original, "representative" value. To demonstrate this situation, consider Table 4.1 in which a number of sample computations are presented. Table 4.1 is an example for an arbitrary barrier elevation of 3,000 feet, although other elevations would provide similar results. Various moisture contents are given in the first column ranging from a mixing ratio (W, the ratio of water vapor to dry air) of 14.0 g/kg to 4.3 g/kg, where 14.0 represents 100 percent of available moisture and 4.3 is about 31 percent. For each moisture content, there are a selection of SST differences between 12°F and 2°F listed across the table. As an example, for a mixing ratio of 14.0 g/kg, and a SST difference of 10°F (maximum SST of 68°F and an observed SST of 58°F), the in-place moisture maximization factor (IPMF) is 1.76 (ratio of precipitable water at maximum SST to precipitable water at observed SST).

What is important to see in Table 4.1 is that over the range of moisture content from 100 to about 30 percent (14.0 to 4.3 g/kg), the in-place moisture maximization factors show little variation through each column. If the SST range (upper limit to observed) is 12°F, the IPMF varies between 1.96 and 2.04, and if the SST range is 4°F, the IPMF varies between 1.25 and 1.27. The importance of this information is that if one assumes at the onset of a trajectory, there is 100 percent moisture and that as the air follows the trajectory, some amount of moisture is removed, the in-place moisture maximization factor remains essentially unchanged as long as the amount removed (the difference between maximum and observed SST) is unchanged. This finding was adopted in the current study and the IPMF observed at the trajectory reference point was used at the storm site for each of the storms in Table 2.1, with the exception of storms 29, 106, 143 and 155. Storm 155 derived its moisture from the Gulf of Mexico, while storms 106 and 143 are indicative of more intense convective storms whose moisture source is more localized. Storm 29 was probably initiated with Gulf of Mexico moisture, but no dew point data were available. Pacific moisture arrived at the site of storm 29 after the first 24 hours of the critical precipitation period (CPP). SST were therefore substituted for storm 29 maximization. CPP, a concept used in the storm analysis procedure, refers to the most significant period of rainfall within a particular storm and can vary in duration.

SST was utilized as a proxy parameter for measuring the total precipitable water content of the inflowing warm air. SST was then used in the same way persisting dew points at land locations have been used to represent total moisture content in other reports. The study relied on the standard deviation of SST as the best available approximation for setting an upper limit on precipitable water content. A marine climatic atlas of the world, (U.S. Navy, 1981), was used to obtain the mean and standard deviation information that set the upper limit of the moisture content for PMP. It was assumed that the mean SST, plus two standard deviations at a location where a reliable SST was obtained previous to the CPP of a storm, would be adequate to define the storms' upper limit or maximum moisture "charge" or availability. A reliable SST will be defined in step 2 below. The choice of two standard deviations, representing about 98 percent of normally distributed values, was intended as another case of a less-

than-extreme value being combined in developing PMP. The point to be made is that while the PMP definition calls for theoretical maximum values, actual applications are based on observed maxima. Use of the mean plus two standard deviations places the magnitude of this parameter at about the level of other estimates used in this study, e.g., the 100-year frequency values.

Table 4.1.--Relationships among in-place maximization factor (IPMF), moisture content ranges at 1000 mb and percentage moisture reduction for a storm site at a barrier elevation of 3,000 feet MSL.

S = SST range (°F) at source location
W = mixing ratio (g/kg) of the listed PMP, 1,000 mb dew points...ex: 14.0 g/kg for 68°F, 4.3/kg for 38°F
( ) = percentage reduction of W from first row

W	S	12	10	8	6	4	2
14.0 (100)	Max. SST =	68	68	68	68	68	68
	Obs. SST =	56	58	60	62	64	66
	IPMF =	1.96	1.76	1.57	1.40	1.25	1.12
11.5 (82)	Max. SST =	63	63	63	63	63	63
	Obs. SST =	51	52	55	57	59	61
	IPMF	1.96	1.75	1.56	1.41	1.25	1.12
9.4 (67)	Max. SST =	58	58	58	58	58	58
	Obs. SST =	46	48	50	52	54	56
	IPMF =	2.00	1.76	1.56	1.39	1.26	1.12
7.8 (56)	Max. SST =	53	53	53	53	53	53
	Obs. SST =	41	43	45	47	49	51
	IPMF =	1.97	1.76	1.58	1.41	1.27	1.12
6.3 (45)	Max. SST =	48	48	48	48	48	48
	Obs. SST =	36	38	40	42	44	46
	IPMF =	2.04	1.75	1.63	1.40	1.26	1.14
4.3 (31)	Max. SST =	38	38	38	38	38	38
	Obs. SST =	26	28	30	32	34	36
	IPMF =	2.00	1.87	1.65	1.47	1.27	1.17

The following practices were followed to obtain an in-place maximization factor:

1. Starting at the location of a maximum 10-mile^2 depth during the CPP, a backward-in-time trajectory was determined toward the source region of the air contributing to the precipitation. Available analyses of sea-level pressure patterns were extrapolated plus or minus one-half of a time interval between map times to establish the orientation and magnitude of trajectory elements. The speed of the gradient level flow over open water could be adequately approximated by the analyzed sea-level pressure gradient. The gradient-level wind was considered to be the appropriate wind in low-level moisture inflow. Timing marks were put on this trajectory at regular time intervals to represent the progress of air parcels toward the storm site. The timing of the trajectory generally ends at the start of the CPP; but, if the major portion of the precipitation fell in the later hours of the CPP, the start time of the backward-in-time trajectory was adjusted to coincide with the beginning of the major portion of the precipitation. The point selected to obtain a SST (the reference location) will be on the trajectory closest to the storm center.

2. A "reliable" estimate of SST was governed by the following rules:

   a. Any SST observation based on a ship observation along the trajectory, in the absence of contrary observations, is considered reliable. The time of the ship observation nearest the trajectory should be within 24 hours of the (interpolated) time mark on the trajectory. This 24-hour limit may be extended if there is evidence that SST's have persisted for more than 24 hours at other locations in the same synoptic weather regime.

   b. An SST isotherm crossing the backward trajectory, based on analysis of ship observations that is within 5 degrees of latitude of the reference location, is considered reliable if these observations fall within the time constraint of a. above. If either the time or the space constraint cannot be met, the analyzed SSTs on the trajectory are considered unreliable.

   c. If a front intersects the trajectory within 6 hours of its interpolated time mark as determined in a., then SSTs along the trajectory upflow from this point are unreliable even if they conform to the rules given in a. or b. However, SST measurements downflow from such a frontal intersection point can be considered reliable. If there is evidence of persisting SSTs following frontal passage, this rule may be waived and the earlier value accepted as reliable.

3. The data used to obtain the maximum SST from the Navy Marine Climatic Atlas was the beginning day of the backward-in-time trajectory plus or minus 15 days toward the warmer month of SSTs at the selected

point. The 15-day rule parallels the time factor used in the traditional land-based maximization procedure (WMO, 1986).

4. For storms 106 and 143 that do not have extended inflow trajectories, the traditional NWS procedures were followed as described in the Manual for Estimation of Probable Maximum Precipitation (WMO, 1986).

5. Calculations of maximizing factors were made with temperatures to the nearest tenth of a degree Fahrenheit and precipitable water amounts used came from interpolation in precipitable water tables (USWB, 1951).

All trajectories were drawn using archived surface weather maps. For storms before 1950, SST measurements came from archived ship reports from the NOAA Environmental Research Laboratory (Boulder, Colorado) and from the National Oceanic Data Center, Washington, DC, supplemented by the daily weather maps. The records of land station observations from the Local Climatological Data Series were used to obtain persisting dew points for traditional maximization.

Within the process of determining the appropriate SST for individual storms, some complications arose that influenced the values adopted in this study. These complications typically involved decisions about timing of the moist air inflow. Relatively small differences in time (order of hours) could result in widely different source regions (order of degrees of latitude/longitude). At times some complications arose in determining the appropriate SST measurements for a storm, and additional analysis was required. For readers who may wish to use SST measurements, or may want added detail, they should contact the NWS authors.

5. AUTOMATED PRECIPITATION DATA (MINI-STORM) ANALYSIS

5.1 Introduction

In all previous PMP studies performed by NWS, storm depth-area-duration (DAD) data relied upon the results available from the COE Storm Rainfall Catalog, or from unofficial DAD studies performed by Reclamation or NWS. As noted previously, almost no officially completed storm studies have been carried out for the western states. The procedure to process the storm data and analyze the numerous work maps involved in these studies was given in a manual (USWB, 1946) which, in application, was a very time-consuming task (extending to more than a year for larger storms). Although storm studies for some early storms in the west were unofficially completed, and others partially completed, there was a general lack of uniformity in both the techniques used to process the data and in the output results.

The present study posed as one of its prime objectives that a sample of major historical storm events would be used to derive the revised level of PMP for the Northwest. In addition, a procedure would be developed that involved automation of the DAD analysis process to a large extent, and to accelerate the time to completion. This automated process became known as the "mini-storm" analysis procedure. Obvious benefits, among others, were to complete a number of storm analyses in a relatively short period of time and do it in a consistent manner.

Another important decision was to base the spatial distribution of storm rainfall in proportion to the 100-year frequency analyses available in NOAA Atlas 2 (Miller et al., 1973). These frequency analyses were available for each western state and showed considerable correlation with the underlying terrain features. While this choice was prompted by necessity and availability of data, it is recognized that actual storms may have quite different spatial distributions.

There was no 100-year precipitation frequency analysis comparable to NOAA Atlas 2 for the region in British Columbia. The Rainfall Frequency Atlas for Canada (Hogg and Carr, 1985) provides a 100-year precipitation frequency analysis on a fairly coarse scale that does not reflect much of the underlying topography. These results further differed from those in NOAA Atlas 2 since the Canadian Climate Center separates rainfall from snowfall data and their atlas is based solely on rainfall data. Differences occur as well in how the 100-year values were determined. The Canadian procedure fits the Gumbel distribution by the method of moments, whereas NOAA Atlas 2 used a least squares plotting position procedure by Gumbel that is dependent on the number of years of record at each station. Comparisons were made for 85 stations in southern British Columbia based on the two procedures and while roughly 80 percent of the stations showed differences of 10 percent or less, there was a 19 percent difference at two stations. The NWS methodology generally gave equal or higher values for all station comparisons.

A decision was made to maintain consistency between the United States and British Columbia portions of the drainage by using NOAA Atlas 2 results as an index for orographic PMP. In order to ensure such consistency, an analysis of the 100-year precipitation frequency for British Columbia made by Miller (1993), the primary author of NOAA Atlas 2, was accepted. Miller (currently retired from NWS) was able to provide these results because of his private involvement in PMP studies in southern British Columbia. It was therefore not difficult to obtain continuous and consistent fields across the United States-Canadian border, and achieve comparable levels of detail.

At the onset of the current study, Reclamation had invested considerable resources into initiating the automated capability needed to process large volumes of data and it was reasonable for Reclamation to tackle this aspect of the study.

Because of the number of new storm data sets which needed to be analyzed for HMR 57, it was decided to perform as much of the processing by computer as possible. The analysis process essentially follows the procedure set forth in Cooperative Studies Technical Paper Number 1 (USWB, 1946) with two exceptions. An isopercental technique was used to develop the isohyetal analysis and a 1-hour interval, instead of the recommended 6-hour interval, was used for the accumulation of precipitation to produce the depth-area-duration analysis.

Programs were written to process precipitation data and generate products similar to those produced when formal storm studies were completed by hand. These products consist of tabulated data for a specific storm period, mass curves for each station, isopercental and isohyetal analyses, depth-area-duration data, and a pertinent data sheet listing average precipitation depths at standard durations and areas. Because of the technique chosen to develop the isohyetal analysis, precipitation frequency maps published in NOAA Atlas 2 for the states in the study area were digitized and these curves were converted to gridded data files. This rest of this chapter will describe briefly the individual steps involved in the analysis of storm precipitation data for the development of HMR 57. Readers interested in greater detail about the specific programs written for this study are referred to the "Manual for Automated Depth-Area-Duration Analysis of Storm Precipitation" (Stodt, 1994).

5.2 Grid Selection, Map Projection Selections.

A Cartesian reference frame centered on the HMR 57 study area was devised so that all digitized or computed data sets were registered with each other. The coverage area for this study was limited to the Pacific Northwest, essentially the Columbia Basin and Pacific Coast drainages and adjacent areas surrounding the basin from Montana to Northern California. Initial templates for digitizing were inadvertently drawn with a slight error in the vertical. The true vertical of the drawn templates was fixed at 117.45W longitude. The map origin was an arbitrary point off the coast a sufficient distance for the entire northwest region to

be in the positive x-y quadrant. A map scale of 1:1,000,000 was chosen as a base for the final analysis, as the terrain is represented adequately at this scale to account for the observed topographic effects on precipitation patterns. A Lambert Conformal Conic projection true at 33°N and 45°N was chosen because the USGS had published a complete set of state base maps on this projection at the desired scale. The NOAA Atlas 2 precipitation frequency maps were also drawn at this scale.

Positions on the grid were referenced in inches from the origin. A grid spacing of 0.1 inch was chosen. At 1:1,000,000 scale, one grid point represents about 2-1/2 mi^2. It was desirable that the analysis be sufficiently accurate to allow estimation of the maximum 10-mi^2 precipitation, but also that the grid spacing not be so small as to demand excessive partitioning of the data sets in order to accommodate memory limitations on Reclamation's CDC CYBER computer. This grid spacing satisfied both criteria. Since locations of meteorological stations are expressed in latitude-longitude coordinates, a program was written to convert back and forth from Lambert Conformal Conic projection x-y coordinates on this grid to latitude-longitude coordinates (Stodt, 1994).

5.3 Precipitation Data Analysis Procedure

Figure 5.1 shows an overview of the analysis and decision making process involved in processing precipitation data using the automated procedure developed for HMR 57. The seven major modules are as follows: 1) Detection and correction of tabulation errors in storm data sets; 2) Computation of a 100-year NOAA Atlas 2 grid file for each storm location, area and duration; 3) Computation, plotting and checking of mass curve data; 4) Creation of an isopercental data grid file; 5) Computation and plotting of Theissen polygons (Theissen, 1911) and creation of a vertex file; 6) Creation of an isohyetal map and vector file; and 7) Computations of intersecting areas between storm isohyets and Theissen polygons, depth-area-duration, and creation of the depth-area-duration plot file and pertinent data sheet information.

Detailed flow diagrams for each of these modules are presented and discussed by Stodt (1994). Figure 5.1 provides a schematic pathway that relates the modules to the final product, depth-area-duration plots and storm pertinent data information tables. In Figure 5.1, the process begins with the precipitation data that represents each particular storm period. These data are edited and corrected. Daily data are assigned to nearby recording rain gage stations in order to convert the daily amounts into approximate hourly distributions.

The automated program also was responsible for storing digitized versions of the NOAA Atlas 2 precipitation frequency maps for the region. The hard copy maps for selected 2-year and 100-year precipitation frequencies at durations of 6 and 24 hours were converted to grid data, and used to obtain frequency information for durations between 1 hour and 10 days. The program to compute 2- to 10-day data followed the procedure described by Styner (1975).

From the above files of gridded data, storm data and the recorder/non-recorder station pairs, five additional files were created. The data were processed through modules 3, 4 and 5 to get 1) individual station mass curves; 2) an isopercental analysis; and 3) Theissen polygons. The mass curve program lists accumulated rainfall for each hour of the core period (up to 240 hours) of the storm. Plots were made of the individual mass curves for each daily station, along with their associated hourly station distribution. The isopercental analysis takes the storm data and determines ratios of observed rainfall to the 100-year information. These percentages were analyzed to develop an isopercental map that was digitized back into the data files. Module 5 performs the Theissen polygon analysis in which a polygon surrounds each gage. Each vertex of each polygon is stored in this module.

Figure 5.1 shows that the grid data file for the isopercental analysis, along with the NOAA 100-year grid file, were combined point-by-point to determine the isohyetal vector file. The isohyetal vector file, the Theissen polygon vector file and

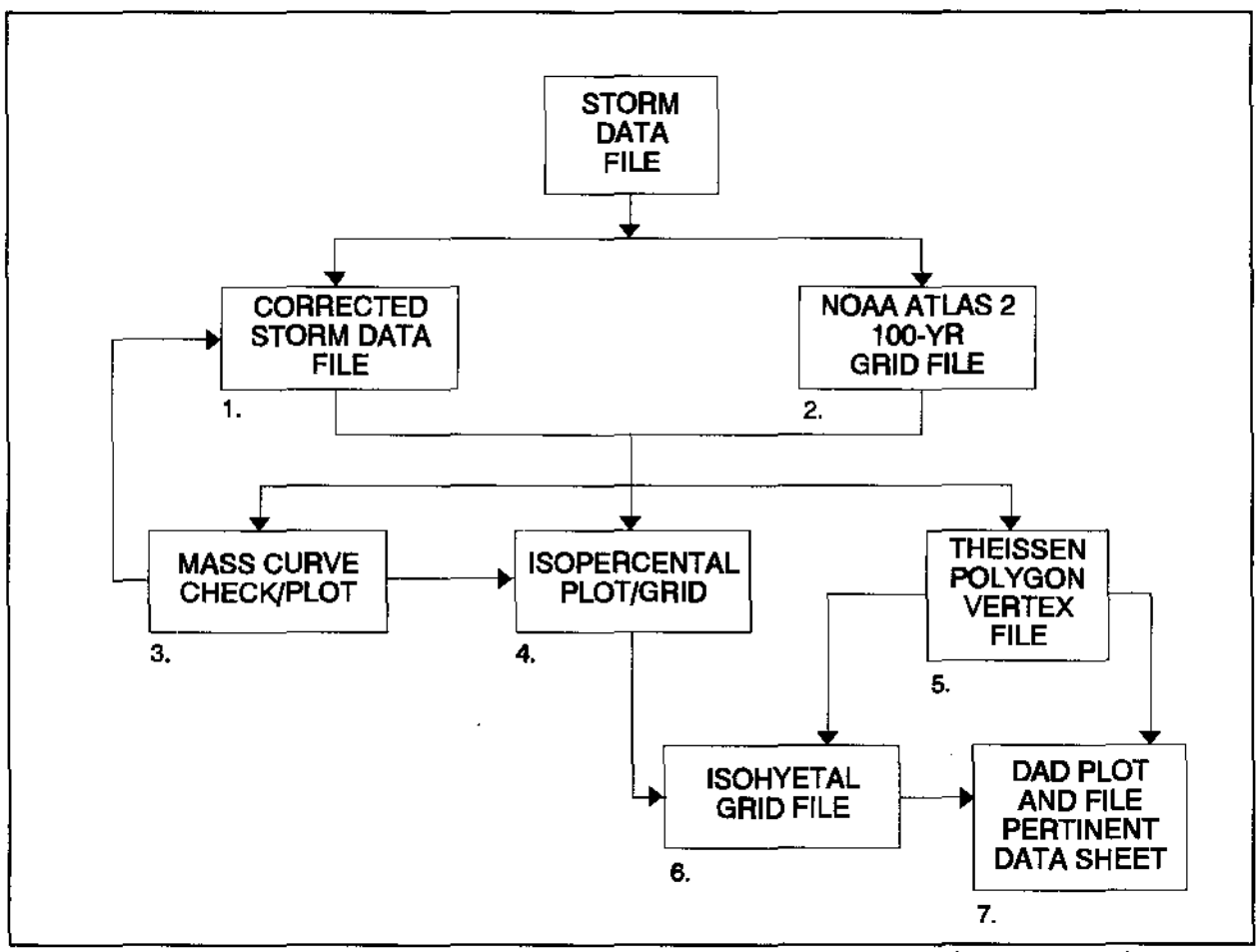


Figure 5.1.--Schematic flow diagram of modules created in processing storm rainfall data by the automated ministorm program. Modules are numbered and referenced in text.

a file containing the contour values were used to compute intersecting areas, where intersecting areas refers to the area between the polygon and each contour of the isohyetal analysis.

Module 7 in Figure 5.1 is a complex procedure beyond the scope of this report but fully documented by Stodt (1994). The output from this module is the object of the ministorm program; depth-area-duration information. The program provides plotted DAD values and fits enveloping durational curves for selected durations. It also presents a matrix of DAD data that comprises the major part of the pertinent data sheet information available for each analyzed storm in the Corps of Engineers Storm Catalog (USCOE 1945-). Table 5.1 is an example of the matrix of storm DAD for storm 78 (10/22-25/34). In developing the DAD data, there is one aspect of the present study that differs from past practice. The present program reorders hourly precipitation according to the maximum 1-hour, and then the maximum consecutive 2, 3, 6, etc. accumulations. This compares to the manual analysis procedure that used only 6-hour increments. DAD matrices for all storms (including multiple centers where noted) in this study can be found in Appendix 2.

Table 5.1.--Example of DAD table produced by ministorm analysis program listing average depths (inches) for storm 78 (10/22-25/34).

Storm 078 - October 22-25, 1934

CASCADES CENTER

AREA (MI^2)	DURATION (HOUR) 1	6	12	18	24	30	36	42	48	54	60	66	72
1.	.81	2.91	4.28	5.84	6.24	6.50	6.88	8.06	8.74	9.12	10.26	11.02	11.02
10.	.81	2.91	4.28	5.84	6.24	6.50	6.85	8.03	8.74	9.10	10.23	10.99	10.99
50.	.78	2.82	4.11	5.62	6.02	6.30	6.60	7.79	8.56	8.85	9.93	10.67	10.67
100.	.71	2.56	3.93	5.40	5.82	6.12	6.48	7.67	8.37	8.73	9.79	10.52	10.52
200.	.64	2.29	3.75	5.18	5.63	5.95	6.21	7.32	8.19	8.37	9.36	10.06	10.06
500.	.58	1.95	3.47	4.83	5.27	5.59	5.82	6.90	7.70	7.85	8.58	9.20	9.20
1000.	.47	1.72	3.13	4.38	4.77	5.15	5.38	6.35	7.03	7.22	7.66	8.17	8.20
2000.	.37	1.48	2.68	3.76	4.23	4.66	4.93	5.76	6.42	6.63	6.87	7.26	7.40
5000.	.27	1.08	2.02	2.86	3.50	3.97	4.25	4.97	5.65	5.91	6.09	6.36	6.70
7068.	.23	.94	1.77	2.52	3.23	3.71	3.99	4.68	5.37	5.64	5.80	6.01	6.43

6. STORM SEPARATION METHOD

6.1 Introduction

The storm separation method (SSM) is an outgrowth of practices that were initiated in the late 1950's for PMP studies in orographic regions. HMR 36 (USWB, 1961) is one of the earliest reports to discuss PMP development in terms of orographic and convergence precipitation components. Convergence precipitation in this context is the product of atmospheric mechanisms acting independently from terrain influences. Conversely, orographic precipitation is defined as the precipitation that results directly from terrain influences. It is recognized that the atmosphere is not totally free from terrain feedback (the absolute level and variability of precipitation depths in some storms can only be accounted for by the variability of the terrain); but cases can be found where the terrain feedback is either too small or insufficiently varied to explain the storm precipitation patterns and in these cases, the precipitation is classified as pure convergence or non-orographic precipitation.

PMP studies, such as HMR 36, 43, and 49, were based on determination of convergence and orographic components through procedures that varied with each report. With the development of HMR 55A (Hansen et al., 1988), a technique was utilized that had some similarities to previous studies, but was based on determination of convergence amounts from observed storms. Convergence precipitation in that report was referred to as free-atmospheric forced precipitation (FAFP). The technique used in HMR 55A is complex and involves the analyst tracking through a set of modules in which knowledge of observed conditions and experience are used to arrive at estimates of the FAFP. The estimates are in turn weighted, based on the analyst's judgment of the amount and quality of overall information, to obtain a result. This process has been referred to as the storm separation method (SSM) and is described at considerable length in HMR 55A.

Since the development of the SSM in HMR 55A, the procedure has been applied in a number of subsequent studies (Fenn, 1985; Miller et al., 1984; Kennedy, et al., 1988; and Tomlinson and Thompson, 1992). Through these various developments, the SSM has undergone minor refinements. The entire development discussed in HMR 55A will not be repeated here, but readers interested in these details will find a reprint of the pertinent chapter (Chapter 7) from HMR 55A in Appendix 3 of this report. Similar information is contained in the 1986 edition of the WMO Manual for Estimation of Probable Maximum Precipitation (WMO, 1986).

The process of estimating FAFP from a storm for a given area size and duration is achieved by using the hydrometeorological information available for the storm to answer certain questions. These questions are contained within several modules which constitute the body of the SSM.

The hydrometeorological information about a storm may be missing over large areas with respect to the storm's full precipitation pattern; or the information when available may be unevenly distributed; or it may be biased or contradictory. In view of such informational dilemmas, a decision about the level of FAFP for a storm may have to accommodate a fair amount of uncertainty. The questions asked in the SSM modules are formulated in such a way that analysts with different levels of experience could estimate different amounts of FAFP. Under such circumstances a consensus among analysts often leads to the best FAFP estimate for a storm, but the consensus process is not a necessary part of the SSM.

Because of the extensive information provided by the storm analysis program and the number of storms studied, the SSM technique was considered most appropriate for the present study. The technique was applied directly according to the original guidance, subject to the modifications described in the following section.

6.2 Changes to the Previously Published SSM

The remainder of this Chapter covers modifications to the modular development presented in Appendix 3. This discussion covers specific changes in detail that may be beyond the casual reader's interest.

Several details concerning questions and procedures used in the SSM were changed in this report from their formulation in HMR 55A. For example, in Module 0, which provides guidance to the analyst regarding decisions on the adequacy of available data, the adjective "reliable" was replaced by "unbiased" in questions 5 and 6 (see Appendix 3). This was done to clarify the fact that isohyetal analyses derived from the isopercental technique, even though reliable, are created based on an assumption which Module 2 attempts to prove. The need to avoid such a fallacy is made more clear by use of the adjective "unbiased" and, consequently Module 2 was not used to analyze any of the storms in this study.

Maximization of the index values was accomplished on the storm separation worksheet (Module 5, see Figure 6.1). This figure is an updated version of Figure 7.8 from HMR 55A (Appendix 3). Some new terms introduced in Figure 6.1 of this report are explained as follows:

$IMAX_n^{1000}$ = the index value of non-orographic precipitation for the storm center, adjusted to 1000 mb and moisture maximized as obtained from the module (n) indicated by the subscripts 1, 2, 3, 4, and 5,

IPMF(SC) = In-place maximization factor applicable at the storm center,

V.ADJC(SC)	=	A factor used to adjust values (to sea level) of precipitation obtained at elevations above sea level,
IPMF(NO)	=	In-place maximization factor at the location of RNOVAL[1],
BE(SC) BE(NO)	=	Barrier elevation at the storm center (SC) and at the location of RNOVAL (NO),
V.ADJ(NO)	=	A vertical adjustment factor used to adjust the value of RNOVAL to sea level,
DP/SST(X) DP/SST(0)	=	The upper limit (X) and observed storm day (0) values representing storm moisture content,
H.ADJ	=	Horizontal adjustment factor,
I_1^{EL}	=	The value of RNOVAL, not yet reduced to sea level, and
I_2^{EL}	=	The calculated value of non-orographic precipitation at the storm center, not yet reduced to sea level.

Module 1 considers the observed precipitation data, where the value of RNOVAL (the highest non-orographic rainfall representative of the storm center) was adjusted to a common barrier elevation (sea level). This avoided the bias toward large values for PCT 1 (percent of storm rainfall that is non-orographic) mentioned in paragraph 7.4.1.2 of HMR 55A. If there was a gradient in the field of maximum 12-hour persisting dew points (see section 4.2) between the location of the storm center and the locations of RNOVAL, a horizontal adjustment factor, H.ADJ, was applied to RNOVAL. It has been assumed that RNOVAL is an appropriate depth of non-orographic precipitation for the area category selected in Module 0. This observation (RNOVAL) is acceptable for an area of 10 mi^2, but this assumption becomes less reliable for larger area sizes. This assumption is compatible with assumption 3 stated in Section 7.3.1.2 of HMR 55A.

[1]See GLOSSARY, Table 6.1, for definition of terms extracted from HMR 55A Chapter 7 (enclosed as Appendix 3).

STORM ID/DATE/NAME			AT OR FOR STORM CENTER: LAT BE(SC) LON KFCTR
MODULE	PARAMETER	VALUE	EVALUATION SCALE:
0.	CATEGORY PD OF MOST INTENSE PRCP (MIPP) RCAT BFAC MXVATS PA PC IPMF(SC) V.ADJ(SC) V.ADJ-TEMP(F)	MI^2, HR Z - Z	COL. D.0-9 COL. E. 1-9. FOR MODULES 1-3: COL. F. IS SUM OF COLS. D & E. MEANINGS: COL. D.: ADEQUACY OF THE INPUT INFORMATION FOR REQUIREMENTS SET BY MODULE'S TECHNIQUE. COL. E.:PREFERENCE LEVEL FOR ASSUMPTIONS MADE BY MODULE'S TECHNIQUE. FOR MODULE 4 SEE SELECTION RULES OVERALL RULE: SELECT INDEX VALUE WITH LARGEST COLUMN F SCORE. LARGEST SUBSCRIPT BREAKS TIES.

				D.	E.	F.
1.	I_1^{EL} (RNOVAL)		AT/FOR LOCATION OF RNOVAL: LAT/LON/NAME: LAT(DP/SST) LON(DP/SST)			
	$IMAX_1^{1000}$ = I_1^{EL} *H.ADJ* V.ADJ (NO) *IPMF (NO)					
	PCT1 = PC + $IMAX_1^{1000}$ /RCAT* V.ADJ(SC)*IPMF(SC)		BE(NO) IPMF (NO) H. ADJ DP/SST(X) DP/SST(O) V.ADJ (NO)			
2.	A1 LOFAC A PB LOFAC HIFX DADFX PA^{-1} PX	n Σ(F+B) DADRF	PCT2 = PC + (Σ (F + B)/2n)(.95 - PC) = I_2^{EL} = (RCAT)(PCT2)+(LOFAC)* (DADRF)(1-PCT2) =			
			$IMAX_2^{1000}$ = I_2^{EL} *V.ADJ(SC)*IPMF(SC) =			
			PCT22 = $IMAX_2^{1000}$ /RCAT*V.ADJ(SC)*IPMF(SC) =			
3.	UP.LIM dd/ff		OBSVD . REP . GRADIENT LVL . INFLOW dd ff dd ff			
		A B C	/ Z / / Z /			
	ADJSTMT.FCTR	N/A N/A	/ Z / / Z /			
	REP.DIR(COMP) REP.SPD(COMP)		/ Z /			
	$IPMF(SC)^{-1}$		/ Z /			
	STABILITY CLASS.		/ Z /			
	OTHER		/ Z /			
		A_O=	/ Z /			
	SFC CHARTS U/A CHARTS RAWINSONDE RADAR SATELLITE OTHER		PCT3=PC+[P_a/(P_a+A_o)](1-PC)= I_3^{1000}=RCAT*PCT3*V.ADJ(SC)= $IMAX_3^{1000}$=I_3^{1000} =*IPMF(SC)=			
		P_A =				
4.	$IMAX_4^{1000}$ = ($IMAX_1^{1000}$ + $IMAX_3^{1000}$)/2 =					
	$IMAX_5^{1000}$ = ($IMAX_2^{1000}$ + $IMAX_3^{1000}$)/2 =					
SELECTED $IMAX^{1000}$ =						

ADJUSTMENT FACTORS

When wind observation is once a day at 12Z

MIPP	#OBS	FACTOR
09-15Z to 09-15Z	(2)	0.90
16-21Z to 16-21Z	(2)	1.05
22-02Z to 22-02Z	(1)	1.15
02-08Z to 02-08Z	(2)	1.20

Multiply observed speed by FACTOR to get REP.SPD

Figure 6.1.--Storm separation method worksheet; Module 5.

Table 6.1.-- Glossary of terms modified in storm separation method.	
A_o:	Term for effectiveness of orographic forcing used in Module 3, (see also P_a). Varies between 0 and 95 percent.
MXVATS:	Average depth of precipitation for the total storm duration for the smallest analyzed area less than 100 mi^2 (from pertinent data sheet for storm).
I_1:	That part of RCAT attributed solely to atmospheric processes and has the dimensions of depth. Subscript 1 associates application to Module 1.
P_a:	Term for effectiveness of actual atmospheric mechanisms in producing precipitation as compared to conceptual "perfect" effectiveness. Varies between 5 and 95 percent.
PC:	Used in calculations of modules to take into account the contribution of non-orographic precipitation to total FAFP (that includes contribution from orographic areas). Varies between 0 and 95 percent.
PCT 3:	The percentage of non-orographic precipitation in a storm from the third module based on comparison of storm features with those from major non-orographic storms.
RCAT:	The average precipitation depth for storm area size and duration being considered.
RNOVAL:	Representative non-orographic precipitation value that is the highest observed amount in the non-orographic part of the storm.
W_o:	A vertical displacement parameter, the product of the wind component perpendicular to the slope (for duration considered) and the slope in feet/miles.

The flowchart used for Module 1 is shown in Figure 6.2, and modified only slightly from that used in HMR 55A to reflect adjustments to sea level. Since hourly values of precipitation were available from automated analysis procedures, PCT1 did not have to be calculated from the variables RNOVAL and MXVATS. Consequently, the value of PCT1 for the total storm duration could be assumed to be the same as the index duration (24-hours). The index depth of non-orographic precipitation from Module 1, was therefore obtained directly from the depth for the index duration at the site selected for RNOVAL. However, since PCT1 is necessary in Module 4, it was derived from the relationship

$$PCT1 = PC + \frac{IMAX_1^{1000}}{(RCAT * V.ADJ(SC) * IPMF(SC))(0.95 - PC))}.$$

The ratio, $IPMF(SC)^{-1}$, listed in Module 3 in Figure 6.1, is relatively large when "observed" storm moisture is close to its upper limit and vice versa. Thus, from a strictly moisture content point of view, values in Column B would be relatively large when this parameter is relatively large and vice versa.

In Module 3 shown in Figure 6.3, the orographic parameter, A_o, was derived using a somewhat revised procedure, when compared to that in Appendix 3. The vertical displacement parameter, W_o, and the elevation gradient were not used. But, the upper-limit wind speed, which was a constant in HMR 55A, was allowed to vary across the region. The variation was based on extreme wind speed data (Simiu et al., 1979) for 10 United States locations in the northwest and five locations nearby. The optimum inflow direction for orographic storms, used in setting the barrier elevations, was determined for each of the 15 locations. Then at each location, the series of annual maximum speeds and their associated directions were searched to find the largest annual wind speed coinciding with the optimum inflow wind direction. This speed became the first approximation of the upper-limit speed for the optimum inflow direction at the site. This first approximation wind speed was changed only if certain conditions were found, as given in the following rules:

(a) If the first approximation speed was less than the mean speed for all directions in the total sample, the mean speed became the upper-limit speed, while the optimum inflow direction remained the same.

(b) If the first approximation speed was larger than the sample mean but less than the 100-year speed, it was compared with the sample mean plus one standard deviation speed, and the larger of these two became the upper-limit speed, while the optimum inflow direction remained the same.

(c) If the first approximation speed was greater than the 100-year speed, the 100-year speed became the upper limit speed, while the optimum inflow direction remained the same.

An analysis of 30-year return period wind speeds, prepared by Donald Boyd for the National Building Code of Canada (Newark, 1984), and kindly supplied to us by D.J. Webster, Atmospheric Environment Service, Canadian Climate Centre, provided a basis for extrapolating the upper-limit isotachs into Canada.

The component of the wind speed along the direction of optimum inflow, representative of the 24 hours of most intense precipitation, was obtained for each storm being analyzed. This speed was modified by empirical adjustment factors shown in Module 3 of the storm separation worksheet, Figure 6.1.

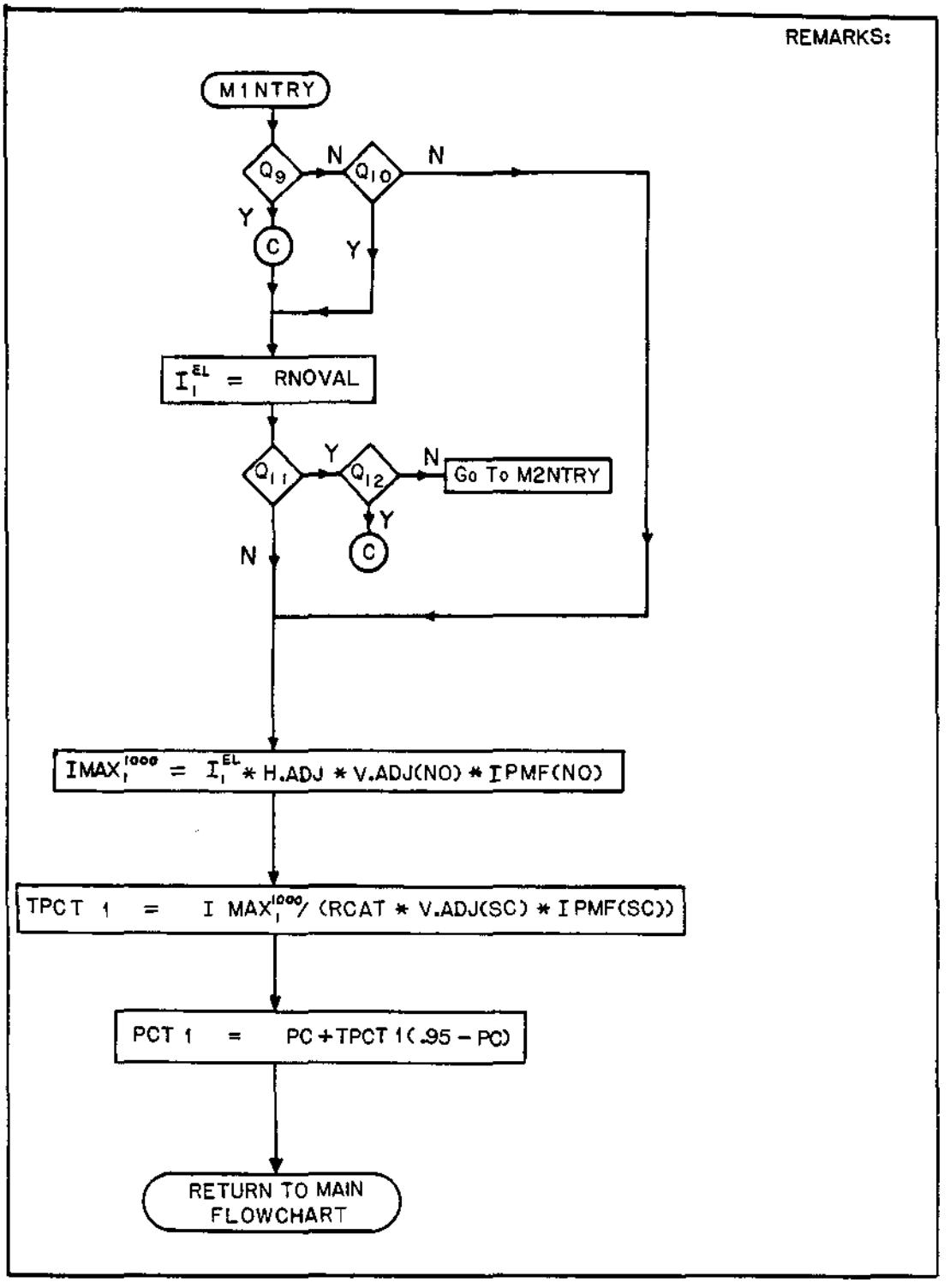
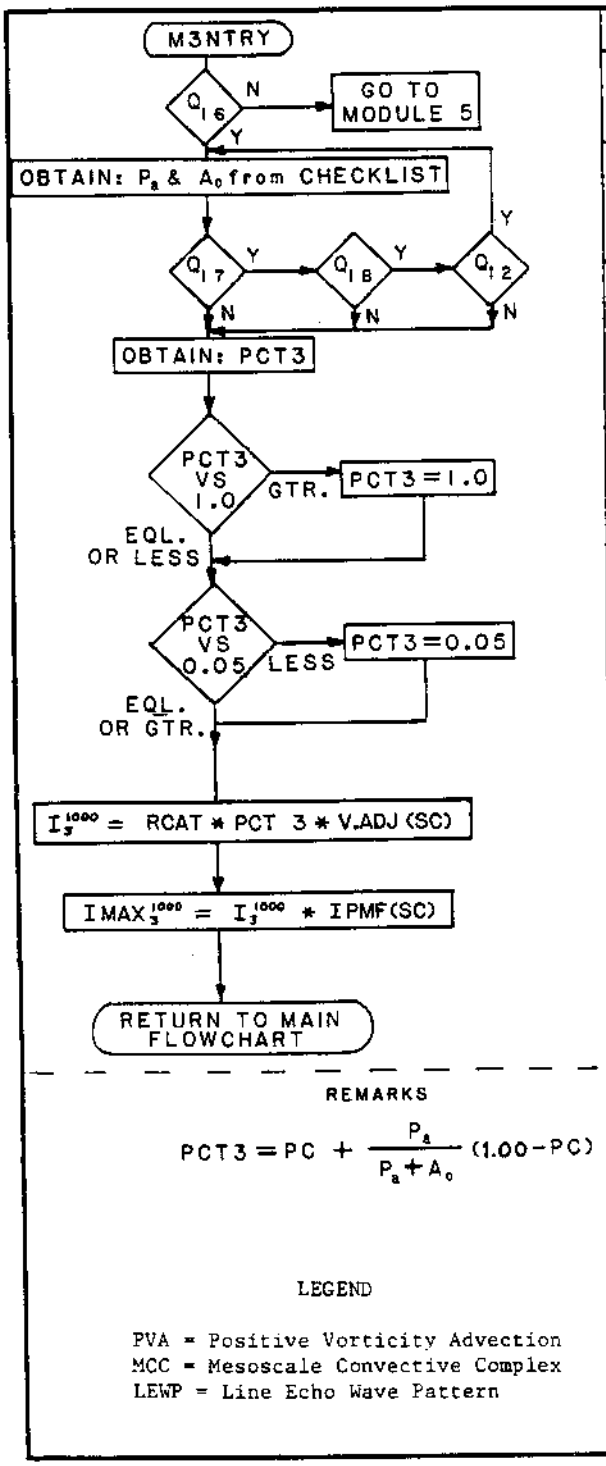


Figure 6.2.--Module 1 flowchart.



REMARKS

$$PCT3 = PC + \frac{P_a}{P_a + A_0}(1.00 - PC)$$

LEGEND

PVA = Positive Vorticity Advection
MCC = Mesoscale Convective Complex
LEWP = Line Echo Wave Pattern

P_a CHECKLIST

Cat. Data	Parameter	A (√)	B .05-.95	C 1-3	D B*C
Surface	Iso.Ptn. Fronts Waves Sq.Ln. Other				
Upper Air	PVA/SW Cutoff Blocking JetStm Other				
Rawinsonde	Stability Shear Other				
Satellite	Diver. Merger MCC Other				
Radar	LEWP Merger Others				
Other					
Duration (%)					
Totals =					
P_a = Total D/Total C =					

A_0 Checklist

Parameter	A Phys. Val.	B 0-±.95	C 1-3	D B*C
1. Adjustment factor		na	na	na
2. Rep. direct.		na	na	na
3. Rep. speed		na	na	na
4. Upper limit speed		na	na	na
5. Ratio of 3. to 4.				
6. Stability				
7. IPMF (SC)''				
8. Others				
9. Totals	na	na		
A_0 = Total D/Total C =				

Figure 6.3.--Module 3 flowchart.

These factors were applied when, during the most intense 24 hours of precipitation, there were only one or two wind observations available at 1200 UTC. These empirical adjustment factors are in the form of ratios based on relations observed in eight recent storms from the storm list in Appendix 1.

These ratios compare the 1200 UTC wind speed(s) noted above to the average wind speeds (when all eight 3-hourly observations are available for the 24 hours of most intense precipitation). This ratio was then divided by the upper-limit speed and the resulting quotient multiplied by 0.95 and put in column B alongside the wind parameter in the A_o portion of Module 3. Because both upper-limit speed and direction (which incorporates moisture availability) are involved in the evaluation of the inflow parameter, the weight assigned to it in column C of Module 3 should be higher than for the stability parameter, assuming a good sample of inflow winds for a storm is available. Here again, the decision to use wind speeds in this section that are at a level less than the theoretical maximum was made as an attempt at limiting the compounding of maxima.

The formulation for PCT3, shown in HMR 55A (Appendix 3) as equal to the sum of the non-orographic rainfall component and a term that accounts for the effectiveness of the storm's atmospheric mechanism to produce precipitation was changed to:

$$PCT3 = PC + \frac{P_a}{P_a + A_o}(1.00 - PC).$$

This was done because, by original definition, P_a and A_o could never exceed a value of 0.95. The formulation used previously had a bias toward lower estimates of FAFP built into it in the term (0.95 - PC). This bias was eliminated by replacing 0.95 by 1.00 in this term.

Figure 6.4 attempts to clarify the use of stability in setting a value for A_o in Module 3. The evaluation of the influence of the stability set in column B of the module is related to variations from the pseudo-adiabatic lapse rate and ranges from 0 to 0.95. This range may be subdivided as follows (see Figure 6.4): 0.65 to 0.95 when the observed lapse rates are optimum for producing orographic enhancement of FAFP, 0 to 0.45 when the lapse rates are least conducive for producing orographic enhancement of FAFP, and 0.45 to 0.65 for the remaining cases. The optimum cases are those where the lapse rates on average are in the range 1°C more stable to 2°C less stable than pseudo-adiabatic within 100-mb layers from the surface to 300 mb. The largest value in column B of Figure 6.3 should be associated with the less stable of these cases. Lapse rates least conducive for producing orographic enhancement of FAFP (i.e., those of greatest instability) would be those greater than -4°C from pseudo-adiabatic. The cases greater than +4°C from pseudo-adiabatic, i.e., the most stable cases, would be given the lowest scores in column B.

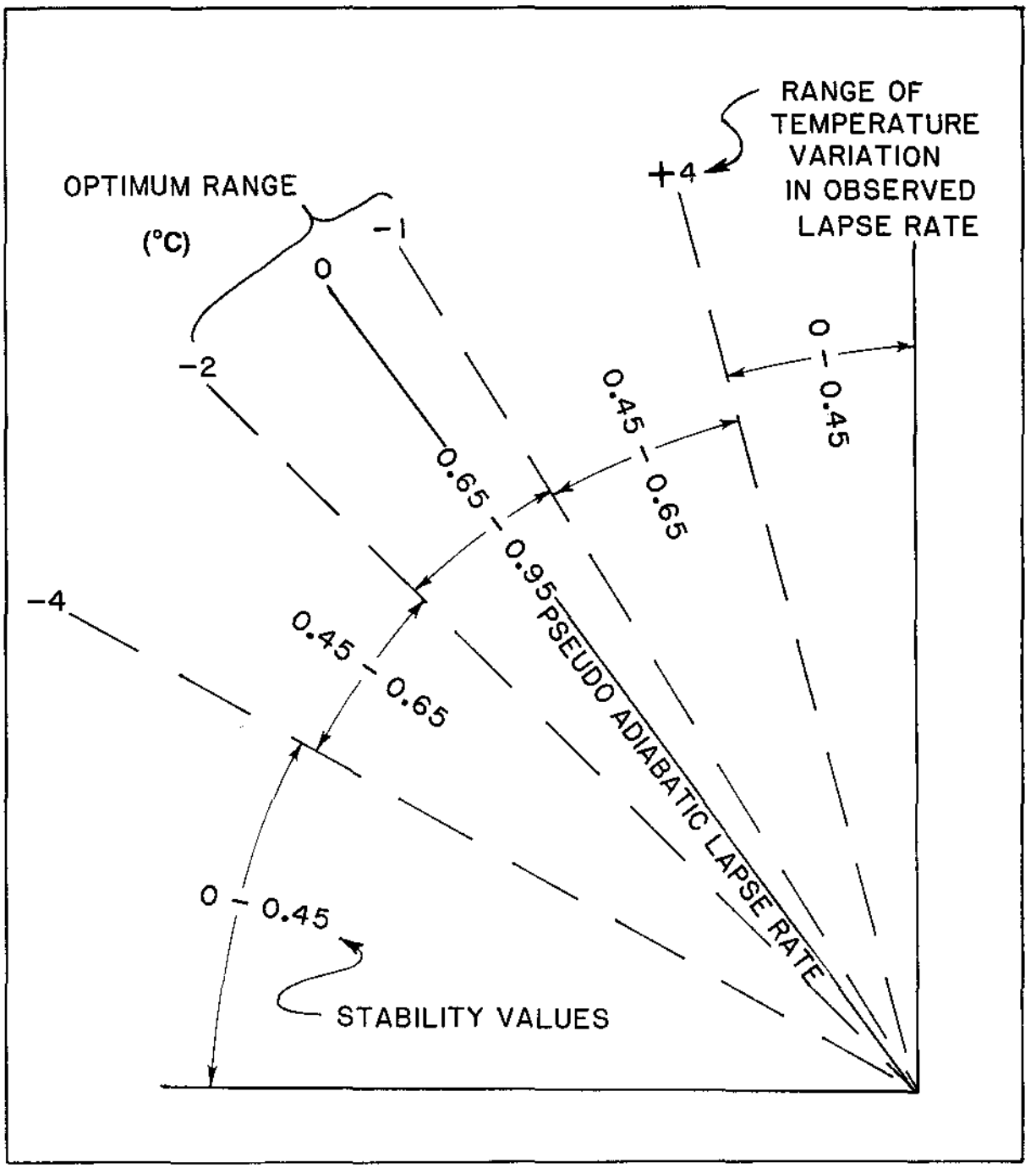


Figure 6.4--Schematic diagram to show relative range of stability values compared to the pseudo-adiabatic lapse rate.

It is reasoned that orographic enhancement of FAFP should increase up to some limit with decreasing stability. Beyond that limit (set subjectively at 2°C more unstable than pseudo-adiabatic) as lapse rates approach the dry adiabatic, there should begin decreases in moisture content sufficient to weaken the production of purely orographic precipitation.

Cotton and Anthes (1989) noted that the orographic (described as orogenic precipitation in that report) enhancement of precipitation involves complex problems in the formulation of atmospheric scale interactions and phase changes. The procedures followed to obtain A_o in Module 3 (Figure 6.3) barely scratch the surface of these problems, but a more sophisticated approach awaits the results of continuing research by atmospheric scientists, and no change is offered here.

It is recognized that the lack of upper-air information for most of the earlier storms of record may make use of the stability parameter impossible in the formulation of A_o. For more recent storms, however, if less than complete information was available, this condition limits the value of the weighting assigned to the stability parameter in column C of Module 3.

Finally, a routine was added to each module which asked the analyst the following question. Once a value for FAFP had been obtained, is the implied orographic factor at the storm center satisfactory in relation to the K factor, derived independently from 100-year precipitation-return intensity at the same location? If significant differences in orographic factor could not be resolved, a low valuation would be given in column D to the estimation of FAFP for the module being used. Apart from these changes, use of the SSM in this report was the same as in HMR 55A (see Appendix 3).

As mentioned above, a process related to, but not part of the SSM, was the reconciliation of differing estimates of FAFP by different analysts. Another procedure adopted for this report and related to the SSM, but not part of it was adjustment of finalized FAFP values to a common reference level of the atmosphere for all storms. The reference level used was 1000 mb. Based on the maximum persisting 12-hour 1000-mb dew point at the location of the derived FAFP, the FAFP was changed in the same proportion as the change in water available for precipitation in a saturated, pseudo-adiabatic atmosphere. No change was made in FAFP; however, for storms occurring between sea level and 1000 feet above sea level. This procedure was adopted so that direct comparisons of FAFP could be made easily among all 30 storms analyzed, and so that the sea-level analysis of the 100-year non-orographic component could be used as guidance for analysis of the field of FAFP. It was also the procedure used as part of storm transposition used in creating the index map of FAFP (refer to Chapter 7).

Since we were dealing with FAFP at sea level, the precipitation depth at the elevation of the largest enclosed isohyet might be potentially as large as the depth at a somewhat smaller valued enclosed isohyet, provided that the second center

was located at a higher elevation. In such cases, both centers were evaluated for FAFP, and the results adjusted to sea level.

From the 28 storms centered in the United States and the two storms located in Canada, FAFP values for 50 isohyetal maxima were set. At least one value was set for each storm. In five of the United States storms, one or more centers for which DAD relationships were developed were not analyzed, either because the central value was significantly smaller than that at the principal center or because the centers were very close to one another with no significant difference in value. Depth-area-duration analyses were not done for all of the isohyetal maxima examined by the storm separation method, but were done for all centers which provided controlling values in the analysis of FAFP (Appendix 2).

7. CONVERGENCE COMPONENT OF PMP

7.1 Introduction

The previous chapter highlights some of the processes for separation of storm precipitation into two components of which the convergence component, or FAFP, is part of the basis for PMP development under the SSM. In non-orographic regions, e.g., most of the region east of the 105th meridian covered by HMR 51 (Schreiner and Riedel, 1978), the inadequate distribution of observed storms is augmented through the process of transposition. Storm transposition is the movement of storms from one location to another. The transposition limits in generalized PMP studies are commonly taken to be meteorologically homogeneous regions wherein storms of similar mechanism could occur. In non-orographic regions, transposition limits are rather broad.

PMP procedures do not allow transposition of storms in orographic regions, and this has been an impediment to PMP development in mountainous regions based on storm analysis. This problem is caused by the inadequate storm data base in orographic regions that will relate individual storm rainfalls to varying terrains at every location. The primary advantage of the storm separation method (SSM) is that the convergence component (FAFP) of orographic storms can be transposed. FAFP transposition is regarded similarly to the traditional transposition considered in non-orographic regions. As in the traditional approach, transposition of the FAFP is limited by the region in which storms with a common mechanism can occur.

This chapter discusses storm transposition and the analysis of the FAFP component of PMP. The FAFP analysis for this study is developed at the 1000-mb surface. That is, the storm convergence component was maximized "in place," and then reduced in elevation to near sea level. Horizontal transposition was then imposed at the 1000-mb level to move the component amounts within the transposition limits set by common storm types. A 1000-mb FAFP analysis was drawn based on the transposed values.

7.2 In-place Moisture Maximization

Moisture maximization has been used almost from the onset of PMP studies to determine the potential for precipitation based solely on moisture availability. Traditionally, the premise is that moisture at any specific location is limited by the maximum observed 12-hour persisting dew point which varies seasonally and geographically. As indicated in Chapter 4, the seasonal variation of the two standard deviation SST represented the upper limit of moisture parameters for this report. Because of the slow variation of SST, it was assumed that a single observation of SST was sufficient for the observation time, plus or minus 6 hours, thus making it similar in nature to a 12-hour maximum persisting dew point.

The in-place moisture maximization computation is a ratio of the SST measured near the source region of the storm's moisture charge, along an upwind trajectory from the storm center, and two standard deviations above the long-term mean SST at the same location (REF). Precipitable water is that amount of water that would be accumulated if all the water vapor in a column of air of unit cross section were condensed. Precipitable water is a function of dew point temperature and elevation, and is commonly available in tables (English units in USWB, 1951; or metric units in WMO, 1986). The ratio is therefore, always equal to or larger than one. It can be represented by the following mathematical equation:

$$R_{Ip} = \frac{W_{p\ max,\ SL,\ SE}}{W_{Ps,\ SL,\ SE}} \tag{7-1}$$

where,

R_{Ip}	=	In-place maximization factor
W_{ps}	=	precipitable water associated with 12-hour persisting dew point for storm, s
max	=	maximum observed
SL	=	storm location
SE	=	storm barrier elevation

Throughout general storm PMP studies, the average time period used to represent maximum moisture supplied to a storm has traditionally been set at 12 hours. After the moisture analysis for the present study was completed, the issue of using other time periods for persisting dew points was discussed in an evaluation of PMP for Wisconsin and Michigan (EPRI, 1993b).

It was concluded that the duration of the representative dew point for a particular storm should be correlated with the storm duration and should vary with an individual storm event. While this conclusion may appear reasonable, insufficient evidence exists from the Northwest study region to show significant differences from use of a singular 12-hour period. Preliminary testing led to the conclusion that because of the storm types controlling PMP in the Northwest, the reduction in persisting storm dew point in going from a 6-hour duration to a 12-hour duration is approximately proportional to the change between the 6-hour and 12-hour maximum persisting dew points. That is, the ratio of 6-hour maximum persisting dew point to 6-hour persisting storm dew point may not be much different from the ratio of 12-hour maximum persisting dew point to 12-hour persisting storm dew point, and likewise for other possible time periods.

Table 7.1 lists barrier elevations and maximization factors for each storm center. Maximization factors were also developed for those storms having

Table 7.1.--In-place moisture maximization factors and other criteria for storm centers in this study.

Storm Number	Maximization Factor	Barrier Elevation (feet)	Maximum Dew Point Degree F
5	1.70	3200	67
12	1.70	5800	57
29	1.70	6500	70
32	1.25	1200	59
38	1.30	2800	61
40	1.47	3200	57
59	1.40	3600	56
60	1.54	2200	57
66	1.53	1200	63
74	1.31	2600	58
78	1.53	1000	62
80	1.62	1800	55
82	1.60	5400	55
88	1.54	1500	58
106	1.70	6400	74
126	1.53	2000	64
133	1.42	5000	61
143	1.49	2900	66
147	1.19	3800	57
149	1.47	2700	63
151	1.54	1800	60
155	1.70	7300	68
156	1.19	2500	62
157	1.37	7100	56
165	1.23	1900	61
168	1.43	5200	54
175	1.24	1400	58
179	1.34	3300	58
Canadian Storms			
MTG	1.70	7300	68
SEY	1.37	2000	53

secondary storm centers. In all instances of multi-centered storms, the secondary maximization factors showed little variation from that of the primary storm. Maximization factors in Table 7.1 are held to an upper limit of 1.7, consistent with the considerations applied to in-place adjustments in HMR 55A. This limit has been adopted to allow for the inadequacies of the storm sample in orographic regions.

After the non-orographic value of precipitation at the principal storm center has been obtained using the SSM (see previous chapter), this value is adjusted (see Section 7.3) to 1000 mb for storm transposition. The maximum dew points shown in the last column of Table 7.1 are used for these adjustments. The dew points were taken from Figures 4.1 to 4.12 at the location of the principal storm center.

7.3 Vertical Adjustment Factor

The vertical relationship used to adjust each maximized FAFP amount to the 1000-mb level was made by imposing the vertical moisture adjustment factor otherwise used in storm transposition. The equation for this adjustment is:

$$R_{vt} = \frac{W_{p\ max,\ SL,\ SE,\ 1000\ mb}}{W_{p\ max,\ SL,\ SE\ \pm 1000\ feet}} \tag{7-2}$$

where:

R_{vt}	=	vertical adjustment factor
$W_{p\ max}$	=	precipitable water associated with 12-hour maximum persisting dew point
1000 mb	=	near sea level equivalent height
SE $\pm$1000	=	1000-foot exclusion from adjustment
SE	=	storm barrier elevation
SL	=	storm location

The $\pm$1000-foot exclusion adopted in this equation was also used in HMR 55A and represents an immunity from adjustment for storms moved vertically less than 1000 feet from their observed barrier elevation. The justification for this comes from the judgment that storms of equal magnitude are possible within a layer $\pm$1000 feet from the level at which they are observed. A brief discussion of the basis for this judgment is given in HMR 55A (see Section 8.4.2.2 of that report).

Equation 7-2 is less than one for increases greater than 1000 feet and greater than one for decreases that are more than 1000 feet. A set of relations is given in Figure 7.1 for use in applying this adjustment. As an example, the factor to

persisting dew point of 70°F, is 1.50. Because of the 1000-foot immunity, this computation is calculated as if the vertical adjustment were between 4000 feet and sea level. It should also be noted that the computation must be reversible so that it is possible to return to the same value. In the example provided here, the adjustment applied to return to 5000 feet from the 1000-mb level is easily determined from Figure 7.1 by using the inverse of the elevation adjustment given at 70°F and 5000 feet (i.e., 1/1.50 = 0.67). Figure 7.1 takes into account the 1000-foot immunity assumption.

7.4 Horizontal Transposition Factor

Storm transposition involves the relocation of storm properties from the place where the storm occurred to places where the storm could have the same properties. Usually the storm property transposed is thought to be the attendant precipitation, but it is actually "the mechanisms" responsible for the precipitation that are transposed. It is assumed that if virtually the same mechanisms can be assembled in another location, the only difference between the observed precipitation and the transposed precipitation would come from the differences between the quantity of water (i.e., the moisture) available for precipitation at the two locations. In this study as in others, only the non-orographic mechanisms are considered transposable. FAFP represents these mechanisms.

Classifying each storm by type is the first step in setting the horizontal limits for transposing FAFP. The storm classification system in HMR 55A (see Section 2.5 of that report) was also used in this study. Of the 30 storms examined in the Northwest, all but two were categorized as cyclonic storms. The two exceptions (storms 106 and 143) were considered to be convective storms. Within the cyclonic designation, all were extratropical storms, and in 18 of these the principal meteorological feature was the circulation itself and the attendant convergence fields. Frontal lifting was paramount in the other 10 storms.

There was no part of the Northwest region from which storms of the cyclonic type could be excluded. However, during certain months of the year, for storms in which thermal gradients were the principal forcing factor, there were regions, i.e., the southern portions in summer, where cyclonic-frontal storms had not been observed. The two storms in the convective class (storms 106 and 143) were of the complex type and occurred in late spring and early fall. Storms of this type could be excluded from most of the drainage in winter, but could be excluded from only a small portion of the drainage in the other seasons. This small portion included the coastline to the foothills of the Cascades and the region surrounding the Puget Sound. Thus, the first stage horizontal limits were much the same for storms within a given classification, and most of the drainage was within these limits regardless of the storm's classification. Since the goal of storm transposition was to create an all-season index map of precipitation, seasonal considerations did not apply at this point.

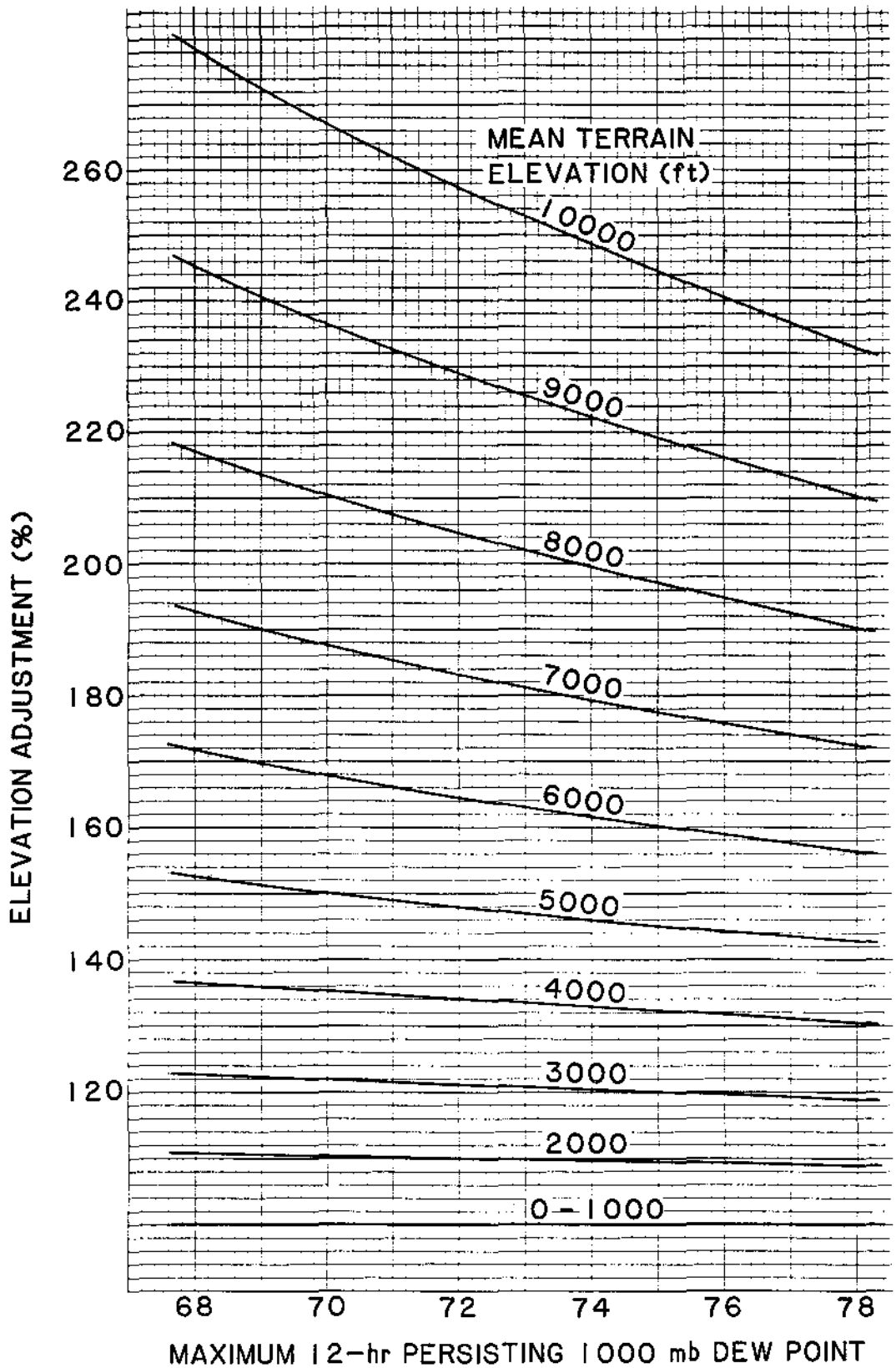


Figure 7.1.--Factors (%) for vertical adjustment of storm amounts at selected barrier elevations and dew point temperatures.

The second step of horizontal storm transposition involves limiting the range of the storm mechanism by considering the specific thermal and moisture inflow characteristics of the given storm. As in HMR 55A, if the boundary-layer moist inflow to the storm at a proposed location encounters significantly different topographic conditions than existed at the original site, the transposition would not be made. Where strong thermal gradients are involved, a transposition would not be made if between the source region of cold air and a proposed transposition location there was a significant topographic barrier. Only in a situation where such an intervening barrier was found in the original storm would the transposition be allowed.

At this second stage, the latitudinal range of transposition was limited if necessary, so that the coriolis parameter component[1] of the absolute vorticity of the system would not change by more than 10 percent (about 5-6 degrees of latitude) between the original storm site and a proposed transposition location.

A final consideration in horizontal transposition is the overall availability of record setting storms within the region. Where there are a sufficient number of such events, the procedure would be applied strictly; when there are few storms available, less restrictive application would be used.

The equation applied to the horizontal adjustment is:

$$R_{HT} = \frac{W_{p\ max,\ TL,\ SE}}{W_{p\ max,\ SL,\ SE}} \tag{7-3}$$

where,

R_{HT}	=	horizontal transposition adjustment factor
$W_{p\ max}$	=	precipitable water associated with 12-hour maximum persisting dew point
TL	=	transposed location
SL	=	storm location
SE	=	storm barrier elevation

When equation 7-3 is applied to storms transposed toward the moisture source, R_{HT} is usually greater than one, and in transpositions away from the source of moisture, R_{HT} is usually less than one.

[1]Coriolis parameter - a component equal to twice the angular velocity of the earth about the local vertical, sometimes referred to as the earth's vorticity.

Whereas these general rules for horizontal transposition of storm mechanisms have been discussed in other Hydrometeorological Reports, (e.g., HMR 55A, 51) and the Manual for Estimation of Probable Maximum Precipitation (WMO, 1986), general rules or guidelines have not been developed for setting limits to vertical transposition of storm mechanism.[2] For this report, the practice followed was to identify the freezing level of precipitation. First, available printed records were examined for information on the freezing level during the storm. The observed precipitation amount was assumed equally possible within 1000 feet vertically of its occurrence. This assumption was based on the highly variable precipitation measurements in mountains.

Next, an upper-air climatology (Crutcher and Meserve, 1970) was used to define the vertical limits of mixed-state precipitation, a combination of rain and frozen precipitation. The vertical limit below which only rainfall would be expected was defined based on upper-air temperatures within 4°F of freezing. The maximum vertical limit below which the storm could possibly have just rain was then determined by raising the critical temperature by one standard deviation. This provided an elevation over which either mixed or frozen precipitation would be expected, and liquid-only precipitation was not transposed above this elevation.

7.5 Analysis of FAFP

As mentioned in the section on storm separation, FAFP values for 50 precipitation maxima from the 30 storms in Table 2.1 were derived. These values were moisture maximized at each site (in-place maximization) and adjusted to 1000 mb using the vertical adjustment procedure of equation 7-2. Further inspection of the 50 values identified 20 storms that were the largest before or likely to be the largest after transposition. These values came from 18 United States and two Canadian storms.

Close to 300 transposition locations were selected, 116 of these being whole latitude/longitude intersections within the region. On occasion, as many as 16 transposition locations were used within a 1-degree latitude-longitude "square." The higher density of transposition locations came about because of their proximity with major topographic features serving as natural barriers for storm transposition. The greater density was needed to better define the gradients of FAFP. Typically, three or four, and sometimes up to seven, maximized transposed storm values could be taken to a single given location.

The largest value at each of the almost 300 transposition locations was extracted and replotted. These largest values were then manually analyzed. Envelopment of certain of these values was limited for those areas where there were many storms, but envelopment was used more freely in areas with few or no

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[2]This is not to be confused with the vertical adjustment factor discussed in Section 7.3

storms. A portion of the finally adopted FAFP analysis appears as Figure 7.2 covering the northwest corner of the region.

Figure 7.2 has been significantly reduced from the working scale 1:1,000,000 analysis developed for this study. The rather smooth nature of FAFP analysis is shown in this figure, but as is apparent, the analysis is not totally independent of terrain features. This fact is a function of the vertical adjustment needed to create a sea level analysis.

7.6 Controlling FAFP Storms

The development of FAFP, as partially represented in Figure 7.2, makes it possible to define which storms controlled (provided the maximized amount) throughout the region. This feature may hold only marginal interest since it is the total storm controlling amounts that most likely are of greatest importance. However, Figure 7.3 shows an approximation of where specific storms controlled the convergence component of PMP. The boundaries shown in Figure 7.3 should not be confused with transposition limits. The boundaries are based on the results of transposition and determination of which storm provides the largest maximized transposed amount at any specific location.

A number of results shown in Figure 7.3 are of interest and in need of further explanation. The first is that in spite of the strength of storm 80 and the fact that it had secondary centers on the western slopes of the Cascades, it is the Seymour Falls storm in British Columbia that controls the Puget Sound Basin and the western Cascades south to the northern one-half of the Willamette Valley. Furthermore, the Seymour Falls storm explicitly controls eastward to the Cascade ridge, while to the east of the Cascades storm 143 controls. There is no storm in our sample that is transposable to the east slopes of the Cascades; therefore, implicit transposition of the Seymour Falls storm is used to fill in the spill-over region east of the Cascade ridge. A similar problem occurs along the Rocky Mountain divide in southwestern Montana. The divide in this part of the region is relatively low and poorly defined. Storm 106 implicitly controls west of the divide while no storm actually is transposable on the east slopes through this region (HMR 55A), but HMR 55A uses implicit transposition of storm 155 to fill this portion of the region. Also apparent in Figure 7.3 are the number of different storms that control portions of western Oregon. Storm 12, by far, controls the greatest portion of the region extending from the base of the eastern slopes of the Cascades eastward almost to the Rocky Mountains.

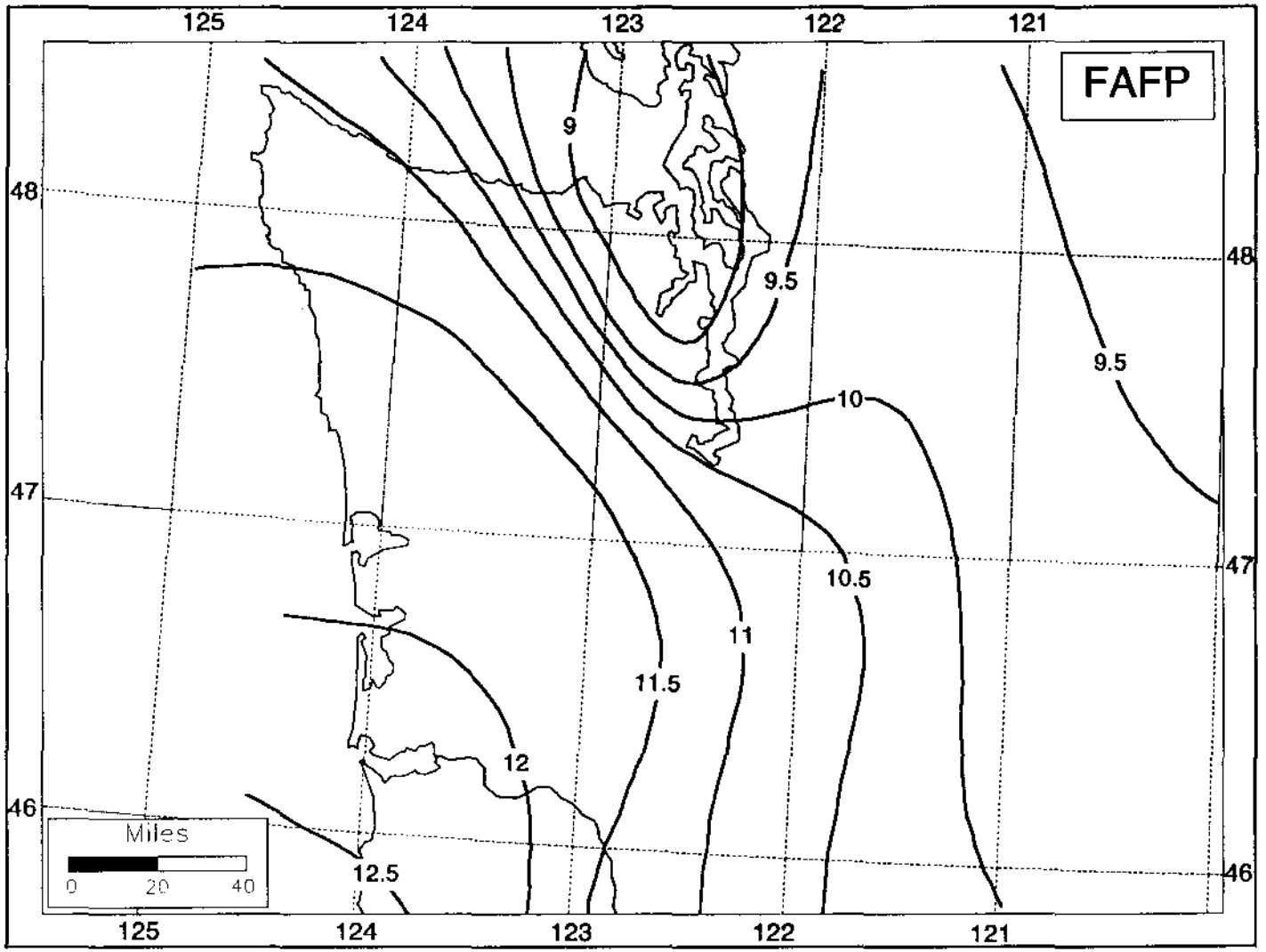

Figure 7.2.--Example of FAFP (inches) analysis for western Washington (at 1000 mb - reduced from 1:1M scale).

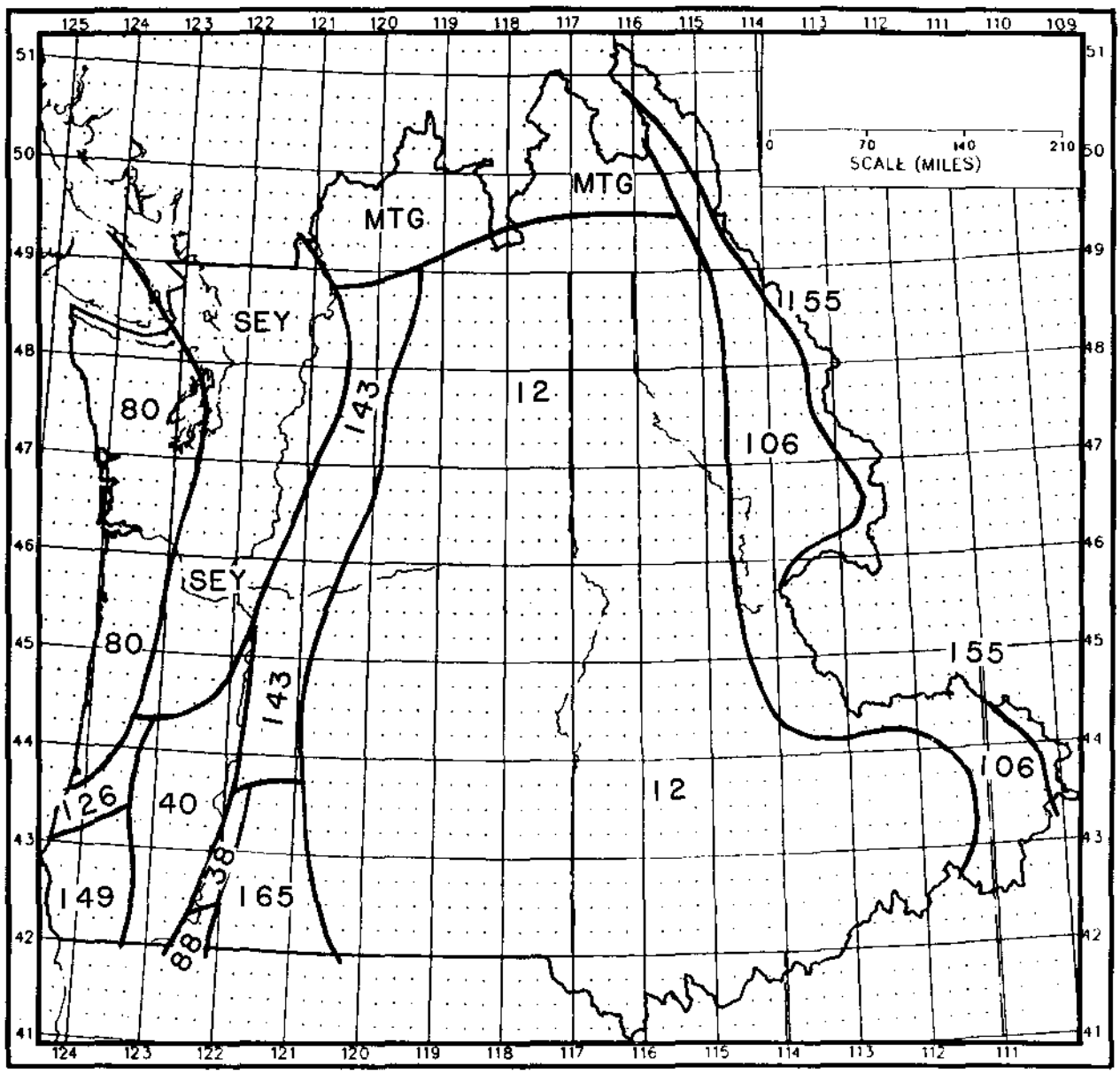

Figure 7.3.--Controlling FAFP subregions for 1000-mb 10-mi^2, 24-hour maximized convergence component (see storm index numbers).

8. OROGRAPHIC FACTOR

The orographic development in this study follows the procedure generally derived during the HMR 55A study. The procedure is founded in a need to evaluate the following equation:

$$K = M^2 (1 - T/C) + T/C. \tag{8-1}$$

where:

K	is the orographic factor,
M	is the storm intensification factor,
T	is the total 100-year precipitation, and
C	is the 100-year convergence component.

Equation 8-1 has been discussed in considerable detail in HMR 55A and other reports (Fenn, 1985; Miller et al. 1984; WMO, 1986). It should be made clear that K is not the orographic component of PMP, but a factor that is applied to the FAFP (the convergence component) to obtain total PMP, as in:

$$PMP = K * FAFP. \tag{8-2}$$

8.1 Determination of T/C

The key step in preparing a distribution of T/C is to identify locations where the effect of topography in determining the level of total 100-year precipitation is absent or close to absent. In general, such locations or areas were found in regions of relative minima in the field of 100-year level precipitation, a finding similar to that cited in HMR 55A. These minimum values of 100-year level precipitation were adjusted for convenience of comparison to sea level or 1000 mb using the vertical adjustment rule (equation 7-2) in combination with the persisting dew points of Figure 4.15 and the barrier elevation analysis. The resulting spatially uneven distribution of adjusted values, after initial analysis, revealed a mostly uniform and simple pattern of low values in the central sections of the Columbia drainage, with maxima along the Pacific coast and east of the Continental Divide. However, when certain of the 100-year relative minima were associated with relatively deep valleys that were much less wide than they were long, an irregular pattern was introduced into the analysis. Because the analysis in such regions was difficult to understand and therefore difficult to accept, it was decided that the precipitation in such locations must be affected by topography in some manner, and the 1000-mb adjusted values for these locations were redrawn subjectively to accommodate the simpler pattern established at surrounding locations. The resulting map of non-orographic, 1000-mb, 100-year, 24-hour precipitation becomes the denominator, C, of the T/C parameter following adjustment for the barrier elevation at which the numerator is observed. A simplified portion of C for the northwestern portion of the study region is shown in Figure 8.1.

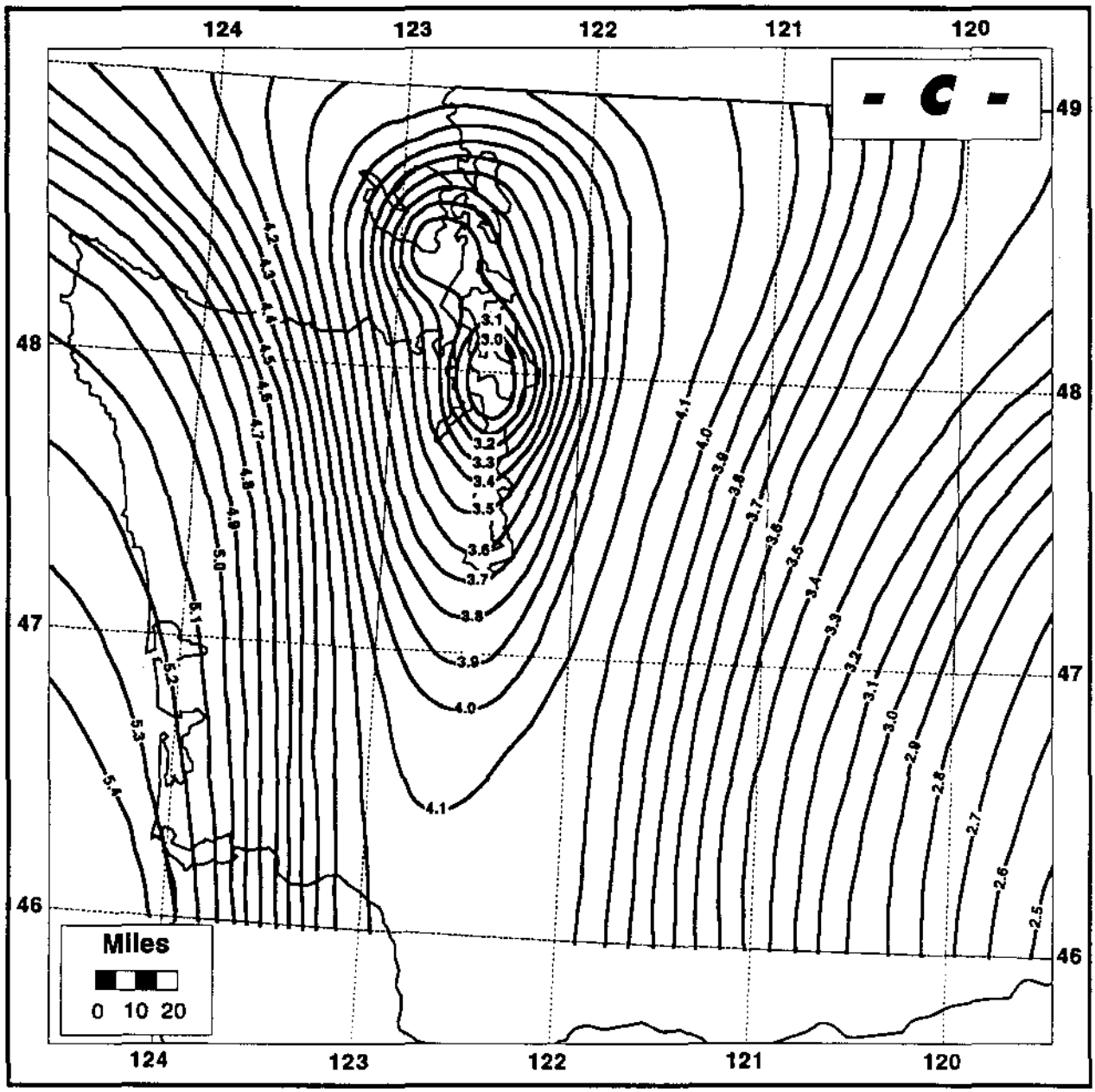

Figure 8.1.--100-year, 10-mi^2 24-hour convergence analysis, C, for western Washington (from NOAA Atlas 2 total precipitation analysis).

An earlier version of this map contained a rather uniform gradient in the region between eastern Washington and Oregon and the Continental Divide. In light of the much weaker gradient of FAFP determined for the same region using the techniques of moisture maximization and transposition, it was decided to bring the separate gradients into closer conformity. Accordingly, the gradient of 100-year values was weakened while the gradient of FAFP was strengthened slightly.

T/C was analyzed in considerable detail for the purposes of calculating the orographic factor. Figure 8.2 however shows only the generalized pattern of T/C, again for the northwestern part of the study area. The level of complexity in this figure is controlled by the detail given by T, the 100-year precipitation intensity. In some limited subregions, values of T/C less than one resulted. When this occurred in places such as in the Snake River plain, where physiographic features could likely account for the low T/C values, the values were accepted. Values as low as 0.84 to the lee of the Olympic Mountains of Washington, where the mountains were believed to disrupt the resupply of boundary-layer moisture to precipitating weather systems in the Puget Sound Basin, were also accepted. Where the physiographic features were not significant, associated T/C values less than one were reanalyzed and set to unity (one).

The largest values of T/C in the region were found in the Olympic Mountains where the values exceeded 5.8 and near the crests of the Cascade Mountains in northern Washington where the values exceeded 5.2. As will be seen in Section 8.2, the M-factor in these regions is zero, thus the K-factors becomes T/C. At such places and all highly orographic areas, the topographic interaction with the atmosphere in major storms will account for more than 80 percent of the most intense 24 hours of precipitation. This occurs when convective potential is low and frontal discontinuities are absent, while boundary-layer transport of air of exceptional moisture content is very strong and maximum lifting occurs caused by terrain features.

8.2 Determination of M

The storm intensification factor, M, relates the precipitation in the most intense rain period to the total rainfall within the storm period, and therefore varies with storm type. The period of most intense rain is referred to as the core duration. M is determined from examination of the mass curves for stations near the storm center.

Fourteen storms in or near the northwest region (see Table 8.1) were identified as producers of the 18 transposable centers accounting for the largest values of 1000-mb FAFP within their respective transposition limits. The mass curves of rainfall during the most intense 24 hours of precipitation at locations of least topographic influence nearby to each of the 18 isohyetal maxima were examined

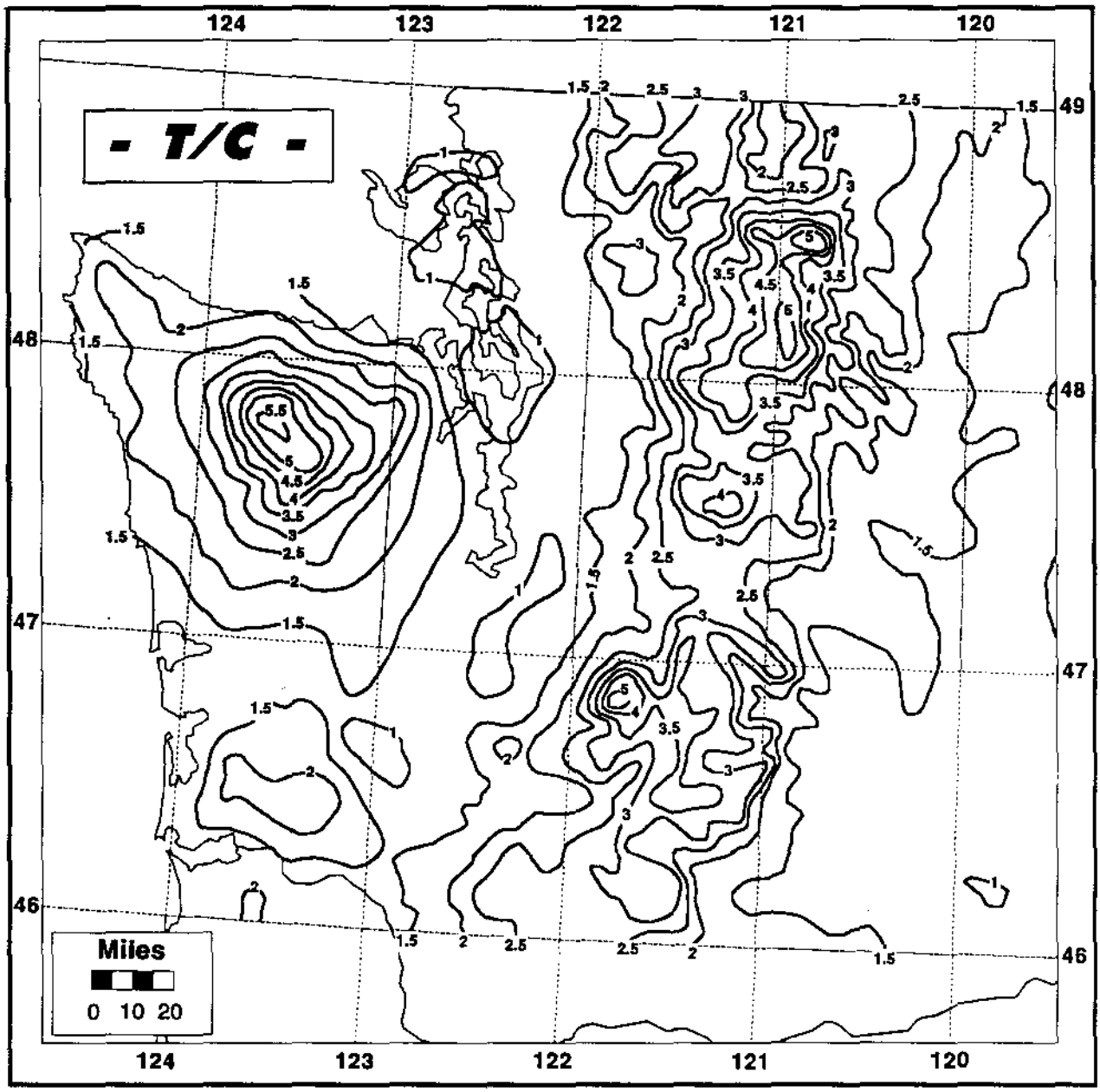

Figure 8.2.--Analysis of T/C for western Washington based on NOAA Atlas 2 100-year, 24-hour data.

significantly greater than the base rainfall rate). When least topographic locations for evidence of core-like behavior (where the rainfall intensity is too far removed from these isohyetal maxima to ensure the plausibility of the same precipitation characteristics at both places, the closest location to the maximum was selected as the place where the mass curve should be examined. In only three (Storms 82, 106 and 143) of the 14 storms was there evidence of core-like behavior. In other words, in 11 of the 14 storms, either there was no core period of most intense rain within the 24 hours of greatest precipitation. If there was a significantly different rain rate, it did not produce an accumulation sufficiently large, as compared to a long return period amount (say, 25-year), for the duration of the core. In two of the three storms (Storms 82 and 106), where both rain rates and accumulations were sufficiently large to meet core criteria, the core period was 4 hours. These two storms occurred at the end of March and June respectively, and were located near the Idaho-Montana border. A third storm occurred on the first of October and located near Hermiston, Oregon, had an 8-hour core-period.

The most recent analysis of the mass curves of rainfall associated with storm 155[1], the Gibson Dam Storm, found that the quantity of precipitation

[1]Storm 155, the Gibson Dam Storm, along the ridge of the Continental Divide in Montana, has been the subject of controversy arising from discrepancies over the true nature of the event and the isohyetal analysis resulting from it. Heavy precipitation was observed on both sides of the Divide, although greater volume fell on eastern slopes. The COE prepared the original DAD and isohyetal analysis, centered somewhat east of the Divide (as shown in Figure 2-11 of HMR 43). During the preparation of HMR 55A, the USBR made another analysis that spread the maximum west of the ridge and increased both the maximum and the volume obtained from the pattern. This reanalysis was accepted at the time by the Joint PMP Study Team. For the current study, the procedure adopted for storm analysis has changed slightly from that used in HMR 55A and again storm 155 was reviewed. The emphasis once again has been placed on east of the Divide and the results more closely follow those originally determined by COE. It can be seen in Table A, that the shifts in centering and in isohyetal volumes have not resulted in appreciable variations in either depth-duration or depth-area for this storm.

Table A.--Comparison of depth-duration (percent of 24-hour amount) and depth-area (percent of 10 mi^2) values for storm 155

Duration (hours)	1	6	12	24	30	36	48	
COE		.40	.66	1.00	1.06	1.11	1.13	
HMR 55A	.08	.41	.72	1.00	1.05	1.09	-	
HMR 57	.08	.41	.68	1.00	1.03	1.07	1.07	
Area (mi^2)	10	100	200	500	1000	2000	5000	10000
COE	100.	94.4	90.8	83.1	76.8	67.6	52.8	41.5
HMR 55A	100.	97.7	95.3	88.6	82.6	75.8	64.1	48.0
HMR 57	100.	95.1	90.3	83.1	77.1	70.3	56.7	44.4

accumulated during the 6-hour core period used in HMR 55A was too small to conform with core-like criteria. However, the M-factor for this storm from HMR 55A was accepted (rather than a value of zero) so that discontinuities in K factors at the Continental Divide between this report and HMR 55A would be avoided. Note that by having M factors greater than zero in the region near the Continental Divide so that continuity might be preserved, K factors were determined and as a consequence, PMP values were somewhat smaller than would otherwise be the case in this transitional region.

Table 8.1.--Storms that were used to derive the storm intensity analysis, M-factor map

Storm Number	Core Duration	M-factor
12	0	0
38	0	0
40	0	0
80	0	0
82	4	0.44
88	0	0
106	4	0.58
126	0	0
143	8	0.73
149	0	0
155	0	0
165	0	0*
Mount Seymour	0	0
Mount Glacier	0	0

*M-factor for storm 165 modified to 0.38, see footnote page 78

In completing the analysis of M factors, a problem arose in deciding how far southwestward from Hermiston, Oregon, to extend positive values of the M factor. The problem followed from the evaluation of storm 165 in which the M factor from the Gibson Highway Center (GIB) was analyzed as zero. This occurred because the absolute level of precipitation during the most intense 4-hour precipitation period at the representative least-orographic location for GIB was less than the 100-year precipitation. However, continuity with the positive values of M factor eastward of the Cascades crests indicated that these positive values commence

near these crests and extend into northern California near GIB. If a level less than the 100-year value had been used as a minimum requirement for core precipitation in storm 165, then a M factor of 0.38 would have resulted. The final analysis of M factors for a PMP storm occurring near GIB shows a value there of approximately 0.24, which represents a reconciliation of the information provided by storms 165 and 143. A digitized version of the M-factor analysis for the entire study region is shown in Figure 8.3.

8.3 The analysis of K

With completion of the analyses of T/C and the M factor, preparation of the K factors is straightforward. A portion of this analysis is shown in Figure 8.4. The reasonableness of this analysis is determined on the basis of meteorological experience. Figure 8.4 shows maxima exceeding 5.0 in the Olympics where it is expected that the largest orographic influence would be. Minimum orographic effects are found in the Puget Sound Basin and extending north through the San Juan Islands. Secondary orographic influences yield K values of 3.0 to 4.0 in the Cascades and there is another secondary drop off just east along the eastern base of these mountains.

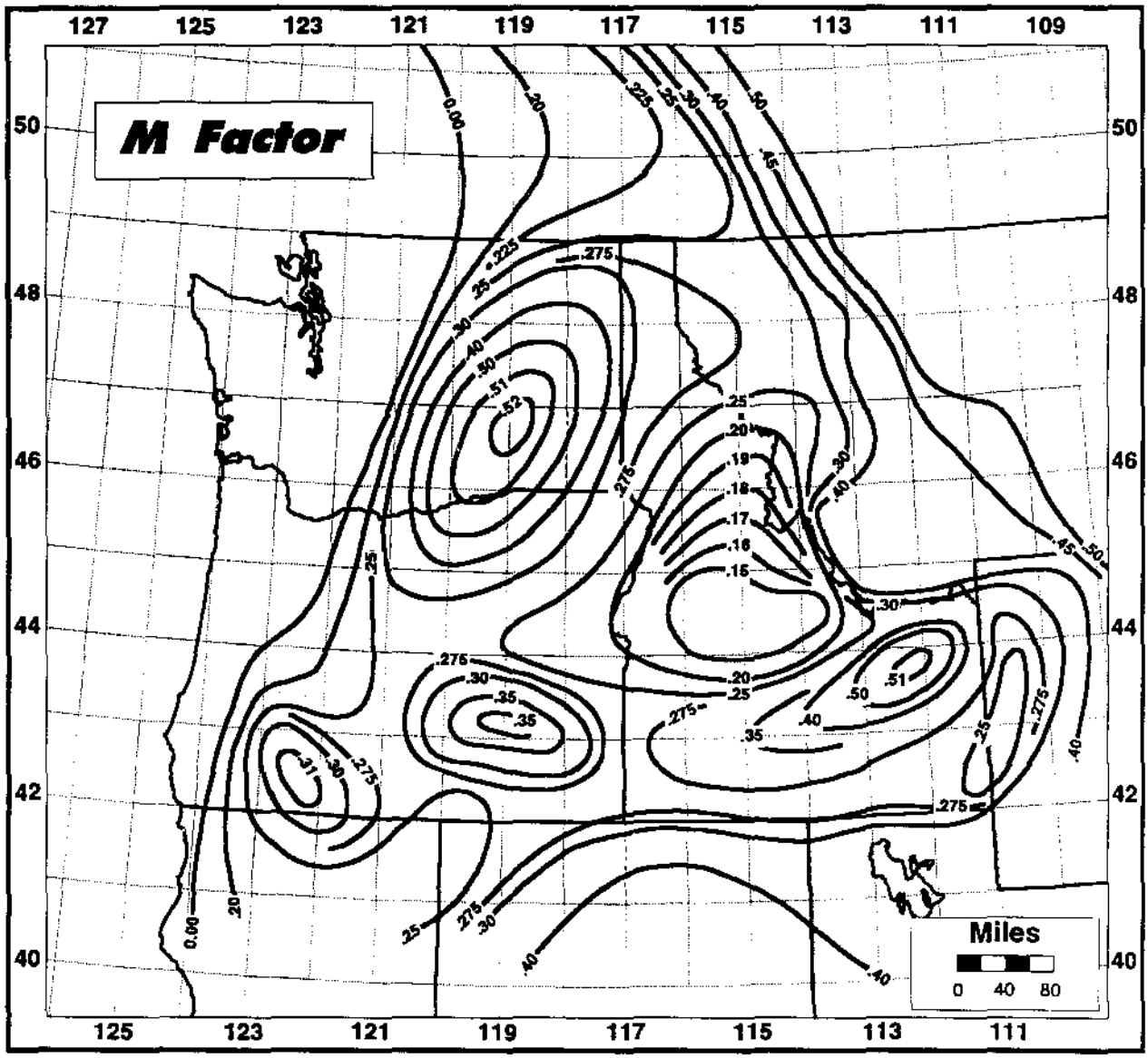

Figure 8.3.--Analysis of M factor (reduced from 1:1M scale).