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Eugene L. Peck

U. S. Department of Commerce
Environmental Science Services Administration
Western Region, Weather Bureau

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PREFACE

This report comprises a dissertation submitted by the author to Utah State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering. The author is assigned as Research Hydrologist, Western Region, Weather Bureau, ESSA, Salt Lake City, Utah.

The study has been based on observations obtained during a cooperative evaporation project conducted from 1962 to 1966 by the U. S. Forest Service, Department of Agriculture and the Weather Bureau, ESSA, Department of Commerce. The study was conducted on the Davis County Experimental Watershed of the U. S. Forest Service near Farmington, Utah. Special thanks are extended to the Forest Service for permission to use the data for the dissertation.

ACKNOWLEDGMENTS

My first thanks go to my dear wife who has given me the support, love and understanding that were so deeply needed during my many years of graduate work.

I would like to express my thanks to my Graduate Committee, Dr. Jay M. Bagley, Chairman, Dr. Rex L. Hurst, Dr. Gaylen L. Ashcroft, Professor Jerald E. Christiansen and Professor Joel Fletcher, who gave so freely of their time and efforts. My thanks also to Professor A. Ronald McKay for his many suggestions and assistance.

I am very appreciative of the support and for the scholarship arranged for by William E. Hiatt, Associate Director, U. S. Weather Bureau for Hydrology and his staff. Excellent support and assistance were also furnished by Hazen H. Bedke (formerly H. D. Spangler), Director, Western Region, U. S. Weather Bureau and members of the regional staff.

Special thanks are extended to Dr. Otis Copeland, Dale Pfankuch, Dr. Norbert DeByle, Alden Blain, Richard Green and the many other permanent and part-time employees of the U. S. Forest Service who worked on the evaporation project. Their cooperation and assistance were sincerely appreciated.

To Marilynn W. Gianelo, Statistical Clerk, U. S. Weather Bureau, go my deepest respect and thanks. During the entire

project, she contributed greatly to any success that was achieved. In addition, she was responsible for most of the physical preparation of the final report.

My personal thanks are also extended to the many others who assisted in so many ways on the project or in the review and editing of the final report.

Eugene L. Peck

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ABSTRACT

Influences of Exposure on Pan Evaporation in a Mountainous Area

by

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Utah State University, 1967

Major Professor: Dr. Jay M. Bagley
Department: Civil Engineering

The effects of exposure on pan evaporation rates were studied at the Davis County Experimental Watershed near Farmington, Utah, by operating a network of 12 class A evaporation stations on the watershed during the summer months of 1962 through 1966. Standard Weather Bureau observations on a daily basis were obtained from a total of 17 different sites representing widely diverse topography with a vertical range of 4,630 feet.

Deviations from mean relations with elevation on monthly values of observed meteorological factors were found to be related to the type of exposure. Dewpoint observations on different slopes were found to be related not only to the differences in station exposure but also to the stability of the air and direction of the upper air flow.

Two commonly-used methods for estimating monthly pan evaporation were found to be within 3 and 6 percent of observed values from the mountain area. Estimates of daily pan evaporation using the mass transfer equations derived from the Lake Hefner and Lake Mead water-loss investigations were found to over-estimate and under-estimate for different types of exposures. The errors in the daily estimates were related to the type of exposure and stability indices.

Revised mass transfer equations were found to correlate well with daily and 2-hourly pan evaporation rates when type of exposure was considered. Further improvement was obtained in the reliability of the mass transfer equations when the daily data were segregated on the basis of the direction and speed of the 700-millibar level wind.

Pan evaporation for the network stations for open locations on top of major ridges and along their southern slopes and on sites subject to strong night time drainage winds were found to have no discernable variation with elevation. For protected sites and those on northern slopes, pan evaporation showed a small decrease with increasing elevation.

The effect of elevation (atmosphere pressure) independently on evaporation rates was investigated through the use of data from stations where the other meteorological factors involved, other than pressure, were the same. The study indicated that pan evaporation increases with increase in pressure, all other factors considered being the same.

(144 pages)

INTRODUCTION

A large percentage of the precipitation that falls over mountainous areas is lost to the atmosphere by evaporation. A knowledge of the variation of the amount of the water removed by the evaporation process with time and space is necessary if we are to make maximum utilization of our water resources.

Need for research in mountainous areas

Most of the results of the studies of evaporation and evapotranspiration during the past few years have not been tested or applied to the mountainous areas of the Western United States. This has been primarily due to the lack of basic data. For these mountainous areas, measurements of evaporation and evapotranspiration rates are very limited, as are the observations of the meteorological factors normally associated with these studies.

Potential evapotranspiration is important for studies of water use by hydrologists, ecologists, foresters and others and has been defined by Thornthwaite, Mather and Carter (1958) as:

> "The only standard measures of evapotranspiration are those from a large vegetation-covered land surface with adequate moisture at all times. This condition defines potential evapotranspiration or water need; since moisture is not restricted, potential evapotranspiration is limited solely by available energy." (Thornthwaite and Hare, 1965, p. 168).

Evaporation from shallow free water surfaces may be used as an index to potential evapotranspiration as described above (Kohler, Nordenson, and Baker, 1959). However, there are very few measurements of evaporation from shallow lakes and reservoirs in mountain areas and estimates for this factor are necessary.

Many methods for estimating lake or free water evaporation have been developed. These include those based on water budget analysis, energy budget considerations, mass transfer methods, combinations of aerodynamic and energy balance approaches and the use of pan and lysimeters with empirically developed coefficients.

The most common extensively tested method for estimating lake evaporation has been the use of an aerodynamic equation or what is also referred to as a mass transfer equation. Following the comprehensive water-loss investigation at Lake Hefner, Oklahoma (U. S. Geological Survey, 1954), Kohler, Nordenson and Fox (1955) developed a new mass transfer equation and tested it for locations throughout the United States. Procedures for correlating meteorological factors with pan and lake evaporation were also developed. These procedures were based on the work of Penman (1948) who combined the aerodynamic and energy balance approaches to eliminate the need for water surface temperature measurements. The Lake Mead water-loss investigations, U. S. Geological Survey Professional Paper No. 298 (1958), were a continuation of the Lake Hefner studies.

These investigations further tested the validity of the mass transfer equation and the procedures for estimating lake evaporation.

In mountainous areas, due to drainage winds and other local effects, the time distribution of wind movement is not the same on the mountain slope as that observed in the valley below. It can be assumed that equations developed from data at valley stations are not directly applicable to stations on the mountain slope.

Maps of annual lake evaporation have been prepared by various researchers for the United States (Myers, 1942 and Kohler, Nordenson and Baker, 1959). Those by Kohler, Nordenson and Baker (1959) utilized procedures developed earlier by these authors to estimate lake and pan evaporation using meteorological observations from U. S. Weather Bureau stations throughout the country. These annual evaporation maps provide the most accurate generalized estimates of evaporation available. However, the authors did state that the reliability of the maps was lower for areas of high relief (mountainous areas) than for areas in the plains region. Only limited data were available from stations above 5,000 feet mean sea level. These data were from valley locations and provided little information on the amount, or variability, of evaporation in the mountainous areas.

The use of present procedures for application to mountainous areas would also be somewhat difficult without further testing. Blaney (1958) and Longacre and Blaney (1961) found that pan evaporation from higher elevations in southern California decreased with increasing elevation. Christiansen (1966) in his procedure for estimating monthly pan evaporation based on world-wide data, applies a correction term which increases with elevation. The effect of this correction is to increase the estimated evaporation by 3 percent for each 1,000 foot increase in elevation above 1,000 feet mean sea level. As the results of the first two studies indicate a decrease in the evaporation with elevation and the latter study indicates an increase, clearly further study is necessary.

Scope of present study

As indicated previously, there has been very little research or basic data collected on evaporation rates in mountainous areas. Many of the more advanced techniques that have proven to be of value for lower, relatively flat areas do not appear to be applicable to the rugged topographic conditions of the higher mountain areas. These techniques generally require highly specialized measurements of wind and moisture gradients and are based on assumptions that would not be expected to be met in the mountainous areas. Some of these assumptions are that the wind speed and moisture distribution in the vertical are logarithmic and that atmospheric lapse rates be essentially adiabatic.

Because of the many possible complicating factors, it was decided that the present study, being a pilot project for mountainous terrain, should be limited to investigating the validity of the more commonly used methods.

The first requirement was for adequate reliable basic data. To obtain this data, standard procedures were used to collect data from observationsl sites with as large a variation in exposure and elevation as possible.

Objectives

The objectives of the present study are:

1. To determine the variation of the more important meteorological factors affecting evaporation in mountainous areas.
2. To evaluate the validity of commonly used mass transfer equations for estimating pan evaporation in mountainous areas and modify existing equations where possible.
3. To investigate the effect of elevation (atmosphere pressure) independently on evaporation rates through the use of data from stations where the other meteorological factors involved, other than pressure, are the same.

REVIEW OF LITERATURE

Use of mass transfer equations

Literature on the use of mass transfer or aerodynamic equations for estimating pan evaporation is very extensive. The basis for the use of the aerodynamic equations was very early recognized (Dalton, 1798). Rowher (1931) reviewed the use of aerodynamic equations up to that date. Most of these were of the general form:

$$E = (a + b\,U)\,(e_s - e_a) \qquad (1)$$

where E is the monthly evaporation, U a wind movement factor, e_s the saturation vapor pressure of the air or the saturation vapor pressure of air corresponding to the water temperature, e_a the observed vapor pressure of the air, and a and b are empirically determined constants.

Rowher (1931) developed the equation:

$$E = (1.465 - 0.0186\,B)\,(0.44 + 0.118\,U)\,(e_s - e_a) \qquad (2)$$

where B is the mean station barometric reading in inches of mercury. As stations are located at different elevations and the mean station barometric readings correspond to the elevation of the stations, this equation considers the effect of elevation on evaporation. The other symbols in the equation are as defined above.

Penman (1948) in his paper, "Natural evaporation from open water, bare soil and grass," presented additional theoretical basis for the empirical equations developed by Dalton. He combined the aerodynamic and energy balance approaches to eliminate the need for water temperature observations. This equation is:

$$E = \frac{1}{\Delta + \gamma} (Q_n \Delta + \gamma E_a) \qquad (3)$$

where Δ is the slope of the saturation vapor-pressure versus temperature curve at the air temperature T_a, E_a is the evaporation given by the aerodynamic equation, assuming water temperature (T_o) equal to air temperature (T_a), Q_n is the net radiant energy expressed in the same units as those of E, and γ is defined from Bowen's (1926) dimensionless ratio, R:

$$R = \gamma \frac{T_o - T_a}{e_o - e_a} \qquad (4)$$

The subscript "o" is used to represent the pan water surface and e_o is the saturation vapor pressure of the air corresponding to the water temperature.

Anderson, Anderson and Marciano (1950) presented an excellent review of evaporation theory and development of instrumentation prior to the Lake Mead water-loss investigations.

The Lake Hefner, Oklahoma, studies, U. S. Geological Survey Professional Paper No. 269 (1954) shows that the daily evaporation in inches from a class A Weather Bureau evaporation pan could be quite accurately estimated through the use of the equation:

$$E_p = (e_o - e_a)\ (0.42 + 0.0040\ U_p) \qquad (5)$$

where E_p is the daily pan evaporation in inches, e_o is the saturation of air at the temperature of the water surface, e_a as defined above, and U_p the wind movement above the pan in miles per day. Kohler, Nordenson and Fox (1955) found that the error between the estimated and observed evaporation when using the Lake Hefner mass transfer equation correlated with vapor pressure differences. Using graphical techniques they found that by introducing an exponent for the vapor pressure term, the errors were reduced. They arrived at the following equation:

$$E_p = (0.37 + 0.0041\ U_p)\ (e_o - e_a)^{0.88} \qquad (6)$$

Kohler, Nordenson and Fox (1955) also found that Rohwer's (1931) correction for elevation could be removed through the use of the exponent on the vapor pressure difference term. They indicated that this was true since the vapor pressure generally decreases with increases in elevation (decrease in pressure). However, decreasing the vapor pressure term exponent has the same effect as increasing the wind term effect. Since wind speed may also have a correlation with elevation, the reason could be due to this relation rather than that of vapor pressure.

Other authors have empirically determined that the vapor pressure difference term is exponentially related to evaporation. Himus (1929) found that the exponent term should be 0.83. Millar (1937) indicated the fundamental fact in a true mass transfer approach, the evaporation should be proportional to the difference in vapor concentration rather than vapor pressure difference. He also showed that the vapor pressure concentration to the unity power would be approximately the same as the vapor pressure difference to the 0.83 power. Other investigators (Sellers, 1965) using basic turbulent transfer theory of water vapor have indicated that the exponent should be unity.

The revised mass transfer equation of Kohler, Nordenson and Fox (1955), equation 6, and their pan and lake evaporation estimating procedures were checked with the data collected during the Lake Mead water-loss investigations. The results of these tests proved that the equations and procedures were valid for the Lake Mead area.

Braslavskii and Vikulina (1954) developed the following formula from observations made using very large pans of 20 and 100 square meters in area:

$$E = 0.13\ (e_o - e_{200})\ (1 + 0.72\ U_{200}) \qquad (7)$$

where E is in millimeters per day, e_o the saturation vapor pressure in millibars at the given water temperature, e_{200} the vapor pressure in millibars at 2 meters, and U_{200} the wind velocity in meters per second at the 2-meter level. They found the greatest errors were for evaporation for evaporation pans situated in arid regions. These errors reached 25 to 30 percent and were negative (underestimated) in sign. The majority of the cases (75 percent) had errors which did not exceed 8 to 10 percent. They also stated that the rate of water loss from the large pans is not affected by the pans. This is not the case for evaporation pans of smaller surface area.

Both groups of the above mentioned investigators (Braslavskii and Vikulina, 1954 and Kohler, Nordenson and Fox, 1955) found that the estimates using mass transfer equations will either over or underestimate when applied to different geographic locations. In general, the predicted evaporation for the dry-arid regions is underestimated. Pruitt (1963) found a similar result from lysimeter and pan evaporation studies at Davis, California. On days with strong north winds, which blow from a drier region, the dewpoints are generally much lower than average, and the evaporation is greater than computed.

Priestly, McCormick and Pasquill (1958) stated that most theoretical formulae are non-linear combinations of fundamental variables which are themselves often interrelated. Thus, the insertion of mean values into a formula does not, in general, provide the best estimate of evaporation.

Sellers (1965) discussed the effect of using daily average values of wind movement with saturation and actual vapor pressure in theoretical equations. He concluded that estimates of evaporation rates were generally too low. This results from averaging the values when there is a large difference in the diurnal variation. The vapor pressure difference between pan water surface and the atmosphere is normally large when the stronger winds are observed during the day and normally small in value when the winds at night are relatively light. Tanner and Pelton (1960) have indicated that overall results could be obtained if separate estimates were made for the night and day time periods.

Approaches other than the mass transfer equation or the combination of the aerodynamic and energy balance methods have been used to develop methods for predicting pan evaporation. One example is that used by Christiansen and Mehta (1965). This procedure uses the theoretical radiation and adjustment coefficients based on empirically derived equations for air temperature, wind movement, humidity, sunshine, elevation and the month of the year.

Stability effects on evaporation rates

Munn (1961) presented an excellent summary of the mass transfer theory of evaporation. In his discussion of the basic considerations regarding evaporation he stated:

> The rate of diffusion of water vapour away from a moist surface will depend upon the wind speed, the intensity of eddy activity, and the size distribution of the eddies. When there is no horizontal gradient of water vapour, the wind speed has no direct influence on the rate of evaporation. Indirectly, however, increased wind leads to increased eddy energy,

> permitting the water vapour to be transferred upward more rapidly. The ease with which eddies may move vertically in the atmosphere depends upon the stability of the air. (Munn, 1961, p. 10)

The assumption that increased wind speed leads to increased eddy energy may not hold true for mountainous areas. Down-canyon drainage winds are quite often very shallow in depth and the vertical wind speed profile may show decreasing wind speed rather than the normal increasing wind speed with increasing height above ground.

Williams (1961) has discussed the simplified mass transfer equation:

$$E = K \frac{f(U)\ (e_s - e_a)}{f(Z_o)} \tag{8}$$

where

E = evaporation rate

$f(U)$ = function of wind velocity

$f(Z_o)$ = roughness parameter

e_s = vapor pressure at surface

e_a = vapor pressure of air at some level above the surface, and

K = constant (which includes air density and air pressure terms)

The difficulty in using this type of basic equation lies in evaluating the roughness parameter $f(Z_o)$. The values of the roughness parameter Z_o found for the Lake Hefner study varied from 0.55 to 1.15 centimeters. Priestly (1959) showed that the roughness parameter for a snow cover varied from 0.005 centimeters for smooth snow on short grass to 0.10 centimeters for snow surfaces on natural prairie. In a mountainous area it would be difficult to make a measurement of the roughness parameter of the surface under consideration. It is not clear whether the height of the mountains themselves or the surface characteristics of the mountain slope is important.

Webb (1966) found some association between a bulk Richardson number and the ratio of actual lake evaporation to observed pan evaporation. The Richardson number refers to the stability of the air mass above the surface under consideration as is defined as:

$$Ri = \frac{g}{\theta} \frac{\frac{\partial \theta}{\partial Z}}{\left(\frac{\partial U}{\partial Z}\right)^2}$$

where θ is the potential temperature, g the gravitational constant, U the horizontal wind velocity and Z the elevation. The number represents the ratio of the work done against gravitational stability to energy transformed from mean to turbulent motion.

The Lake Mead water-loss investigations (1958) showed that stability was a significant factor when wind data, measured above the vapor blanket at the surface of the lake, was used in the aerodynamic equation. When wind values taken within the vapor blanket itself were used in the aerodynamic equation, stability did not appear to be an important factor. This indicates that the rate at which the moisture is dissipated from the region above the vapor blanket is significant, as the Richardson number relates directly to the physical mechanism which causes the moisture removal. The consideration of air mass stability and its effect on evaporation has not been used in conjunction with the mass transfer approach to any great extent.

The process of evaporation from a water surface is essentially governed by the fundamentals of simultaneous mass, energy and momentum transport processes. Sellers (1965) stated that there are large differences in the time of occurrence of maximum heat flux and maximum momentum flux. Research by Hales, Dickson and Hand (1961) considering air above the Great Salt Lake Desert found the heat flux to be a minimum at sunrise, increasing to a maximum during the late afternoon and decreasing rapidly near sunset; conversely, the momentum flux has a maximum at sunrise, decreasing to a minimum during the afternoon and increasing slowly to sunset. The increase in the heat flux was found to be proportional to the logarithm of the negative Richardson number whereas the decrease in the momentum flux was determined to be approximately proportional to the absolute value of the Richardson number.

Richardson's (1920) development of his dimensionless stability index was made on the basic assumption that the exchange coefficients for heat and momentum transfer were equal. This assumption has since been proven invalid

(Ellison, 1957). Hansen (1966) discusses the factors that adversely affect the use of the value of the Richardson number as a stability index. He also lists revisions that have been made to the original work by Richardson. He states that the accurate determination of the Richardson number is highly dependent upon the proper evaluation of the vertical gradients of wind and potential temperature in the first few meters of the atmosphere above the surface. Failure to take into account the terrain over which the flow occurs also lead to erroneous evaluation of the stability regime. More simplified versions of the Richardson number have been used by Deacon (1949) and Lettau and Davidson (1957) to define the stability regime.

Effect of pressure on evaporation rates

Nordenson (1966) summarized the effects of increasing altitude (decreasing pressure) on various parameters and the resulting influence on evaporation rate:

1. Air temperature tends to decrease, evaporation rate to decrease.
2. Wind movement tends to increase, evaporation rate to increase.
3. Potential short-wave radiation increases, potential evaporation tends to increase. In mountainous areas because of prevalent clouds the radiation, and hence the evaporation rate, tends to decrease.
4. Long-wave radiation tends to decrease, evaporation

rate to decrease.

5. Vapor pressure of the moisture in the air decreases, evaporation rate tends to increase.

It is generally accepted that evaporation decreases with increasing altitude, although not as much as would be indicated by the decrease in air temperature.

Variation of meteorological factors in mountainous areas

The meteorological factors affecting evaporation from a water surface are basically those due to temperature, humidity, wind and radiation. In addition, the successful prediction of evaporation based on station pan evaporation must necessarily follow standardized observational and equipment techniques.

Temperature. A very complete discussion of temperature variations in mountainous areas was reported by Hann (1903). He discussed average monthly lapse rate with increased elevation and found that (1) the rate of decrease is greater for southern slope stations than those on northern slopes; (2) diurnal ranges of temperatures are generally less on mountain sides as compared with valley locations; and (3) on mountain slopes the nights are much milder and the days are less cool than at locations in mountain valleys.

Dickson (1959) found a good relation (correlation coefficient of 0.97) between elevation and July mean temperatures for the Southern Applachian Mountain region of the Eastern United States.

The above references relate to temperature only and not necessarily the effect of temperature on evaporation.

Wind. Many reports concerning mountain and canyon drainage winds are reported in the literature. Hawkes (1947) made a study of the canyon wind patterns in the mountain valleys near Salt Lake City, Utah, just to the south of the present study area reported in this work. The primary wind feature was the canyon drainage winds which occur practically every night, and are strongest during clear weather. Temperature and moisture distribution patterns are related to the drainage wind movements. Koresawa (1960) has described the occurrence of drainage winds in Japan and the associated horizontal and vertical temperature lapse patterns. One of the important findings with respect to evaporation is that the vertical lapse rates of temperature have been found to be significantly different with upslope and downslope drainage winds. This variation of the vertical lapse rate is one of the reasons why the assumptions of near adiabatic lapse rate conditions would not be valid for drainage wind locations.

Radiation

A summary of atmospheric radiation has been prepared by Bliss (1961). The variation of radiation for various exposures is a primary reason for many of the differences that are measured in meteorological factors. Frank and Lee (1966) have presented a method for computing the potential solar radiation for mountain slope locations. The variation of radiation energy in forested areas has been discussed by Reifsnyder and Lull (1965).

Equipment and observational methods

Many of the published records, especially those at mountain locations where daily observers were not available, were not observed on a daily basis or in accordance with standard techniques. Hook gages for the measurement of evaporation rather than point gages were used in many instances and the observers would allow the water level in the pan to decrease considerably before refilling the pan. Nordenson and Baker (1962) and Bonython (1950) have shown that the evaporation rate from a pan varies with decrease in the water level. Bonython reported a 15 percent variation for a 5 cm difference in the level of the water and Nordenson and Baker a 9 percent decrease when the water was maintained 4.5 inches below the level of the rim of the pan as compared with the recommended standard of 2 to 3 inches.

Type of pan has been reported by Nordenson and Baker (1962) to cause variation in the measured evaporation rates. Stainless steel pans were found to have evaporation about 6 percent less than the standard galvanized-iron pan. Monel metal pans were within one percent of the standard class A pan.

PROCEDURE

Description of evaporation stations

During the spring and early summer of 1962, a network of 12 class A pan evaporation stations was established on the U. S. Forest Service Davis County Experimental Watershed located in the Wasatch Mountain Range midway between Ogden and Salt Lake City, Utah. The watershed is located just east of Great Salt Lake within an area of approximately 8 x 5 miles. Station number 1 is located in the town of Farmington, Utah, and is typical of evaporation stations commonly found in the Intermountain West. This station has been considered to be the control or base station. Elevations of the evaporation stations varied from 4,334 to 8,960 feet mean sea level. Within this range of elevations, the climate varies from semidesert to subhumid, and the vegetation from sagebrush-grass to aspen-fir types. The topography is generally steep and rough.

A listing of the 12 original stations, those which were installed later and others in the immediate area, is given in Table 1. The locations of all stations in the study area are shown on a map with contours (Figure 1).

Stations 1, 2, 3 and 4 are within an airline distance of 3.6 miles of each other and provided an elevation profile with a vertical range of 4,630 feet over widely diverse topography. The remaining eight of the original stations

Table 1. Names and identification numbers of evaporation stations

Station	Network number	Weather Bureau alpha number
<u>In study area</u>		
Farmington Warehouse	1	42-2726
Halfway Lower	2	42-3574
Farmington Rice	3	42-2725
Upper Halfway	4	42-8943
East Chicken Creek	5	42-8941
West Chicken Creek	6	42-5222
Upper Snow Course	7	42-8947
Farmington Parrish Field Station	8	42-2727
Parrish South	9	42-6700
Centerville Canyon	10	42-1362
Buckland-SE	11	42-1015
Buckland-NW	12	42-1014
Miller Creek	14	42-5274
Steed Creek	15	42-8271
Parrish Mouth	16	42-6698
Gold Ridge	18	42-3252
Davis Creek	19	42-2042
<u>Other stations</u>		
Morgan	13	42-5826
Farmington Bay	17	42-2729
Saltair	20	42-7578

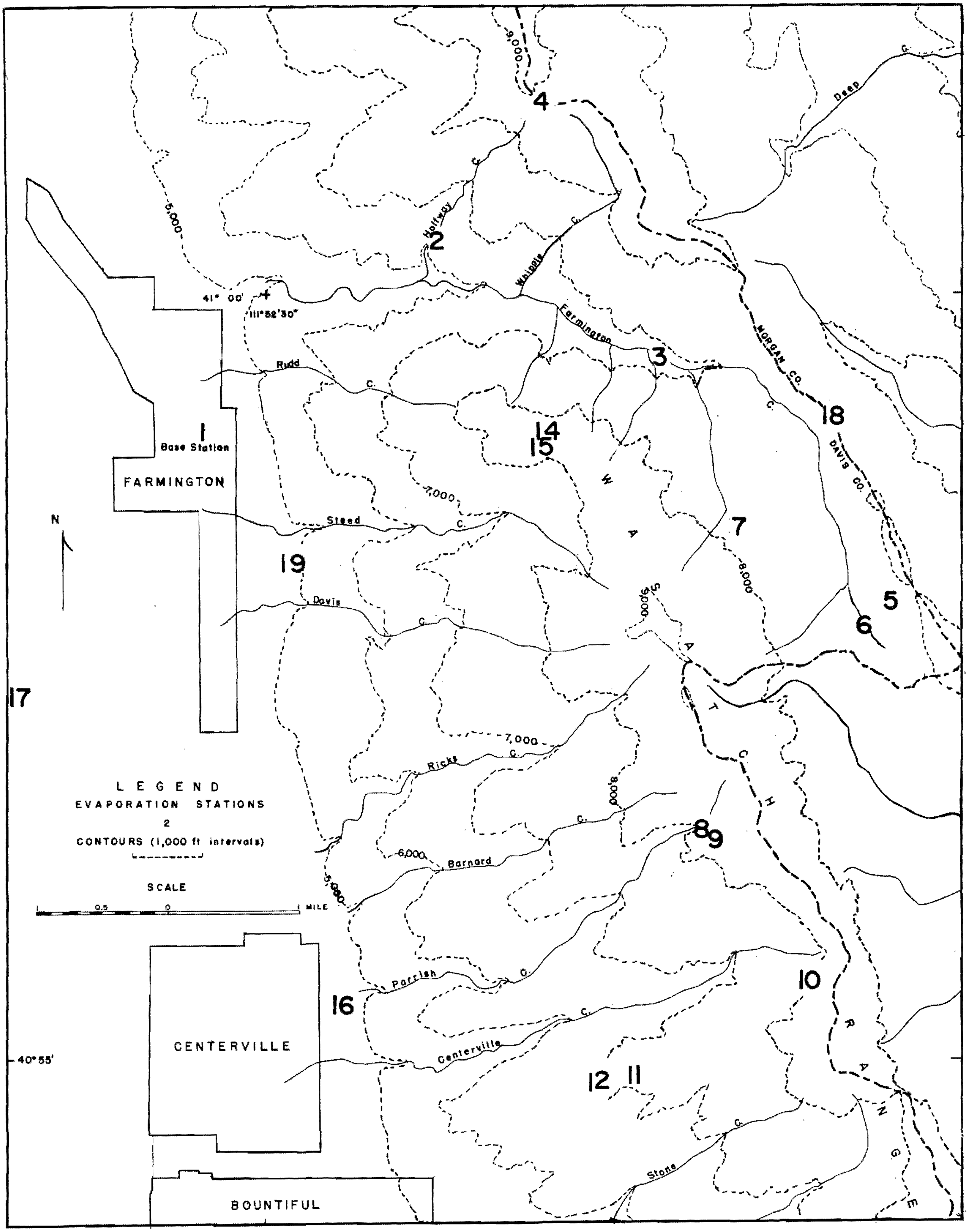


Figure 1. General topography and study area and location of evaporation stations

on the experimental watershed were located in pairs at approximately the same elevation and with similar vegetation types, but with different exposures as to orientation and topography.

The network of stations was operated for five summer periods (1962 through 1966 inclusive). Changes in locations of some stations were made at different times during this period in order to obtain information on additional type of exposures. Following the first summer season, stations 5, 6 and 10 were removed. Stations 14 and 15 (Figure 1) were installed to obtain a pair of stations on the north and south slopes of the major east-west ridge on the watershed. Station 16 was located at the mouth of Centerville Canyon to evaluate the effect of the strong drainage winds and to provide additional information at lower elevation. Before the start of the 1965 summer season, stations 7 and 10 were removed and stations 18 and 19 were installed. Station 18 was located on the major drainage divide on the eastern side of the watershed to provide information on a ridge location in the lee of the major mountain ridge line. Station 19 was placed at a lower elevation on the western face of the general slope of the mountain where it would not be affected directly by drainage winds from a canyon.

Class A evaporation stations were installed at Morgan and Farmington Bay Bird Refuge, Utah, during the study period. Station number 13 was assigned to Morgan, Utah, and number 17 to Farmington Bay Bird Refuge, Utah. The station at Morgan, Utah, is situated in a small valley community at an elevation of 5,070 feet. The Farmington Bay Bird Refuge is located near large wildlife water areas at an elevation of 4,205 feet (location is shown on Figure 1).

For convenience, all reference to the Salt Lake City Weather Bureau Airport Station will be as station 21. This station is located at an elevation of 4,220 feet mean sea level. Complete weather observations are taken at this station including two rawinsondes and two windsondes at alternate 6-hourly periods. However, no evaporation measurements are made.

All stations were uniform in size, 16 by 20 feet, and were enclosed by a 6-foot chain link fence topped by three strands of barbed wire to exclude large wildlife species and to discourage disturbance and vandalism.

Each station was equipped with standard U. S. Weather Bureau equipment, including a 47.5 inch diameter monel metal evaporation pan 10 inches deep with the pan mounted on a lattice platform constructed of 2 x 4-inch lumber. A totalizing anemometer, attached to the platform at a height of 6 inches above the pan rim recorded the wind data. Non-floating Six's thermometers were used to measure the pan water temperature, and standard maximum and minimum thermometers in cotton region shelters to measure the free-air temperatures. These instruments, plus a standard 8-inch rain gage, were located within the enclosure according to instructions in Circular B, U. S. Weather Bureau (1962).

During the initial season, four stations were instrumented with thermographs, four with hygrothermographs, and eight with recording rain gages. During the five years of the project, additional hygrothermographs were installed and all 12 of the stations of the main network had hygrothermographs during the final season.

Four actinometers (Belfort pyrheliographs) were added to the network during the 1963 season. One was maintained at the base station and at stations 2 and 4. The other actinometer was rotated among the remaining stations. A temperature compensated Eppley pyrheliometer with a Brown circular chart recorder, equipped with an integrator, was installed at the base station prior to the 1964 season.

A recording wind speed and direction assembly was erected on a 4-meter mast located on the ridge near station 9. Dial-type anemometers installed on 4-meter masts were located at stations 1 and 3, and occasionally at other stations.

Station characteristics

The locations of the 17 evaporation stations on the experimental watershed provided major differences in station characteristics. The variations in the size of clearing, land slopes, and general aspects of the stations are difficult to define, but some descriptive material is given in Table 2. All stations are located in natural

Table 2. Description of evaporation station sites

Station number	Elevation feet	Slope percent	General aspect	Location
1	4,329	0	None	In town of Farmington
2	6,200	60	S	Steep narrow canyon
3	6,860	5	NW	Large opening in aspen type
4	8,960	0	None	Crest of open ridge
5	7,750	20	W	Small aspen opening
6	7,640	10	N	Large opening in aspen type
7	7,830	15	N	Median opening in aspen type
8	8,060	40	N	Open mountain brush and aspen type
9	8,160	30	S	Open mountain brush and aspen type
10	7,960	25	NW	Medium opening in aspen type
11	7,130	20	SE	Large opening in oakbrush type
12	7,010	35	NW	Small opening in oakbrush type
13	5,070	0	None	In town of Morgan
14	8,340	40	N	Sagebrush type near crest of ridge
15	8,340	40	S	Sagebrush type near crest of ridge
16	4,680	5	W	Bonneville Lake terrace
17	4,205	0	None	At bird refuge headquarters
18	7,600	0	None	Crest of an open ridge
19	4,880	22	W	Bonneville Lake terrace
20	4,210	0	None	At Morton Salt Company

clearings varying in size from approximately 60 by 80 feet to completely clear at the ridge stations numbers 4, 15 and 18. Panoramic photographs of each station are shown in Figures 2-8. These photographs were taken by U. S. Forest Service personnel with each succeeding picture being tilted so that the horizon would be visible. It is very difficult to obtain any real concept of the steepness and roughness of the topography from the photographs of the stations.

Daily measurements

Daily observations were scheduled to begin at the control station at 8:00 a.m. MST and to be completed at all 12 stations by 3:30 p.m. MST. Most observations were usually made within 5 minutes of the scheduled time at each station. Variation in the time of reading from year to year for some stations resulted when stations were relocated.

Each evaporation pan was recharged to the fixed point with water measured to the nearest thousandth of an inch in a graduated plastic cylinder. Total 24-hour wind movement to the nearest one-tenth of a mile, maximum and minimum air and water temperatures to the nearest whole degree and the amount of precipitation (if any) to one-hundredth of an inch were recorded. Point measurements of wind speed and direction, wet and dry bulb psychrometric readings at the shelter height, and estimates of percent of sky covered by clouds, were made at the time of observation. Factors which might affect the interpretation of the records, such

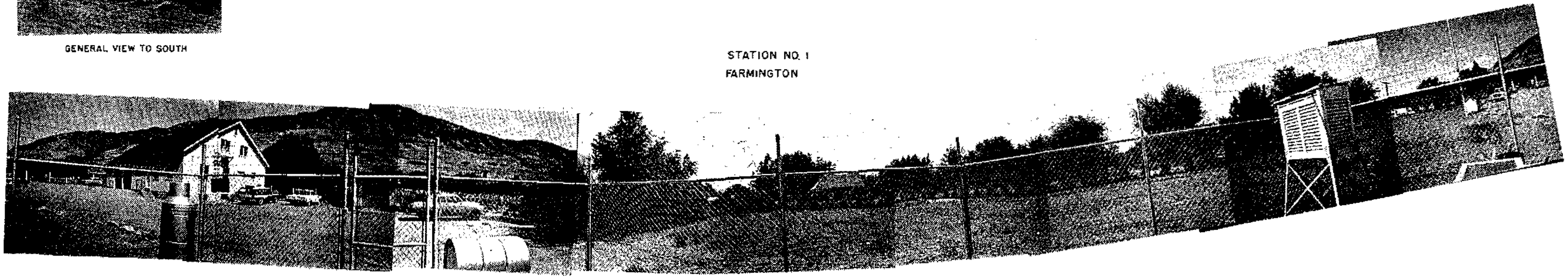
Figure 2. Photographs, stations 1 and 2

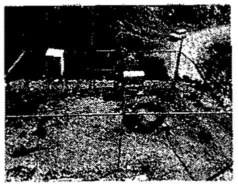
EVAPORATION STUDY

INT-1605-501

GENERAL VIEW TO SOUTH

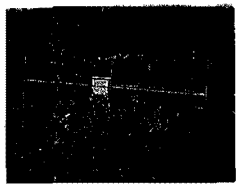
STATION NO. 1
FARMINGTON





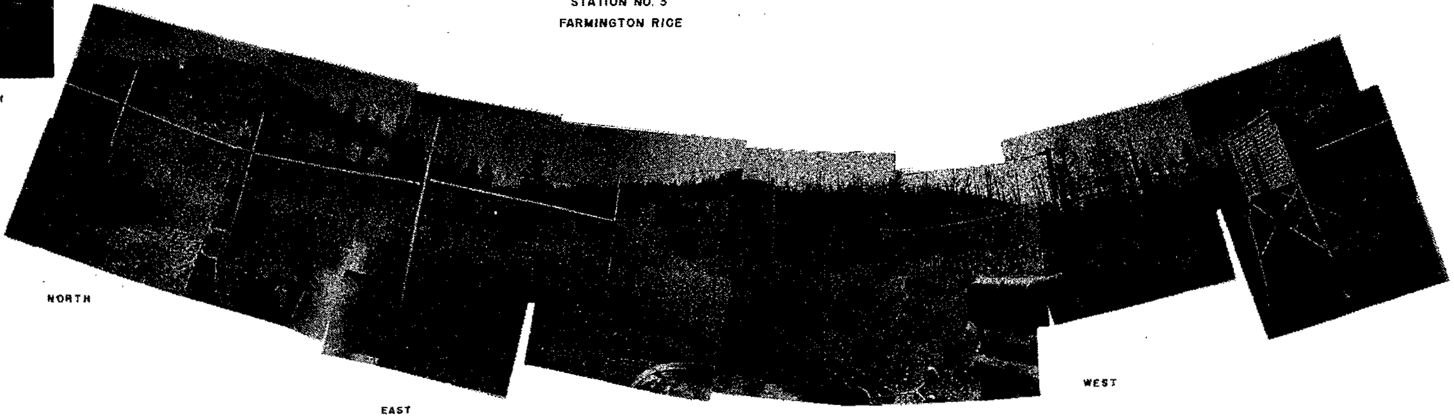
STATION NO. 2
LOWER HALFWAY

Figure 3. Photographs, stations 3 and 4



GENERAL VIEW TO NORTH

STATION NO. 3
FARMINGTON RICE



GENERAL VIEW TO NORTHWEST

STATION NO. 4
UPPER HALFWAY

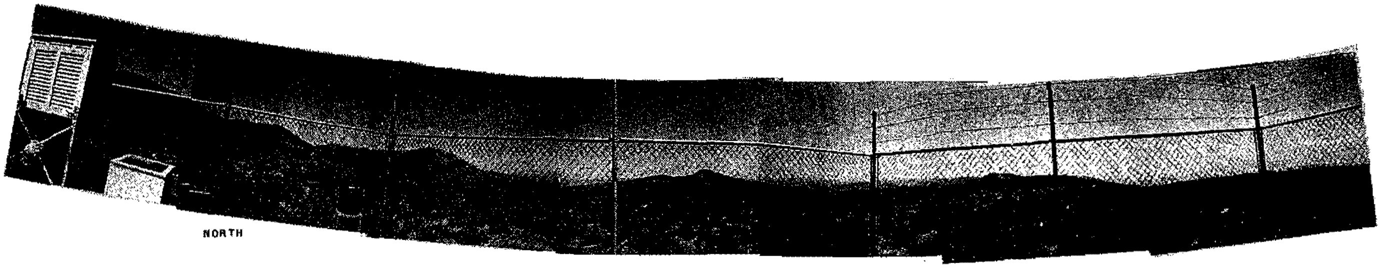
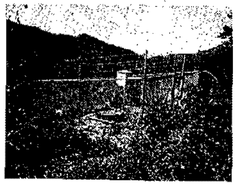
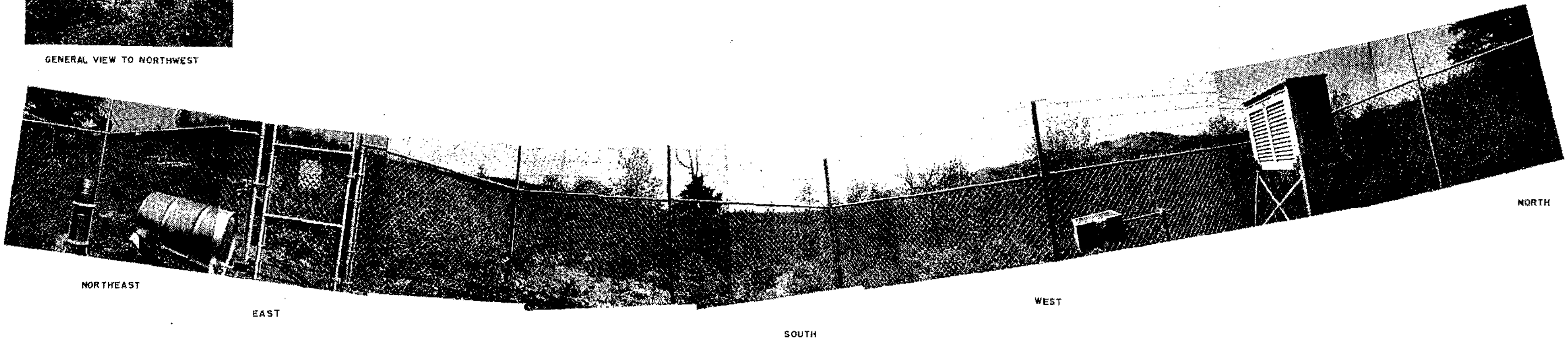


Figure 4. Photographs, stations 5 and 6

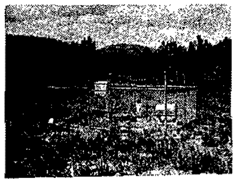
STATION NO. 5
EAST CHICKEN CREEK



GENERAL VIEW TO NORTHWEST



STATION NO. 6
WEST CHICKEN CREEK



GENERAL VIEW TO NORTHWEST

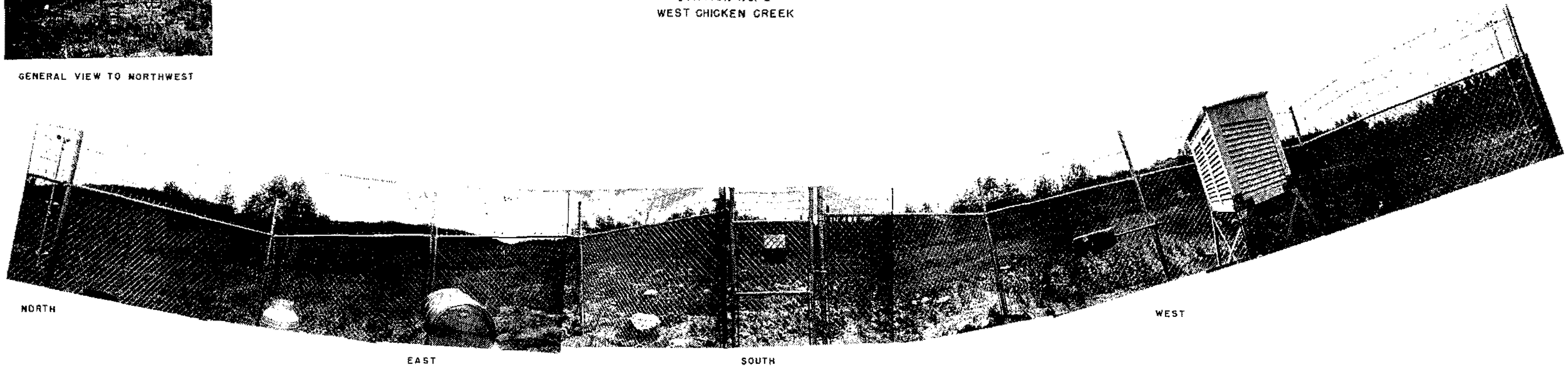
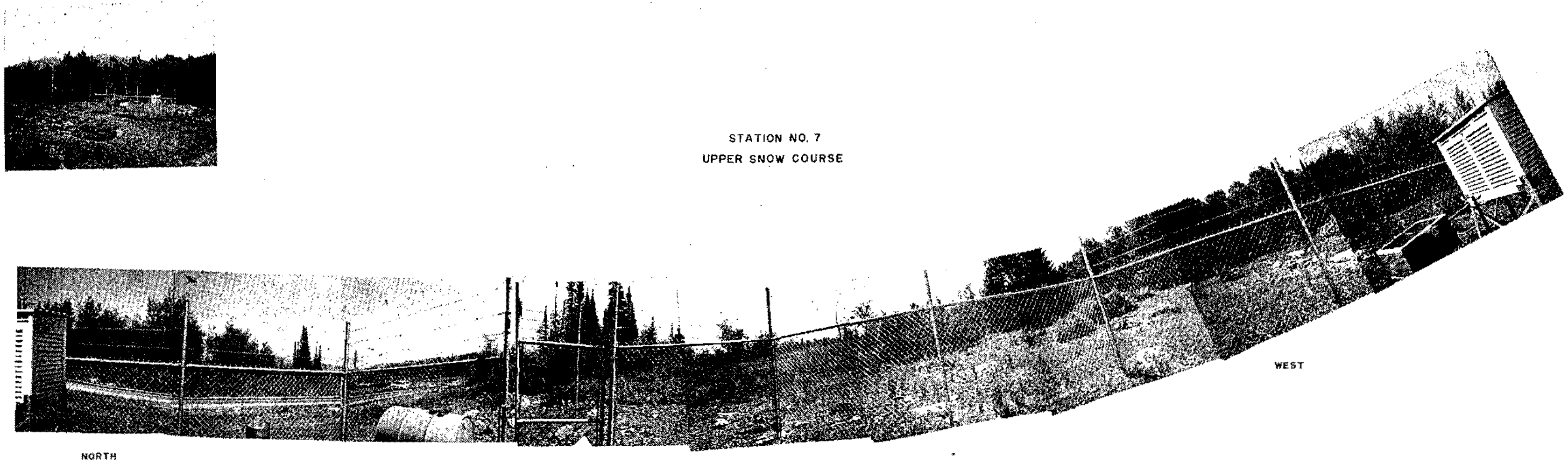


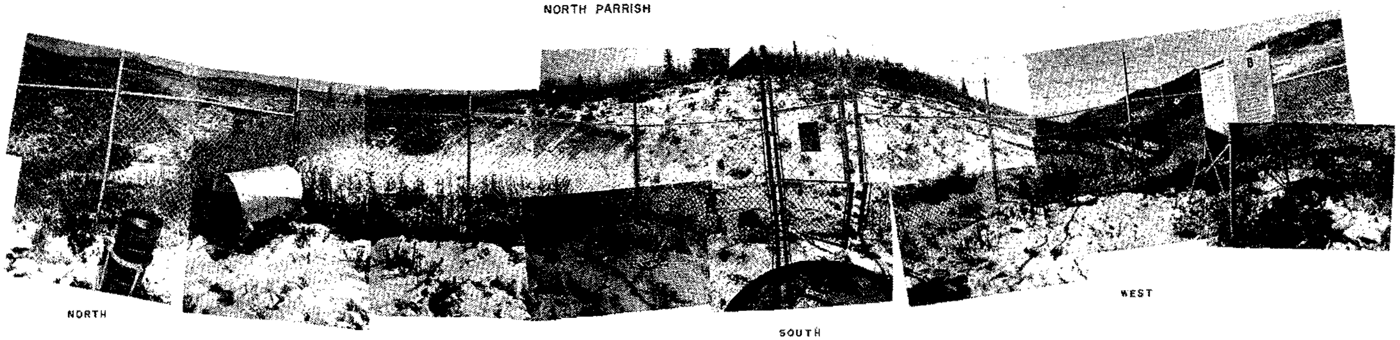
Figure 5. Photographs, stations 7, 8 and 9

STATION NO. 7
UPPER SNOW COURSE

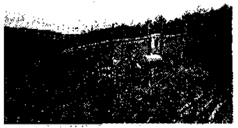


STATION NO. 8
NORTH PARRISH

GENERAL VIEW TO WEST



STATION NO. 9
SOUTH PARRISH



GENERAL VIEW TO SOUTHWEST

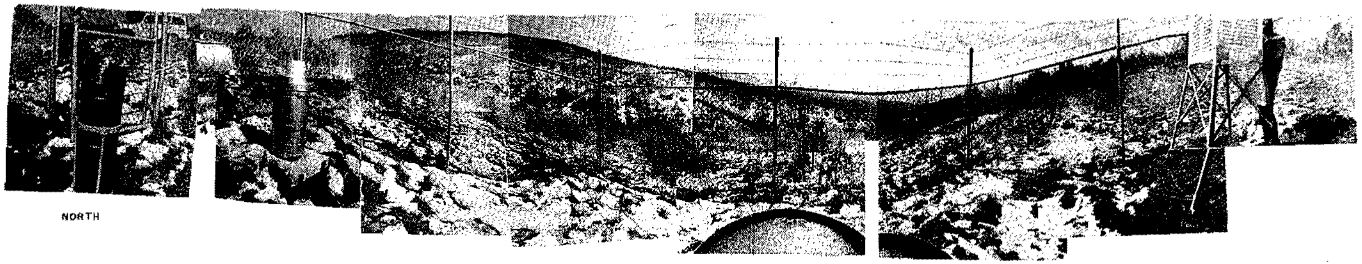
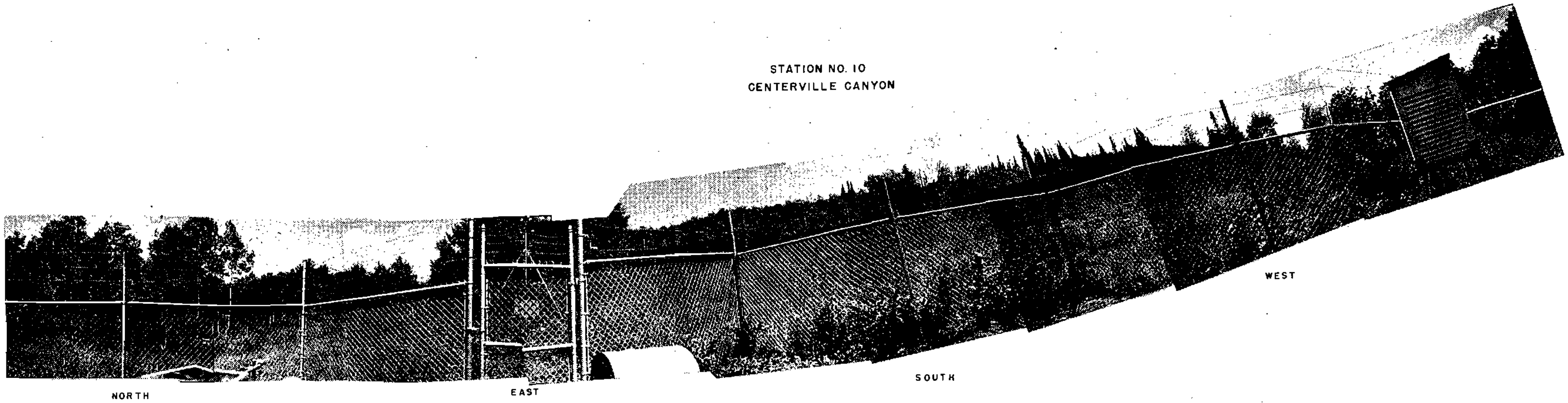
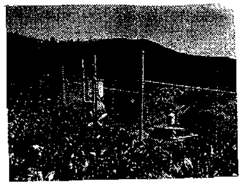


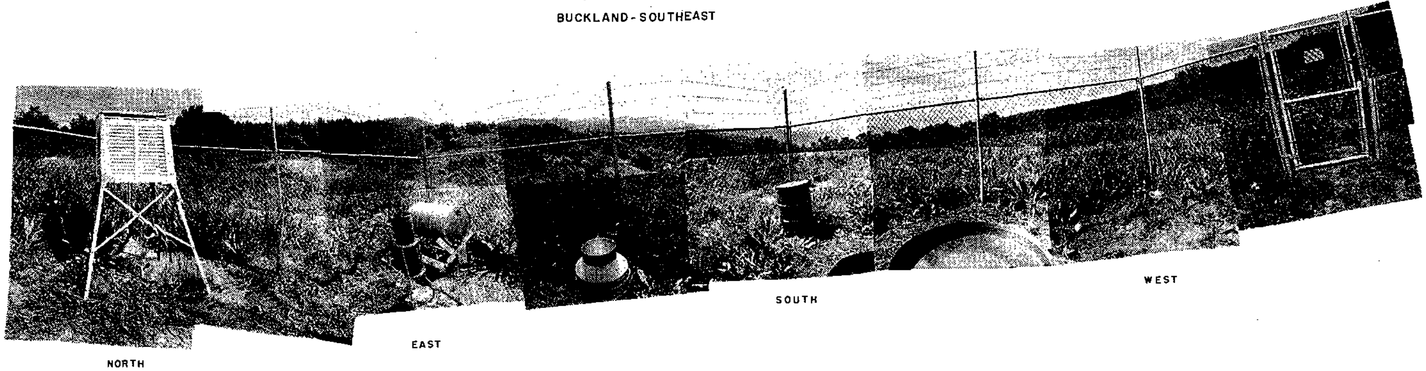
Figure 6. Photographs, stations 10, 11 and 12

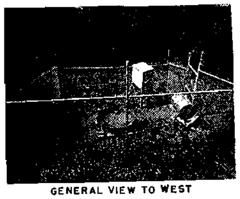
STATION NO. 10
CENTERVILLE CANYON



STATION NO. 11
BUCKLAND - SOUTHEAST


GENERAL VIEW TO EAST




GENERAL VIEW TO WEST

STATION NO. 12
BUCKLAND - NORTHWEST

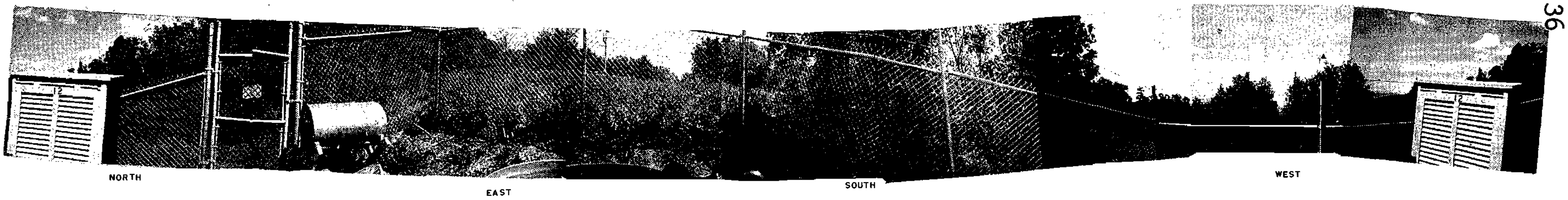
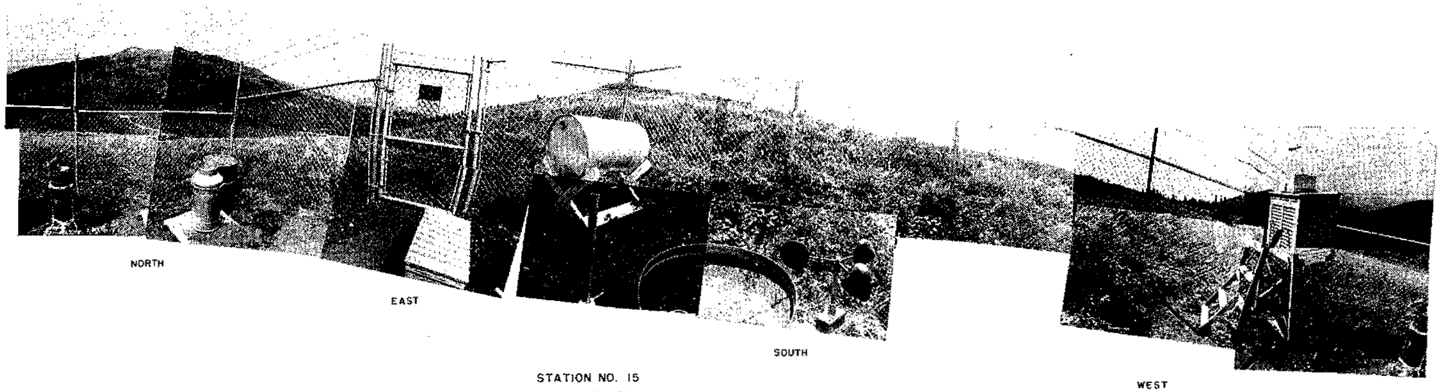


Figure 7. Photographs, stations 14 and 15

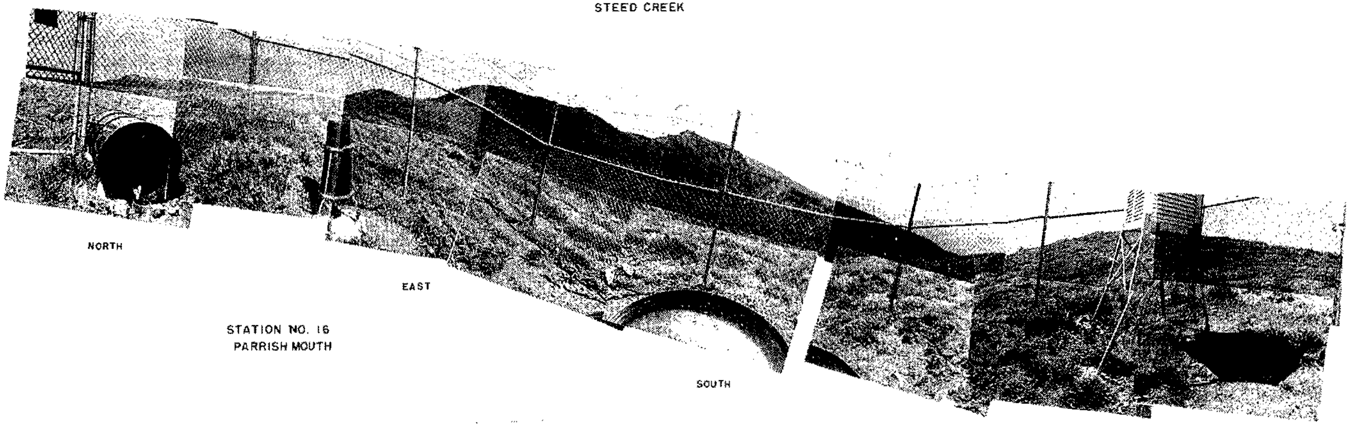
STATION NO. 14
MILLER CREEK

GENERAL VIEW TO NORTH



STATION NO. 15
STEED CREEK

GENERAL VIEW TO EAST



STATION NO. 16
PARRISH MOUTH

GENERAL VIEW TO NORTHWEST

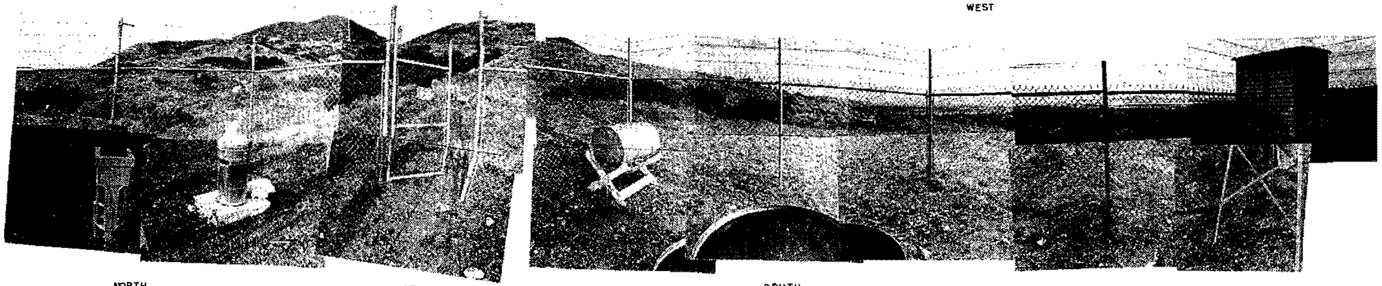
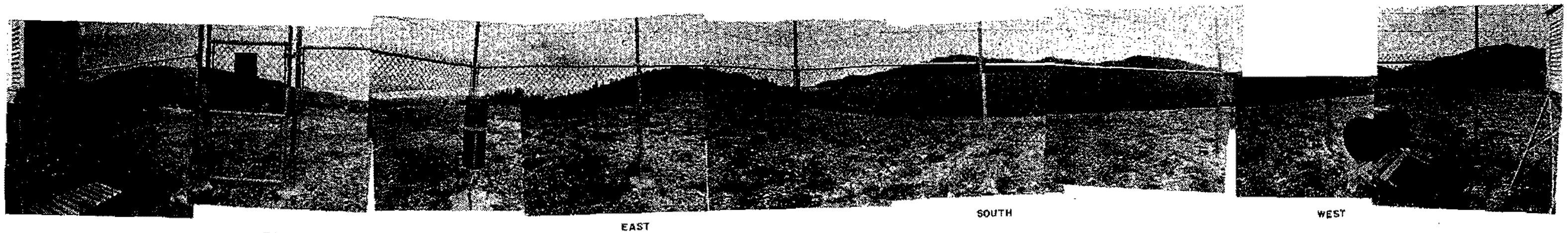


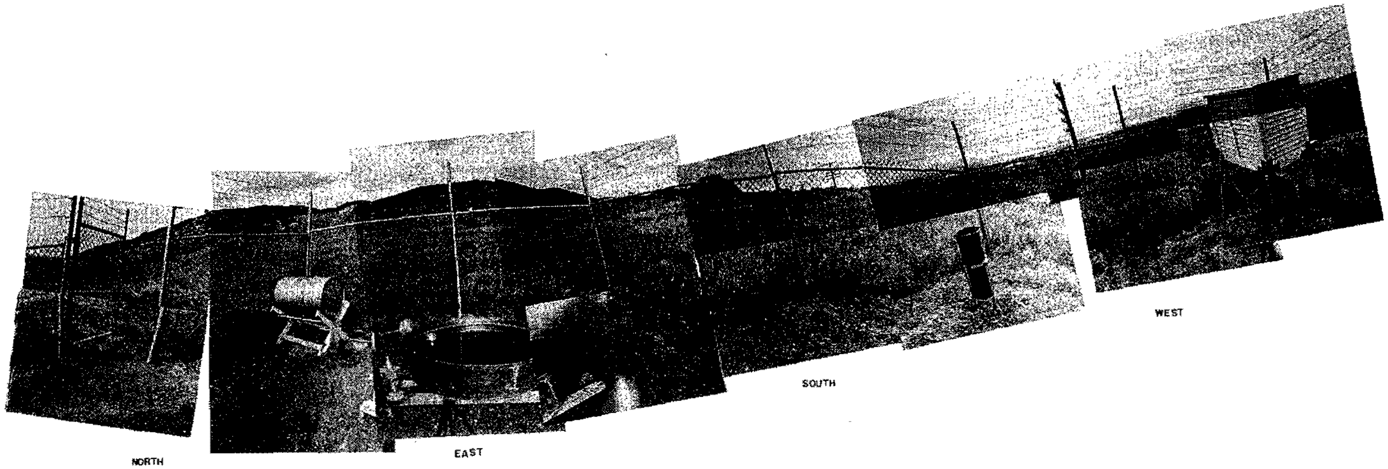
Figure 8. Photographs, stations 18 and 19

STATION NO. 18
GOLD RIDGE



STATION NO. 19
DAVIS CREEK

GENERAL VIEW TO NORTH



as the amount and cause of pan shading, ice formation in the pan, and any evidence of disturbance were also noted.

As a quality control on the hygrothermograph, the observers computed the humidity from the psychrometric readings and checked the value against the chart reading.

Special measurements

In 1962, special hourly observations during daylight hours were taken at each station during one 24-hour period. Simultaneous hourly observations for the same period were made at the base station. During the 1965 summer season two similar sets of 24-hour readings were made at all 12 evaporation stations simultaneously. One set of simultaneous readings for all stations was made during the 1966 season but only during the daylight hours of one calendar day. Overnight observations were recorded during the special observational periods in 1962 and 1965.

Observations of the sun azimuth and vertical angles at sunrise and sunset were made for each station during the 1962 hourly observations. Changes in meteorological events as type and amount of cloud cover, shifts in wind speed or direction, and other phenomena which might provide additional correlative information, were recorded during all hourly observational periods.

Basic data

Standard measurements. The standard observations for a class A evaporation station were placed on a specially prepared punch card. These measurements include:

1. Maximum, minimum and observational time air temperatures.
2. Maximum, minimum and observational time water temperatures.
3. 24-hour pan wind movement
4. Evaporation (read to thousandths of an inch rather than standard reading of one hundredth of an inch), and
5. Precipitation.

Additional data were also placed on the daily cards. These included the 4-meter mast winds where observed, 6-hourly dewpoints and daily radiation in Langleys.

Dewpoint computation. Hygrothermograph traces of temperature and humidity were adjusted by using the observed temperature and psychrometric readings. Using the corrected trace, 6-hourly dewpoints were computed beginning at 5:00 a.m. MST. These times are the regular synoptic weather observation times. Surface and upper-air observations at the Salt Lake City, Utah, Weather Bureau Airport Station are made at these same intervals.

Radiation. Daily radiation values in Langleys were taken from the digital integrator for the Eppley pyrheliometer. Values for the remaining stations were calculated by planimetering the area on the pyrheliograph charts and using factors obtained by calibration of the instruments with the Eppley pyrheliometer.

Hourly measurements

Since it was recognized that the hourly measurements of evaporation would be subject to some degree of error, the values were computed for 2-hourly intervals. Data for the 2-hour periods were placed on punch cards as was done for daily data. Separate cards were punched for each overlapping 2-hour period. For example, one card for the 2-hour period from 8:00 a.m. to 10:00 a.m. and a separate one for 9:00 a.m. to 11:00 a.m.

Identification of stations

All stations were assigned a Weather Bureau identification number (two digits for the state, 42, and four for the station number). These numbers are listed in Table 1. All punch cards contain the identification number, the year, month and day. For the 2-hourly data, the hour ending the period was entered on the card. Tabulations of mean monthly values for all network stations are listed in Table 3.

Table 3. Average monthly values of meteorological factors and computed lake evaporation

Months	Mean air degrees F	Mean water degrees F	Mean dewpoint degrees F	Pan wind movement miles per day	Evaporation inches	Radiation langleys	Computed lake evaporation inches
				Station 1			
	1962-66	1962-66	1962-66	1962-66	1962-66	1964-66	1962-66
June	69.0	58.8	45.1	21.2	.265	609	.193
July	76.2	62.9	46.8	23.2	.306	660	.216
August	73.6	60.9	45.3	22.3	.268	584	.190
September	64.7	53.0	39.9	19.0	.171	476	.122
				Station 2			
	1962-66	1962-66	1963-66	1962-66	1962-66	1964-66	1962-66
June	64.7	65.4	36.3	55.5	.290	604	.196
July	72.4	70.3	40.0	58.7	.355	719	.240
August	69.9	67.5	41.5	59.3	.311	651	.205
September	61.5	59.0	35.8	60.8	.227	516	.144
				Station 3			
	1962-66	1962-66	1966	1962-66	1962-66	1964-66[a]	1962-66
June	53.4	42.5	28.5	137.2	.317		.167
July	60.6	47.1	32.5	118.4	.354	666	.169
August	58.1	46.1	32.4	114.2	.304	610	.151
September	50.1	40.1	26.6	129.3	.246	487	.096

Table 3. Continued

Months	Mean air degrees F	Mean water degrees F	Mean dewpoint degrees F	Pan wind movement miles per day	Evaporation inches	Radiation langleys	Computed lake evaporation inches
				Station 4			
	1962-66	1962-66	1962-66	1962-66	1962-66	1964-66	1962-66
June	53.2	54.9	28.5	137.2	.317	786	.228
July	60.6	60.4	32.5	118.4	.354	820	.248
August	58.1	58.5	32.4	114.2	.304	701	.215
September	50.1	50.3	26.6	129.3	.246	593	.172
				Station 5			
	1962	1962		1962	1962		
June	65.9	67.7		22.4	.262		
July	63.4	66.2		23.9	.242		
August	64.0	63.5		31.3	.234		
September	59.3	57.0		33.3	.187		
				Station 6			
	1962	1962		1962	1962		
June	59.9	66.6		24.9	.256		
July	58.5	65.1		24.1	.240		
August	58.3	62.0		34.7	.234		
September	52.8	54.8		37.8	.183		

Table 3. Continued

Months	Mean air degrees F	Mean water degrees F	Mean dewpoint degrees F	Pan wind movement miles per day	Evaporation inches	Radiation Langleys	Computed lake evaporation inches
Station 7							
	1962-64	1962-64		1962-64	1962-64		
June	55.6	45.9		45.0	.235		
July	61.3	50.5		31.2	.255		
August	60.3	49.7		31.9	.220		
September	53.5	42.4		37.7	.152		
Station 8							
	1962-66	1962-66	1962-66	1962-66	1962-66	1964-66[a]	1962-66
June	55.4	61.2	32.5	48.4	.238	613	.182
July	61.6	66.9	36.7	38.1	.258	696	.196
August	59.1	64.5	36.2	33.5	.225	666	.171
September	51.5	54.2	29.0	36.0	.164	506	.121
Station 9							
	1962-66	1962-66	1962-66	1962-66	1962-66	1965-66[a]	1962-66
June	57.5	61.0	31.8	49.4	.252	656	.185
July	63.9	66.3	35.1	38.7	.274	810	.198
August	61.7	64.4	35.8	34.1	.237	709	.200
September	54.8	55.6	29.2	39.0	.181	698	.129

Table 3. Continued

Months	Mean air degrees F	Mean water degrees F	Mean dewpoint degrees F	Pan wind movement miles per day	Evaporation inches	Radiation langleys	Computed lake evaporation inches
				Station 10			
	1962	1962		1962	1962		
June	65.4	67.9		37.5	.252		
July	60.7	65.9		31.8	.233		
August	62.3	63.1		32.6	.212		
September	57.7	56.2		31.9	.160		
				Station 11			
	1962-66	1962-66	1963-66	1962-66	1962-66	1966[a]	1963-66
June	60.4	66.0	36.9	37.8	.249	676	.182
July	66.6	70.3	40.8	36.6	.287	732	.209
August	64.6	67.3	40.4	36.9	.258	658	.184
September	57.1	58.3	33.1	38.0	.192	514	.132
				Station 12			
	1962-64	1962-64	1963-64	1962-64	1962-64	1964[a]	
June	63.0	65.4	37.7	44.0	.240		
July	69.7	71.4	39.3	41.3	.283	656	
August	68.2	68.5	41.0	41.0	.247		
September	61.5	59.0	33.1	40.1	.172		

Table 3. Continued

Months	Mean air degrees F	Mean water degrees F	Mean dewpoint degrees F	Pan wind movement miles per day	Evaporation inches	Radiation langleys	Computed lake evaporation inches
				Station 14			
	1963-66	1963-66	1965-66	1963-66	1963-66	1964-66[a]	1965-66
June	60.5	63.6	35.2	58.1	.268	711	.197
July	65.5	68.4	40.9	57.8	.291	769	.201
August	61.3	64.0	37.7	62.4	.240	681	.171
September	53.1	54.9	32.9	65.3	.168	495	.111
				Station 15			
	1963-66	1963-66	1965-66	1963-66	1963-66	1964-66[a]	1965-66
June	61.1	61.5	31.3	118.8	.355	790	.246
July	66.0	64.1	36.1	140.4	.398	756	.265
August	61.7	61.6	35.6	118.8	.345	692	.218
September	53.5	52.8	31.6	147.5	.268	551	.180
				Station 16			
	1963-66	1963-66	1963-66	1963-66	1963-66	1964-65[a]	1963-66
June	70.2	69.2	40.9	65.0	.342	587	.250
July	79.5	74.6	42.0	72.3	.432		.284
August	76.1	72.4	42.7	67.6	.374		.267
September	66.8	63.6	37.4	64.0	.256	587	.165

Table 3. Continued

Months	Mean air degrees F	Mean water degrees F	Mean dewpoint degrees F	Pan wind movement miles per day	Evaporation inches	Radiation langleys	Computed lake evaporation inches
				Station 18			
	1965-66	1965-66	1965-66	1965-66	1965-66	1965-66[a]	1965-66
June	59.2	58.7	34.4	129.8	.359	715	.248
July	65.8	63.9	40.0	126.0	.384	702	.262
August	62.1	61.3	39.3	113.0	.332	676	.228
September	52.3	51.5	36.2	138.2	.271		.180
				Station 19			
	1965-66	1965-66	1965-66	1965-66	1965-66	1966[a]	1965-66
June	71.1	70.0	41.9	58.3	.314	715	.215
July	77.7	74.4	44.6	69.2	.373	662	.201
August	73.7	71.6	43.4	58.6	.316	645	.214
September	63.9	62.6	41.3	59.2	.209	503	.133

[a] Few days only

RESULTS

Air temperature relations

Mean temperature. Monthly values of air temperatures were plotted versus elevation to determine its variation with elevation. Samples of these curves for July, August and September 1966 are shown in Figures 9, 10 and 11. Data on these graphs indicate the stations to be divided into two groups in order to best show the temperature-elevation relation. Stations with good drainage located on ridges or steep slopes generally had higher mean temperatures than those which were protected by vegetation and/or had poor drainage. This is in general agreement with the findings of Hann (1903). The two curves on the graph have been used to indicate the general relation for each type of station.

Since observations were made at some stations during 1962 and not during 1965, a composite graph showing the temperature-elevation relation for all stations in the network is shown in Figure 12.

The mean of the upper air temperatures for approximately 5,000 (850-millibar level) and 10,000 (700-millibar level) feet mean sea level for 5:00 a.m. and 5:00 p.m. from the Salt Lake City, Utah, radiosonde runs were also plotted on the graphs.

The relations for the three months were very similar for both groups except for colder temperatures in August

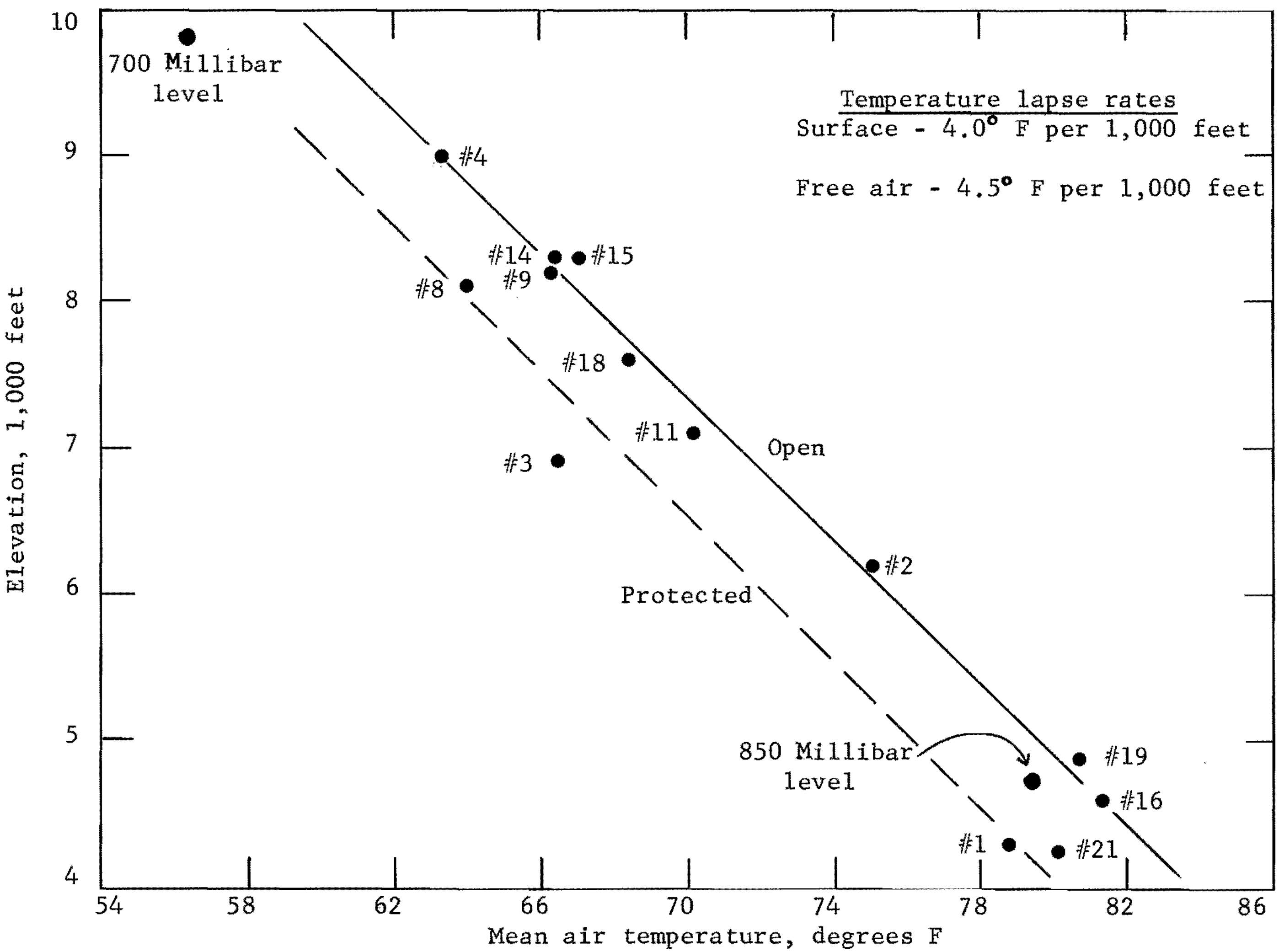


Figure 9. Mean air temperature-elevation relation, July 1966

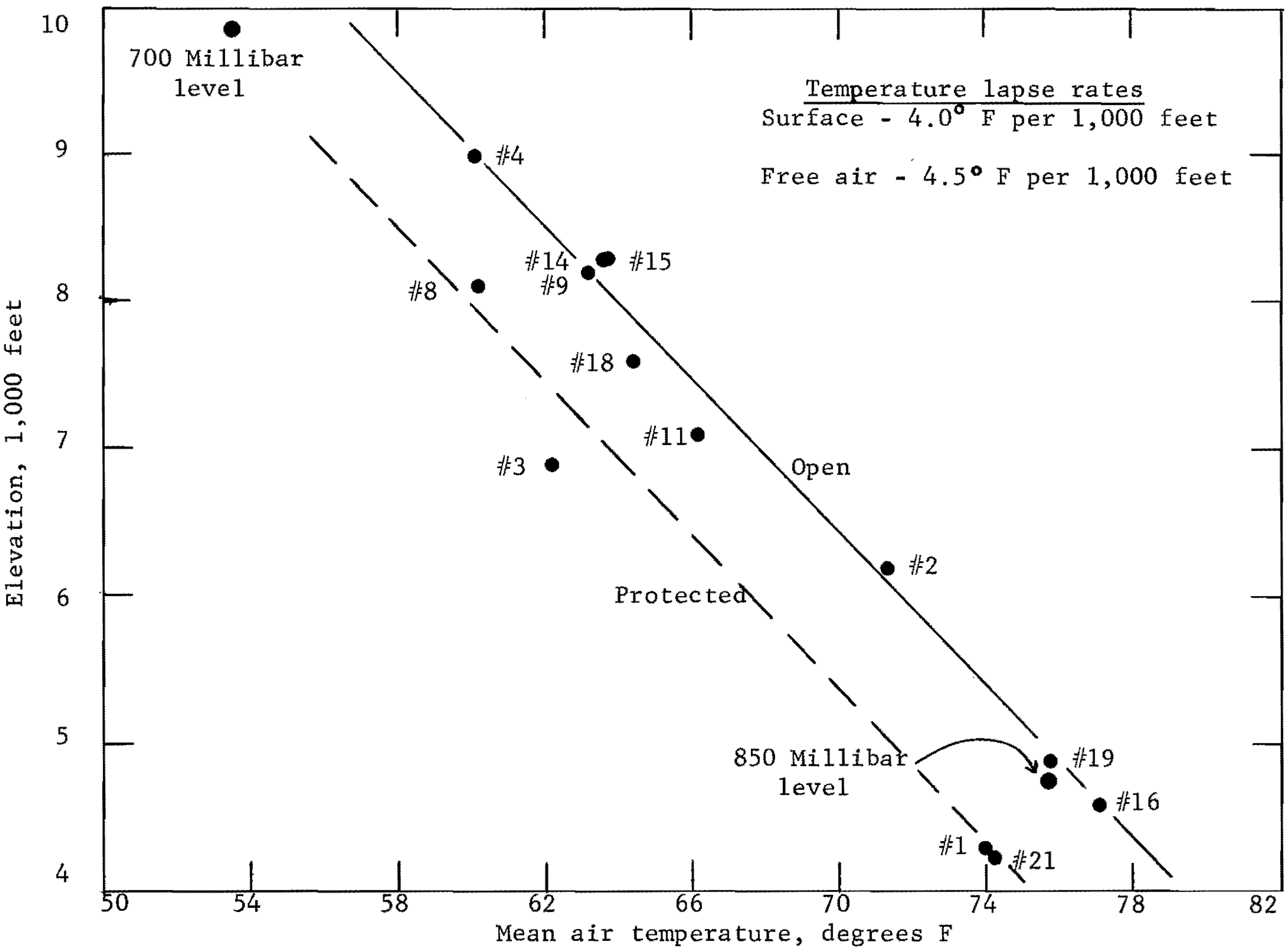


Figure 10. Mean air temperature-elevation, August 1966

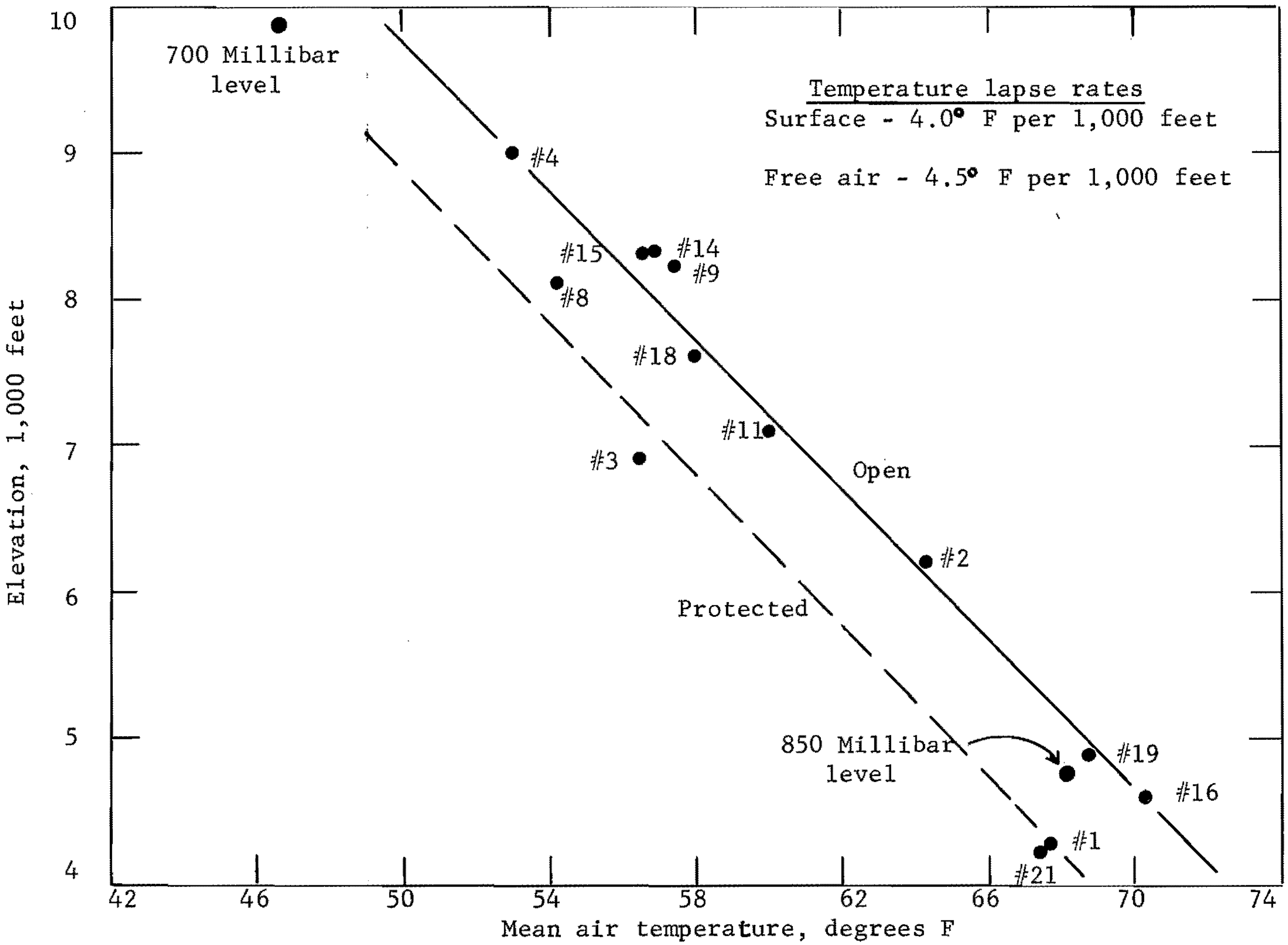


Figure 11. Mean air temperature-elevation relation, September 1966

and September. The lapse rate of temperature was found to be 4 F per thousand feet for both groups of stations and 4.5 F for the mean upper air temperatures.

Maximum and minimum air temperature relations. To investigate the cause of the difference in the mean air temperature relations with elevation as found for the different exposures, curves for maximum and minimum temperature relations were developed in a manner similar to the procedure for mean temperature. Relations for the months of July, August and September 1966 are shown in Figures 13, 14 and 15. A composite relation for July 1962 and July 1966 as prepared for the mean air temperature is shown in Figure 16. Maximum air temperature was found to be well correlated with elevation for all stations. The minimum temperature plottings fell into two groups similar to those experienced for the mean air temperature relations.

The temperature lapse rate for the maximum temperature-elevation relation was 5 F per thousand feet and that for both groups of minimum temperature-elevation curves 3.2 F. Similar plots were made for clear days only during July.[1] The same general characteristics were noted with the lapse rate being slightly less for each set of curves.

Dewpoint relations. A simple plot of dewpoint versus elevation for July 1966 is shown in Figure 17 with the

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[1] Clear days as used in this study are days when all pyrheliographs recorded only smooth curves and no cloudiness was observed at the Salt Lake City Weather Bureau Airport Station.

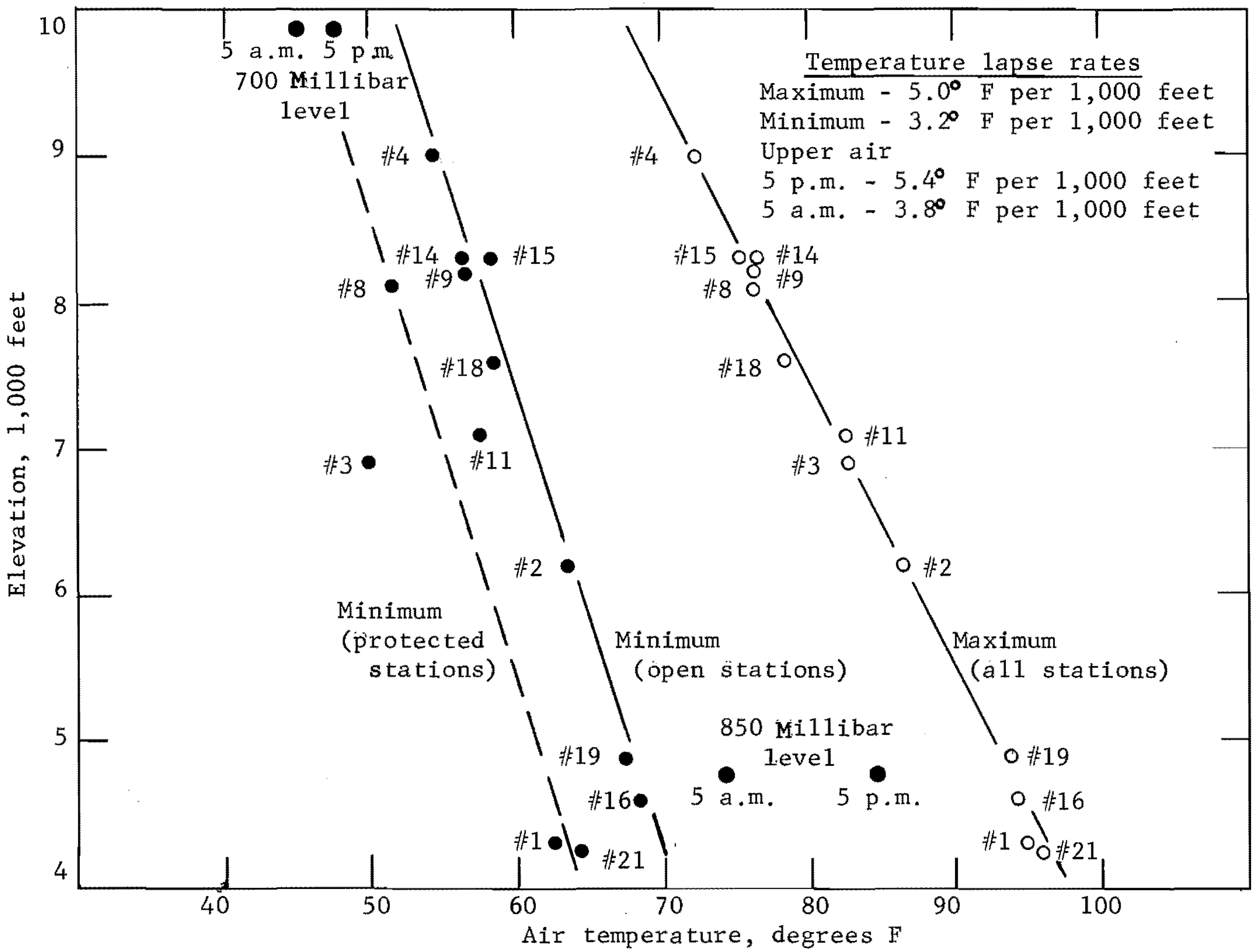

Figure 13. Relations of maximum and minimum temperatures with elevation, July 1966

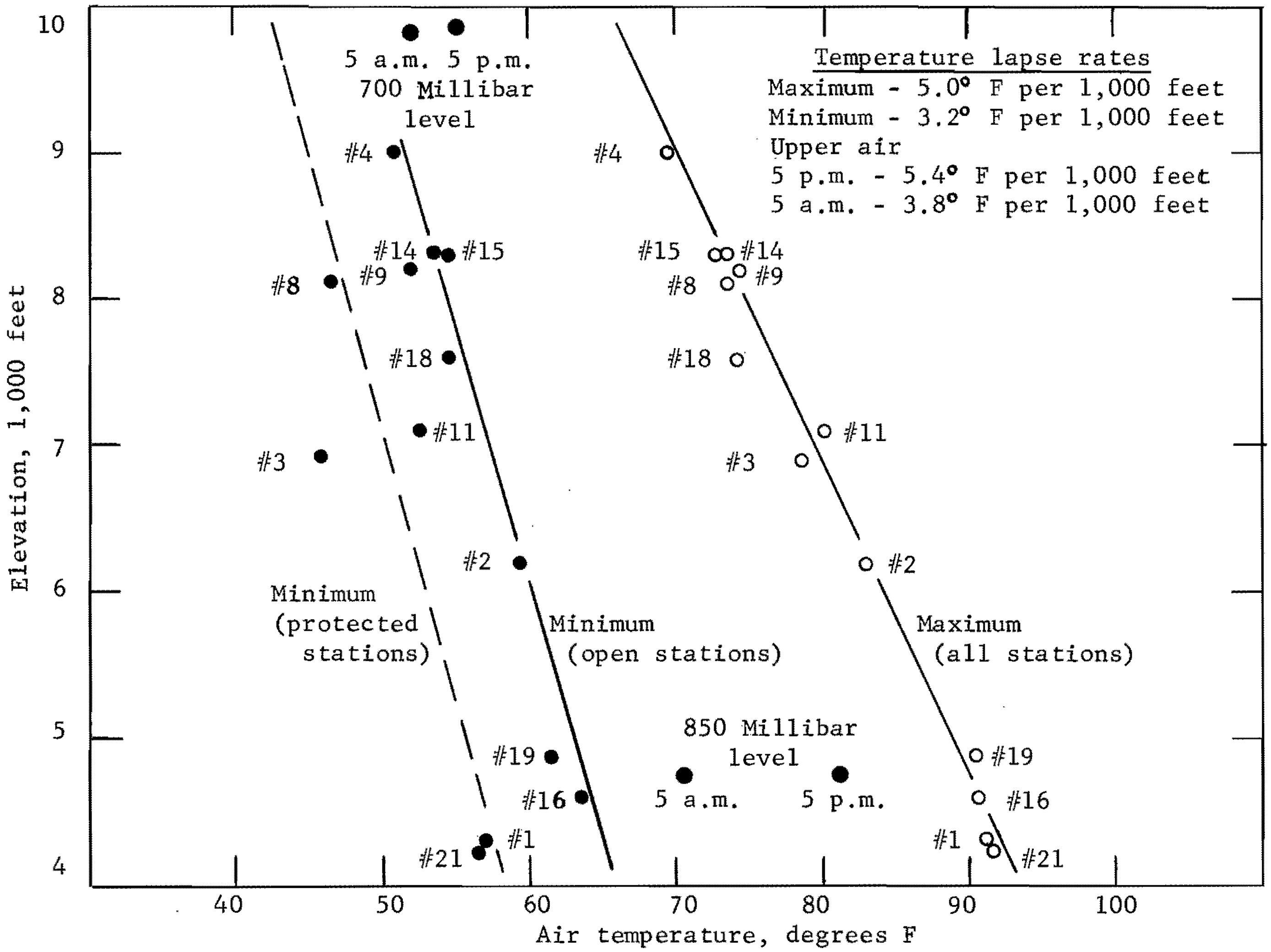

Figure 14. Relations of maximum and minimum temperatures with elevation, August 1966

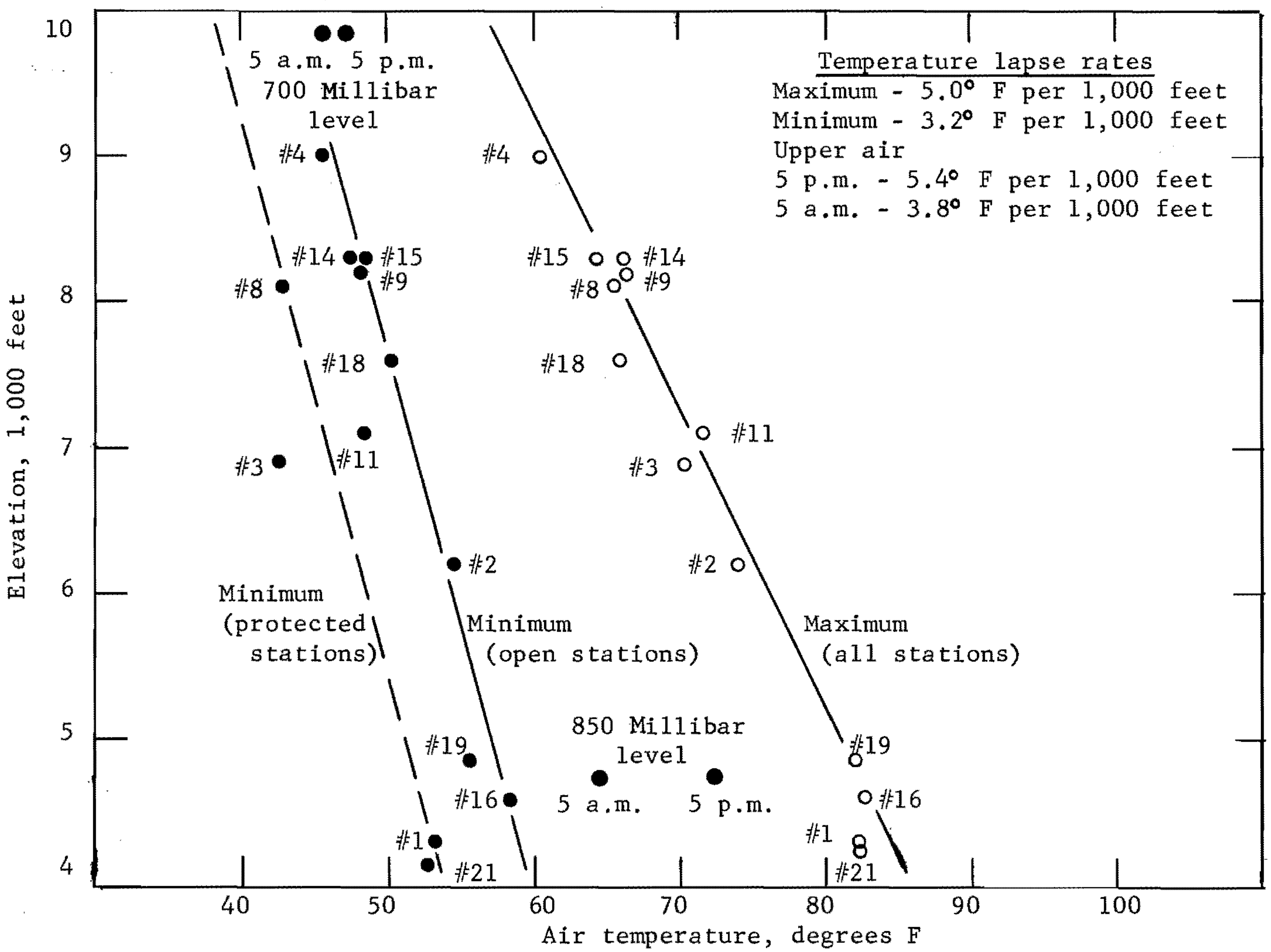

Figure 15. Relations of maximum and minimum temperatures with elevation, September 1966

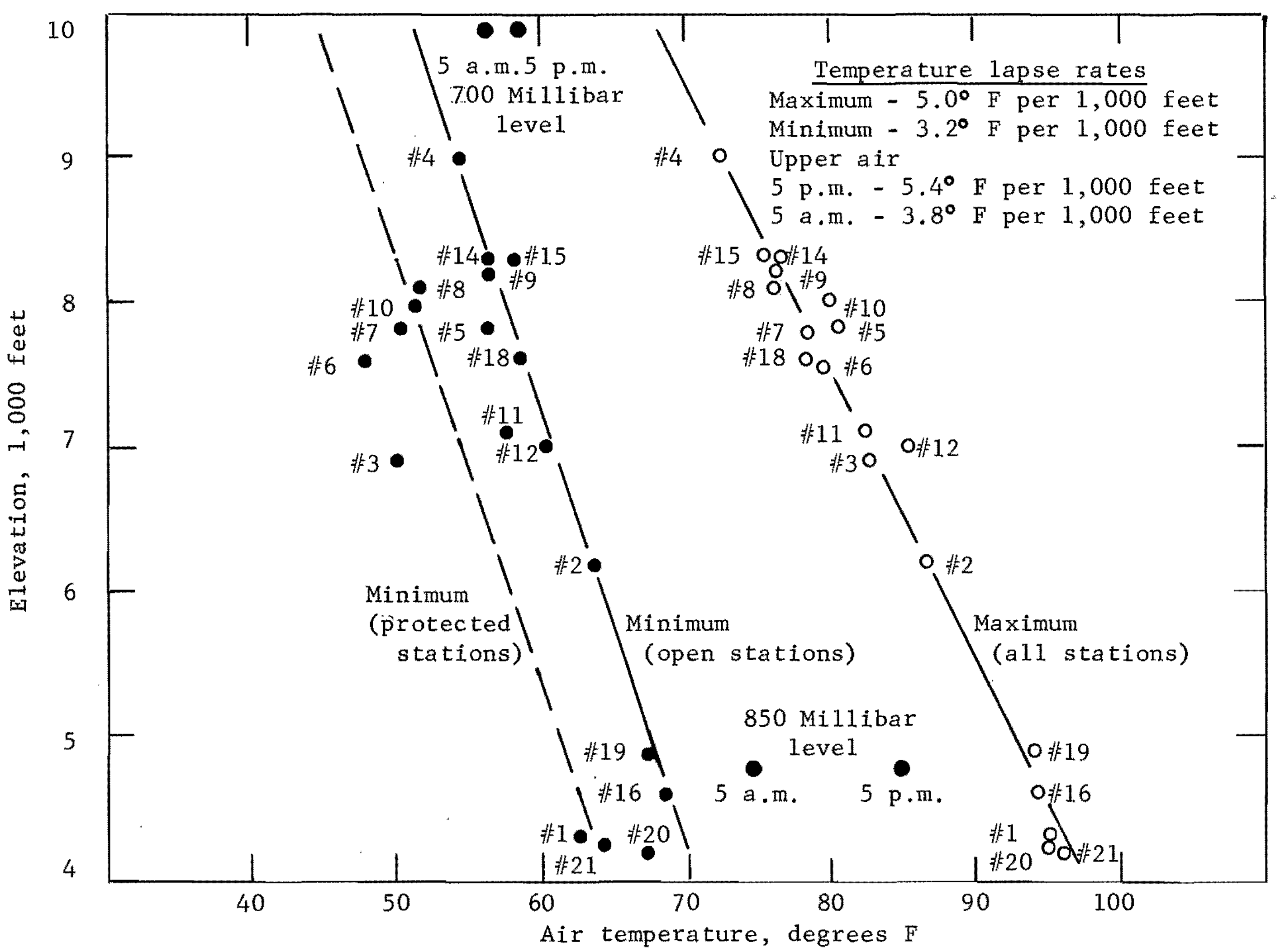

Figure 16. Relations of maximum and minimum temperatures with elevation, composite July 1962 and July 1966

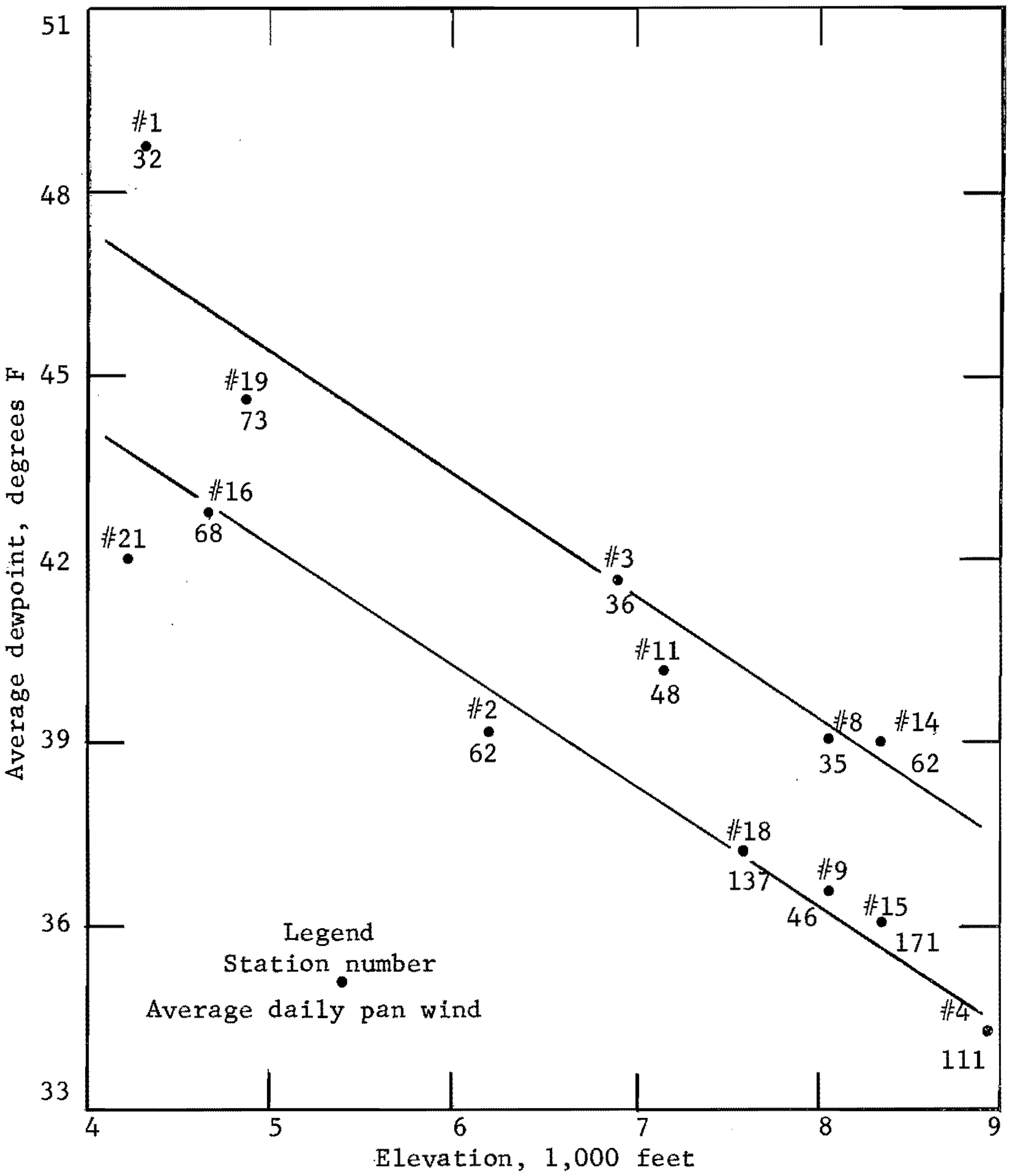

Figure 17. Dewpoint-elevation relation, monthly averages, July 1966

average daily pan wind movement for each station. Analysis of the plot shows that dewpoints for stations located on top of ridges (4 and 18), high elevation south ridge stations (9 and 15), and those that have strong drainage winds (2, 16 and 19), apparently have a different relation with elevation. The remaining stations are those having north-oriented slopes and protected locations.

A similar plot of dewpoint data for August 1966 (Figure 18) shows a single relation for all stations. Investigation into the possible reason for the difference in the relations indicated that the upper air wind direction was an important factor. During July 1966 there were only 7 days when the 5:00 p.m. 700-millibar upper air wind had a northerly component. During August 1966, 21 days were observed to have a northerly component. The lapse rate with elevation for the dewpoint in July is about 2.0 F per thousand feet while that for August 1966 is 2.35 F.

A plot of dewpoint versus elevation relation for clear days only during July 1965 and 1966 is shown in Figure 19. The same general pattern as found for July 1966 in Figure 17 may be observed but somewhat more pronounced.

An unusual method of presentation was developed to help visualize the diurnal changes in dewpoint over the watershed. Figure 20 is a plot of the elevation versus the total 24-hour pan wind movement for each station for clear days

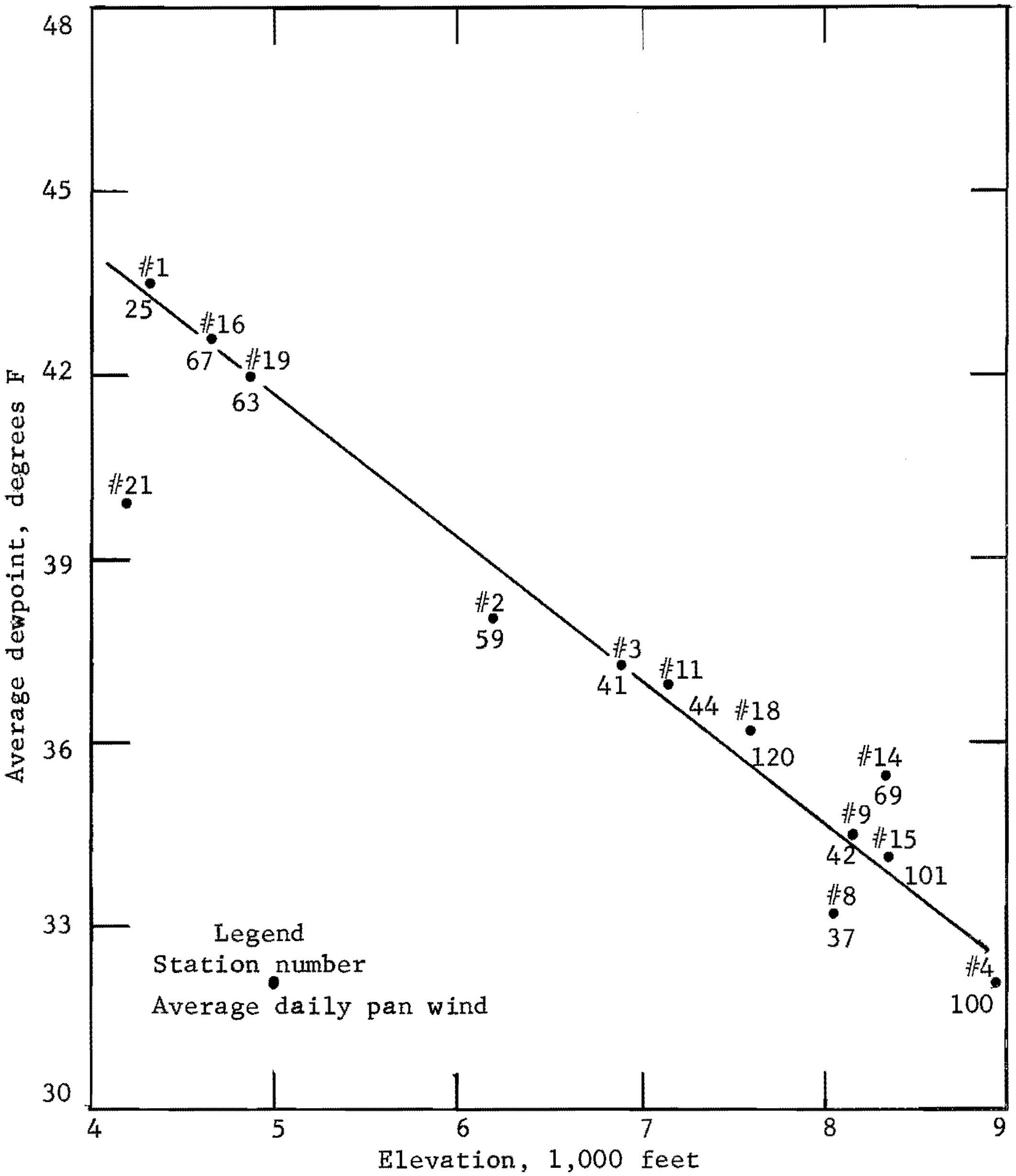

Figure 18. Dewpoint-elevation relation, monthly averages, August 1966

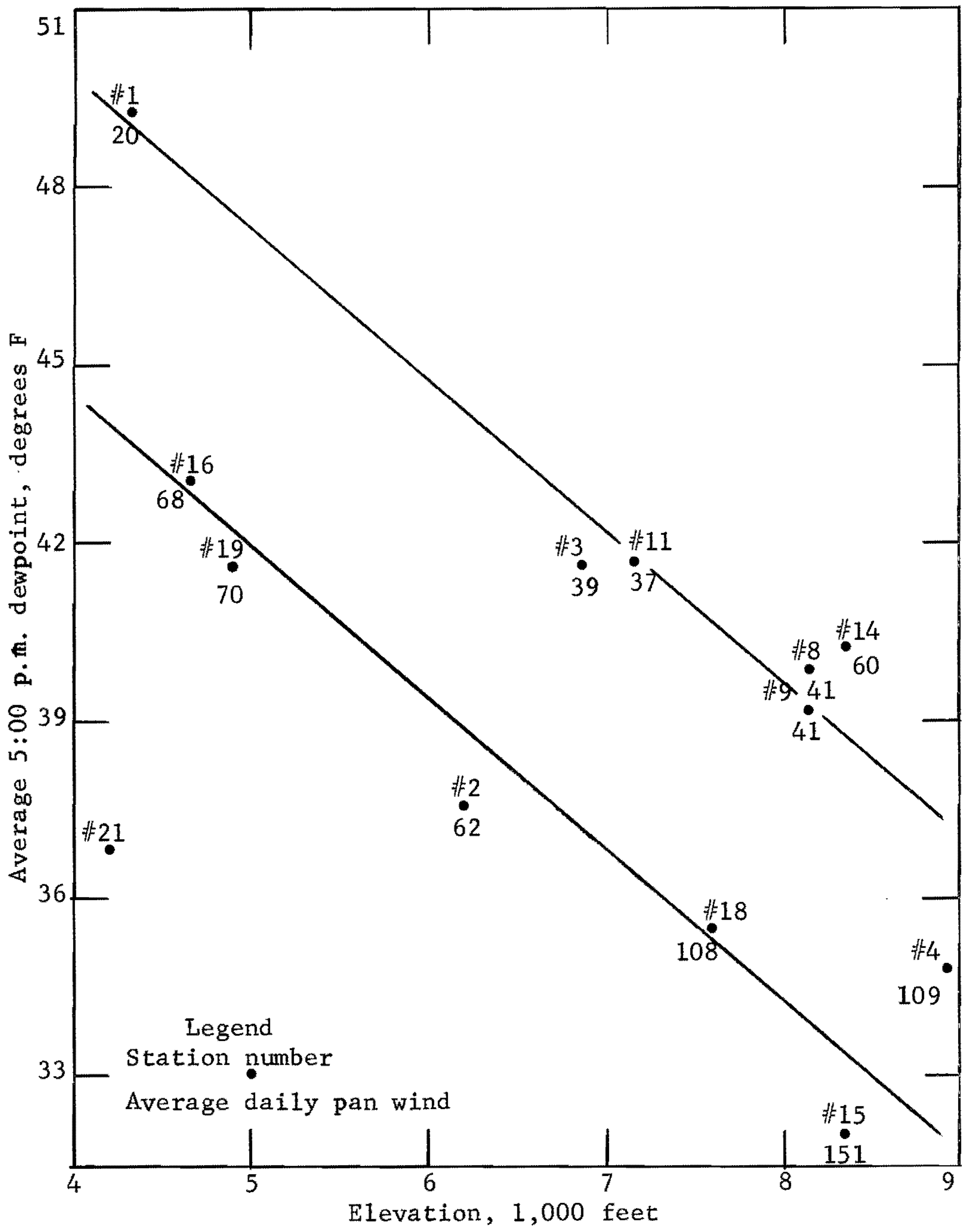

Figure 19. Dewpoint (5:00 p.m.)-elevation relation, clear days only, July 1965 and July 1966

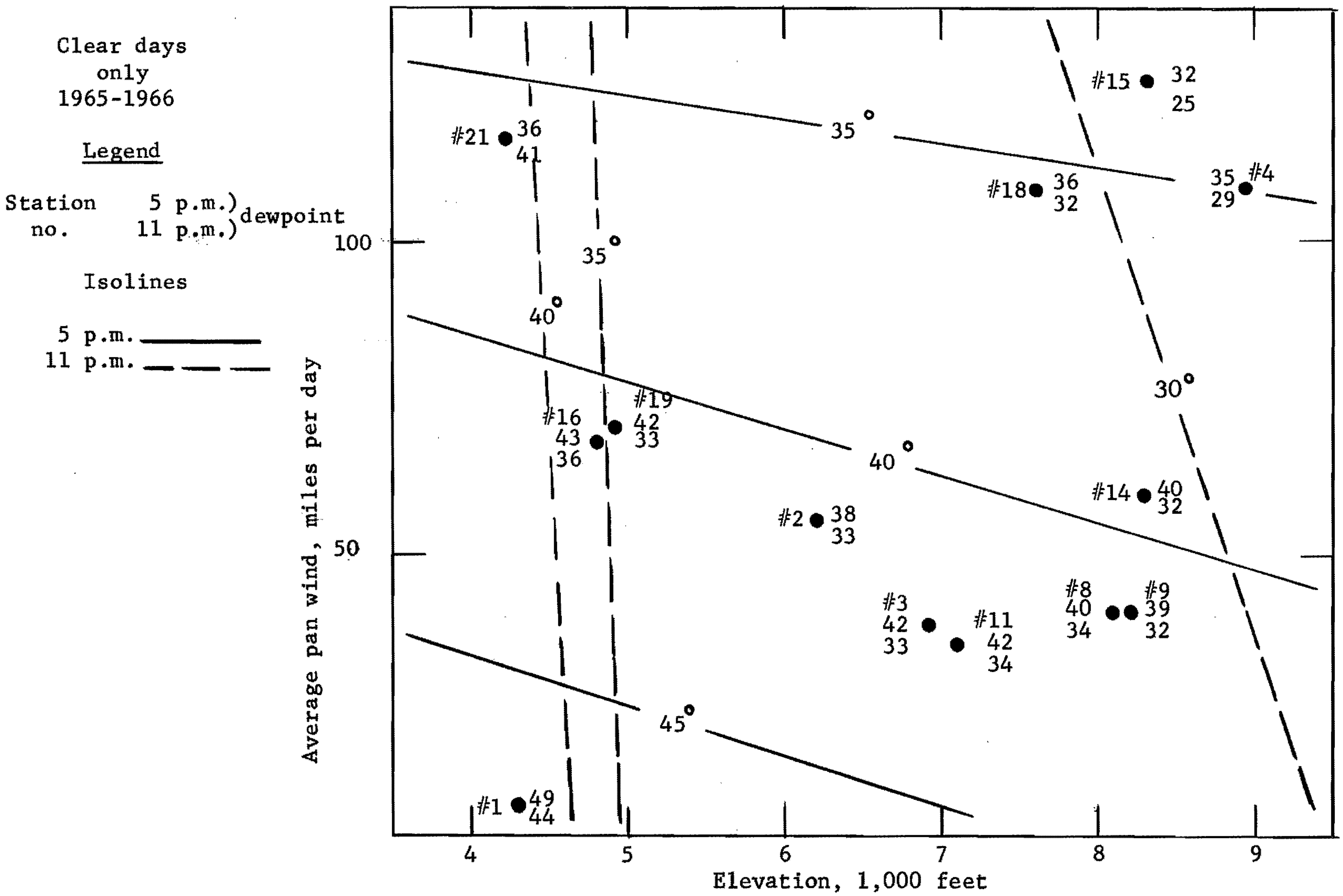

Figure 20. Elevation-pan wind-dewpoint relation, 5 p.m. and 11 p.m., July

during July 1965 and July 1966.[1] Entered at each point are the 6-hourly dewpoint averages for 5:00 p.m. and 11:00 p.m. MST. The 5:00 p.m. observation is after the heating of the day has mixed the air and the up-canyon winds have been established for several hours. The moisture is fairly well distributed over the watershed. The lapse rate of dewpoint with elevation is not materially different for varying values of pan wind movement. A set of curves has been entered on the chart representing the analysis of the dewpoints on the graph.

The second values of dewpoints are those for 11:00 p.m., after down-canyon winds have been established. At this time of day the lines of equal dewpoints are nearly vertical. The graph reflects a considerable drying at the upper elevations over the entire watershed. Only stations 1 and 21 (Salt Lake City, Utah) have dewpoints above 40 F.

Similar plots for 5:00 a.m. and 11:00 a.m. are shown in Figure 21. The isolines for the 5:00 a.m. dewpoints are very similar to those for the 11:00 p.m. data. The down-canyon winds are still in progress at this time of the morning.

The last set of equal dewpoints lines is for the 11:00 a.m. observation time. This is generally shortly after the

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[1] An estimated pan wind for the Salt Lake City Airport Station was obtained by reducing the observed 20 foot above ground wind measurement to the pan wind level by the method explained by Weiss and van de Erve (1966).

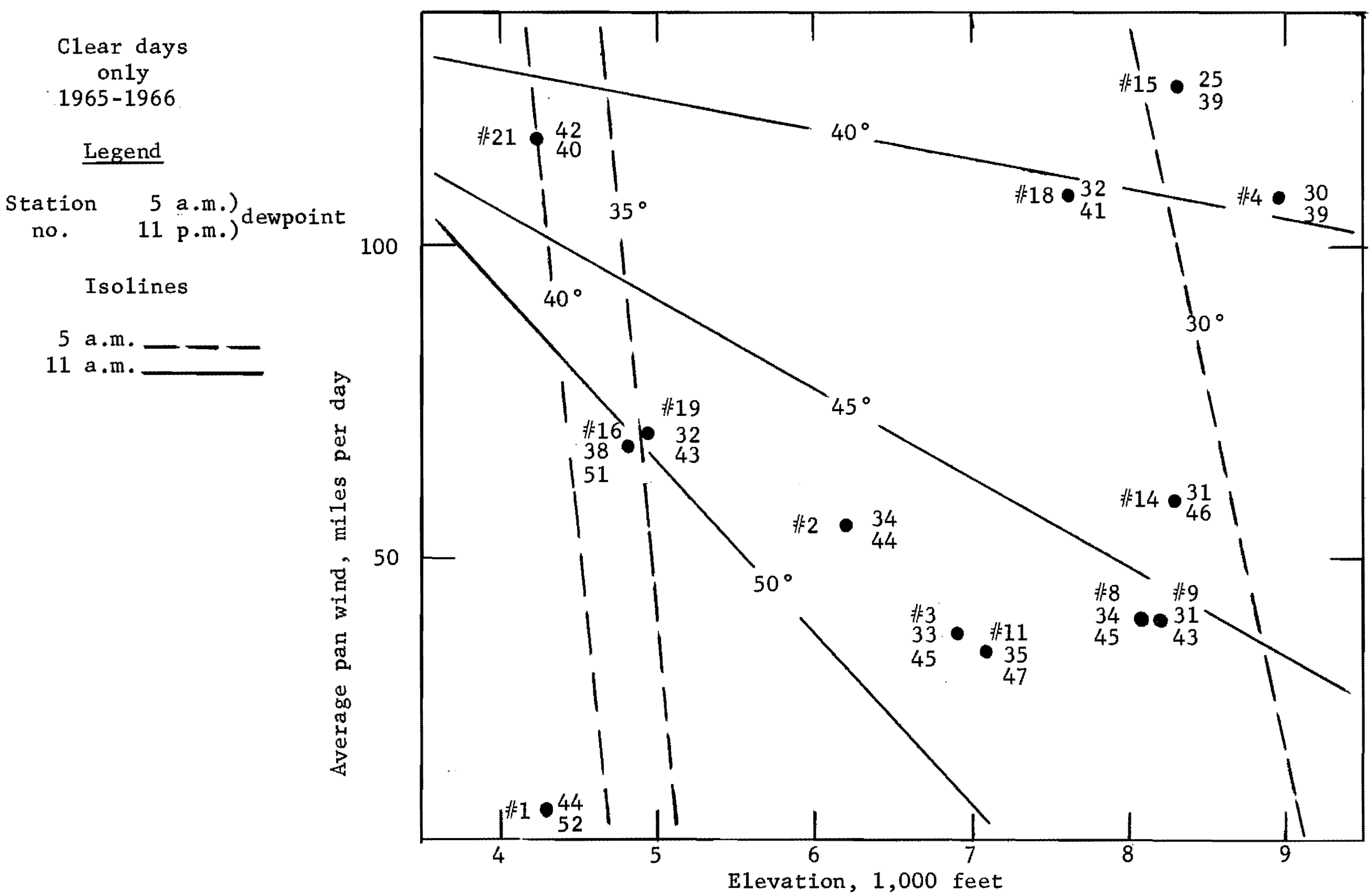

Figure 21. Elevation-pan wind-dewpoint relation, 5 a.m. and 11 a.m., July

up-canyon winds have been established. The position of the lines would indicate that moisture is moving up the hillsides to the higher elevations. These higher dewpoints reflect to some extent the moisture that was over the large water areas immediately east of the study area along the shorelines of Great Salt Lake during the night.

The lower dewpoint values at 5:00 p.m., as compared with those at 11:00 a.m. undoubtedly are the result of the heating and mixing with the drier air aloft during the hottest portion of the day.

The diurnal variation in dewpoint at a single location may be seen in the plottings of hourly dewpoints in Figure 22. The curve for station 4 shows the variation in dewpoint experienced by ridge locations. There is an increase in dewpoint during the morning hours until about 9:00 a.m., after which there is little change until the late afternoon when a rapid decrease in dewpoint values may be noted. At lower stations, subject to strong canyon winds, station 2, for example, the dewpoint continues to increase until about 11:00 a.m., after which there is a moderate decrease until late in the evening when the down-canyon winds again cause the dewpoint to decrease rapidly.

Station 17 was included to show the difference in dewpoint at valley locations. The dewpoints remain high during the night hours until heating is sufficient in the morning (about 9:00 a.m.) to cause mixing with drier air aloft and the dewpoint remains lower until the mixing is

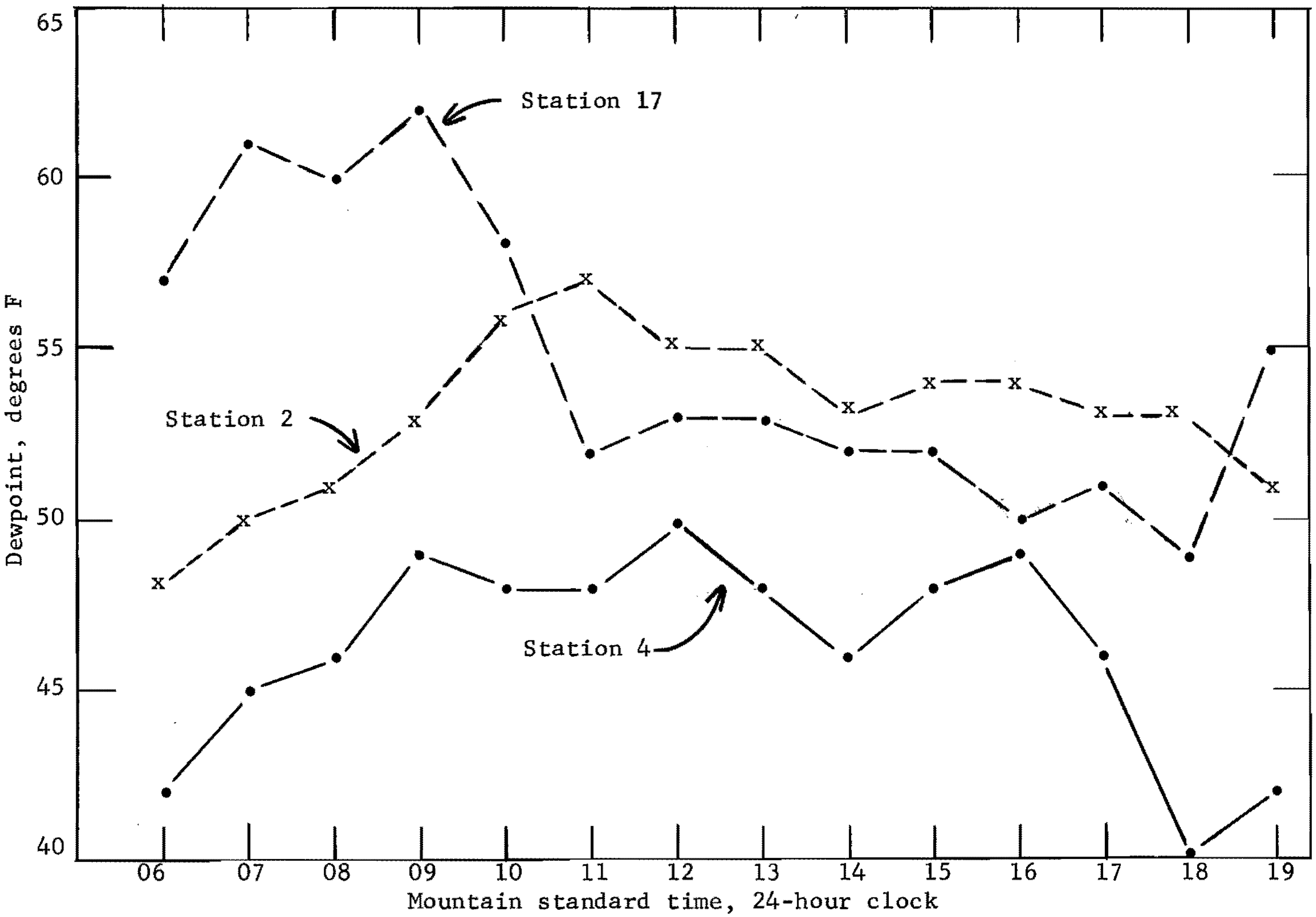

Figure 22. Dewpoint variation during daylight hours for representative stations, 27 July 1966

discontinued at sundown.

Radiation relations

The daily radiation values from the Eppley pyrheliometer at the base station were checked with those from the Weather Bureau regular installation at the Salt Lake City, Utah, Airport Station for the period of record during July and August 1966 (Figure 23). Values for the base station are for the 24-hour period ending 8:00 a.m. MST, while those for Salt Lake City, Utah, are for the calendar day. The relation indicates that the two records are in good agreement.

The pyrheliographs were calibrated with the Eppley at several times during the study. Since the pyrheliographs were installed on the top of the instrument shelters and subject to possible damage by gunfire, steel covers were used to protect the sides of the instruments.

Relations of observed radiation values between individual stations and the base station were developed, using period or monthly totals when available. These relations were found to be nearly linear and in general, parallel to one another. For the same radiation at the base station, the range in estimated values was slightly over 100 Langleys per day with the lowest values observed for station 3 and the highest for station 4. Figure 24 is a plot of the elevation-radiation relation for the month of July. The points for stations 1, 2 and 4 are observed values while

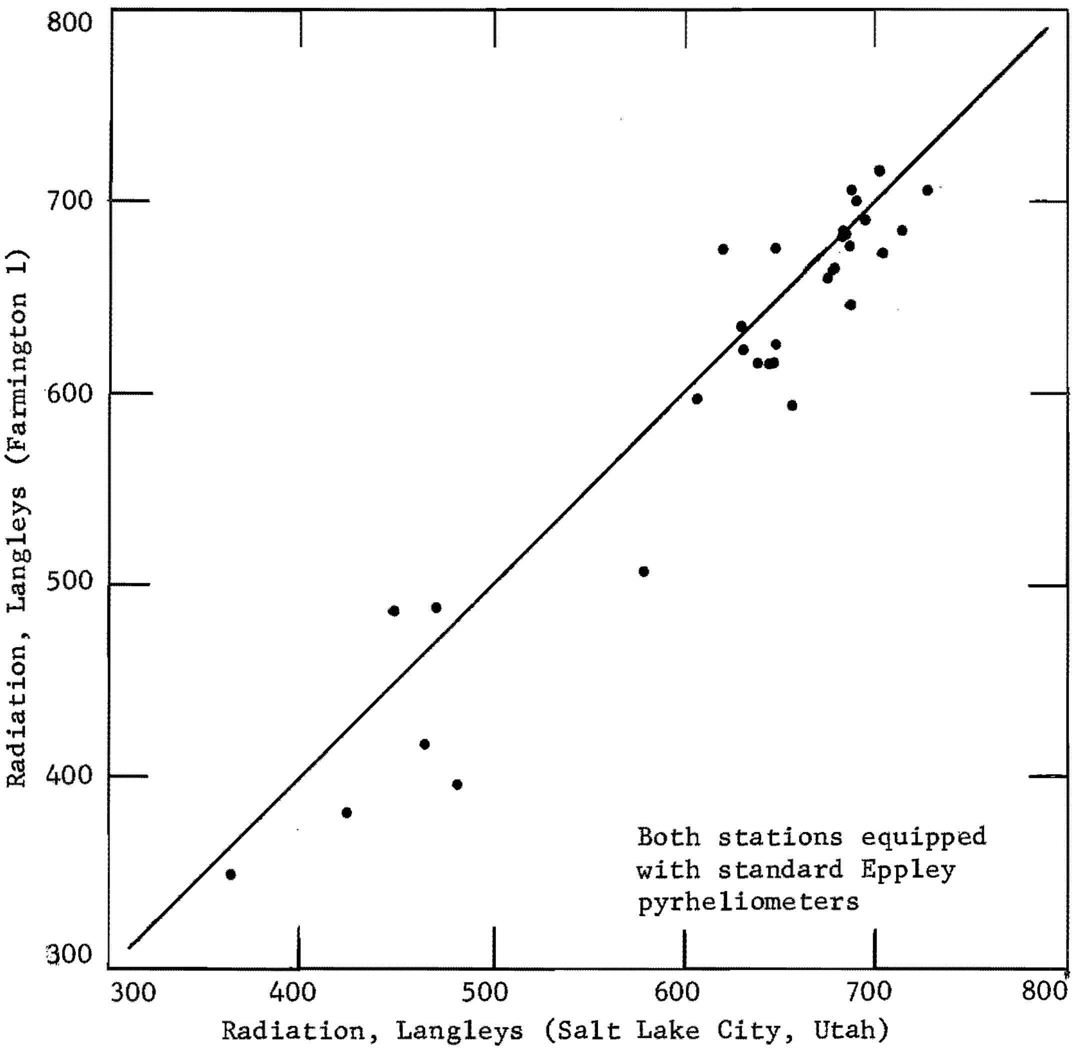

Figure **23**. Comparison of observed radiation Farmington 1 and Salt Lake City, Utah, July-August 1966

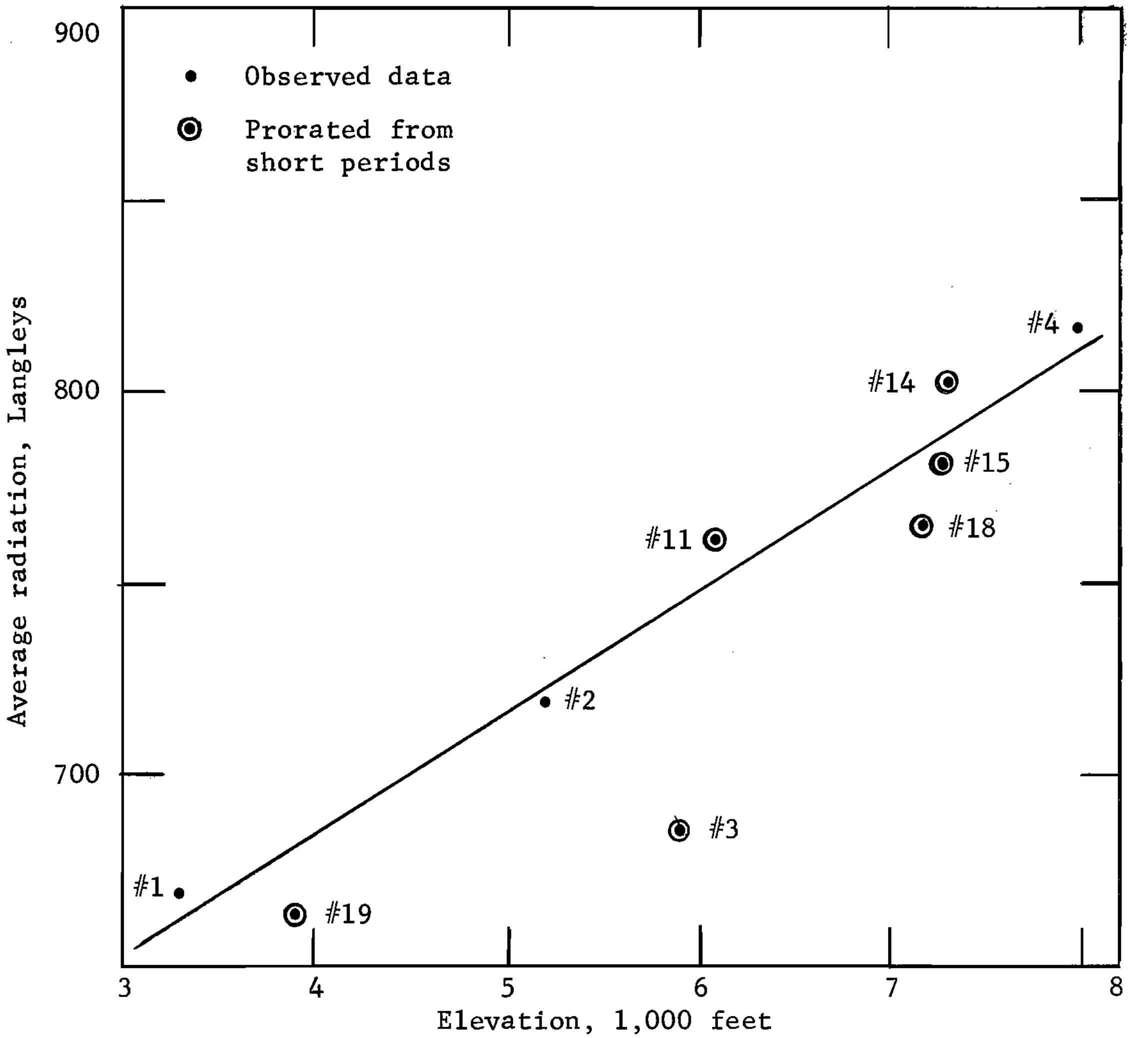

Figure 24. Elevation-radiation relation, July (all seasons)

those for the remaining stations were based on short periods of record. The relation for the three stations with observed values seems to be a straight line with a good fit.

The length of day (maximum possible sunshine) for the different stations varies considerably. Table 4 is a comparison of the length of day as observed during the special hourly observations during the 1962 season.

Station 2 is located in a rather narrow canyon surrounded on both sides by rock cliffs. This station receives considerable reflected short-wave radiation from these rocky areas.

Generalized relations between radiation and pan evaporation were developed from average values for periods when radiation data were available at each station. The slope of the best fit lines for these relations indicated that the daily average pan evaporation increased approximately .05 of an inch for each 100 Langleys increase in radiation.

Wind relations

The anemometers used in the study were Weather Bureau F104D and have a normal starting speed of 1.5 miles per hour. The exposures of the various stations produced considerable difference in pan wind movement. The highest wind movements per day were observed at stations located on major ridges, on southern slopes of ridges and at lower stations subject to strong drainage winds. Lowest wind speeds were observed

Table 4. Comparison of length of day for each station with base station during special observations in 1962

Station number	Dates of observation 1962	Length of day hours	Length of day base station hours
2	17-18 Sep	8.2	10.6
3	12-13 Sep	10.4	10.8
4	25-26 Jul	14.3	11.9
5	22-23 Aug	11.6	11.6
6	21-22 Aug	11.4	11.6
7	4-5 Sep	10.9	11.1
8	15-16 Aug	11.7	11.7
9	14-15 Aug	11.6	11.7
10	7-8 Aug	10.9	11.7
11	28-29 Aug	11.6	11.4
12	29-30 Aug	11.8	11.4

for stations in canyons with considerable vegetation and at stations with relatively flat surrounding terrain. Values of monthly pan wind movements are shown in Table 3 for all stations.

The diurnal wind movement during the day varied considerably from station to station. Highest wind movement at ridge stations was generally observed during the afternoon. At lower elevation stations with strong drainage winds the highest wind movement (down canyon) occurred during the night and early morning hours. The most comprehensive analysis on canyon winds in the Salt Lake City area has been presented by Hawkes (1947). Peck and Pfankuch (1963) showed that the pan wind movement on southern slopes was considerably greater than that on northern slopes during periods of southerly winds.

Pan water temperature relations

Plotting of mean pan water temperatures with elevation shows a general decrease in pan water temperature with increase in elevation. As was noted for dewpoint and air temperature, the pan water temperatures were found to be different for stations with different exposures (Figures 25 and 26). The stations with high pan wind movements had colder pan water temperatures than protected stations at the same elevations. Values of average pan water temperatures, difference between air and pan water temperatures and average daily pan wind movement are shown for July 1966

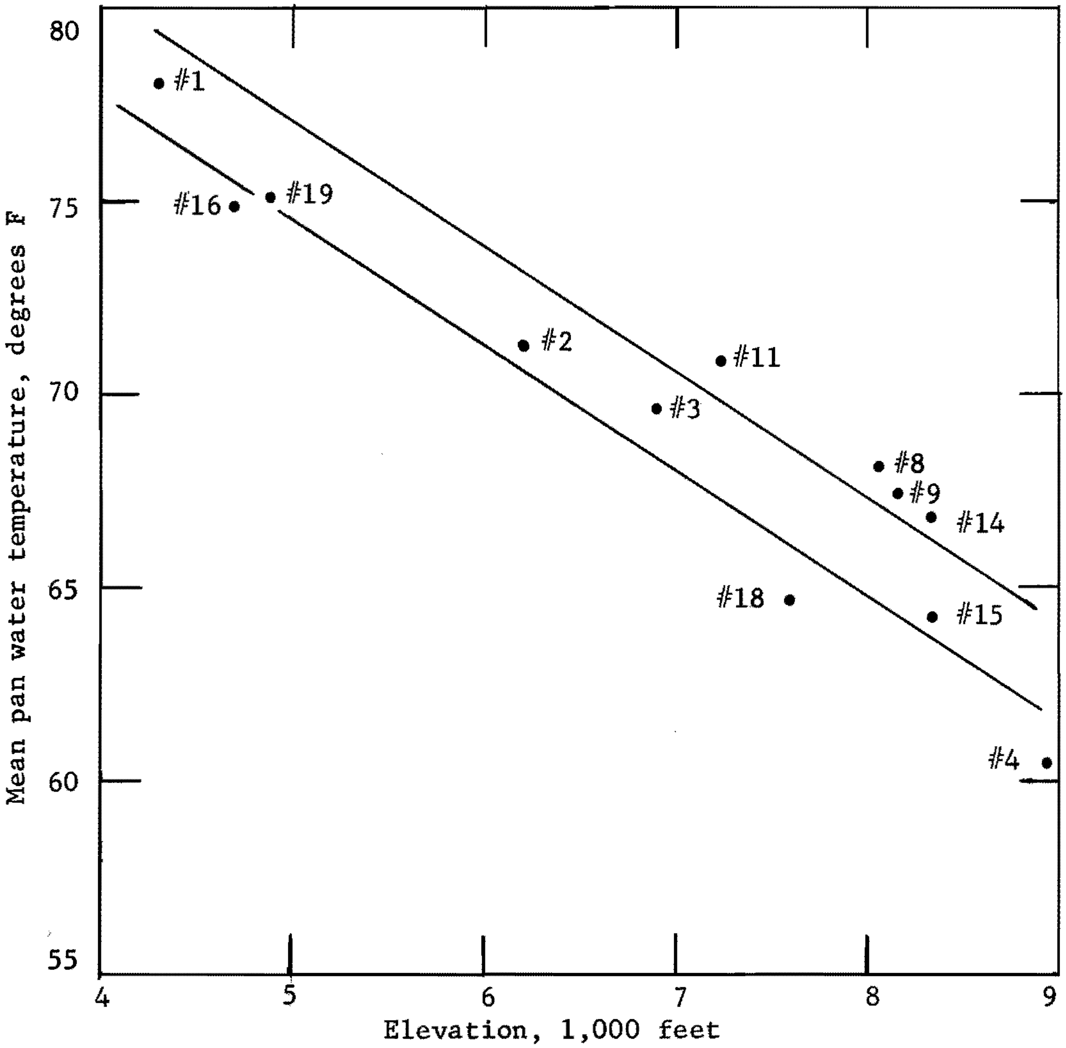

Figure 25. Elevation-pan water temperature relation, July 1966

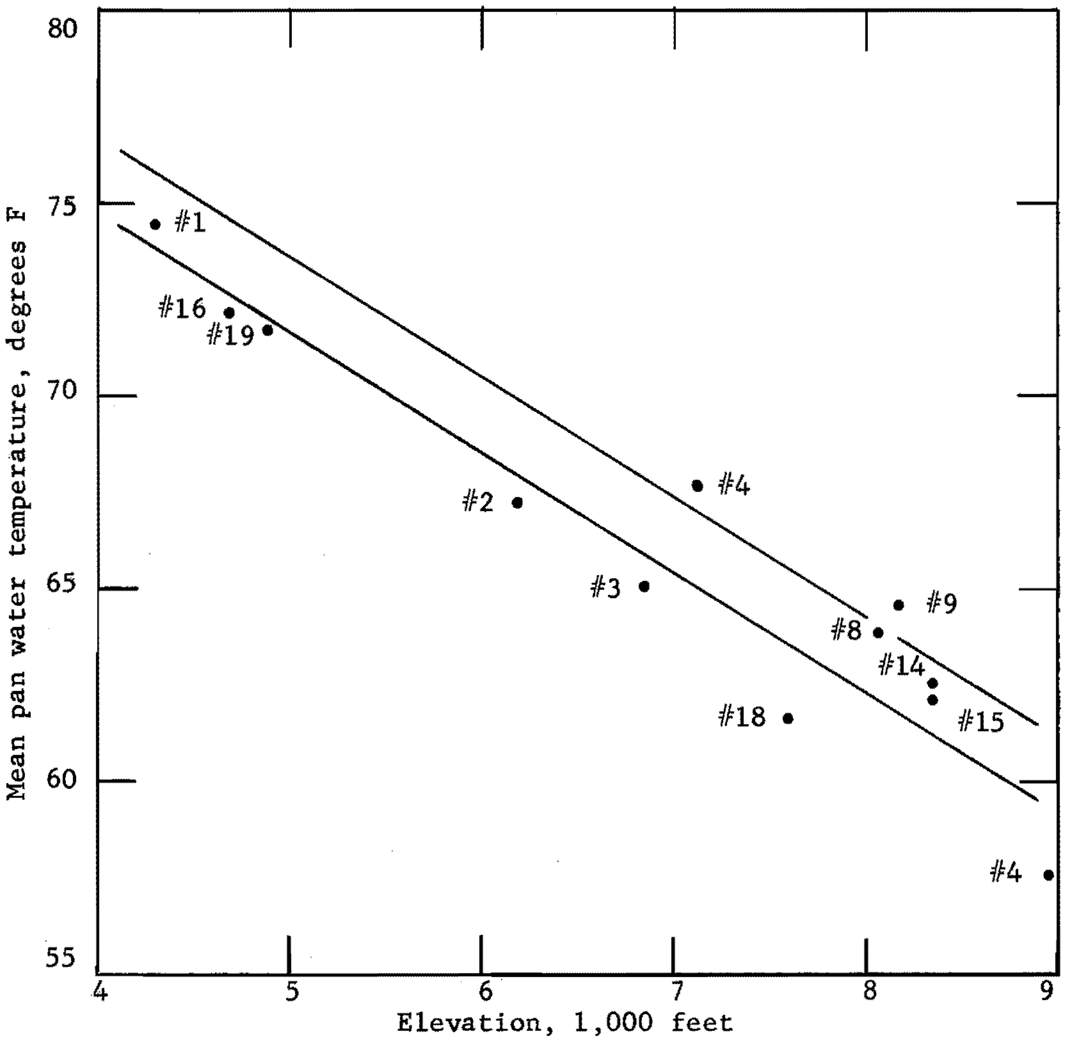

Figure 26. Elevation-pan water temperature relation, August 1966

on Figure 27, and on Figure 28 for August 1966. Stations which have observed average pan water temperatures colder than the average air temperatures have been enclosed by circles. It is evident that these stations are divided into about the same grouping as was noted for the temperature relations. Values for stations 13, 17 and 20 (non-project stations) have been entered and seem to fit the general pattern. The general lapse rate for pan water temperature with elevation is approximately 3.25 F per thousand foot increase in elevation.

The diurnal variations in air and pan water temperatures from station to station were found to be considerably different for the various types of locations. Figures 29, 30 and 31 show the hourly variations in air and pan water temperatures for protected (station 1), ridge (station 4) and drainage wind locations (station 19) as observed during hourly readings on 25 August 1965.

Evaluation of standard equations for estimating monthly pan evaporation

Three methods were selected to check on the validity of commonly-used procedures for estimating monthly pan evaporation for the mountain stations in the project area.

The first one was developed by Christiansen (1960) for the Utah area and later revised by Christiansen and Mehta (1965). The procedure is based on the equation:

$$E_p = KRC \qquad (9)$$

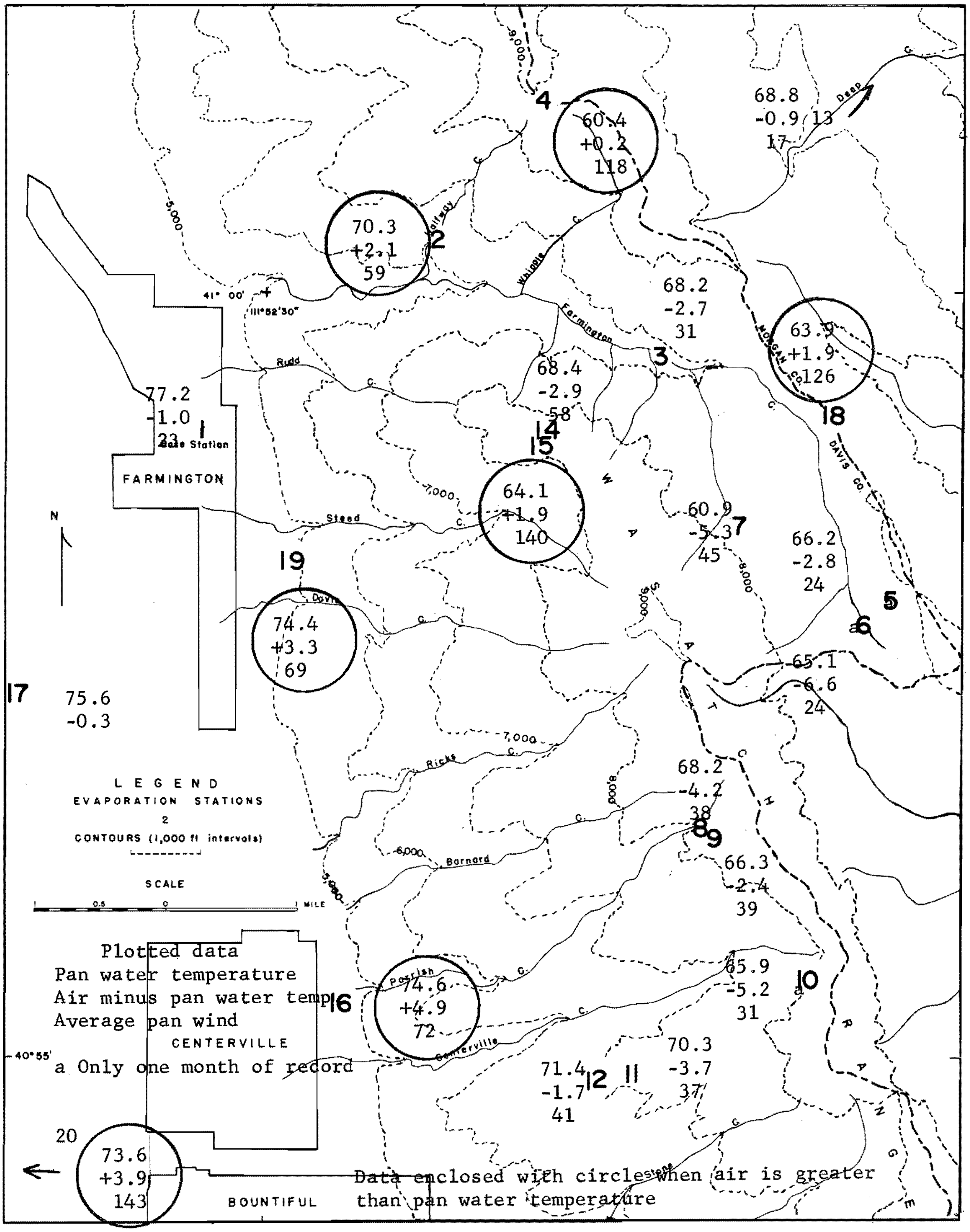

Figure 27. Pan water temperatures, air minus pan water temperatures, and pan winds. Daily average for July, all seasons

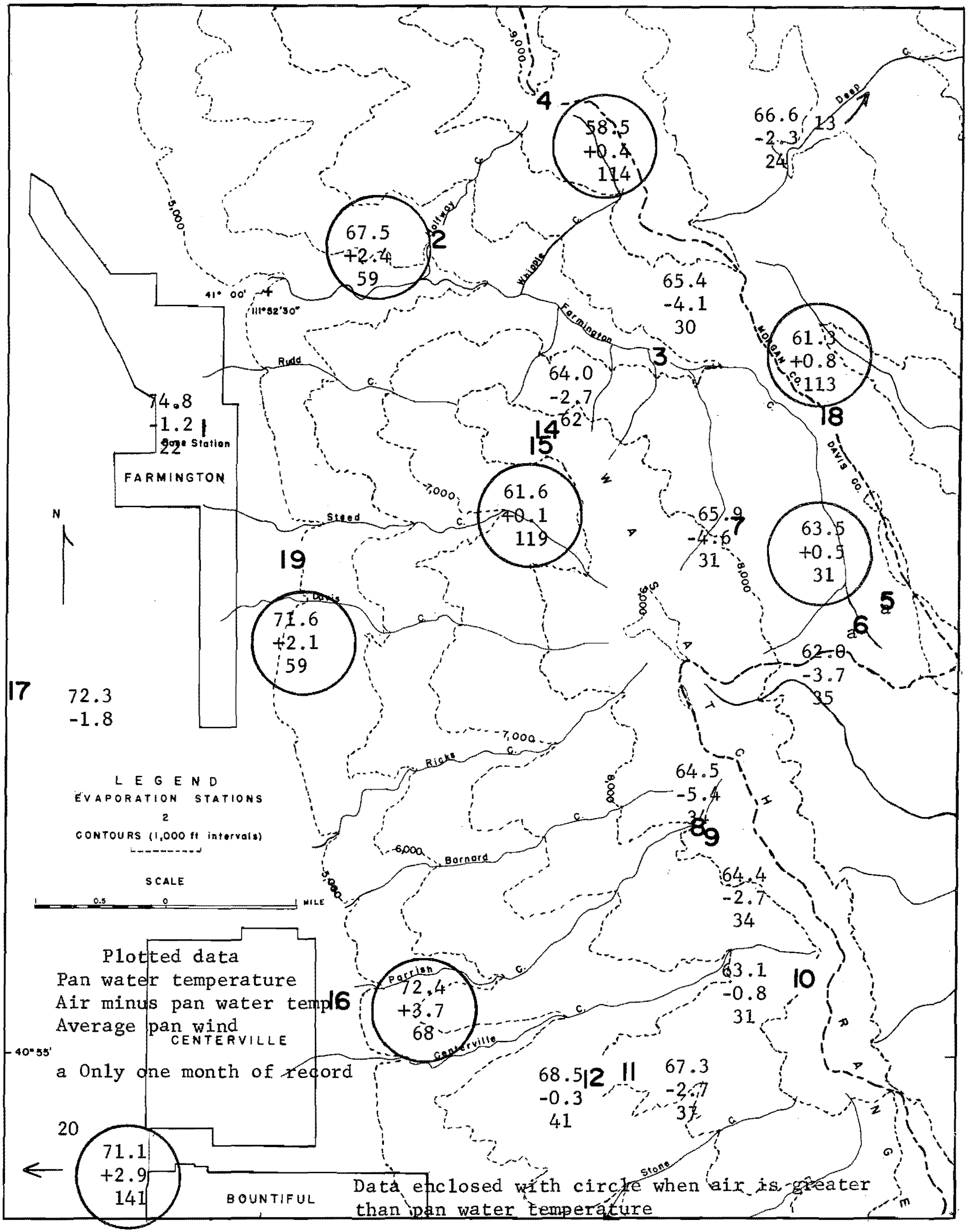

Figure 28. Pan water temperatures, air minus pan water temperatures, and pan winds. Daily average for August, all seasons

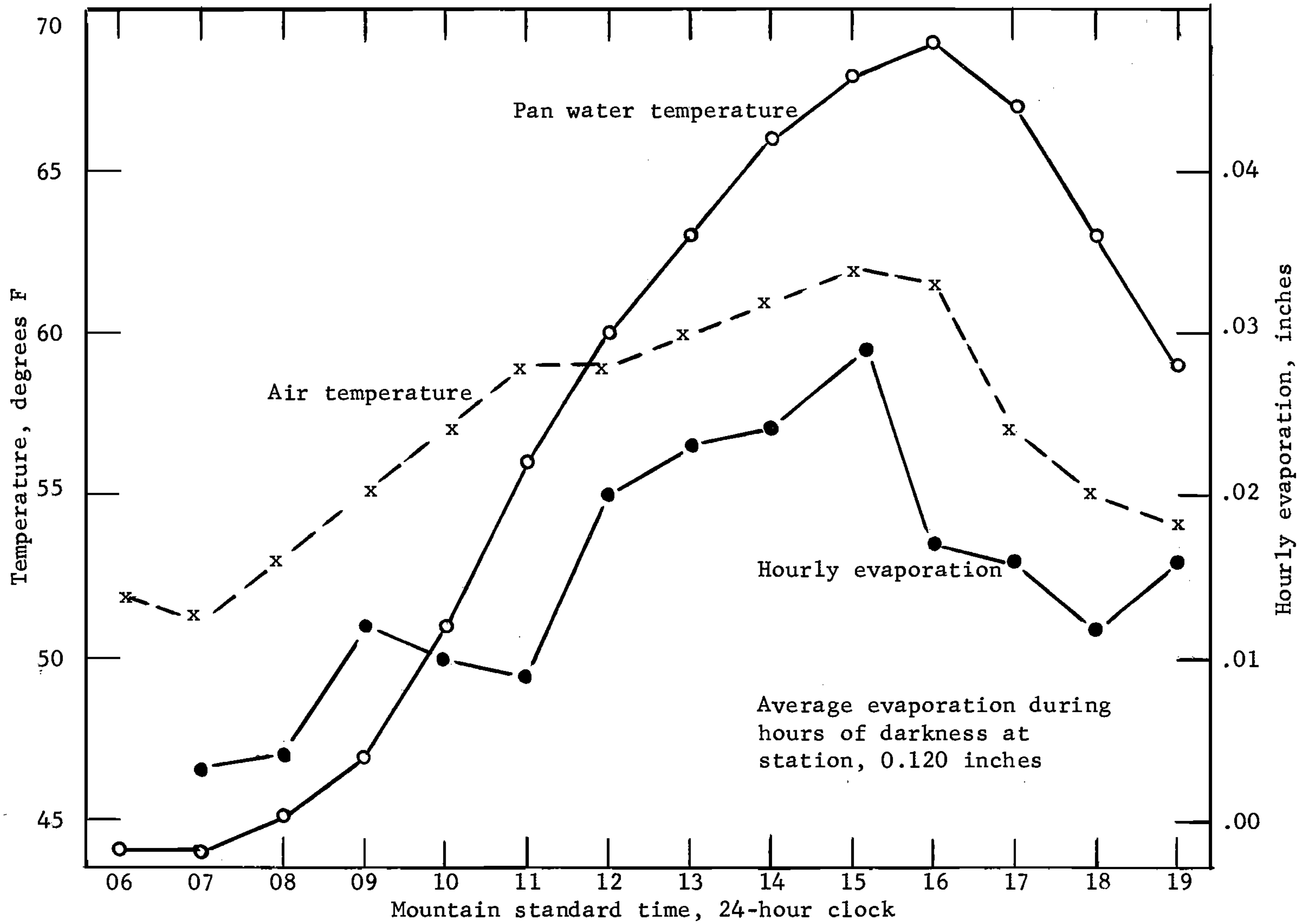

Figure 29. Hourly pan evaporation with air and pan water temperatures, station 4, 25 August 1965

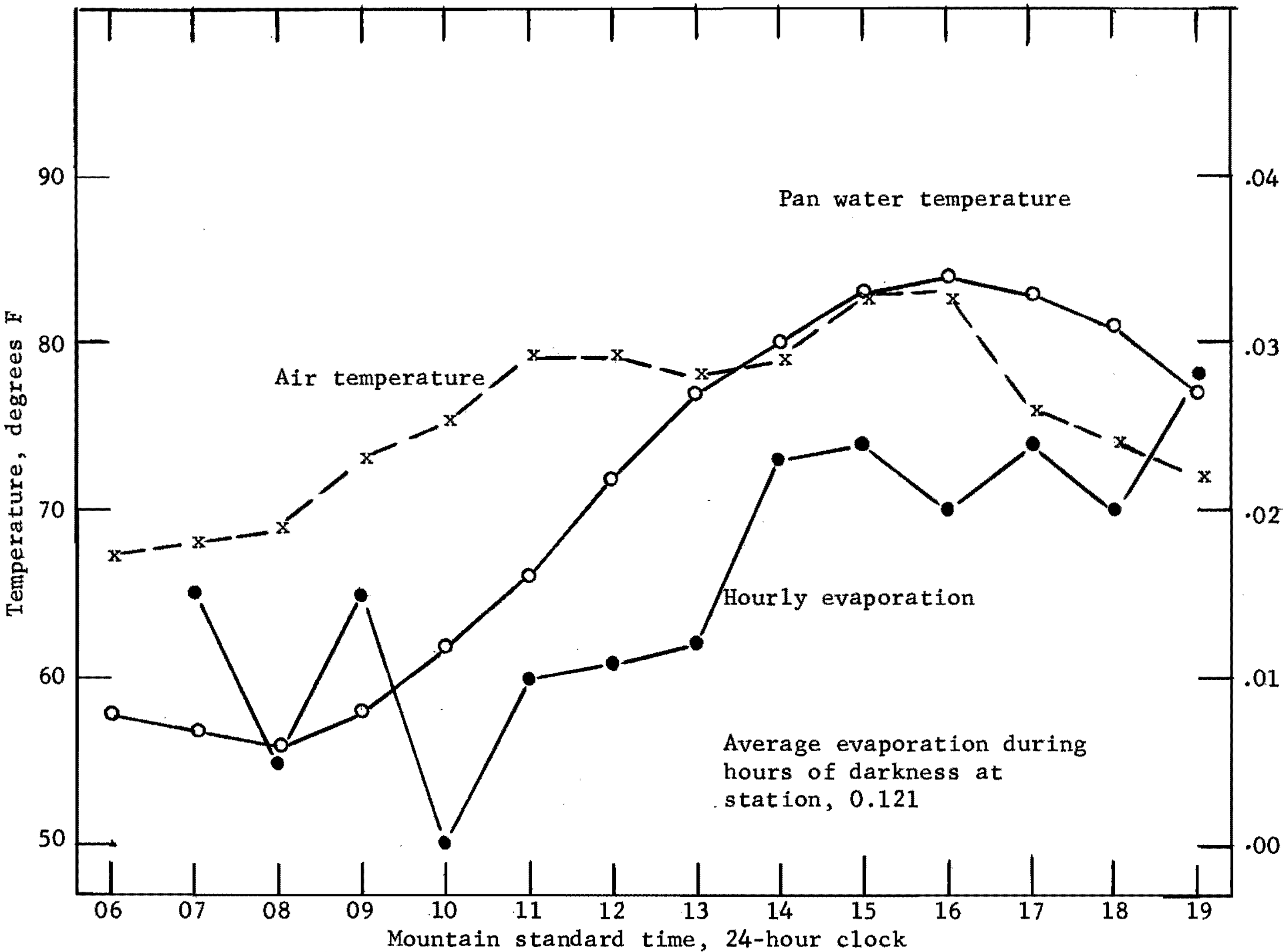

Figure 30. Hourly pan evaporation with air and pan water temperatures, station 19, 25 August 1965

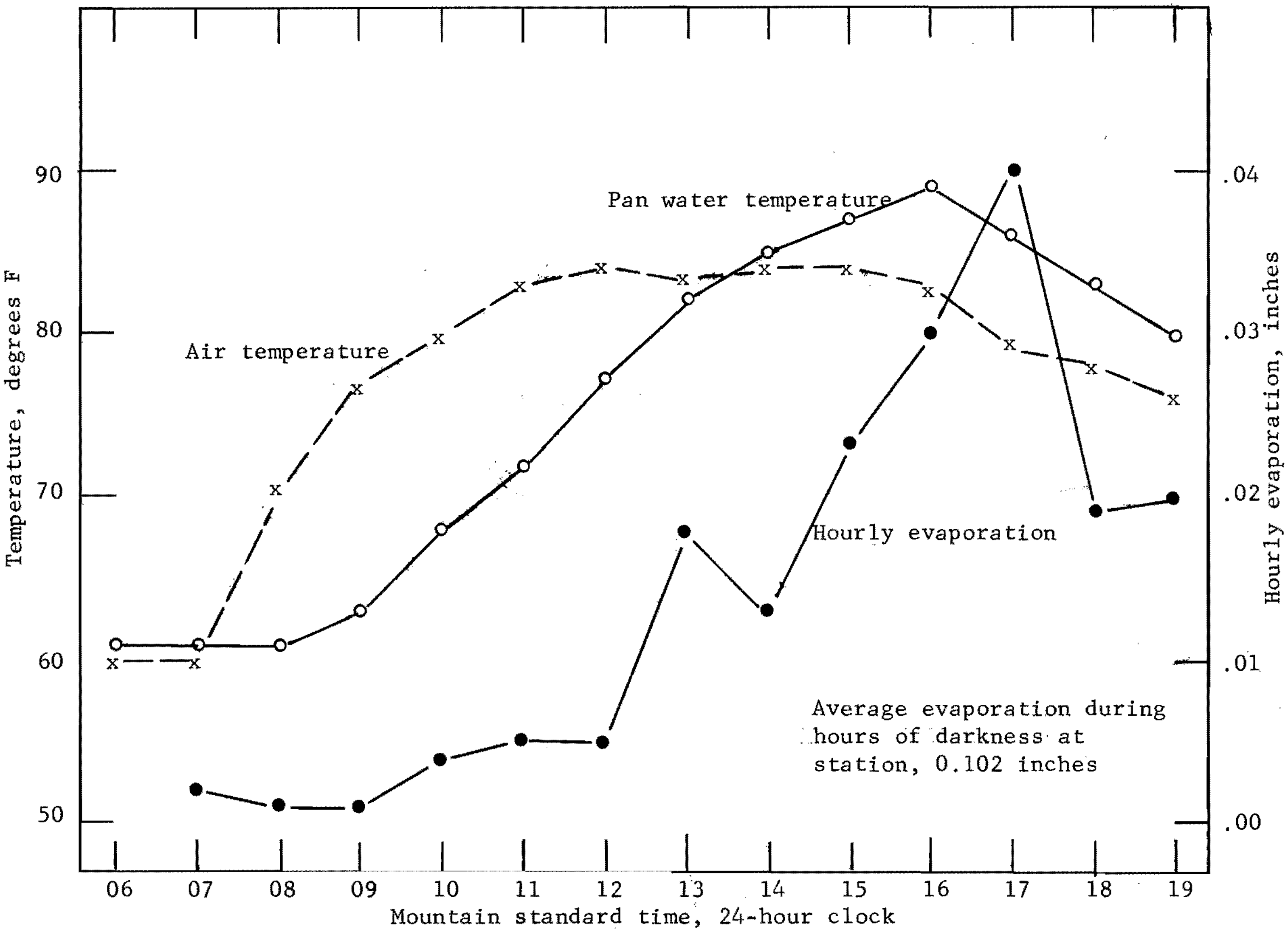

Figure 31. Hourly pan evaporation with air and pan water temperatures, station 1, 25 August 1965

where E_p is the monthly pan evaporation in inches, K an empirical dimensionless constant, R the theoretical solar radiation reaching the earth's outer atmosphere, and C a dimensionless empirical coefficient which is the product of subcoefficients expressing the effect of a given climatic or other factor. The original equation developed using data from northern Utah and the revised equation based on worldwide data were used to compute estimates for all stations for the months of July and August 1966. The results of these computations are shown in Table 5.

The Utah equation produced estimates that had only a very small negative bias with an average error of slightly over 5 percent. A slightly greater negative bias was noted for the higher elevation stations. This greater bias could have been the result of using the Salt Lake City, Utah, percent of possible sunshine in place of actual observed sunshine for the various stations.

The use of the universal equation gave a greater and a positive bias but only a slightly higher average error for the monthly estimates. Maximum errors were about 16 percent for both equations.

The most tested methods for estimating pan evaporation are those by Kohler, Nordenson and Fox (1955). These include the mass transfer equation:

$$E = (0.37 + 0.0041\ U_p)\ (e_o - e_a)^{0.88} \qquad (10)$$

Table 5. Results of applying Christiansen method for monthly estimates of pan evaporation to network stations, July and August 1966

		Utah Equation		Universal Equation	
Station	Month	Monthly estimate inches	Error inches	Monthly estimate inches	Error inches
1	July	9.71	.62	10.08	.24
	August	8.52	.02	9.16	-.64
2	July	11.23	.12	11.69	-.34
	August	10.18	.20	10.85	-.47
3	July	8.15	-.49	8.73	-1.07
	August	7.77	-.42	8.48	-1.13
4	July	11.61	-.54	11.48	-.42
	August	10.22	-.15	10.57	-.49
8	July	7.58	.66	8.27	-.02
	August	7.21	.69	8.11	-.21
9	July	8.62	.50	9.35	-.24
	August	7.83	.51	8.78	-.44
11	July	9.43	.80	10.06	.17
	August	8.46	.35	9.32	-.51
14	July	9.45	-.40	10.03	-.98
	August	9.22	-.66	9.95	-1.39
15	July	15.73	-2.16	13.78	-.20
	August	10.98	-.34	11.26	-.63
16	July	13.07	1.38	12.81	1.64
	August	11.46	1.22	11.71	.97
18	July	14.30	-.57	13.26	.47
	August	12.12	.19	11.80	.51
19	July	12.86	.34	12.82	.39
	August	11.07	.09	11.43	-.28

Table 5. Continued

Equation	Average bias	Average error	Average error percent
Utah equation	-.080	.558	5.38
Universal equation	.210	.577	5.57

and the procedure using meteorological factors of mean daily temperature, mean daily dewpoint, pan wind movement and solar radiation in Langleys per day (Figure 2 in Weather Bureau Research Paper No. 38, Kohler, Nordenson and Fox, 1955).

The researchers have stated that approximately the same results are obtained if monthly averages are used in the procedures or if daily estimates are made and then summed for monthly totals. The findings of the present study verified this statement. Table 6 is a summary of the results of applying these procedures to the data obtained during the present study. Observed data required for the meteorological factor methods, including radiation, were available for 1,148 station days. The estimates from the meteorological factor methods were found to be 10.2 percent too high on the average. No definite reason for this apparent error could be established; however, errors in radiation measurements could be a factor since these are difficult to evaluate.

The average error for the mass transfer equation method was only 3.1 percent low. The bias on the low side was greatest during the month of July.

Evaluation of standard mass transfer equation for daily and 2-hourly pan evaporation

Estimated daily pan evaporation from the mass transfer equation of Kohler, Nordenson and Fox (1955) were plotted

Table 6. Results of applying Weather Bureau Research Paper No. 38 equations to estimate monthly pan evaporation, records from all seasons included

Station(s) or period	Number of days	Average observed pan evaporation inches	Computed average inches	Bias inches	Average error percent	Computed average inches	Bias inches	Average error percent
1	330	.259	.285	.026	10	.265	.006	2
2	209	.307	.335	.028	9	.290	-.017	6
3	30	.239	.270	.031	13	.244	.005	2
4	241	.322	.363	.041	13	.308	-.014	4
8	44	.244	.270	.026	11	.243	-.001	0
9	33	.256	.289	.033	13	.230	-.026	10
11	66	.236	.269	.033	14	.228	-.008	3
12	7	.267	.311	.044	16	.300	.033	12
14	35	.249	.309	.060	24	.249	.000	0
15	45	.338	.371	.033	10	.335	-.003	1
16	9	.384	.415	.031	8	.398	.014	4
18	56	.358	.367	.009	3	.311	-.047	13
19	43	.403	.415	.012	3	.387	-.016	4
By months								
June	110	.325	.363	.038	12	.309	-.016	5
July	362	.349	.379	.030	9	.327	-.022	6
August	400	.280	.306	.026	9	.275	-.005	2
September	276	.224	.259	.035	16	.231	.007	3
All stations	1148	.293	.323	.030	10	.284	-.009	3

with observed daily pan evaporation for each station. For most stations the estimates were found to be too high for low evaporation rates and too low for days of high pan evaporation.

For stations subject to strong canyon drainage winds, the mass transfer estimates were generally lower than observed values as shown in Figure 32 for station 16. For protected sites, such as at the base station, there was little or no bias except for some days with high evaporation (Figure 33).

Values of upper air wind direction and speed were plotted on the graphs of computed versus observed daily pan evaporation and it was noted that for the protected stations the greatest deviations from the observed values (low estimates) were for days with strong southerly winds aloft. Errors of estimates for the ridge stations did not show any consistency in the departures from observed pan evaporation for days with strong southerly upper air winds.

Development of mass transfer equations for study area

The modified Gauss-Newton method for the fitting of non-linear regression function by least squares was used to evaluate the constants for mass transfer equations from the observed data for the study area. A computer program developed by Hurst (1966) based on the work of Gauss (1821), Hartley (1961) and Hartley and Booker (1965) was used. The procedure is under further development and at present does

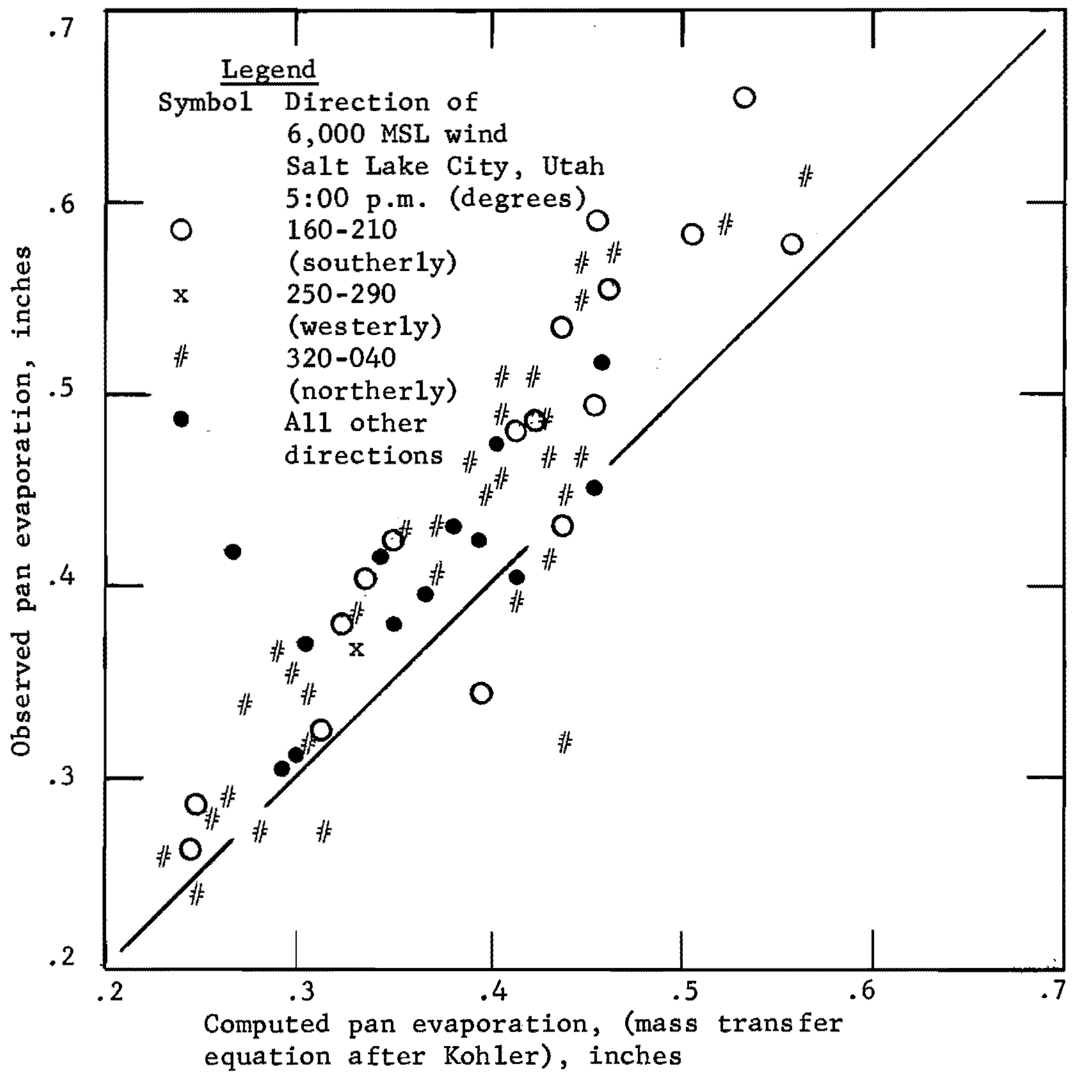

Figure 32. Relation of daily computed mass transfer pan evaporation with observed, station 16

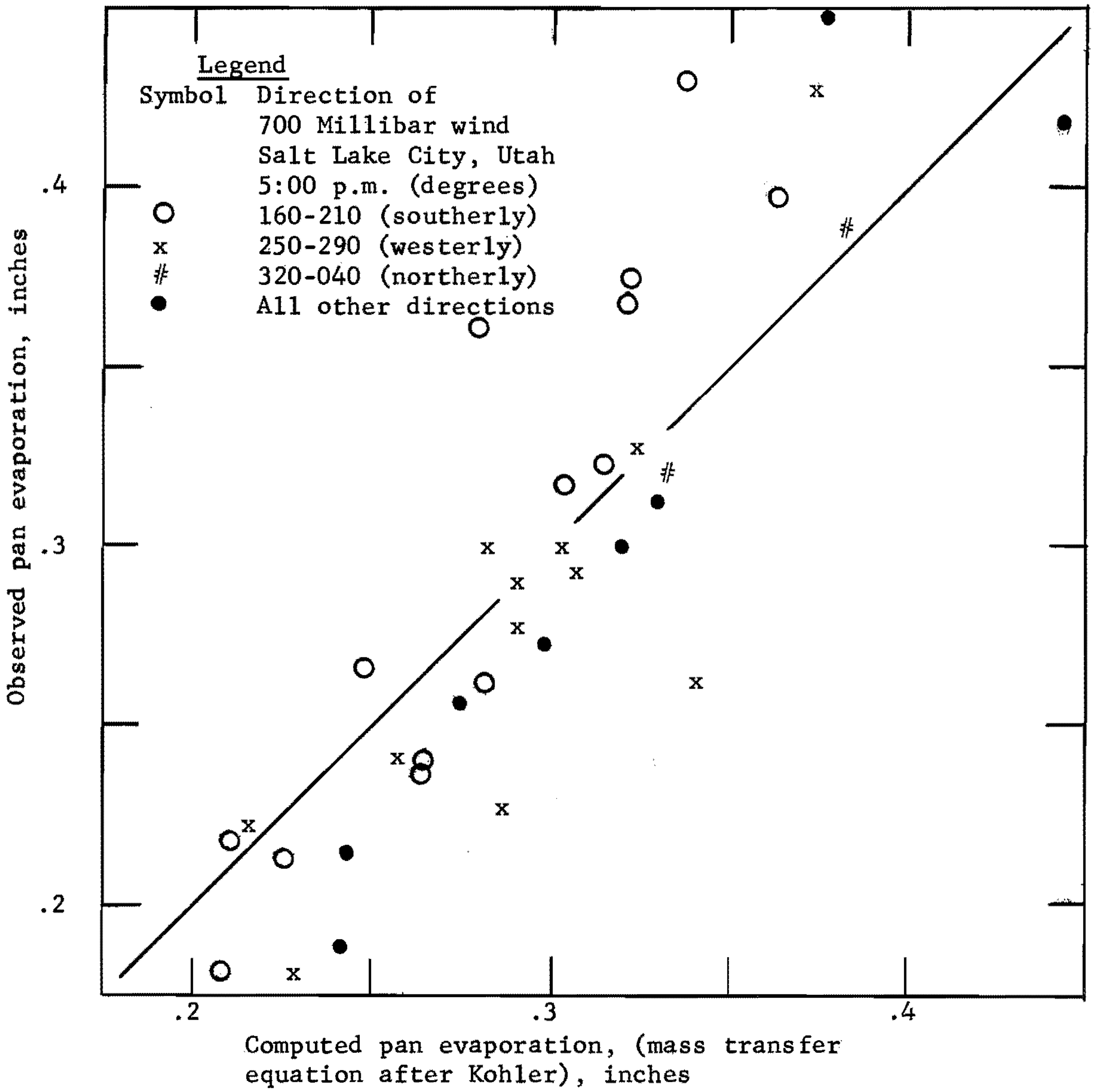

Figure 33. Relation of daily computed mass transfer pan evaporation with observed, base station 1

not always provide complete answers for some cases. However, the method is functional and was considered the best approach available.

The general form of the mass transfer equation was first used:

$$\text{Model I} \quad E_p = (b_1 + b_2 U_p)(e_o - e_a)^{b_3} \qquad (11)$$

where the b's are the coefficients or exponents to be determined by the non-linear fitting technique. This equation allows for a non-linear variation for the vapor pressure difference but not for the pan wind factor. After several analyses had been made, the results indicated that the wind factor might also be non-linear and a second model was used to allow for this:

$$\text{Model II} \quad E_p = (b_1 + b_2 U_p^{b_3})(e_o - e_a)^{b_4} \qquad (12)$$

When daily records from all stations were used in either model the resulting coefficients of determination (regression correlation squared) were found to be near 0.60. Considerable improvement was obtained when the stations were divided into separate groups. Based on the experience gained from the study of the meteorological factors, the stations were divided into two groups. Group I (stations 4, 9, 11, 15 and 18) were those that were on top or on high southern slopes of major ridges. The remaining stations, Group II (stations 1, 2, 3, 8, 11, 14, 16 and 19) were those with northern exposures, protected areas, or stations at lower elevations.

Table 7 is a listing of the coefficients determined for Models I and II for both groups of stations using daily and 2-hourly data.

Although the inclusion of the exponent on the pan wind factor in the equations did not significantly increase the value of the coefficients of determination, the relative changes in these exponents are considered significant.

In all cases, for both daily and hourly data, the vapor pressure exponent was found to be greater for the June and September analyses than for the July and August data. Normally the overall stability of the air would be greater during June and September than during July and August. This is also reflected by the difference in the exponents for the two groups of stations. The vapor pressure difference exponents were greater for both sets of months for Group II stations than for the Group I. Stations in Group I had the highest observed pan winds.

The large shift in the value of the exponents and coefficients in the wind term (using Model II) between those found for July and August and for June and September, may also be a result of stability effects. No large differences exist in the average pan wind movements between the two sets of months within station groupings.

Effect of wind direction on stability

The mass transfer equation does not take into account

Table 7. Mass transfer equations developed for groups of stations and different periods

Group	No. of cases	Period	b_1	b_2	b_3	b_4	Variance	R^2
Model I $E = (b_1 + b_2 U_p) \; (e_o - e_a)^{b_3}$								
Daily								
1	57	Jul-Aug	.0385	.00035	0.64	-	.00280	.783
	92	Jun and Sep	.0325	.00023	0.72	-	.00260	.730
2	150	Jul-Aug	.0215	.00029	0.79	-	.00230	.749
	140	Jun and Sep	.0108	.00018	0.98	-	.00127	.872
Hourly								
1	150		.0009	.00019	1.02	-	.000112	.697
2	146		.0006	.00013	1.13	-	.000115	.754
Model II $E = (b_1 + b_2 U_p^{b_3}) \; (e_o - e_a)^{b_4}$								
Daily								
1	92	Jul-Aug	.0168	.00310	0.62	0.66	.00269	.797
	57	Jun and Sep	-.0800	.06380	0.14	0.82	.00260	.734
2	150	Jul-Aug	.0198	.00046	0.91	0.79	.00236	.749
	140	Jun and Sep	.0005	.00345	0.43	1.01	.00124	.875
Hourly								
1	150		.0007	.00035	0.75	0.99	.000112	.700
2	146		.0006	.00010	1.11	1.13	.000116	.754

the effect of variation in stability on evaporation rates other than that which is directly related to wind speed. Errors in mass transfer equations may be related to indices of stability and/or turbulence. Wind direction and speed, especially in mountain areas because of terrain effects on turbulent conditions, are considered to be related to the degree of stability and/or turbulence.

Figures 34 and 35 are plots of the computed pan evaporation (after Kohler, Nordenson and Fox, 1955) with observed pan evaporation for stations 14 and 15. These two stations were selected since they are located at the same elevation on the north and south slopes of the most prominent projecting ridge on the study area (see Figure 1). This pair of stations is somewhat free from complicating effects of nearby high terrain. Different symbols have been used on the graph to identify the direction of the 8,000 foot mean sea level 5:00 p.m. MST winds associated with each daily observation. The circles are for those days having upper air wind direction from 160 to 210 degrees (southerly winds). For station 14 (Figure 34) the observed values for these cases are greater than computed, while for northerly wind cases (those marked with an "x") the plotted values are very near the 45-degree line. Westerly winds (those marked with a "#" symbol) have values that average more than observed but not as much deviation as those with southerly winds.

For station 15, Figure 35, the results are quite

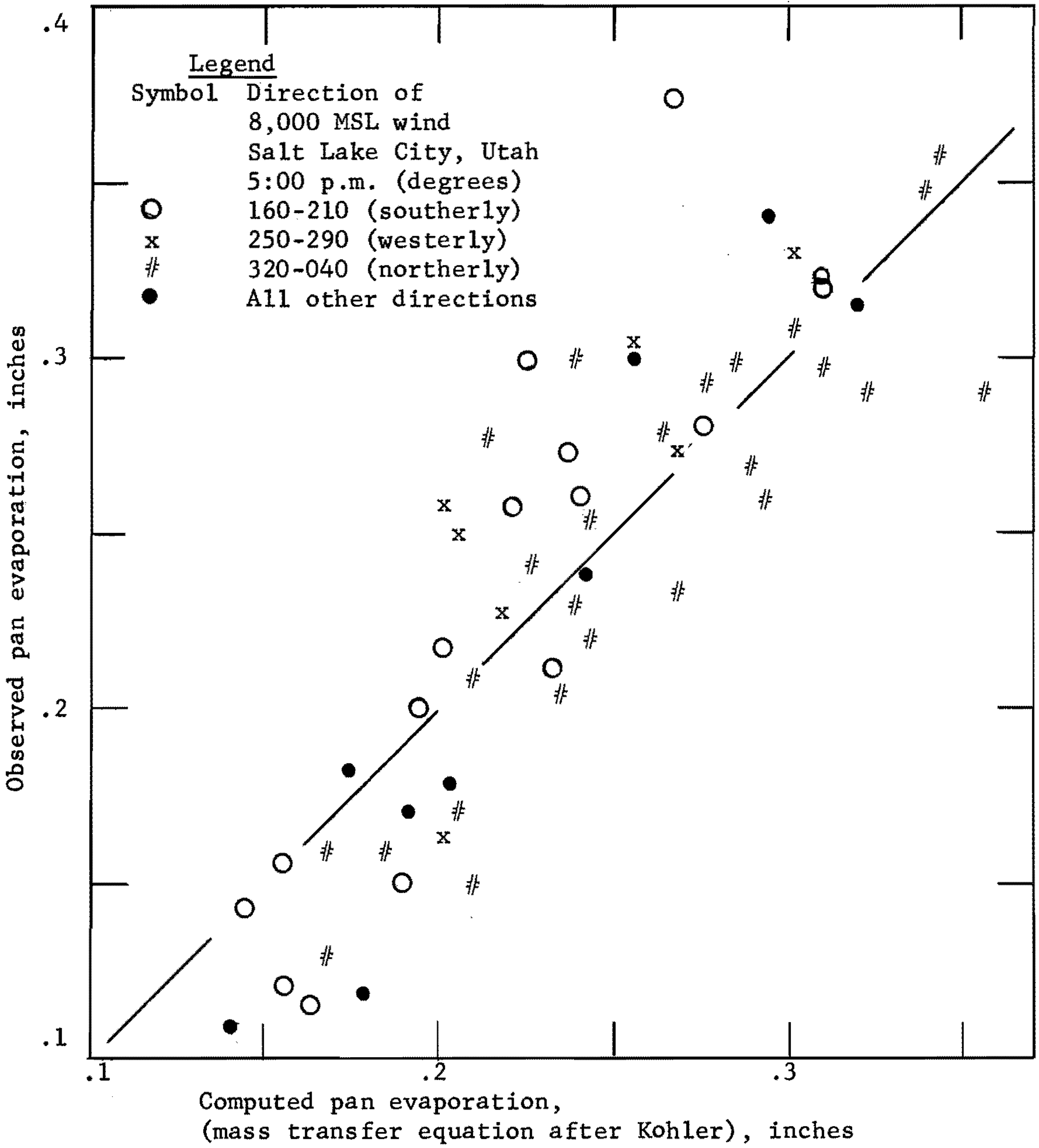

Figure 34. Relation of daily computed mass transfer pan evaporation with observed, station 14

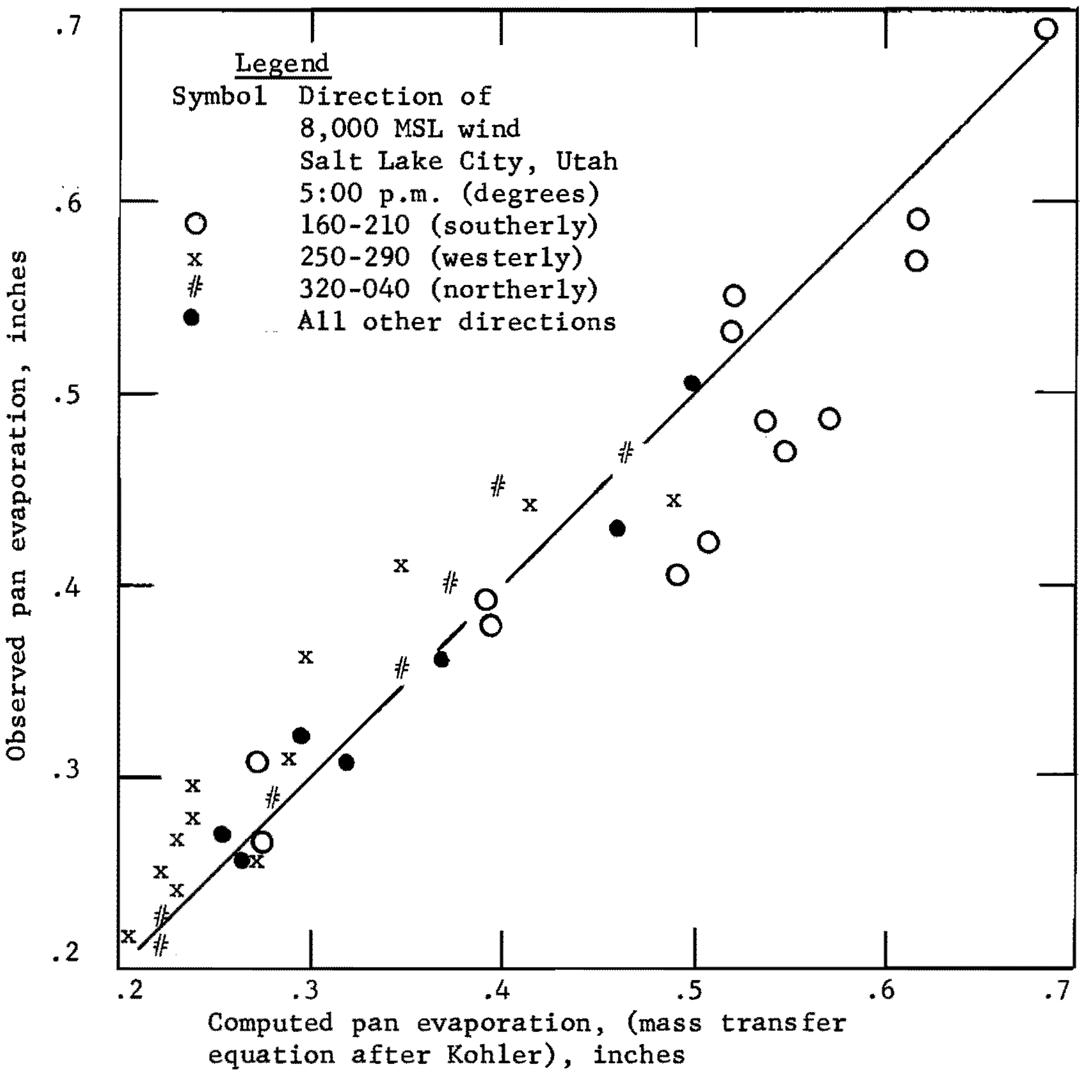

Figure 35. Relation of daily computed mass transfer pan evaporation with observed, station 15

different. Southerly winds are mainly associated with overestimates in contrast to that observed for station 14, while with northerly flows the value tends to be under-estimated, also in direct contrast with station 14. Westerly wind directions for station 15 are primarily associated with under-estimates, which was also observed for station 14.

The computed pan evaporation values are generally closer to observed values at station 15 than for station 14. This is probably due to pan winds at station 15 being affected by the southerly wind flow more than those at station 14. Thus the wind term in the mass transfer equation would tend to correct for the effect of the unstable flow to a greater extent at station 15 than at station 14. For northerly wind directions, the reverse conditions are noted.

During the summer months, winds from the south are more frequently stronger than those from the northern quadrant. The air flow over the mountain ridge would also have the effect of producing more and larger eddies in the flow pattern on the lee side of the ridge. Thus the evaporation at the lee station should be expected to have a greater departure from the computed pan evaporation (which is based only on average stability and turbulent conditions). The observations at stations 14 and 15 substantiate this assumption.

Upper air wind direction and mass transfer equations

If the upper air wind direction is as important as the analyses for stations 14 and 15 seem to indicate, then the mass transfer equation for specified upper air wind direction should show a significant improvement over those when wind direction is not considered. The direction and speed of the 700-millibar 5:00 p.m. MST winds were used to classify the observational days. Coefficients and exponents for Model II were computed using the non-linear technique for each classification of days having more than 50 cases. The grouping of the data and the results of the non-linear analyses are summarized in Table 8.

The coefficients of determination for the groups are generally much higher than those found when the data were not separated on the basis of upper air wind direction. This difference is especially significant in view of the fact that the stations are not separated by exposure and data from all months are included. The lowest coefficients of determination were for light upper air winds (less than 10 knots) from the southwest and west.

Upper air dewpoints and stability

Several investigators have reported that dewpoints are lowest in the afternoon when heating and instability are most pronounced and surface air becomes mixed with drier air aloft. To determine if the differences between free air

Table 8. Mass transfer equations by stratifying on direction and speed of upper air wind, data for all stations and all months included, (Model II)

700 Millibar wind direction and speed	Number of cases	b_1	b_2	b_3	b_4	Variance	R^2
170-190 degrees							
Greater than 10K	119	.0105	.00297	.60	.74	.00258	.822
200-220 degrees							
Less than 10K	68	.0088	.00056	.81	.95	.00219	.829
Greater than 10K	74	.0024	.00203	.60	.92	.00260	.867
230-250 degrees							
Less than 10K	97	.0259	.00119	.80	.63	.00195	.752
260-280 degrees							
Less than 10K	72	-.0017	.00670	.35	.93	.00204	.741
10 to 14K	58	.0223	.00093	.80	.72	.00135	.852
15 to 19K	87	.0188	.00028	1.04	.78	.00171	.780
290-350 degrees							
Less than 10K	59	-.0081	.01017	.37	.79	.00151	.831
Greater than 10K	91	.0106	.00167	.69	.79	.00152	.830

dewpoints and those measured on mountain ridges were related to stability, a study was made of the dewpoint differences for station 4 and the free air at the 700-millibar level.

Figure 36 is a plot of the 5:00 p.m. MST dewpoints at station 4 (elevation 8,960 feet mean sea level) and the dewpoint at the same time for the 700-millibar level. Only data for clear days during the 1965 and 1966 seasons were included. The plotting indicated a general relation but the differences ranged from near zero to 24 F.

A bulk Richardson number was developed for the entire air mass using the temperatures and wind data from the 700- and 850-millibar levels. The high values for this number were found to be associated with large differences in the two dewpoints. High values of the Richardson number have been indicated on the relation in Figure 36.

Since air mass instability is normally considered to be associated with strong southerly winds, points representing days when the 700-millibar 5:00 p.m. MST wind direction (with wind speed greater than 5 knots) was from 140 to 220 degrees have been circled. Points for the southerly wind conditions are generally related to small differences in the dewpoint values.

Although these indications are not adequate for definite conclusions, it is believed that the findings are sufficient to suggest that the difference in the dewpoint values is related to stability of the air mass. Plots of the differ-

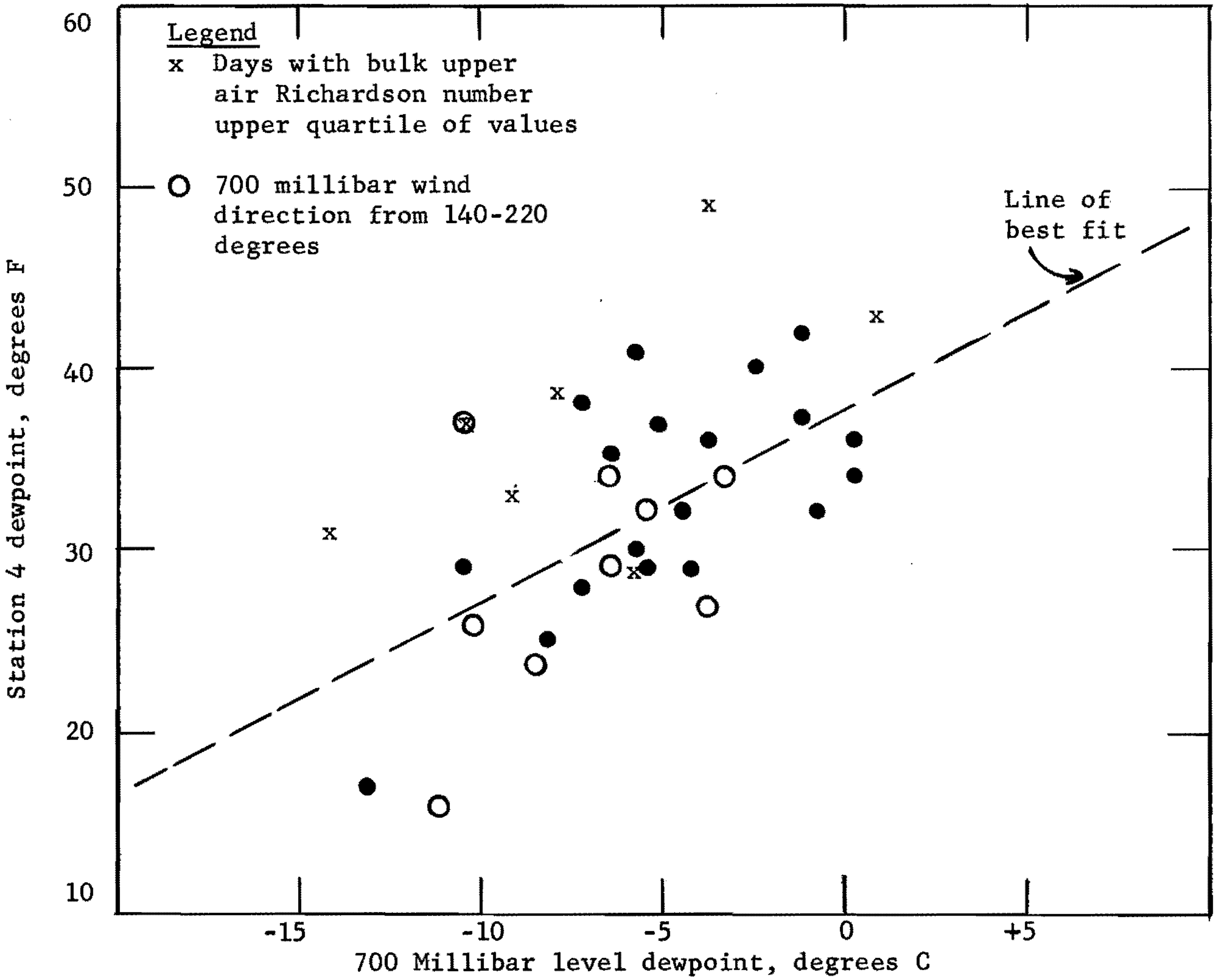

Figure 36. Dewpoint relation, 700 millibar level versus station 4, 5 p.m., clear days only 1965-1966 seasons

ences of the upper air and station dewpoints for other stations showed the same general relations as found for station 4.

Stability relation with upper air dewpoint differences

As shown in the previous section, the difference between the 5:00 p.m. dewpoint at station 4 and that for 700 millibars seems to be related to the overall air mass stability. Stations 1, 3 and 8 are representative of protected sites and should not be affected by upper air eddies in the same way as stations 14 and 15. To further establish that the errors in the estimates for pan evaporation by the mass transfer equation are related to stability, the errors were plotted against the differences in the dewpoints at station 4 and 700 millibars at 5:00 p.m. MST. These plottings (Figures 37, 38 and 39) show a fair relation with little or no bias for large differences and negative bias for small differences. Since it was previously assumed that small differences were associated with unstable conditions, these findings would tend to lend credence to the assumption that air mass instability is a more important factor in increasing pan evaporation other than computed by the mass transfer equation which considers pan wind velocity alone.

Effect of pressure on evaporation

A dimensional analysis approach was used to determine

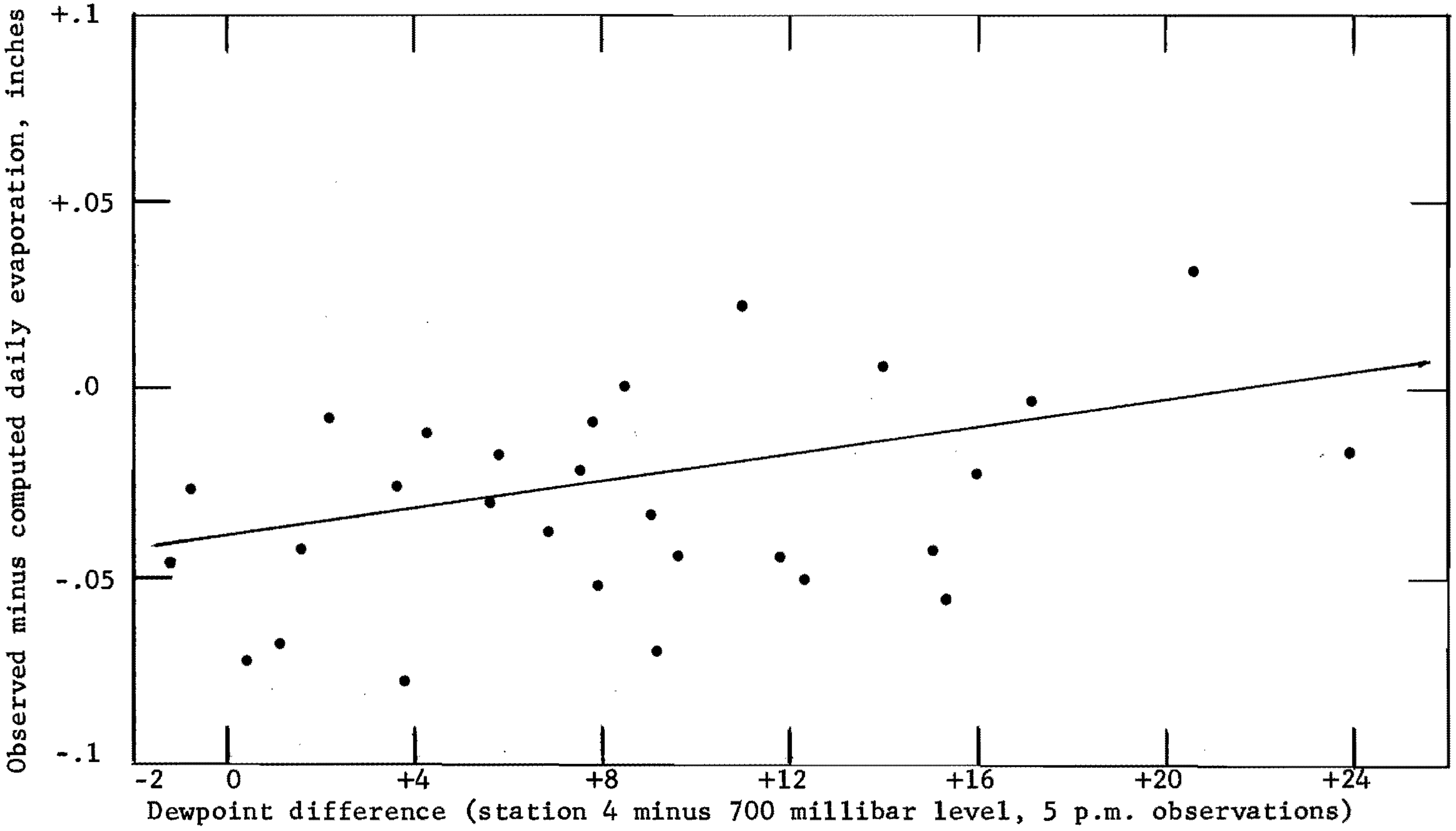

Figure 37. Relation of dewpoint difference with errors in mass transfer equation, station 8, July-August 1966

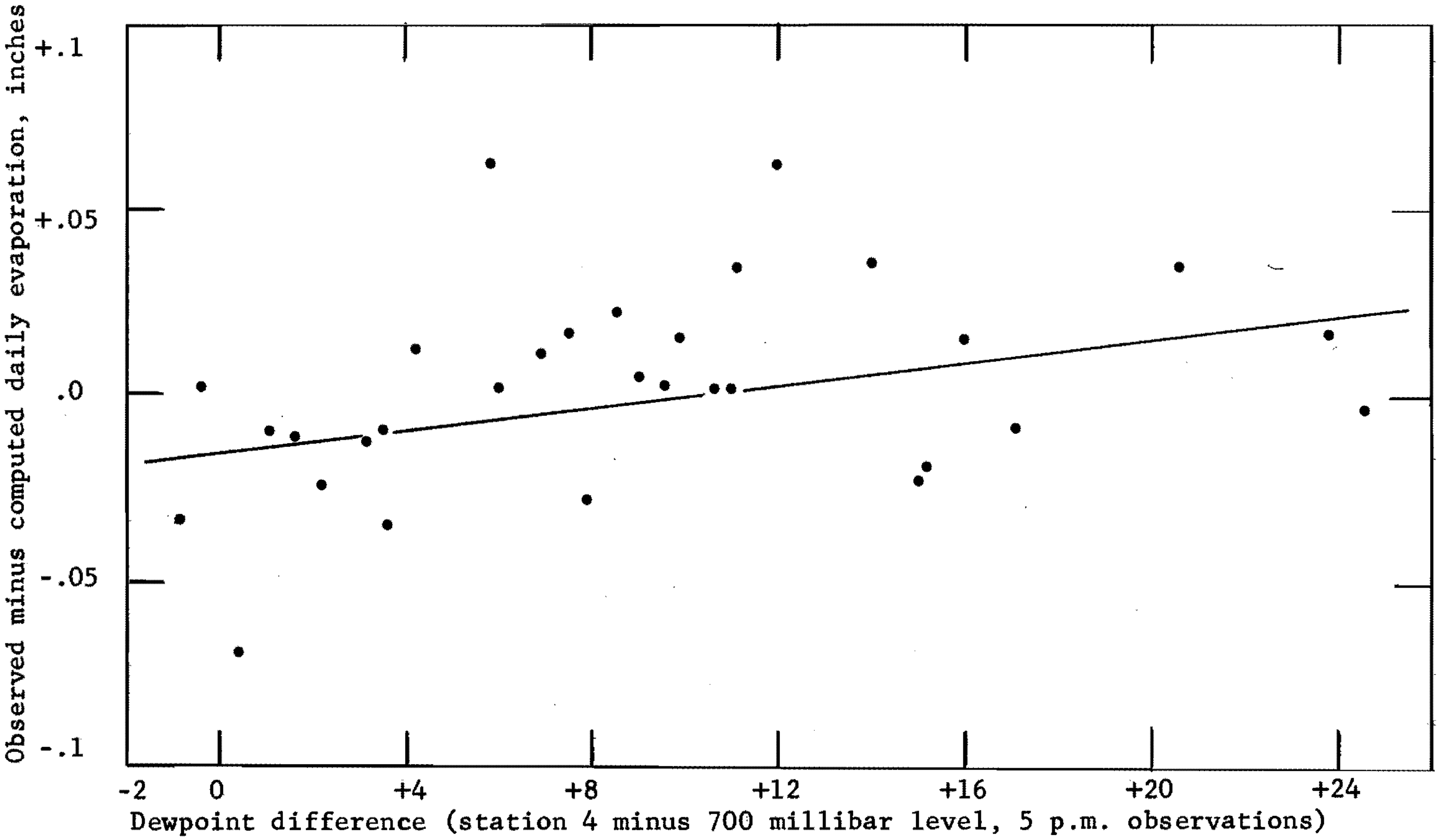

Figure 38. Relation of dewpoint difference with errors in mass transfer equation, station 3, July-August 1966

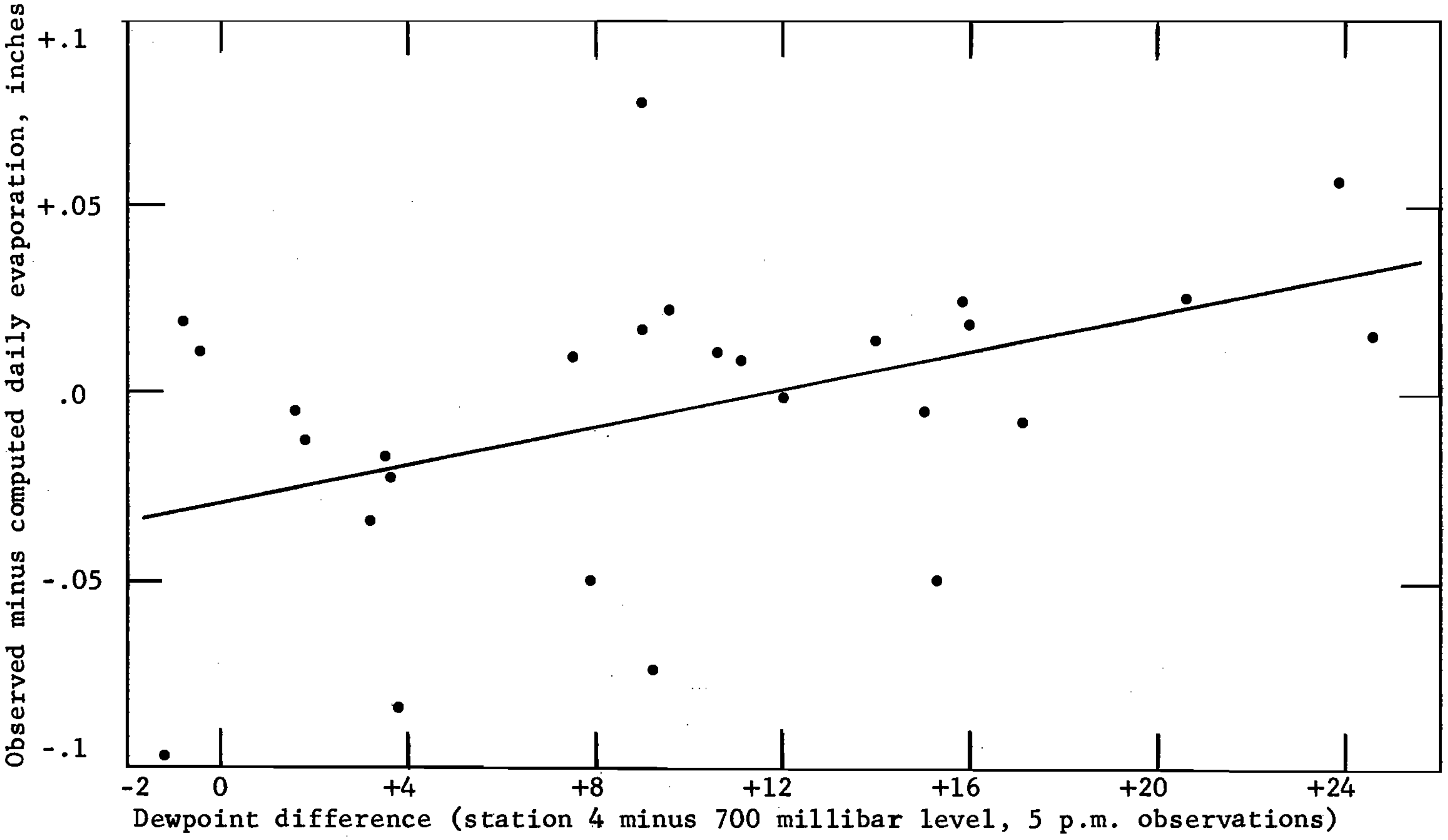

Figure 39. Relation of dewpoint difference with errors in mass transfer equation, station 1, July-August 1966

if the effect of pressure on evaporation might be determined independently of the other factors. The Buckingham Pi Theorem as described by Murphy (1950) was used to arrive at the following relation:

$$\frac{EU_p}{g(Del)} = f\left\{\frac{Del}{P}, Ri, C\right\} \qquad (13)$$

where the term on the left is a dimensionless term including pan evaporation (E) in inches, U_p the pan wind movement, g constant for gravity, and Del the vapor pressure difference $(e_o - e_a)$. This term is some function of the three dimensionless terms on the right. The first term is the ratio of Del to the atmospheric pressure (P), the second the Richardson number, an index of stability, and C a term for the physical characteristics of the topography immediately surrounding each station. The development of the dimensional analysis is given in the Appendix.

The functional relationships among the three dimensionless groupings was found by considering stations which had similar wind movement and vapor pressure differences. It was assumed that the functional relation for the stability, as represented by the Richardson number, was accounted for as nearly constant by using data from stations experiencing only low winds.

Analyses were made using daily data from all stations with pan winds between 40 and 50 miles per day and vapor pressure between 20 and 29 millibars. It was found that the ridge and high south ridge stations did not fit a general pattern but that the rest of the stations gave the relation shown in Figure 40. Values of P in tens of millibars are plotted on the points. These results indicated that the evaporation increases with increase in pressure, all other factors being held constant. Such a conclusion is contrary to the usual statement that evaporation should probably decrease with increase in pressure with all other influences eliminated.

Similar plots for pan wind movement less than 40 miles per day or greater than 60 miles did not show significant results. The starting speed of the anemometers used in the project was near 1.5 miles per hour and this is probably a factor for the lack of significant results with the lower wind speeds. From the study of stability and turbulence effects these factors are probably much more variable from station to station and override the effect due to pressure alone with strong winds. The assumption that the Richardson number is constant for all stations is undoubtedly in error for stronger winds.

The same type of analysis was made on the 2-hourly data. In these cases using pan wind movement near 4 miles (3.6 to 4.4 for the 2-hour period) the results were similar to those obtained for daily data (Figure 41). For higher wind speeds or lower wind speeds the results were again not as conclusive.

It was considered that for the relations found other factors which were not used in the computation such as

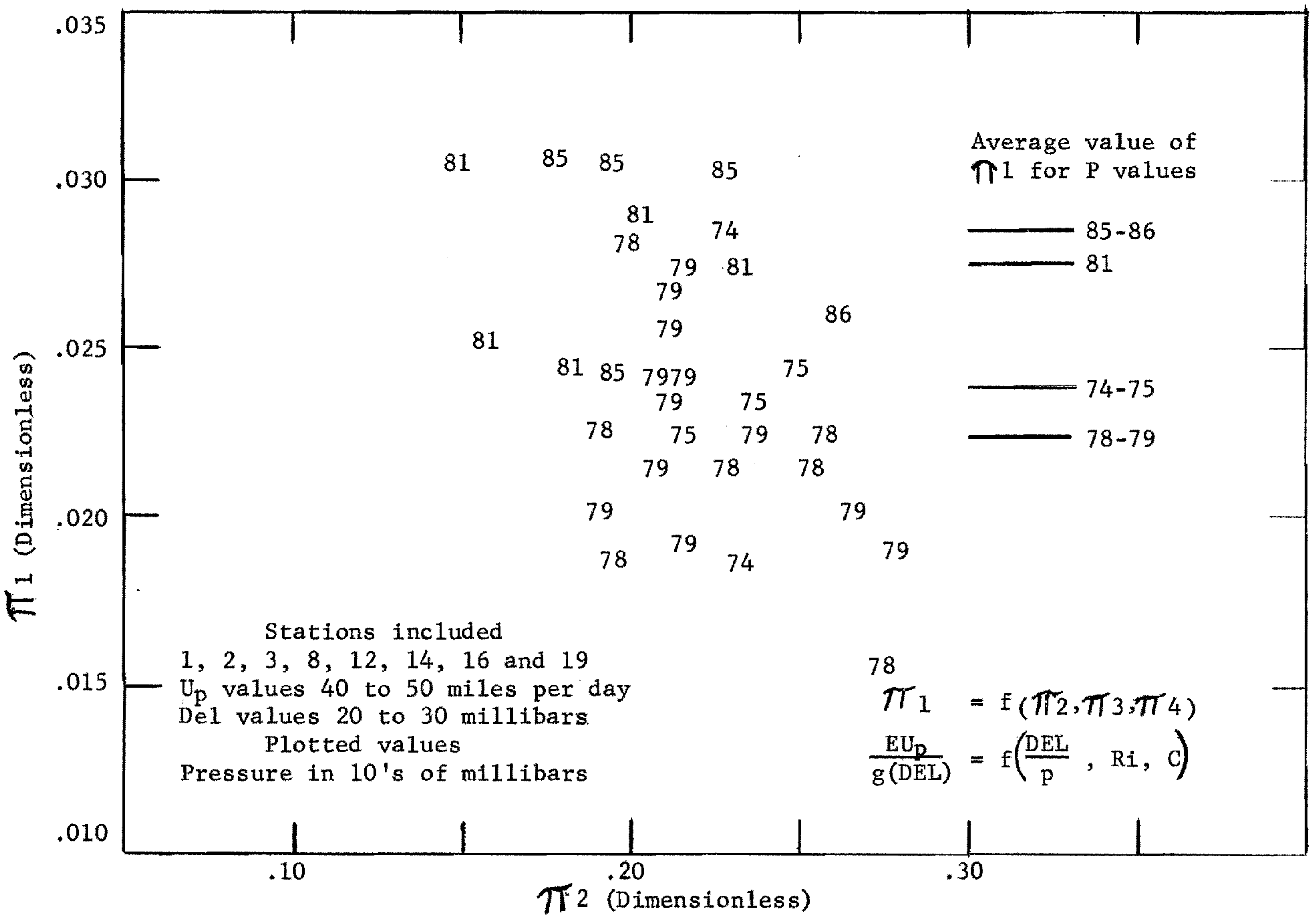

Figure 40. Relation of dimensionless Pi terms for daily data

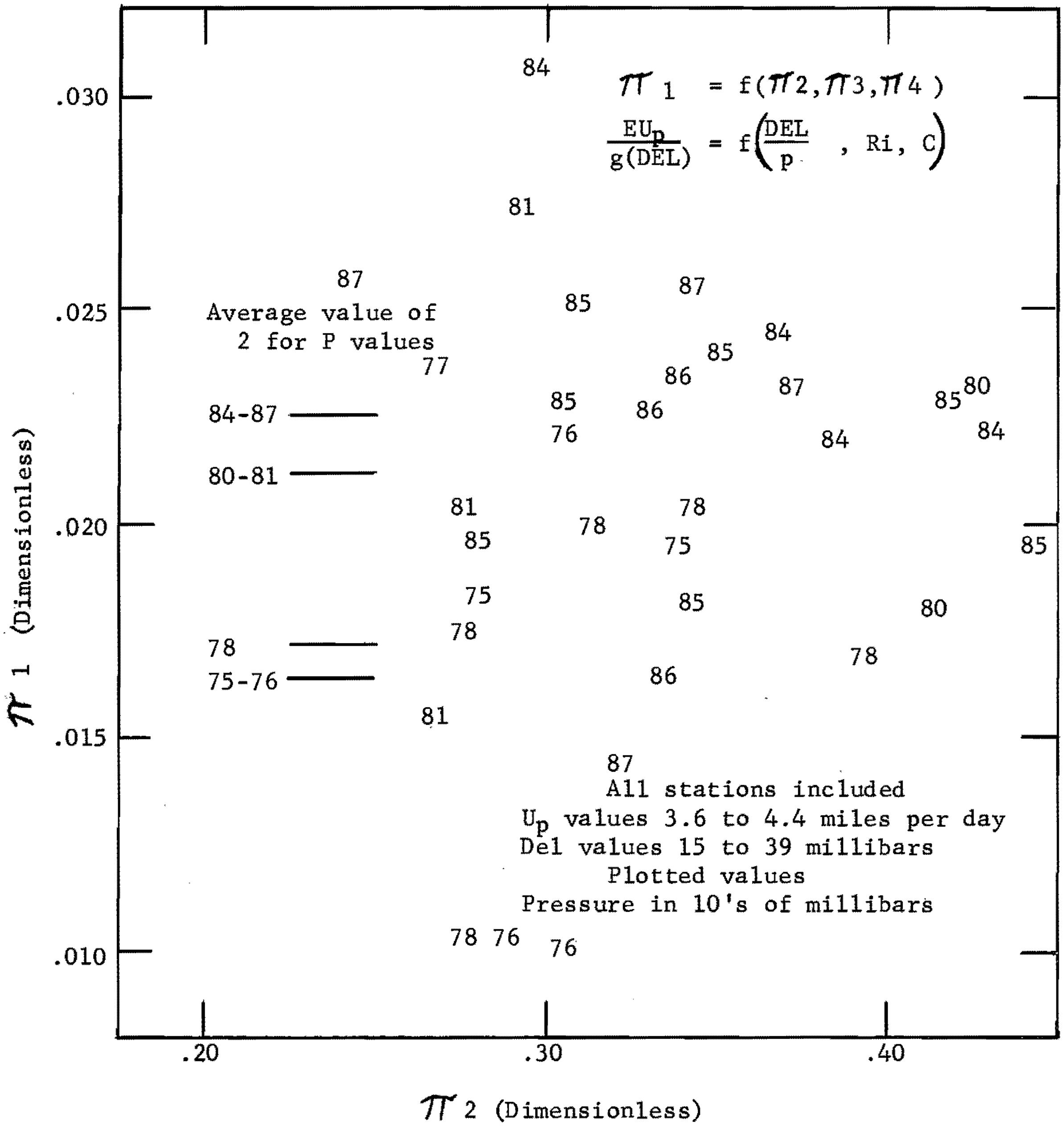

Figure 41. Relation of dimensionless Pi terms for 2-hourly data, 1965-1966

differences in pan and air temperature, etc., might be inter-related with the pressure. Checks were made to establish whether or not such an inter-relation might exist. With the type and range of data available no inter-relation was found that seemed to influence the results.

Radiation-pan-evaporation relations

The radiation-evaporation curves that were developed for each station were used to estimate the evaporation that would occur at each station for specific radiation values. Figure 42 is a plot of elevation with the average pan evaporation for each station for 650 Langleys of radiation.

Plotted on each point is the average pan wind movement. The wind movement values seem to be an important factor for the relation. Stations with high wind movement have higher evaporation for the same radiation than do stations with light wind movement. For the same radiation, the high wind stations are about 20 percent above the mean relation while the low wind stations are about 20 percent below.

Computed lake evaporation

Weather Bureau Research Paper No. 38 by Kohler, Nordenson and Fox (1955) presented two methods for estimating lake evaporation as well as the previously discussed methods for estimating pan evaporation. Computer programs as developed by Lamoreux (1952) were used to compute estimated lake evaporation for all stations.

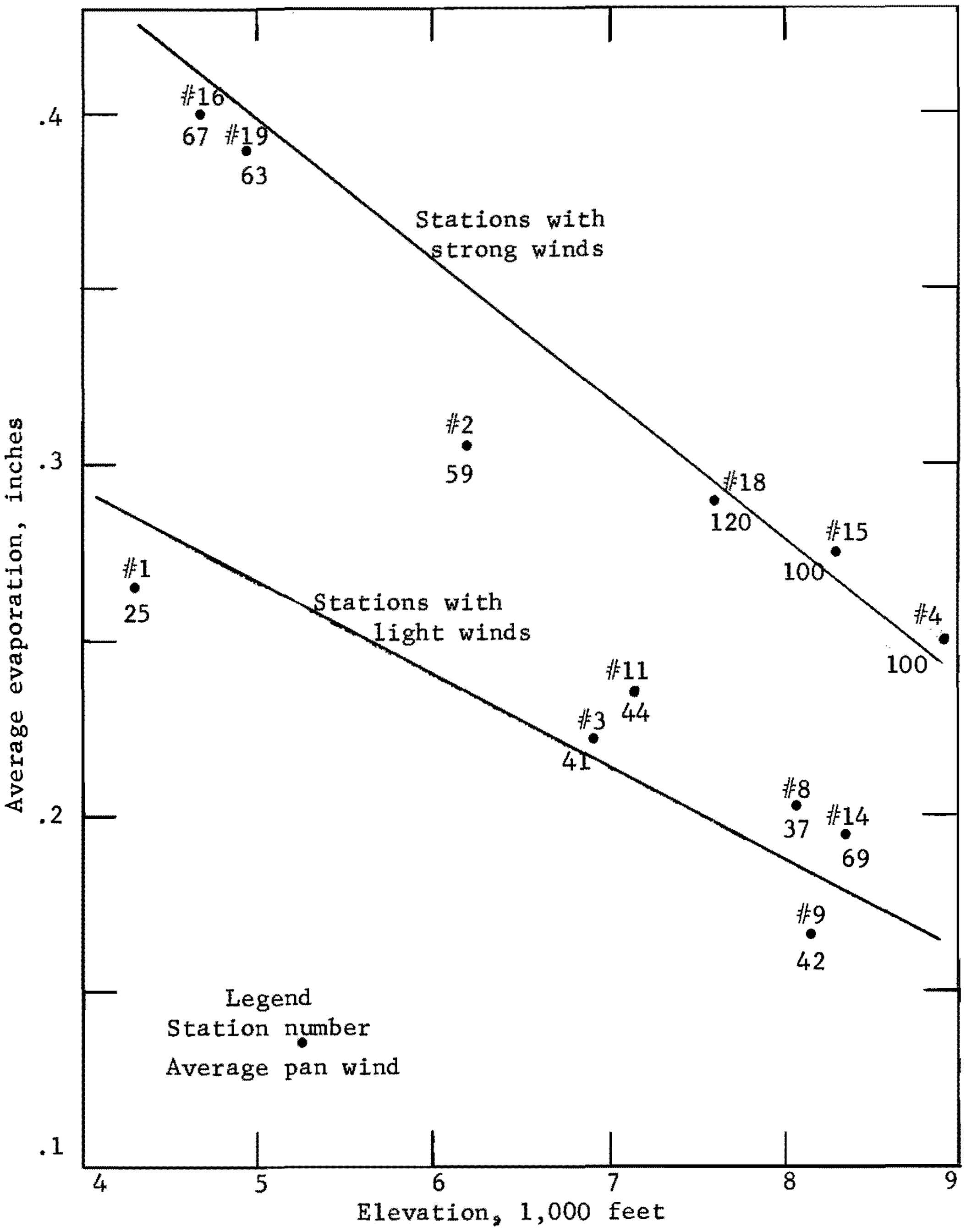

Figure 42. Elevation-evaporation relation for radiation of 650 Langleys at all stations

The method using meteorological factors (equation 10 in Research Paper No. 38) gave estimates that were about 15 percent greater than those by the second method (equation 14 in Research Paper No. 38).

Estimates for pan evaporation using the meteorological factor method were found to be biased on the high side. It was assumed that this type of method for lake evaporation estimation might also be biased in a like manner for the data from the study area. It was also believed that the method using the observed pan data might better integrate the unusual influences due to the mountain exposures.

Figure 43 is a plot of the observed monthly pan evaporation averages with elevation for clear days only during July 1965 and 1966. As found for many of the other relations between meteorological parameters and elevation the data seemed to be divided into two groups. Stations located on major ridges, on southern slopes of high ridges and on open steep slopes have a higher pan evaporation rate for the same elevation than do stations that are protected or located on northern slopes. There is little evidence from the plot that evaporation for the exposed sites changes with elevation.

For the protected and northern exposed sites, the evaporation rate does appear to decrease slightly with increase in elevation. This is in general agreement with the mean altitude-evaporation curve (Figure 44) found by Longacre and Blaney (1962). However, from personal

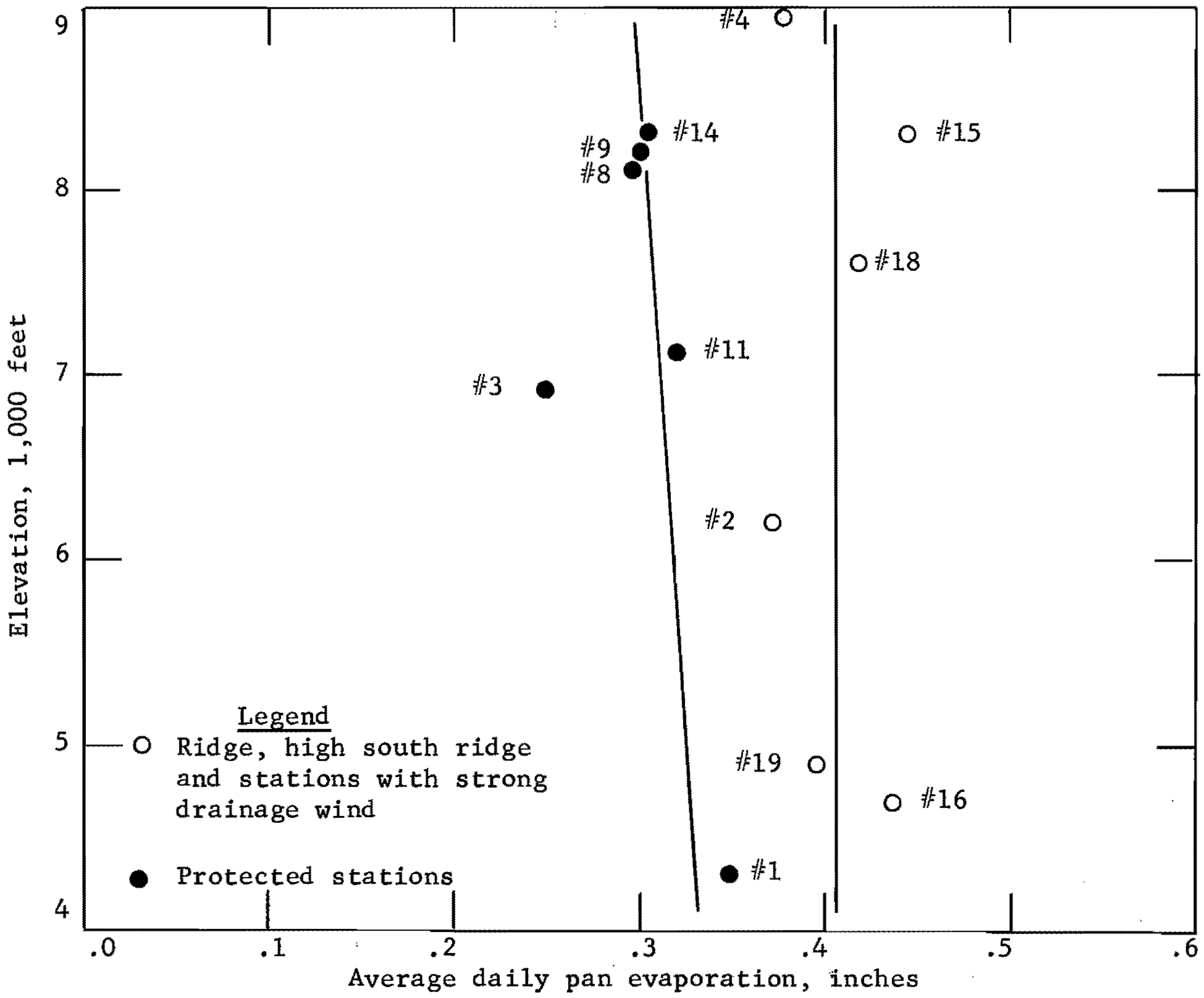

Figure 43. Elevation-observed pan evaporation relation, clear days only, July 1965 and July 1966

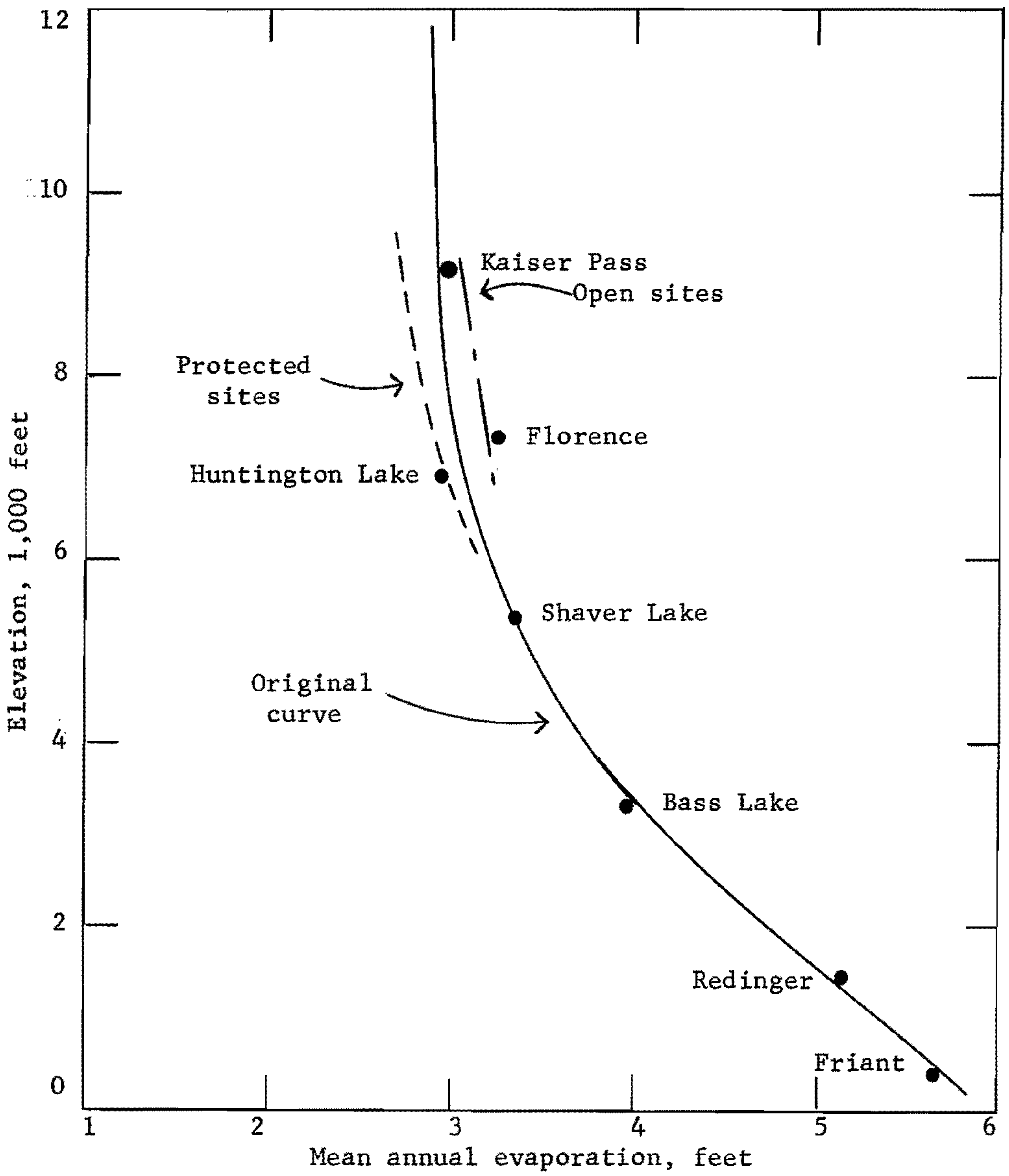

Figure 44. Altitude-evaporation curve of mean annual evaporation from reservoirs (after Longacre and Blaney, 1962)

conversation with Blaney he indicated that the two highest points, Florence Lake (elevation 7,345 feet) and Kaiser Pass (9,194 feet) were the only stations used that had open exposures. In view of the findings of the present study, it is easy to draw curves for open and protected sites as has been done on Figure 44. The separation of the curves for type of exposure would then be in good agreement with the curves shown in Figure 43.

The computed values of lake evaporation for clear days only during July 1965 and 1966, based on equation 14 of Research Paper No. 38, are plotted against elevation on Figure 45. The same general grouping of the stations may be noted. There is about a 20 percent difference between the mean lines representing the two general relations.

Similar plots were made for other months and periods and the same general relations with elevation were noted. Monthly values of computed lake evaporation for all stations having sufficient measurements are listed in Table 3.

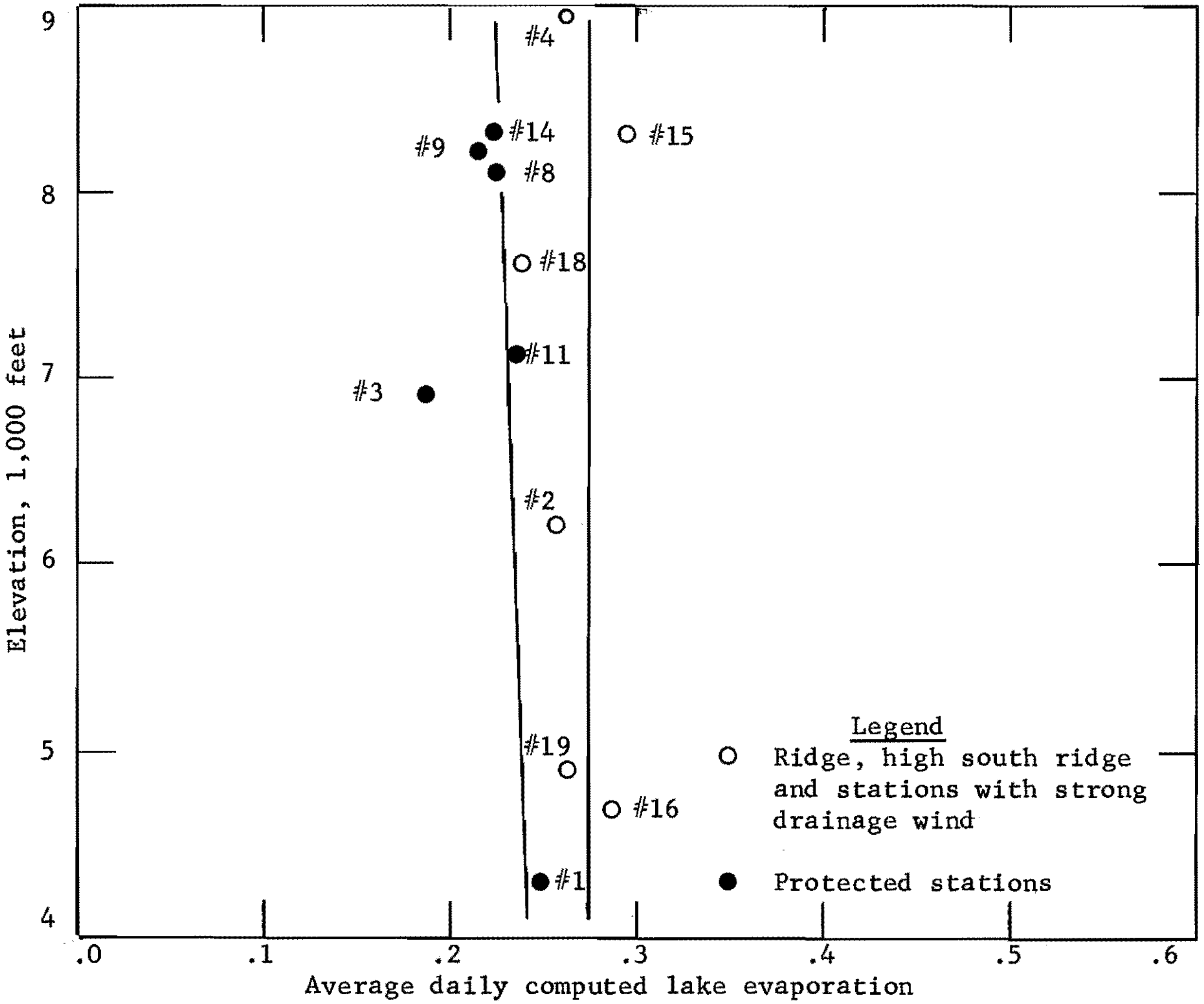

Figure 45. Elevation-computed lake evaporation relation, clear days only, July 1965 and July 1966

DISCUSSION OF RESULTS

Variation of meteorological factors

Departures of meteorological factors from mean relations with elevation were found to be related to stations' exposures. Stations having poor drainage, for example, were found to have lower minimum temperatures. The additional cooling at these sites resulted in a slower rate of evaporation the following day until the heat deficiency was compensated for by incident radiation. This in turn is one of the reasons why the protected sites were observed to have less pan evaporation than stations with open exposures and good drainage.

The absolute moisture of the air, as measured by the dewpoints, was also greatly affected by exposure. Differences in dewpoints for stations at the same elevation but with different exposures were found to be related not only to exposure but to the direction of the general flow of the air mass over the mountain range as indicated by the direction of the 700-millibar level wind. The large decrease in the measured dewpoints which was found to occur after dark for most stations was a result of the down canyon drainage winds.

Diurnal variations in the wind movement at the various stations also influenced the diurnal variation in the evaporation rates. The large decrease in night time dewpoints at higher elevations results in a large increase in the vapor pressure difference between the water surface and the air. This causes a large increase in the evaporation rate. At ridge-top locations where winds quite often attain a maximum during the afternoon, the maximum potential evaporation would likewise occur at this time. For the lower canyon sites, where the maximum winds are associated with the night-time drainage winds, the maximum potential evaporation may well occur during the late evening. Such variations in the timing of potential evapotranspiration should be important to ecological studies in mountain areas.

The relations for the different type of sites for pan evaporation with elevation should be of value in extrapolating observed pan measurements to higher elevations in mountain areas. Reference to topographic and ecologic maps would provide the necessary subjective background to make such extrapolations for developing improved maps for pan and lake evaporation.

Validity of mass transfer equations

The verification of the mass transfer equation of Research Paper No. 38 for estimating pan evaporation on a monthly basis indicates that the equation is reliable for this purpose. However, pan evaporation estimates on a daily basis were not found to be reliable. Nor was work in other previous reports where the time interval was less than a week. Departures from the reliable methods for estimating monthly values when used for daily estimates were found to be related to station exposure and stability indices. The effects of the stability (as indicated through the indices used) on evaporation when taken over a long period of time tend to average themselves out. From a knowledge of the type of exposure and applying the developed mass transfer equations in Table 7 and 8, reasonable estimates for daily values of pan evaporation can be obtained.

Reasons for variations in the exponents in mass transfer equations

The rugged topography and unusual wind conditions of the study area were the underlying reasons why stability had so large an influence on pan evaporation.

Many investigators have found that observed wind speed is related to the stability of the air near the surface. The changes in the exponents on the vapor pressure term of the mass transfer equations developed using daily and 2-hourly data for stations with different exposures reflected variations in stability. The change to lower exponent values was also found when equations were developed for July-August data as compared with the exponents for equations based on June and September observations.

The many variations in constants for the general mass transfer equation as found in the literature could be the result of differences in stability conditions at the sites where data were obtained.

Pressure effect on evaporation

The dimensional analysis indicated that pressure effect, independent of other factors, caused an increase in pan evaporation with increase in pressure. This effect was shown only for light wind conditions, with the assumption that the Richardson number (or stability of the air near the ground) was approximately the same for all stations. The results of an approach of this type are no better than the assumptions on which they are based. Many other factors, not considered in the dimensional analysis development, may also have an important relation to evaporation, and these might offset the effect observed for pressure if considered. It should again be emphasized that this author does not assume that indications found in this preliminary study are actually related to physical reality. The findings are of interest but need considerable more verification than can be made in this study.

CONCLUSIONS

The conclusions are:

1. Deviations from mean relations with elevation of monthly values of meteorological factors were found to be related to station exposure.
2. Differences in dewpoints for stations at the same elevation are related not only to differences in station exposure but also to the stability of the air and direction of the upper air flow.
3. Diurnal variation of meteorological parameters at a location are associated primarily with diurnal variations of the wind movement. Diurnal variations of wind movement, in turn are dependent upon the location of the station with respect to the topographic features.
4. The Christiansen method for estimating mean monthly pan evaporation was found to have an average error of less than 6 percent for the network stations.
5. The mass transfer equation given in Weather Bureau Research Paper No. 38 gave estimates of mean monthly evaporation within 3 percent of observed values.
6. Errors in the Weather Bureau mass transfer

equation for daily values were found to be related to stability indices.

7. Improvement between observed and estimated daily pan evaporation by mass transfer equations was found when the station exposures and the time of the season were considered.
8. Further improvement in mass transfer equations was found when the daily data were separated on the basis of direction and speed of the 700-millibar level wind.
9. Pan evaporation for well exposed locations on top of major ridges and along their southern slopes, and also on sites where strong night time drainage winds occur, was found to have no discernable variation with elevation.
10. For protected sites and those on northern slopes, pan evaporation showed a small decrease with increasing elevation.
11. Computed lake evaporation values, for different types of exposures, were found to have the same relations with elevation as did the observed pan evaporation.
12. Mass transfer equations were developed that gave good correlation with observed 2-hourly evaporation measurements from network stations.
13. Observed daily and 2-hourly measurements of pan evaporation at different altitudes were

found to increase with increase in pressure (decrease in elevation) for periods when the pan wind averaged near 2 miles per hour. This is opposite to the general theory that evaporation should decrease with elevation, all other effects being the same.

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APPENDIX

Development of dimensional relation

The basis for the Buckingham Pi Theorem is that all pertinent, independent primary quantities should be included in the general relationship from which the analysis is made. Based on the known relations, the following statement of evaluation as a function of other factors is assumed to contain the primary quantities.

$$E = f\left\{g,\ \theta,\ (e_o - e_a),\ P,\ \frac{\partial U}{\partial Z},\ \frac{\partial \theta}{\partial Z},\ U_p,\ C\right\} \quad (14)$$

Where:

E = evaporation $\doteq F\ L^{-2}\ T^{-1}$

g = gravity $\doteq L\ T^{-2}$

θ = potential temperature $\doteq 0$

$(e_o - e_a)$ = vapor pressure difference $\doteq F\ L^{-2}$

P = atmosphere pressure $\doteq F\ L^{-2}$

$\frac{\partial U}{\partial Z}$ = wind variation with height $\doteq T^{-1}$

$\frac{\partial \theta}{\partial Z}$ = variation of potential temperature with height $\doteq 0\ L^{-1}$

U_p = daily pan wind movement $\doteq L\ T^{-1}$

C = physiographic characteristics of station not accounted for in other terms $\doteq$ dimensionless

The basic units are F force, T time, L length, θ potential temperature.

Following the standard procedure as outlined by Murphy (1950) the development is as follows:

The dimensional equation is:

$$(F\ L^{-2}\ T^{-1})^{C_1}\ (L\ T^{-2})^{C_2}\ (\ \theta\ )^{C_3}\ (F\ L^{-2})^{C_4}\ (F\ L^{-2})^{C_5}$$

$$(T^{-1})^{C_6}\ (\ \theta L^{-1})^{C_7}\ (L\ T^{-1})^{C_8} = 0 \qquad (15)$$

The auxiliary equations are:

$$F; \quad C_1 + C_4 + C_5 = 0 \qquad (16)$$

$$L; \quad -2C_1 + C_2 - 2C_4 - 2C_5 - C_7 + C_8 = 0 \qquad (17)$$

$$T; \quad -C_1 - 2C_2 - C_6 - C_8 = 0 \qquad (18)$$

$$\theta; \quad C_3 + C_7 = 0 \qquad (19)$$

Equating the exponents of dimensions the following Pi terms are derived:

$$\text{Pi } 1 = \frac{E\ U_p}{g(e_o - e_a)} \qquad (20)$$

$$\text{Pi } 2 = \frac{P}{(e_o - e_a)} \qquad (21)$$

$$\text{Pi } 3 = \frac{U_p\ \frac{\partial U}{\partial Z}}{g} \qquad (22)$$

$$\text{Pi } 4 = \frac{U_p^{\,2} \frac{\partial \theta}{\partial Z}}{g \, \theta} \qquad (23)$$

$$\text{Pi } 5 = C \qquad (24)$$

From theory Pi 1, containing the evaporation rate, may be equated with some function of the remaining Pi 's terms. If there is a known relation between two Pi terms, they may be combined to form one.

If Pi 3 is inverted and is squared and multiplied by Pi 4 as below, the result is the basic form of the Richardson number (Richardson, 1920):

$$\left(\frac{g}{U_p \frac{\partial U}{\partial Z}} \right)^2 \frac{U_p^{\,2} \frac{\partial \theta}{\partial Z}}{g \, \theta} = \frac{g}{\theta} \frac{\frac{\partial \theta}{\partial Z}}{\frac{\partial U}{\partial Z}^2} \qquad (25)$$

Combining Pi 3 and Pi 4 into the Richardson number (Ri) the final relation may be written:

$$\frac{E \, U_p}{g(e_o - e_a)} = f\left\{ \frac{P}{(e_o - e_a)} , \text{Ri}, C \right\} \qquad (26)$$