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National Oceanic and Atmospheric Administration
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NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM-SNOW ACCUMULATION AND ABLATION MODEL

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CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

The techniques used by the National Weather Service (NWS) for making river and flood forecasts have been changing in recent years (Sittner, 1973). Conceptual watershed models are replacing previously used empirical procedures. In 1972 the Hydrologic Research Laboratory of the Office of Hydrology, NWS, prepared a technical memorandum entitled "National Weather Service River Forecast System, Forecast Procedures" (referred to as HYDRO-14 throughout this report) as a guide for the implementation of conceptual river forecasting models by field offices. HYDRO-14 describes the techniques and computer programs needed for developing operational river forecasts based on the use of a continuous conceptual watershed model from the processing of the basic data to the preparation of the forecasts. The procedures described in HYDRO-14 did not include techniques to model snow accumulation and snowmelt. This Technical Memorandum describes a conceptual model of the snow accumulation and ablation process and the associated computer subroutines and programs which enable the model to be used in conjunction with the National Weather Service River Forecast System (NWSRFS). Guidelines and methods for determining model parameter values for a given area are also presented. Even though the snow subroutines are written for use with the NWSRFS, the snow accumulation and ablation model itself can be used with almost any soil-moisture accounting (rainfall-runoff relationship) and channel routing procedure. The output from the snow model would be the input to the soil-moisture accounting procedure. The output from the snow model is snowpack outflow (snowmelt water and rainwater leaving the snowpack) plus rain that fell on bare ground.

1.2 DATA REQUIREMENTS

The snow accumulation and ablation model uses air temperature as the sole index to energy exchange across the snow-air interface. Air temperature is the only additional data needed to use the snow model in conjunction with the NWSRFS soil-moisture accounting and channel routing models. Streamflow, precipitation, and some form of potential evapotranspiration (PE) data are needed for the NWSRFS (see chapter 2, HYDRO-14). The basic computational interval of the NWSRFS is six hours, thus, six-hourly mean areal air temperature data are required. Chapter 2 of this Technical Memorandum describes a procedure and associated computer programs for computing six-hourly mean areal air temperature from daily maximum-minimum air temperature observations Since the NWSRFS models and the snow model are continuous models, a continuous record of six-hourly mean areal air temperature data is required. However, the snow subroutines contain a provision that eliminates the requirement for valid air temperature data during periods when there is no snow on the ground

There are two basic reasons for using air temperature as the sole index to energy exchange across the snow-air interface:

a. Air temperature data are readily available throughout the United States on a real time operational basis.

b. Comparison tests conducted by the Hydrologic Research Laboratory have shown that on two experimental watersheds the temperature index

> method of estimating energy exchange across the snow-air interface has produced simulation results which are at least as good as those produced using a combination energy balance - aerodynamic method. The combination energy balance - aerodynamic method tested is essentially the same as the method described by Anderson (1968). The two watersheds on which these tests were made are Upper Castle Creek, Central Sierra Snow Laboratory, and Watershed W-3, Agricultural Research Service (ARS), Sleepers River Research Watershed.
>
> The combination method will give more accurate estimates of energy exchange at a point than the temperature index method if accurate measurements of all the necessary meteorological variables are available (these variables are air temperature, dew-point, wind speed, incoming and reflected solar radiation, and atmospheric longwave radiation). However, on the two experimental watersheds the combination method results were affected by several sources of error: 1) errors in point measurements, especially in regard to incoming solar radiation, 2) errors in estimating variables which were not measured (primarily atmospheric longwave radiation), and 3) errors in estimating mean areal values of the variables (primarily determining the effect of slope, aspect, and forest cover on incoming solar and atmospheric longwave radiation, determining the areal albedo of the snowpack, and determining the mean areal wind speed). The integrated effect of these errors was estimates of energy exchange across the snow-air interface which were no better than estimates from the temperature index method on the two experimental watersheds.
>
> It is felt that the data available at these two experimental watersheds is superior to that which is generally available on a real-time operational basis in the United States. Thus, it does not appear practicable to use a physical energy balance approach like the combination method to estimate energy exchange across the snow air interface until improved measurements of the meteorological variables affecting snowpack energy exchange are obtained and until improved methods of accounting for the effects of physiographic factors on snowpack energy exchange variables are developed.

The Hydrologic Research Laboratory is currently involved in a project to obtain the highest possible quality data for the purpose of developing and testing snowpack energy exchange equations at a point. This study is the NOAA - ARS Cooperative Snow Hydrology Project on the Sleepers River Research Watershed (Johnson and Anderson, 1968). Ultimately these measurements of the variables affecting snowpack energy exchange will be used along with data from an adjacent watershed to develop improved methods of accounting for the effect of physiographic factors, such as slope, aspect, elevation, and forest cover on the mean areal values of the meteorological variables.

Air temperature is a very good index to snowpack energy exchange in a dense coniferous forest. The only energy exchange mechanism showing much variability is longwave radiation exchange, which is a function of the difference between canopy temperature and snow surface temperature. Canopy temperature is closely related to air temperature. The other primary energy exchange mechanisms, shortwave radiation exchange, sensible heat exchange, and latent heat exchange show very little variability because there is only a slight amount of solar radiation penetrating the forest canopy and because wind movement is limited. On the other hand, in an open area there generally is a large amount of variability in solar radiation exchange, longwave radiation exchange, sensible heat exchange, and latent heat exchange. Because of this variability, air temperature is not nearly as good an index to snowpack energy exchange in an open area. Therefore, there is a greater potential for improvement in estimating snowpack energy exchange by using a physical energy balance method, rather than a temperature index method, in areas where the values of the variables affecting energy transfer can exhibit large variations. It is felt that in the near future when accurate measurements of the variables affecting snowpack energy exchange are available and when techniques of accounting for the areal variability of the variables are improved that physical energy balance equations will provide a more accurate estimate of the energy exchange across the snow-air interface.

In regard to the data period required for model parameter calibration, the recommendation given in HYDRO-14 is generally applicable to watersheds where snow is included. HYDRO-14 indicates that it is desirable to sample each mathematical relationship in the model over its maximum possible range; thus, a long data period is indicated. However, in many cases watershed characteristics change with time. For river forecasting we are interested in parameters which express the near future. Since the future cannot be sampled, a short record representing the immediate past is the second choice. Based on these considerations, HYDRO-14 recommends that "A suitable compromise seems to be the most recent 10 years of record.". For most watersheds, 10 years of record is completely adequate for determining model parameter values. However, in arid or semi-arid areas and in areas where significant snowpacks do not accumulate every year, more than 10 years of data may be required to determine adequately all the model parameters. In areas with considerable hydrologic activity and where large snowpacks accumulate every winter, less than 10 years of data may be sufficient to determine model parameter values.

1.3 TEST WATERSHEDS AND RESULTS

This Technical Memorandum does not present detailed results of tests of the snow accumulation and ablation model. However, for the benefit of potential users it is felt that a listing of the watersheds tested to date and a brief summary of the simulation results on these watersheds might be informative. Table 1-1 lists the watersheds tested and presents several statistics which summarize the comparison between observed and simulated mean daily discharge. Data from the Central Sierra Snow Laboratory were used for testing various mathematical formulations during the development stage of the snow model. The estimation of energy exchange when air temperature is below 32°F was modified based on tests using data from Sleepers River Watershed W-3. The other watersheds were used to test the applicability of the model to different size areas and to different physiographic and climatic conditions.

1.4 COMPUTER PROGRAMS AND COMPUTER REQUIREMENTS

There are three basic computer programs in the NWSRFS which include the snow accumulation and ablation model. These are: 1) the verification program (NWSRFS4) which is used to check the simulation accuracy of various sets of parameter values, 2) the optimization program (NWSRFS3) which is used to determine parameter values by an automatic optimization technique, and 3) the operational river forecasting program (NWSRFS5) which is used to prepare river discharge forecasts on an operational basis. The NWSRFS also contains a number of data processing programs (see chapter 3 of HYDRO-14). Chapter 2 of this Technical Memorandum describes three additional data processing programs for use in computing mean areal air temperature. These are: 1) the basic mean areal air temperature program (MAT Program), 2) the MAT consistency check program (Program MATCØN) which checks the consistency of each station used in the mean areal temperature analysis, and 3) the MAT temperature check program (Program TEMPCK) which compares the estimated and observed maximum and minimum temperatures at a given air temperature observation station. Table 1-2 lists the program dimensions, storage requirements, and typical run times for the six programs involving the snow accumulation and ablation model and the computation of mean areal air temperature. The programs are written in FØRTRAN IV for use on a CDC 6600 computer system. Minor revisions may be necessary for use on other computer systems.

The computer programs and test data sets described in HYDRO-14 are availal on magnetic tape from:

Acquisition Office
National Technical Information Service
U. S. Department of Commerce
Springfield, Virginia 22151

Accession number: COM 73-10298
Cost: $97.50

These programs contain all the necessary statements for use with the snow subroutines (One exception; a few changes were made to Program NWSRFS5 after preparation of the magnetic tape. The changes are only needed when the snow model is included. Appendix H lists these changes to Program NWSRFS5). Information on how to obtain the snow subroutines for programs NWSRFS3, NWSRFS4, and NWSRFS5, plus the programs for the computation of mean areal ai temperature can be obtained from:

Hydrologic Research Laboratory, W23
Office of Hydrology
National Weather Service, NOAA
Silver Spring, Maryland 20910

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Johnson, Martin L., and Anderson, Eric, "The Cooperative Snow Hydrology Project - ESSA Weather Bureau and ARS Sleepers River Watershed", Proceedings of the Eastern Snow Conference, 1968, pp. 13-23.

Sittner, W. T., "Modernization of National Weather Service River Forecasting Techniques", Water Resources Bulletin, Vol. 9, No. 4, August 1973.

Staff, Hydrologic Research Laboratory, "National Weather Service River Forecast System, Forecast Procedures", NOAA Technical Memorandum NWS HYDRO-14 U. S. Department of Commerce, Silver Spring, Md., December 1972.

Table 1-1.--Summary of simulation results on the watersheds tested with the snow accumulation and ablation model in conjunction with the NWSRFS as of June 1973.

Watershed	Data Period	Area mi^2	Elev. Range[1]	Number of Stations				Mean Annual Runoff Inches and CFSD	RMS Error CFSD	Correl Coef.	% Bias	Best Fit Line Obs.=a+b·Sim.	
				Precip	Elev. Range	Air Temp.	Elev. Range					a CFSD	b
Upper Castle Creek, Central Sierra Snow Laboratory	10/46-9/51	3.96	6880-9105 7050-8250	1	6890	1	6890	46.1" 13.5 CFSD	8.3	.971	-2.0	-0.4	1.05
Skyland Creek, Upper Columbia Snow Laboratory (UCSL)	10/46-9/50	8.1	4800-7610 5200-6800	1	4840	1	4840	31.5" 18.8 CFSD	6.7	.981	1.5	-0.3	1.0
Bear Creek, UCSL[2]	10/46-9/50	12.6	4480-8605 4900-6350	1	4840	1	4840	29.5" 45 CFSD	13.8	.983	0.2	-0.3	1.01
W-3, ARS Sleepers River Watershed	10/62-9/67	3.23	1140-2260 Unknown	3	1350-2200	1	1140	21.7" 5.2 CFSD	2.1	.955	1.6	0.2	0.95
W-8, ARS Sleepers River Watershed[2]	10/62-9/67	2.81	920-1680 Unknown	2	1150-1350	1	1140	17.2" 7.7 CFSD	2.2	.970	2.3	0.2	0.95
W-1, ARS Sleepers River Watershed[2]	10/62-9/67	10.54	740-2430 Unknown	4	1150-2200	1	1140	17.1" 20.9 CFSD	8.7	.964	3.5	-1.7	1.04

Table 1.1 (continued)

Passumpsic R. at Passumpsic, Vermont	10/63-9/71	436.	530-3400 780-2240	4	699-1140	3	699-1140	20.3" 653 CFSD	294.	.939	-1.5	49.	0.94
Rock River at Rock Rapids, Iowa	10/59-9/69	788.	1330-1950 Unknown	6	1350-1700	6	1350-1700	3.1" 179 CFSD	444.	.906	5.9	28.	0.80

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[1] First range is for the total area. Second range is for 90 percent of the area, excluding the upper and lower 5 percent. All elevation ranges are in feet above m.s.l.

[2] Streamgage is downstream from another calibrated watershed. Local area was calibrated using observed upstream inflows. Area, elevation range, and station information are for local area only. Mean daily discharge comparisons are based on the total flow at the streamgage.

Table 1-2.--Program dimensions, storage requirements[1], and typical run times[1] for NWSRFS programs using the snow model and programs for computing mean areal air temperature.

Program	Dimensions	Storage Requirements Decimal Words	Typical Run Times
Verification Program (NWSRFS4)	5 snowpack and soil-moisture accounting areas. 5 streamflow points. 3 upstream inflow points. 2 PE stations	39K	2 sec./year for each snowpack and soil-moisture accounting area, plus 3 sec./year for each streamflow point
Optimization Program (NWSRFS3)	2 snowpack and soil-moisture accounting areas. 1 streamflow point. 4 upstream inflow points. 2 PE stations 50 months of data	32K for program, plus 75K for data storage	5.5 sec./50 months for each snowpack and soil-moisture accounting area, plus 1 sec./50 months for the streamflow point
Operational River Forecasting Program (NWSRFS5)	10 snowpack and soil-moisture accounting areas. 10 streamflow points. 5 upstream inflow points. 3 PE stations. 14 days of data.	29K To enlarge river system requires approx. 350 words/snowpack and soil-moisture accounting area, plus 600 words/streamflow point	1 sec./14 days for each streamflow point
Mean Areal Air Temperature Program (MAT Program)	40 maximum-minimum air temperature stations 10 areas to compute mean areal temperature 4800 months of data storage	37K for program, plus 744 words of random access data storage per station year	7 sec./year for an analysis involving 10 stations

Table 1-2.(continued)

MAT Consistency Check Program (Program MATCON)	40 maximum-minimum air temperature stations 5 groups for double mass analysis 25 years of record	33K for program, plus 24 words of data storage per station year (data are generated by MAT Program)	1 sec./year for an analysis involving 10 stations
Program TEMPCK		40K for program, plus 1488 words of data storage per year (data are generated by MAT Program)	0.5 sec./year

1 Storage requirements and run times are based on a CDC 6600 computer system.

CHAPTER 2. DATA PROCESSING

2.1 INTRODUCTION

In order to calibrate a conceptual model for use in forecasting streamflow in a river system, large amounts of continuous hydrologic data are required. The conversion of the raw data into the form required for model calibration must be accomplished in an efficient manner.

HYDRO-14 (Appendix B) describes the format of data tapes containing raw hydrologic data which can be obtained from the National Climatic Center (NCC) at Asheville, North Carolina. Tapes containing two types of data are available: 1) hourly precipitation data, and 2) daily observations (precipitation, maximum-minimum air temperature, snowfall, snow on ground, water-equivalent of snow on ground, wind movement, and evaporation). HYDRO-14 (Chapter 3) also describes a method of estimating point values, for periods of missing data or locations having no data, and for computing areal means of precipitation. The computer program which utilizes this method and the NCC data tapes to compute mean areal precipitation is also described.

This chapter discusses the methods and the computer programs needed to compute mean areal air temperature for use in the calibration of the snow accumulation and ablation model. In addition, two supplementary data programs for the tabulation of monthly and annual means of precipitation, air temperature, wind movement, and evaporation are described. A summary of the necessary steps to process the raw data into the form required by the NWSRFS model calibration programs concludes the chapter.

2.2 ESTIMATION OF POINT VALUES OF AIR TEMPERATURE

2.2.1 INTRODUCTION

Since maximum-minimum air temperature data are measured as point values, the use of the data to compute mean areal values involves, implicitly or explicitly, inferences concerning the air temperature at all other points within the area. This section outlines a method of estimating the maximum and minimum daily air temperature at any point as a function of that at surrounding points. The method is objective in non-mountainous areas and quasi-objective in mountainous areas. The method can easily be programmed for use in computing mean areal air temperature for a long period of record. The program will use a minimum of computer time.

2.2.2 THEORY OF ESTIMATION

Referring to Figure 2-1, let point X be the point at which the maximum or minimum air temperature is to be estimated. Points A through G are points at which the maximum or minimum temperature is known.

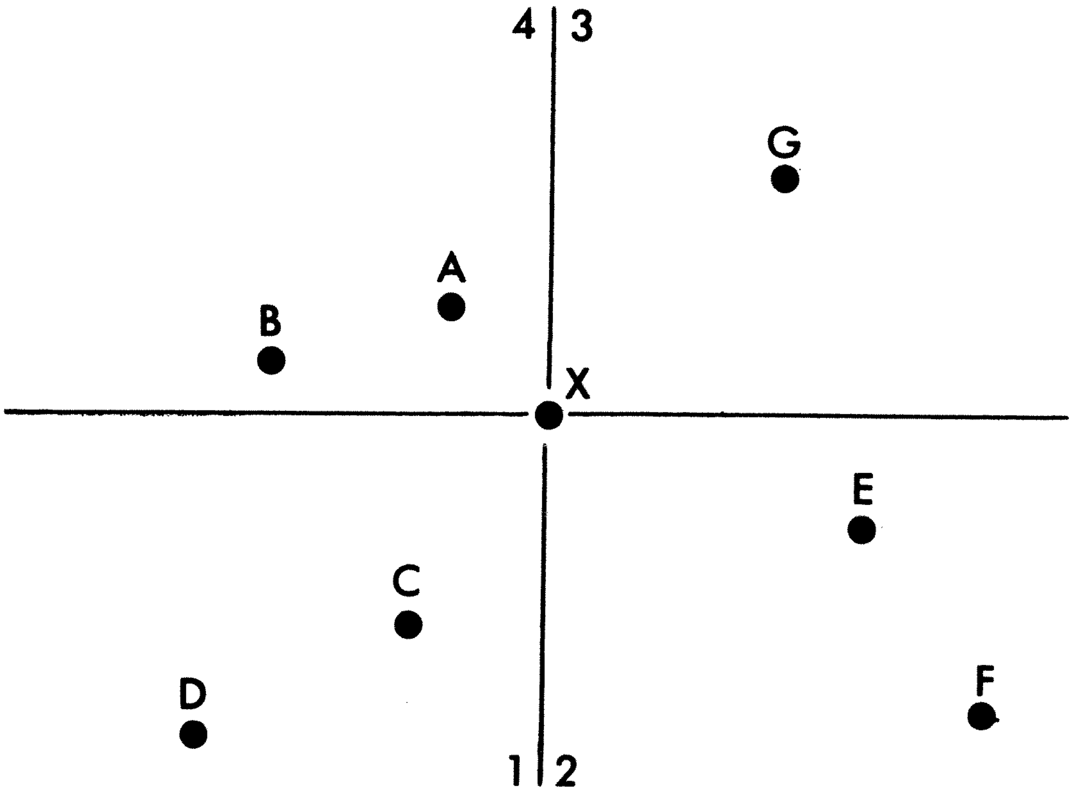

Figure 2-1.--Station location and quadrants for the estimation of air temperature at station X.

Perpendicular lines through point X divide the surrounding area into fou quadrants. It should be noted that perpendicular axes of any orientation can be used.

The estimate of temperature at X is now computed as a weighted average o "adjusted" station temperatures, using the station within each quadrant wi the largest station weight. Thus, the estimate of the temperature at any point X can be expressed as:

$$T_x = \frac{\sum\limits_{i=1}^{i=n} [AT_i \cdot W_i]}{\sum\limits_{i=1}^{i=n} W_i}, \qquad (2.1)$$

where: T_x = maximum or minimum temperature at the station being estimated.
i = the station used as an estimator,
n = number of estimators (the station with the largest station weight in each quadrant is used as an estimator),
AT_i = "adjusted" maximum or minimum temperature at station i, and
W_i = **weight function** for station i.

The procedure used to calculate "adjusted" station temperatures and the weight functions depends on whether the area is mountainous or non-mountainous

2.2.2.1 Non-mountainous Areas

As far as temperature estimation is concerned, a non-mountainous area is an area where topography does not appear to affect temperature variations and the gradients observed are approximately a linear function of distance. The weight function in this case is equal to the reciprocal of the distance from the station to point X. The "adjusted" temperature for each station used to estimate point X is then the same as the measured temperature at that station. Thus, the estimation equation for non-mountainous areas is:

$$T_x = \frac{\sum_{i=1}^{i=n} [T_i \cdot \frac{1.0}{d_{i,x}}]}{\sum_{i=1}^{i=n} \frac{1.0}{d_{i,x}}} , \qquad (2.2)$$

where: T_i = maximum or minimum temperature at estimator station i, and
$d_{i,x}$ = the distance from the station being estimated to the estimator station i, in terms of map coordinates.

2.2.2.2 Mountainous Areas

In reality, the differences in temperature between a number of stations in a mountainous region can vary from day to day depending on the meteorological situation. Operationally, the temperature differences between stations could be expressed as a function of a number of topographic and meteorological variables. However, in calibrating a conceptual hydrologic model, due to retrieval and processing problems, it is generally not feasible to use any additional meteorological data other than air temperature measurements. Experience has shown that the differences between station means are a good indication of the typical variations in temperature that exist over a mountainous area. In some cases, these differences are small (e.g., stations at approximately the same elevation may have slightly different means because of the exposure of the thermometers) and for practical purposes can be ignored. However, in other cases, especially in areas with significant topographic variation, these differences between stations are important and must be accounted for. Thus, as far as temperature estimation is concerned, a mountainous area is an area over which considerabl variations in temperature usually exist.

Because of seasonal variations, a procedure for estimating point values in mountainous regions should use the mean monthly maximum and minimum temperature for each station as indices. Therefore, the "adjusted" station temperature can be expressed as:

$$AT_i = T_i + (N_x - N_i), \qquad (2.3)$$

where: N_x = mean maximum or minimum temperature at the station being estimated, and

N_i = mean maximum or minimum temperature at the estimator station i.

By substituting Eq. 2.3 for AT_i and rearranging the terms, Eq. 2.1 can be expressed as:

$$T_x - N_x = \frac{\sum_{i=1}^{i=n} [(T_i - N_i) \cdot W_i]}{\sum_{i=1}^{i=n} W_i} \quad . \tag{2.4}$$

Thus, it can be seen readily that for a mountainous area the deviation of temperature at point X from the mean at the same point can be estimated from the deviation of temperatures at surrounding stations from their respective means.

In regard to station weights, the most important factors in mountainous areas are probably distance and elevation. If two stations are equi-dista from station X, studies have shown that the one closest in terms of elevat is usually the best estimator. This suggests that the weight function use in the estimation scheme should include elevation difference as a paramete A functional form for W_i which has produced improved estimates of temperature is:

$$W_i = \frac{1.0}{G_1 \cdot d_{i,x} + F_e \cdot \Delta E_{i,x}} \quad , \tag{2.5}$$

where: $d_{i,x}$ = the distance between stations X and i expressed in map coordinates,
G_1 = a scale factor to convert map coordinates to miles,
$\Delta E_{i,x}$ = the absolute difference in elevation, expressed in 1,000 feet, between stations X and i, and
F_e = an arbitrarily selected elevation weighting factor (if $F_e = 10$, then two stations, one which is 10 miles further from station X in distance, but 1,000 feet closer in elevation, would have the same station weight).

When either $\Delta E_{i,x}$ is zero or F_e selected to be zero, Eq. 2.5 is, of course equivalent to the weight function used in Eq. 2.2.

The final equation for the estimation of maximum or minimum air temperature at a point in a mountainous area can be determined by the substitutio of Eqs. 2.3 and 2.5 into Eq. 2.1. This substitution yields:

$$T_x = \frac{\sum_{i=1}^{i=n} \{[T_i + (N_x - N_i)] \cdot [\frac{1.0}{G_1 \cdot d_{i,x} + F_e \cdot \Delta E_{i,x}}]\}}{\sum_{i=1}^{i=n} [\frac{1.0}{G_1 \cdot d_{i,x} + F_e \cdot \Delta E_{i,x}}]} \tag{2.6}$$

2.2.3 DETERMINATION OF F_e

It can be seen readily from Eq. 2.6 that F_e affects the station weight of each station being used to estimate the temperature at point X. Increasing F_e will give more weight to stations with the smallest values of $\Delta E_{i,x}$ and less weight to stations with the largest values of $\Delta E_{i,x}$. The estimate of temperature at point X is computed using the station within each quadrant with the largest station weight. Thus, as F_e is increased, the stations used to estimate the temperature at point X may change. Changes will occur if the station weight of more distant stations in each quadrant becomes greater than the station weight of stations which are closer to point X. This will occur as F_e increases if the distant stations have a smaller value of $\Delta E_{i,x}$. The dominant effect of F_e in most cases is the effect it has on the selection of the stations used to estimate temperature at point X.

Eq. 2.6 is used in mountainous areas for two purposes: (1) to estimate periods of missing data at an air temperature observation station, and (2) to estimate the maximum-minimum air temperature at a location which has no observed data. To estimate periods of missing data, the optimum value of F_e can be determined through a cut-and-try (iterative) technique, utilizing the available valid data from the station. To estimate air temperature at a location which has no observed data, the magnitude of F_e must be arbitrarily selected. F_e values for other stations in the area may provide a guideline for the selection. However, it should be noted that the optimum value of F_e for a station is dependent on the location of the stations being used to make the estimate (e.g., the magnitude of F_e could vary considerably depending on whether distant stations had large values of $\Delta E_{i,x}$ or small values of $\Delta E_{i,x}$ relative to stations that are close to point X).

A computer program is provided for determining the optimum value of F_e at any selected temperature observation station (program is described in section 2.4.4). The program compares the estimated and observed maximum and minimum air temperatures. By varying the magnitude of F_e, the effect of F_e on the results can be determined. The root-mean-square (RMS) error (square root of the sum of the squares of the observed minus estimated values) is used to compare results. Figs. 2-2 and 2-3 show the effect of various values of F_e on RMS for two locations; one in Arizona, and the other in New Hampshire. These figures suggest that the magnitude of F_e for estimating maximum temperatures should be different from the magnitude of F_e for estimating minimum temperatures.

If a plot of RMS versus F_e is not prepared and thus the magnitude of F_e is selected arbitrarily, experience would indicate the following guidelines:

1. If the stations that are closest to point X also have the smallest values of $\Delta E_{i,x}$, the magnitude of F_e is not critical. $F_e = 0.0$ would be appropriate.

2. If the stations that are closest to point X have the largest values of $\Delta E_{i,x}$, a value of F_e in the range 10.0 to 30.0 would be appropriate.

It should be noted that these guidelines are based on a limited amount of testing of the temperature estimation procedure on data from Arizona, Vermont, and New Hampshire.

2.2.4 TYPICAL ESTIMATION RESULTS

In order to give the user a feel for the accuracy that can be expected from Eq. 2.6, a summary of typical results is given in Table 2-1. In all cases F_e was arbitrarily selected as 10.0. In addition to the station elevations, the observation times should be noted. For stations taking their observations in the afternoon (including midnight) the maximum and minimum are assumed to have occurred on the day of observation. For stations taking morning observations the minimum is assumed to have occurred on the day of observation while the maximum is assumed to have occurred on the previous day. In reality these assumptions do not always hold, thus, a group of stations with mixed observation times can have mismatched maximums and minimums on some days. In addition to the RMS error, the standard deviation of the observed temperatures about the monthly mean is also given. If the RMS error exceeds the standard deviation, no intelligence is imparted by the technique, as the monthly mean would make a better daily estimate. Table 2-1 shows only the RMS error and standard deviation for the total test period. The monthly ratios of the RMS error to the standard deviation were similar to those for the total test period. However, in most cases both figures are greater during cold periods than during warm periods.

2.3 COMPUTATION OF MEAN AREAL AIR TEMPERATURE

2.3.1 INTRODUCTION

Mean areal air temperature is computed by utilizing stations within or close to the area and in some cases other available meteorological information. The basic procedure consists of: 1) examine the available maximum-minimum air temperature data to determine if the available data adequately represents all portions of the area, 2) if the available data does not represent all portions of the area, assign "dummy" stations to those portion that are not represented, 3) determine the mean monthly maximum and minimum temperature for each "dummy" station, 4) determine station area weights for all stations, 5) estimate daily maximum and minimum temperature at all stati having missing periods of record, and 6) multiply station temperatures by station area weights to get mean areal air temperature. This section elaborates on the use of this basic procedure in non-mountainous and mountainous areas.

2.3.2 NON-MOUNTAINOUS AREAS

Since temperature varies linearly with distance in non-mountainous areas, "dummy" stations are not needed. Any area weight assigned to a "dummy" station could be proportioned to the stations used to estimate the temperature at the "dummy" station. Thus, the use of "dummy" stations would not change the estimate of mean areal temperature.

Several procedures could be used for computing station area weights in non-mountainous areas. One method is the use of grid point weights (section 3.3.4 of HYDRO-14) where the grid points correspond to the X, Y coordinate system used to locate the stations. For temperature the reciprocal of the distance is used rather than the reciprocal of the distance squared as with precipitation. Other methods would include Thiessen weights or an arithmetic average, if stations are distributed in a reasonably uniform manner.

Missing data should be estimated using Equation 2.2. It should be noted that to get a good estimate for missing data periods at stations near the border of the area, it is usually necessary to include additional outlying stations.

2.3.3 MOUNTAINOUS AREAS

In some cases there is an adequate distribution of temperature observation stations to represent all portions of a mountainous area. However, for most mountainous areas this is not the case. This is especially true for the high elevation portions of most mountainous areas. Thus, it is usually necessary to create "dummy" stations to represent those portions of a mountainous area for which actual data does not exist.

If "dummy" stations are needed, the next step is to determine the mean monthly maximum and minimum temperature for each "dummy" station. An analysis to determine these values would include an examination of the variation in monthly means for stations with actual data that are within the area, an examination of monthly means for stations with actual data in the surrounding area, especially high elevation stations, and possibly an examination of other meteorological information, such as radiosonde data. If radiosonde data **are** used, the difference in the thermal gradient up the side of a mountain and the lapse rate in the atmosphere must be considered.

The station area weight for each station in a mountainous area is equal to the portion of the area that the station represents.

Missing daily maximum and minimum temperatures at all stations should be estimated using Eq. 2.6. This will complete the data record at all actual stations, plus create a data record for each "dummy" station (since a "dummy" station is just a station with all missing data).

2.4 COMPUTER PROGRAMS FOR COMPUTING MEAN AREAL TEMPERATURE

2.4.1 INTRODUCTION

A computer program has been written which uses the techniques described in previous sections of this chapter to compute mean areal air temperature. The basic computational interval of the NWSRFS is six hours, thus, the final product of the program is six hourly mean areal temperature. In addition to the basic program to compute mean areal temperature, there are two programs to aid in preliminary analysis, a program to check the consistency of the basic temperature data, and a program to compare estimated and observed data at an individual station.

2.4.2 PROGRAMS TO AID IN PRELIMINARY ANALYSIS

To aid in station selection and to provide helpful data for isohyetal, temperature variation, and model calibration analyses, two preliminary data processing programs are provided to summarize the data on the NWSRFS-NCC tapes. In each program the stations and the period of record to be summarized are preselected. A brief description of the tasks performed by each program is as follows:

- a. Daily observation tape program (Program PRELIM2).
  1. Lists snowfall and snow on ground for each month that there was snowfall or snow on ground.
  2. Computes average daily evaporation and wind movement for each month at stations that make pan evaporation measurements.
  3. Computes mean monthly and mean annual precipitation, maximum temperature, minimum temperature, evaporation, and wind movement for the period being summarized.
  4. Writes the data for the selected stations and for the selected period onto a new tape. The format of the new tape is exactly the same as the original NWSRFS-NCC tape. Thus, the daily data for a reasonably large area (maximum number of stations equal 75), which may encompass several states, can be placed on a single tape. This will save on tape reading and tape handling costs during the computation of mean areal temperature and precipitation.

- b. Hourly precipitation data tape program (Program PRELIM1).
  1. Computes mean monthly and mean annual precipitation.
  2. Writes the selected data onto a new tape.

A listing of programs PRELIM1 and PRELIM2 are given in Appendix A.

2.4.3 MEAN AREAL TEMPERATURE PROGRAM

The Mean Areal Temperature (MAT) program provides an efficient means to process air temperature data for use in the snow accumulation and ablation model. The program is described in sequential order of the major steps involved in the computation of MAT.

2.4.3.1 Input Data

The program uses maximum-minimum temperature observations to compute areal means. The maximum-minimum temperature data are input in NWSRFS-NCC daily observation tape format (Appendix B.2.3, HYDRO-14). In addition to the raw temperature data, station and areal information is also needed. Appendix B. contains the input summary for the MAT program.

2.4.3.2 Estimation of Missing Maximum-Minimum Temperature Data

The MAT program uses Eq. 2.2 for non-mountainous areas and Eq. 2.6 for mountainous areas to estimate missing data at each station. When using Eq. 2.6, the program allows for different values of F_e for maximum temperatu and minimum temperature at each individual station. The program is written so that no estimated value will be used in the estimation of another missing value. If all the stations are missing on a given day, the temperature at each remains as a missing value and a message is printed. The six hourly means resulting from periods when all the maximums or minimums are missing will also be missing and must be estimated later by hand. To avoid cases of missing data remaining in the program output, a reasonable number of stations should always be included in the analysis. When more than five stations are used, cases of missing data in the program output will probably never occur.

2.4.3.3 Conversion of Maximum-Minimum Temperature Data to Six-hourly

In the MAT program, the maximum temperature is assumed to occur in the afternoon and the minimum near sunrise. The relationship between each six-hour period and the maximum and minimum temperature varies throughout the year because of variations in the number of daylight hours. In snow computations, the most important time of the year is the spring melt period. The relationships used in the MAT program were derived from maximum-minimum and hourly air temperature data available for the spring snowmelt period from the Central Sierra Snow Laboratory near Donner Summit, California and the NOAA-ARS Cooperative Snow Research Station near Danville, Vermont. The relationships used in the MAT program are:

a. Midnight to 6 a.m.

$$T_6 = 0.95 \cdot T_{min_n} + 0.05 \cdot T_{max_{n-1}} \tag{2.7}$$

b. 6 a.m. to noon

$$T_6 = 0.40 \cdot T_{min_n} + 0.60 \cdot T_{max_n} \tag{2.8}$$

c. Noon to 6 p.m.

$$T_6 = 0.925 \cdot T_{max_n} + 0.025 \cdot T_{min_n} + 0.05 \cdot T_{min_{n+1}} \tag{2.9}$$

d. 6 p.m. to midnight

$$T_6 = 0.33 \cdot T_{max_n} + 0.67 \cdot T_{min_{n+1}} \tag{2.10}$$

where: T_6 = Mean six-hourly air temperature,
T_{min} = Minimum air temperature,
T_{max} = Maximum air temperature, and
n = Current day.

2.4.3.4 Computation of Areal Means

The computation of six-hour areal means is simply a matter of multiplying the six-hourly temperatures for each station by the station weight for that station. Station area weights for MAT computations can be predetermined, based on the portion of the area represented by each station, or grid point weights can be computed within the program. It is strongly recommended that predetermined station area weights be used in mountainous areas. The final product, six-hourly mean areal air temperatures, can be output onto tape in

NWSRFS Standard Tape Format (section 3.7.2 in HYDRO-14) or on Office of Hydrology Standard Format cards (Appendix A in HYDRO-14) with a field length equal to three.

2.4.3.5 Consistency Checks

A separate program to be used in conjunction with the MAT program is pr vided to check the consistency of the basic maximum-minimum temperature data. The data needed for the consistency checks are written onto a disk scratch tape in the MAT program. The consistency check program is then executed immediately after the MAT program. The consistency check progra has no input other than that given it by the MAT program.

The difference in monthly mean temperature between two stations should nearly constant, though in some cases the difference may exhibit a season variation. Thus, a double-mass plot showing the deviation of the cumulati mean monthly temperature at an individual station from the average cumulat mean temperature at a group of stations should be a good check on the cons tency of the temperature data at the individual station. For a consistent record the double-mass plot should be a straight line, or a straight line waves on it if a seasonal variation between stations exists. Figure 2-4 shows some typical consistency check plots. Stations A and B are consist over the period while station C is not. The consistency check program produces such a plot for both maximum and minimum temperatures at all the stations used in the areal analysis.

In addition to the consistency of the record, the plots also give some insight as to how representative certain stations are. For example, if there are a number of stations within the same area at a similar elevatio their consistency plots should be fairly similar. If the plot for one station shows large negative deviations from the others, it is likely that the station is influenced significantly by cold air drainage and, thus, may not be a representative station.

2.4.3.6 Correcting Inconsistent Stations

The initial run of the MAT program and the consistency check program may show that certain stations have inconsistent records while others may not be representative of the portion of the area that they are supposed to represent. Thus, the program needs to be rerun to correct these deficienc Unrepresentative stations can be dropped from the analysis, or their stati weight can be revised, or they can be corrected by the addition or subtrac tion of a constant temperature so that their data will be representative. Inconsistent stations need to be corrected so that their record will be consistent. For example, in Fig. 2-4 station C could be made consistent applying a correction of -1°F to all observations from November 1965 throu April 1968. A provision for making such corrections is included in the in to the MAT program. It should be noted that when applying a correction it is necessary to adjust the mean station temperature if the data being corrected were used to compute the station mean.