEX.EQ.-99.0)LIFT3=-99
LIFT4=(BNZ(2,5)*PWATER*KINDEX*(10/(SPREAD+1)))/10
IF(BZN(2,5).EQ.-99.0.OR.PWATER.EQ.-99.0.OR.KINDEX.EQ.-99.0)LIFT4=-99
C
C******************************************************************
C DYNAMIC LIFTING PARAMETERS
C******************************************************************
C
Calculate parameter DYN# which attempts to predict
dynamic lifting.

135 DYN1=ADV+1)*PWATER
DYN2=((KINDEX+40)*PWATER)/10
DYN3=(AREA*PWATER)/10
DYN4=(ABS(10+VORTADV)*PWATER*(KINDEX+40))/10
IF(ADV.EQ.-99.0.OR.PWATER.EQ.-99.0)DYN1=-99.0
IF(KINDEX.EQ.-99.0.OR.PWATER.EQ.-99.0)DYN2=-99.0
IF(AREA.EQ.-99.0.OR.PWATER.EQ.-99.0)DYN3=-99.0
IF(VORTADV.EQ.-99.0.OR.PWATER.EQ.-99.0.OR.KINDEX.EQ.-99.0)DYN4=-99
C
C******************************************************************
CChange directions back to compass directions again.
DO 140 I=2,3
   DIR(I)=DIR(I)+180
   IF(DIR(I).GT.360)DIR(I)=DIR(I)-360
140 CONTINUE
C******************************************************************
C********************AVG MORN & AFTN PARAMETERS********************
C******************************************************************
C
This section of the program stores morning and afternoon parameters
into arrays so they can be averaged for the day. Some parameters
are calculated from upwind stations so they are delayed for
12 hours by averaging the morning value with the afternoon
values the day before.

VARIABLE DIRECTORY:

BZNSAVE (READCOUNT,I,J) = Array that stores the values for the
weighted average for the Bozeman area. where:
READCOUNT = 1 is for the morning data
READCOUNT = 2 is for the afternoon data.
1 = The level (as defined before).
J = The parameter (as defined before).

GRADSAVE(READCOUNT, I, J) = Array to store the temperature and pressure gradients.

PARAM(READCOUNT, #) = An array which stores the various parameters each assigned to a location designated by #.

BNZSAVE(I, J) = an array containing the average of morning and afternoon readings for the array BZNSAVE.

GRADAVE(I, J) = The average of the morning and afternoon parameters from the array GRADSAVE.

PARAMAVE(I, J) = The average of the two readings from the array PARAM.

STORE(I) = Contains the stored values for the parameters which are measured from upwind stations.

LASTFOR = The minimum temperature from the Forsyth Ranch climate station from the day before.

LASTBZN = The minimum temperature from the Belgrade airport climate station from the day before.

FORCHANGE = The 24-hour change in minimum temperature at Forsyth Ranch climate station (Bozeman 12 NE)

BZNCHANGE = The 24-hour change in minimum temperature at Belgrade Airport climate station.

Store morning and afternoon parameters into various arrays described above.

DO 160 I=1,3
  DO 150 J=I,3
  150 BZNSAVE(READCOUNT, I, J)=BNZ(I, J)
160 CONTINUE

DO 170 I=1,3
  170 BZNSAVE(READCOUNT, I, 5)=BNZ(I, 5)
C
C
DO 190 I=1,3
  DO 180 J=I,2
  190 GRADSAVE(READCOUNT, I, J)=GRAD(I, J)
190 CONTINUE

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)=SOADV
PARAM(READCOUNT, 8)=SQUARM
PARAM(READCOUNT, 9)=SQCOLD
PARAM(READCOUNT, 10)=AREA
PARAM(READCOUNT, 11)=SQAREA
PARAM(READCOUNT, 12)=VORTICITY
PARAM(READCOUNT, 13)=VORTADV
PARAM(READCOUNT, 14)=SVOORTADV
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)

Change READCOUNT to the afternoon value (2) and return to the beginning to read the afternoon readings. If afternoon readings have already been calculated and stored, go to the to averaging section of the program below.

IF(READCOUNT.EQ.1)THEN
READCOUNT=2
GO TO 4
END IF

Average the morning and afternoon data and store in the various arrays as defined above.

DO 210 I=1,3
DO 200 J=1,3
BZNAVE(I,J)=(BZNSAVE(I,I,J)+BZNSAVE(2,I,J))/2
* BZNAVE(I,J)=BZNSAVE(2,I,J)
* BZNAVE(I,J)=BZNSAVE(1,I,J)
* BZNAVE(I,J)=BZNSAVE(I,2,1,J)
200 CONTINUE

210 CONTINUE

DO 220 I=1,3
DO 230 J=1,2
GRADAVE(I,J)=(GRADSAVE(I,I,J)+GRADSAVE(2,I,J))/2
* GRADAVE(I,J)=GRADSAVE(2,I,J)
* GRADAVE(I,J)=GRADSAVE(1,1,I,J)
* GRADAVE(I,J)=-99
230 CONTINUE

220 CONTINUE

240 CONTINUE
DO 245 I=1,9
    PAVE(I)=(STORE(I)+PARAM(I,I))/2
    IF(STORE(I).EQ.-99.0.AND.PARAM(I,I).NE.-99.0)PAVE(I)=PARAM(I,I)
    IF(STORE(I).NE.-99.0.AND.PARAM(I,I).EQ.-99.0)PAVE(I)=STORE(I)
    IF(STORE(I).EQ.-99.0.AND.PARAM(I,I).EQ.-99.0)PAVE(I)=-99.0
    CONTINUE
    IF(FIRST)THEN
        DO 247 I=1,9
        PAVE(I)=-99.0
        END IF
    DO 250 I=10,25
        PAVE(I)=(PARAM(I,I)+PARAM(2,I))/2
        IF(PARAM(I,I).EQ.-99.0.AND.PARAM(2,I).NE.-99.0)PAVE(I)=PARAM(2,I)
        IF(PARAM(I,I).NE.-99.0.AND.PARAM(2,I).EQ.-99.0)PAVE(I)=PARAM(I,I)
        IF(PARAM(I,I).EQ.-99.0.AND.PARAM(2,I).EQ.-99.0)PAVE(I)=-99.0
        CONTINUE
    Now store the values calculated from the upwind stations so
    can be averaged on the next loop of the program (tomorrow).
    STORE(1)=KINDEX
    STORE(2)=SPREAD
    STORE(3)=PUATER
    STORE(4)=ADV
    STORE(5)=WADV
    STORE(6)=CADV
    STORE(7)=SQADV
    STORE(8)=SQWARM
    STORE(9)=SQCOLD

    Here, I calculate a temperature change parameter. I do this
    by taking the difference between today's minimum
    and yesterday's minimum temperature. The difference
    must be more than 15 degrees in order to register other
    than a zero. This parameter is designed to indicate
    the passage of a cold front.
    FORCHANGE=LASTFOR-CLIM(3,2)-10
    BZNCHANGE=LASTBZN-CLIM(2,2)-10
    IF(FORCHANGE.LT.0)FORCHANGE=0
    IF(BZNCHANGE.LT.0)BZNCHANGE=0
    IF(FIRST)THEN
        FORCHANGE=-99
        BZNCHANGE=-99
    END IF
    IF(LASTFOR.EQ.-99.0.OR.CLIM(3,2).EQ.-99.0)FORCHANGE=-99
    IF(LASTBZN.EQ.-99.0.OR.CLIM(2,2).EQ.-99.0)CLIM(2,2)=-99

    Now, change variable FIRST to .FALSE. so I know I have been
    through the program at least once.
    FIRST=.FALSE.

    ******************************************************
    * WRITE THE PARAMETERS *
    ******************************************************
WRITE(106,266)YEAR,MONTH,DAY
WRITE(106,267)(BZNAVE(1,J),J=1,3),BZNAVE(1,5),
*(BZNAVE(2,3),J=1,3),BZNAVE(2,5),
*(BZNAVE(3,3),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,BZCHANGE
WRITE(106,268)((CLIM(1,J),J=1,4),I=1,13)
C
266 FORMAT(3(X,D12))
267 FORMAT(X,3(4(F5.0))3(X,F4.0)/,
*8(X,F4.0),3(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
Now, store today's minimum temperatures into yesterday's
minimum temperatures.
LASTFOR=CLIM(3,2)
LASTBZN=CLIM(2,2)
C
IF(READCOUNT.EQ.2)THEN
READCOUNT=1
GO TO 4
END IF
C
270 END
C
*******************************************************************
*******************************************************************
* SUBROUTINES *
*******************************************************************
*******************************************************************
C
*******************************************************************************
*******************************************************************************
* SUBROUTINE WATER *
*******************************************************************************
*******************************************************************************
C
SUBROUTINE WATER(SIG,MAN,H20)
In this subroutine, both mandatory and significant data are used
to total up the precipitable water in a column of air. First
mandatory levels must be inserted into the proper order within the
significant levels according to pressure. I do this by putting
in an array called LIST. The 850 and 500 mb. data go on the top
and bottom and the 700 mb. data goes in the middle wherever it
belongs according to pressure. Then the water in each layer of
air (now contained in the array LIST) is summed up to produce
total precipitable water in the column of air.
C
VARIABLE DIRECTORY:
MAN(J,K) = Mandatory data.
SIG(J,K) = Significant data.
LIST(J,K) = A list of mandatory and significant data in
order of pressure.
K = the parameter (as defined before)
J = pressure level (as defined before)
W(I) = contains precipitable water for each level.
H20 = total precipitable water.
COUNT = the count of the number of layers with missing data.
MARK700 = Logical variable signaling when the 700 mb. level was inserted into array LIST.
FIRST = Logical variable signaling the first time through loop which sums precipitable water.
ES = Saturated vapor pressure.
E = Vapor pressure.
LASTMIX = Mixing ratio from the next layer below.
LASTHEIGHT = Pressure height for the next layer below.

REAL SIG(12,6),H2O,W(15),MAN(3,5),LIST(15,4),LASTMIX
LOGICAL FIRST,MARK700
COUNT=0
H20=0
FIRST=.TRUE.
MARK700=.FALSE.

Put 850 and 500 mb. data on the bottom and top respectively.
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)

Here, I loop through the 12 possible significant levels and in the data below 700 mb. into array LIST. Then, when the first above 700 mb. is encountered, I insert the 700 mb. data.

DO 40 J=2,13
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

Test for first significant level encountered above 700 mb. If so, 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.
END IF

If the 700 mb. data hasn't been inserted yet by the time the 13th position has come up, insert the highest significant data into the 13th slot and insert the 700 mb. data into the 14th slot.
IF(J.EQ.13.AND..NOT.MARK700)THEN
DO 23 K=1,4
23 LIST(J,K)=SIG(J-1,K)
LIST(14,1)=700
DO 27 K=2,4
27 LIST(14,K)=MAN(2,K-1)
MARK700=.TRUE.
END IF
Insert data above 700 mb. into LIST.

```fortran
IF(MARK700) THEN
   DO 30 K=1,4
      LIST(J+1,K)=SIG(J-1,K)
   END IF

30 CONTINUE
```

Test list to make sure it is in order of declining pressure. Something is wrong. Make H2O = -99.0 and return.

```fortran
DO 45 J=1,14
   IF(LIST(J,1).NE.-99.0 .AND. LIST(J+1,1).NE.-99.0 .AND. (LIST(J,1)
*   -LIST(J+1,1)).LE.0) THEN
      WRITE(6,43)
53 FORMAT(X,'TROUBLE! ARRAY LIST IS TURNED AROUND.')
      RETURN
   END IF
45 CONTINUE
```

Calculate water (mixing ratio) for each layer and store in W(I).

```fortran
DO 50 I=1,15
   IF(LIST(I,1).EQ.-99.0 .OR. LIST(I,3).EQ.-99.0 .OR. LIST(I,4).EQ.
*   -99.0) THEN
      W(I)=-99.0
      GO TO 50
   END IF
   ES=10**(9.286-(2322.3789/(LIST(I,3)+273))
   E=((LIST(I,4)+.00001)/100)*ES
   W(I)=(.622*E)/(LIST(I,1)-E)
50 CONTINUE
```

Test for missing data; If so, increment COUNT and loop again. If not, add up precipitable water.

```fortran
IF(W(I),EQ.-99.0 .OR. LIST(I,2),EQ.-99.0) THEN
   COUNT=COUNT+1
   GO TO 60
END IF
```

Store the lowest non-missing mixing ratio and height.

```fortran
IF(FIRST) THEN
   LASTMIX=W(I)
   LASTHEIGHT=LIST(I,2)
   FIRST=.FALSE.
   GO TO 60
```

Multiply average water in each layer by the thickness of each layer and sum the layers to determine total precipitable water.

```fortran
ELSE
   H2O=H2O+(((W(I)+LASTMIX)/2)*((LIST(I,2)-LASTHEIGHT)/.98))
   LASTMIX=W(I)
   LASTHEIGHT=LIST(I,2)
END IF
```

CONTINUE
If more than 7 layers are missing, assign -99.0 (missing) to precipitable water (H2O).

IF(W15.EQ.-99.0.OR.LIST(15,2).EQ.-99.0).AND.COUNT.GE.7)
  *H2O=-99
IF(COUNT.GE.9)H2O=-99.

Test for unreasonable data.

IF((H2O.NE.-99.0).AND.(H2O.GT.40.0 .OR.H2O.LE.0 .I ) ) Then
  WRITE(6,78)H2O

RUN
RETURN
END

***************************************************************************
SUBROUTINE ADVECTION
***************************************************************************

This is a subroutine to calculate thermal advection from raob sounding based on the change of wind direction and magnitude with height. It figures thermal advection in two layers. It first figures thermal advection for the 850 to 700 mb. levels, then for the 700 to 500 mb. level. Then it averages the values in the two layers. It calculates both warm and cold advection in each layer and also an absolute value for each layer.

VARIABLE DIRECTORY:

MAN(I,J) = Mandatory data, where:
  I = Level (as defined in the main program)
  J = Parameter (as defined in the main program)

ADV = The absolute thermal advection value.
COLD = Cold advection value.
WARM = Warm advection value.
LOW(J) = Lower level parameters of each layer considered
HIGH(J) = Upper level parameters of each layer considered
HALFWARM(I) = Warm advection for each layer.
HALDCOLD(I) = Cold advection for each layer.
HALFADV(I) = The absolute value for advection for each layer
H = The thickness of each layer.
TEMP = Average temperature of the layer.
ANGLE = The radian measure of the angle created by the difference in wind directions between the bottom and the top of each layer.
SHEAR = The shear vector between the two winds.
TG = Temperature gradient.
XISO = The cross-isotherm component of the wind.
SIGN = The sign (+ or -) of variable ANGLE.

SUBROUTINE ADVECTION(MAN,ADV,COLD,WARM)
INTEGER LOW(5),HIGH(5)
REAL H,HALFADV(2),HALDCOLD(2),HALFWARM(2),MAN(3,5)
LOGICAL SWITCH

DO 5 I=1,2
  SWITCH=.FALSE.
  DO 4 J=1,5

RETURN
END
LOW(J) = MAN(I,J)
HIGH(J) = MAN(I+1,J)

Check for missing data and assign -99 to advectrons.
*HIGH(4).EQ.-99.0.OR.HIGH(5).EQ.-99.0) THEN
HALFADV(I) = -99.0
HALFCD(I) = -99.0
HALFWA(I) = -99.0
GO TO 5
END IF

Calculate thickness of layer.
H = HIGH(I) - LOW(I)

Calculate average temperature of the layer.
TEMP = ((LOW(2) + HIGH(2))/2) + 273

Find angle change of wind as you go up. If two points
staddle 360 degrees, I am in trouble, so in that case, I
will add 360 degrees to those between 0 and 90, then
subtract to find the difference.
IF (LOW(4).GT.270.0.OR.HIGH(4).GT.270.0).AND.(LOW(4).LT.90.0.
*HIGH(4).LT.90.0) THEN
IF (LOW(4).LT.90.0) LOW(4) = LOW(4) + 360
IF (HIGH(4).LT.90.0) HIGH(4) = HIGH(4) + 360
END IF
IANGLE = ABS(HIGH(4) - LOW(4))
IF (IANGLE.GT.180.0) THEN
IANGLE = 360.0 - IANGLE
SWITCH = .TRUE.
END IF
ANGLE = IANGLE * .0174533

Calculate the shear vector using the law of cosines.
SHEAR = SQRT((LOW(5)**2 + HIGH(5)**2 - (2*LOW(5)*HIGH(5)*COS(ANGLE))))

Calculate thermal gradient which is (shear/thickness)*
(coriolis parameter*average temperature)/acceleration
of gravity.
TG = (SHEAR * 18000 / TEMP) / (H*9.8)

Calculate the cross isotherm component of winds which is
derived from the law of sines.
IF (SHEAR.EQ.0) SHEAR = SHEAR+.00001
XISO = (LOW(5)*HIGH(5)*(SIN(ANGLE)))/SHEAR

Calculate the thermal advection in degrees per hour.
(3600 seconds in one hour).
HALFADV(I) = TG * XISO / 3600

Determine whether advection is warm or cold. If winds back
with height, there is cold advection; warm, veer.
SIGN = HIGH(4) - LOW(4)
IF (SWITCH) SIGN = -SIGN
IF (SIGN.GT.0) THEN
HALFWA(I) = HALFADV(I)
HALFCD(I) = 0
END IF
IF (SIGN.LE.0) THEN
HALFWA(I) = 0
HALFCD(I) = HALFADV(I)
END IF
Average low advection and high advection.

\[
\text{ADV} = \frac{\text{HALFADV}(1) + \text{HALFADV}(2)}{2}
\]

\[
\text{COLD} = \frac{\text{HALFCOLD}(1) + \text{HALFCOLD}(2)}{2}
\]

\[
\text{WARM} = \frac{\text{HALFWARM}(1) + \text{HALFWARM}(2)}{2}
\]

Test for unreasonable values.

\[
\text{IF} (\text{ADV} \lt 0 \text{ OR } \text{ADV} \gt 10) \text{ AND } (\text{ADV} \neq -99.0) \text{ THEN}
\]

\[
\text{WRITE}(6,7) \text{ADV}
\]

END IF

RETURN

END

*******************************************************************************

SUBROUTINE TO CALCULATE K-INDEX
*******************************************************************************

SUBROUTINE STABLE(MAN,KINDEX,SPREAD)

This subroutine calculates K-index which is:
850 mb. temperature - 500 mb. temperature + 850 mb. dew point - 700 mb. dew point spread.

VARIABLE LIST:

\[
\text{TEMP8} = 850 \text{ mb. temperature.}
\]

\[
\text{TEMP7} = 700 \text{ mb. temperature.}
\]

\[
\text{TEMP5} = 500 \text{ mb. temperature.}
\]

\[
\text{RH8} = 850 \text{ mb. relative humidity.}
\]

\[
\text{RH7} = 700 \text{ mb. relative humidity.}
\]

\[
\text{KINDEX} = \text{K-index.}
\]

\[
\text{SPREAD} = 850 \text{ mb. dew point spread.}
\]

\[
\text{ES8} = \text{Saturation vapor pressure at 850 mb.}
\]

\[
\text{ES7} = \text{Saturation vapor pressure at 700 mb.}
\]

REAL MAN(3,5),KINDEX

\[
\text{IF}(\text{MAN}(3,2) \leq -99.0 \text{ OR } \text{MAN}(2,3) \leq -99.0 \text{ OR } \text{MAN}(2,2) \leq -99.0 \text{ OR } \text{MAN}(1,3) \leq -99.0 \text{ OR } \text{MAN}(1,2) \leq -99.0) \text{ THEN}
\]

\[
\text{KINDEX} = -99.0
\]

\[
\text{SPREAD} = -99
\]

GO TO 30

END IF

Put array variables into variables.

\[
\text{TEMP7=MAN}(2,2)
\]

\[
\text{TEMP5=MAN}(3,2)
\]

\[
\text{RH7=MAN}(2,3)
\]

\[
\text{TEMP8=MAN}(1,2)
\]

\[
\text{RH8=MAN}(1,3)
\]
Calculate saturation vapor pressure at 850 and 700 mb.
\[
E_{58} = 10^{((9.286 - \frac{2322.378}{TEMP8 + 273}))}
\]
\[
E_{57} = 10^{((9.286 - \frac{2322.378}{TEMP7 + 273}))}
\]

Calculate dew points.
\[
DP8 = \frac{2322.378}{9.286 - \log_{10}((RH8/100) \times E_{58})} - 273
\]
\[
DP7 = \frac{2322.378}{9.286 - \log_{10}((RH7/100) \times E_{57})} - 273
\]

Calculate K-index.
\[
K_{INDEX} = TEMP8 - TEMP5 + DP8 - (TEMP7 - DP7)
\]

Test for unreasonable values.
\[
\text{IF}((K_{INDEX} > 100 \text{ OR } K_{INDEX} < -100) \text{ AND } (K_{INDEX} \neq -99.0)) \text{ THEN}
\]
\[
\text{WRITE}(6,10) \text{ KINDEX}
\]
\[
\text{ENDIF}
\]
\[
\text{IF}((\text{SPREAD} > 60 \text{ OR } \text{SPREAD} < -0.5) \text{ AND } (\text{SPREAD} \neq -99.0)) \text{ THEN}
\]
\[
\text{WRITE}(6,20) \text{ SPREAD, TEMP8, RH8}
\]
\[
\text{FORMAT}(X, 'TROUBLE! SPREAD = ', F10.2, '9X, 'TEMP8 = ', F10.2/
\]
\[
\times 9X, 'RH8 = ', F10.2)
\]
\[
\text{ENDIF}
\]
\[
30 \text{ RETURN}
\]

*** * SUBROUTINE VORTICITY * *
*** * VARIABLE DIRECTORY * *

This subroutine calculates relative vorticity values based on the direction and magnitude of the 500 mb wind vectors for the three rawinsonde stations as described in the main program. Recall that the main program "rotates" the winds to the west to simplify calculations. Therefore, I refer to the stations by name as if the wind is coming from the west.

********************

VDIR= the average vector direction the wind blows.
VDIR(J) = The direction the wind blows from in compass directions.
CHANGE= Direction change between Lander and Boise. Positive means counterclockwise.
V#= Velocities at stations in meters per second.
AVEV= Average wind velocity of Lander and Boise.
ADIR= Average wind direction of Lander and Boise in compass direction
DCHANGE= Absolute value of wind direction change between the Lander/Boise average and Great Falls.
DV= The wind velocity change between the Lander/Boise average and Great Falls.
THEDA= conversion of CHANGE to radians.
R= The radius of curvature of the wind streamline. Positive means counterclockwise.
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

Test individual winds to see if they straddle 360 degrees
If so, add 360 degrees to the ones between 0 and 90 degrees
and subtract to get change in direction.

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

Change knots to meters per second.
V1=VEL1*.514
V2=VEL2*.514
V3=VEL3*.514

Average velocities at Lander and Boise.
AVEV=(V3+V2)/2

Here, I calculate the change in velocity between Great
Falls and the average velocity calculated above, but I use
only the component parallel to the streamline flow.
ADIR=(DIR2+DIR3)/2
DCHANGE=ABS(ADIR-DIR1)*.0174533
DV=AVEV-((COS(DCHANGE))*V1)

In this method, if the wind blows from the west,
counterclockwise flow is positive, but if the wind blows
from the east in counterclockwise flow I must change the
signs on CHANGE and DV to get them to come out positive.
So, I test for east flow and also for flow from the other
two quadrants which correspond to east flow after rotation.

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

Change degrees to radians.
THEDA=.0174533*CHANGE

Calculate the radius of curvature of the streamline.
IF(THEDA.EQ.0)THEDA=THEDA+.00001
R=S/THEDA

And (finally) calculate vorticity. Here, I multiply by
\(10^5\) to get a workable number and I add 10.3 which is the
vorticity caused by the rotation of the earth at 45
degrees latitude.
VORT=((DV/N)+(AVEV/R))*100000+10.3

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
```