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Documentation of Meteorological Data from the Coniferous Forest Biome Primary Station in Oregon

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Abstract

As part of the International Biological Program, a primary meteorological station was installed in the west-central Cascade Range of Oregon. Short-wave solar radiation, air temperature, dewpoint temperature, windspeed, and precipitation are recorded continuously. Climatic data are summarized in a daily record available from May 11, 1972, to date. This report details the measurements, processing, and analyses of these variables at the H. J. Andrews Experimental Forest.

KEYWORDS: Climatography, meteorology, Oregon (H. J. Andrews Experimental Forest).

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Introduction

As part of the International Biological Program, the National Science Foundation supported research on the structure and function of coniferous forest. In 1969, the H. J. Andrews Experimental Forest was selected for intensive study by the Coniferous Forest Biome because the 6 075-hectare forest represents diverse forest communities and stream systems characteristic of the central Cascade Range in Oregon. Through the program, both Forest Service and university scientists study processes controlling water, carbon, and mineral distribution in forest and aquatic ecosystems. The participating scientists selected five primary climatic variables affecting the rates at which materials accumulate or move through ecosystems: (1) solar radiation, (2) air temperature, (3) dewpoint temperature, (4) windspeed, and (5) precipitation. This report details the measurement, processing, and analyses of these variables at the H. J. Andrews Experimental Forest. Previously the Pacific Northwest Forest and Range Experiment Station of the U.S. Forest Service collected valuable streamflow data and records of precipitation, air temperature, and relative humidity in the Andrews Experimental Forest. This information is now supplemented by data collected at the primary meteorological station maintained at the forest.

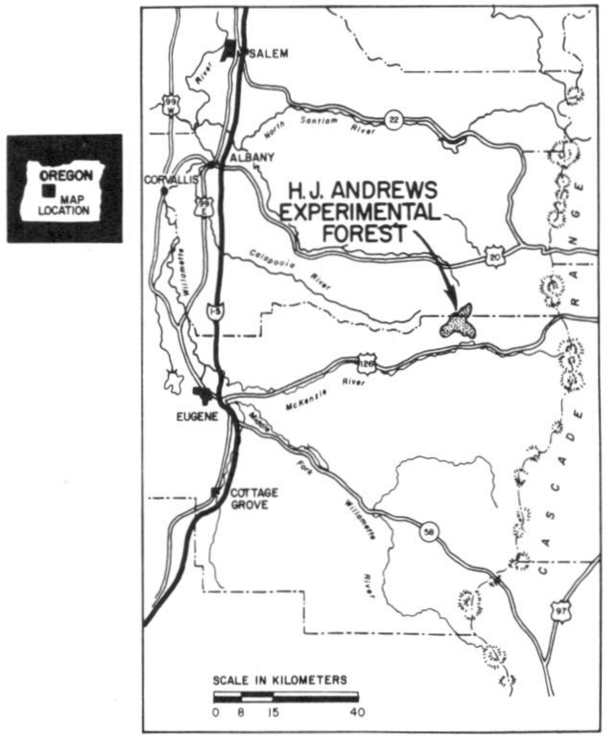


Figure 1.--Map of the H. J. Andrews Experimental Forest, the western Cascade Range of Oregon, and the major rivers draining westward into the Willamette Valley.

Site Description

Located in the central part of the Oregon Cascades (fig. 1), the H. J. Andrews is about 64 km east of Eugene (lat. $44^{\circ}15'$N., long. $122^{\circ}10'$W.). The forest occupies a rugged mountain basin. Elevation ranges from 420 to 1 630 m, and mountain slopes are generally steep with gradients between 20 and 60 percent. Stream drainages are dendritic and deeply incised.

Vegetation typifies the west-central Cascades with extensive Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and hemlock (*Tsuga heterophylla* (Raf.) Sarg.) communities at lower elevations and subalpine forests, characterized by abundant silver fir (*Abies amabilis* (Dougl.) Forbes), at elevations above 1 000 m. Table 1 summarizes the distribution of broad age classes within the major vegetation zones.

Table 1--*Vegetation zones and broad age classes (by percentage) of the H. J. Andrews Experimental Forest and notes on dominant species*

Zone	Forest condition classes			Nonforested communities
	Cutover stands[1/]	Mature forest[2/]	Old-growth forest[3/]	
Temperate forest or *Tsuga heterophylla* Zone	Successional stands of herbs, shrubs, and tree seedlings	Dominated by *Pseudotsuga menziesii*; minor amounts of other species	Dominated by *Pseudotsuga menziesii*, *Tsuga heterophylla*, and *Thuja plicata*	Narrow riparian or flood plain zones; rock outcrops
60 percent	15 percent	10 percent	35 percent	<1 percent
Subalpine forest or *Abies amabilis* Zone	Successional stands of herbs, shrubs, and tree seedlings	*Abies procera* dominant, but greater mixture of other species (*Pseudotsuga menziesii*, *Abies amabilis*, *Pinus monticola*, and *Tsuga mertensiana*)	Mixtures of *Abies procera*, *A. amabilis*, *Tsuga heterophylla*, *T. mertensiana*, and *Psuedotsuga menziesii*	*Alnus sinuata* thickets (3 percent), mountain meadows of various types (2 percent), and rock outcrops (<1 percent)
40 percent	5 percent	15 percent	15 percent	5 percent
Percent of H. J. Andrews in each condition class	20 percent	25 percent	50 percent	5 percent

1/ Clearcuts and shelterwood cuttings are from 1 to 25 years in age.

2/ Mature forest stands are mostly 100 to 150 years in age.

3/ Old-growth stands are stands dominated by trees more than 250 years old.

The vegetation has been detailed by Dyrness et al. (1974).

Soils, poorly developed morphologically, may rest on deep deposits of weathered and unconsolidated parent material. Generally very porous, the soils prevent overland flow of water. Originally described as belonging to the Regosol, Lithosol, Reddish-Brown, and Acid Brown forest soils groups[1] (Rothacher et al. 1967), most of the soils now are classified as Incepticols with a few Alfisols (Soil Conservation Service 1975). For more information, see Brown and Parsons who used the latter classification.[2]

Wet, relatively mild winters and dry, cool summers characterize the climate of the experimental forest (figs. 2 and 3), according to U.S. Forest Service records since 1952 from elevations between 400 and 1 000 m. At the meteorological station, temperatures range from -15°C during unusually cold winters to more than 40°C for brief periods almost every summer. Annual temperatures average 9.5°C; the January mean is 2°C and July, 22°C.

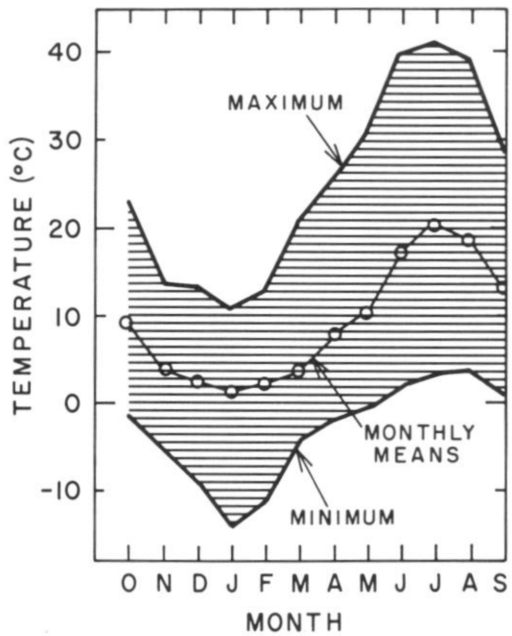
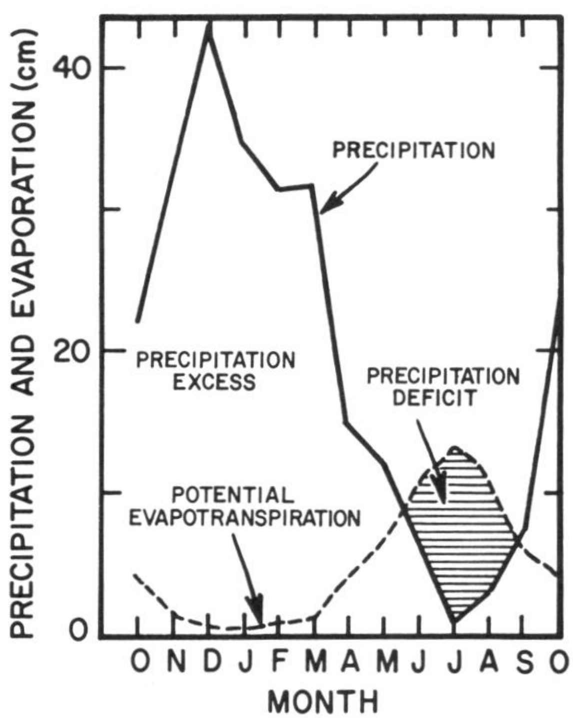


Figure 2.--Typical monthly temperatures at an elevation of 600 m in the H. J. Andrews Experimental Forest.

Figure 3.--Characteristic pattern of precipitation and potential evapotranspiration on the H. J. Andrews Experimental Forest.



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[1] U.S. Department of Agriculture, Forest Service. 1964. Soil survey report of the H. J. Andrews Experimental Forest, Willamette National Forest. 52 p. USDA For. Serv., Portland, Oreg.

[2] Brown, R. B., and R. B. Parsons. 1973. Soils of the reference stands--Oregon IBP. Coniferous For. Biome Intern. Rep. 128, 76 p. Univ. Wash., Seattle.

Annual precipitation averages 240 cm; more than 70 percent occurs from November through March; only 7 percent falls during the growing season (fig. 3). Most precipitation in this area results from warm, moist airmasses that move in from the Pacific Ocean. As the airmasses rise over the Cascade crest, prolonged periods of rain may occur. The longest single storm on record (December 18-20, 1957) produced 31.8 cm of rain in 3 days, with a maximum of 15.9 cm in one 24-hour period. A total of almost 70 cm fell during two consecutive major storms in December 1957. In contrast, the months of July, August, and September may be entirely rain free; periods of 60 days without rain are common.

The pattern of maximum temperatures and minimum precipitation during summer months creates a water deficiency. Computed from Thornthwaite's table (Thornthwaite 1948, Thornthwaite and Mather 1957), the difference between potential and actual evapotranspiration ranges from 59 to 11 cm per year. Estimated average evapotranspiration is 54 cm.

Relative humidity, generally high throughout the winter, typically approaches 100 percent each night throughout the rest of the year except when dry air moves west from the high desert east of the Cascade Range. Then minimum relative humidity, generally ranging from 40 to 50 percent during the summer, drops to 10 percent or less. In the winter, extremely low temperatures associated with dry air flowing in from the east considerably reduce the air's capacity to hold water vapor.

Elevation markedly affects precipitation, especially winter snowpack. In the subalpine zone, precipitation shows the same seasonal pattern of wet winters and dry summers. Total precipitation, however, increases with elevation and totals 30 to 40 percent more at 1 500 m than at 600 m and approaches 400 cm annually in some places (U.S. Army Corps of Engineers 1956). Furthermore, much of that precipitation--equivalent to 100 to 180 cm of water--accumulates in snowpacks as deep as 5 m in the subalpine forest. In general, temperatures also decrease with elevation so a permanent winter snowpack occurs above 1 000 to 1 200 m; below those elevations, snow cover is sporadic, developing during cold periods and disappearing during warmer winter weather.

Elevational changes in temperature are complex, varying with season and the particular temperature characteristic; e.g., mean day or night temperature, diurnal range, maximums, and minimums.[3/] Subalpine stands above 1 200 m have daily means near -2° to -4°C in midwinter and 13° to 16°C in July. A mid-elevation thermal belt results in warmer winter minimums at higher elevations and cooler minimums at lower elevations. In fact, as elevation increases to 1 100 m, average daily minimum temperatures in July also increase because of cold air drainage (see footnote 3).

[3/] Zobel, D. B., W. A. McKee, G. M. Hawk, and C. T. Dyrness. 1973. Variation in air and soil temperatures in forest communities on the H. J. Andrews Experimental Forest, 1970-1972. Coniferous For. Biome Intern. Rep. 127, 43 p. Univ. Wash., Seattle.

At a depth of 20 cm, soil temperatures range from summer maximums of 15^{o} to 20^{o}C, depending on elevations and site; they drop to winter minimums of 0^{o}C at all sites. Largest differences between sites exist in spring when the temperatures at sites retaining a snowpack lag behind those where snowmelt is complete. Soil rarely freezes, mainly because of the insulating snowpack.

The Meteorological Station and Its Operation

The primary meteorological station, generally accessible year round is located on an alluvial terrace at an elevation of 430 m. The immediate area 100 m or more in all directions from the station has been cleared of trees. Solar radiation and wind are measured on a 2-m boom located 5 m above ground on the south side of a tower. Air temperature and dewpoint temperature sensors are located inside a standard meteorological shelter 1 m above ground. A standard precipitation collector located 18 m up the tower funnels precipitation into a large, covered storage tank buried in the ground. These measurements have been compared with the sum of daily measurements taken by the U.S. Forest Service at an adjacent site 0.2 km away.

Originally the battery-powered station was serviced monthly. Because of equipment malfunctions (table 2), more frequent servicing has recently been instigated, but data still are occasionally lost. Furthermore, the sensors differ in their dependability. Table 2, indicating equipment failures since the station was established in 1972, shows that temperature sensors are most reliable and that radiometers and dewpoint sensors require careful attention. The extensive data missing in 1973 reflect instrument failure and an administrative shift in the responsibility for maintenance of equipment.

Table 2--*Days with missing data for three meteorological variables measured from 1972 through 1975*[1/]

Year and day	Solar radiation[2/]	Air temperature[3/]	Dewpoint temperature[4/]
1972:			
269-270			X
287-306			X
322-340			X
341-344	X	X	X
345-359	X		X
360-366			X
1973:			
3-12	X		X
13-86			X
121-129			X
130	X		X
131-133	X	X	X
144			X
163			X
167-168			X
176	X	X	X
195-200		X	X
220-224	X	X	X
225-306			X
307-319	X		X
320-348	X	X	X
349-365	X		X
1974:			
1-11	X	X	X
12-73	X		X
96-101			X
105-106			X
136-140			X
161			X
308		X	X
1975:			
79-100			X
131-139			X

[1/]X represents days when equipment failed and data are missing.

[2/]Missing solar radiation data were estimated from correlations with diurnal fluctuations in temperature during a given month.

[3/]Missing temperature data were supplied from a nearby secondary station.

[4/]Missing dewpoint temperature data were estimated from correlations with average night temperature.

Procedures such as checking to make sure that no water is inside the radiometer and that desiccant is fresh greatly extend the operation and accuracy of the instruments. Periodic calibration and servicing of equipment are also essential. Better maintenance (especially of the batteries), the installation of a backup station, and more frequent inspection of the records by knowledgeable personnel substantially reduced the amount of data missing in 1975. A number of temporary stations are operated to permit extrapolation of data from the primary station.

Measured Meteorological Variables

So that data records can be accurately synchronized, at exact 1-hour intervals, a central clock simultaneously interrupts the trace on the recorders for four of the five measured variables--solar radiation, air temperature, dewpoint temperature, and wind. Only precipitation is recorded without interruption.

SOLAR RADIATION

Incoming short-wave solar radiation is measured with a Lintronic dome solarimeter.[4/] Use of a desiccant and periodic calibration generally keep the instrument's accuracy within 10 percent. Photosynthetically active radiation (wavelength of 400 to 700 nanometers) important for primary production can be estimated by assuming that approximately 47 percent of the incoming short-wave solar radiation is in this spectrum.

An empirically determined heating coefficient (Gay 1971) can be used to estimate net radiation if the long-wave reflectivity or reradiation of the surface--whether forest canopy, soil, or snow--is known. For Douglas-fir, net radiation is about 65 percent of the measured daily total solar radiation. This means that, on a day recording 650 cal cm^{-2}, the net radiation on a horiztonal surface having the reflectivity of a coniferous forest is 422 cal cm^{-2}. Of this, about half normally is dissipated by evaporating water. Because about 580 cal are required to evaporate a cubic centimeter of water, evapotranspiration rarely exceeds 0.5 cm of water without additional energy supplied by advection (drier or hotter air from another area).

On different slopes and aspects, solar radiation can be estimated with trigonometric calculations (Buffo et al. 1972, Buelow 1967). By this technique, total daily potential solar radiation at any location can be estimated and shading effects by topography corrected.

The solarimeter signal is recorded continually on a 30-day RUSTRAK strip chart scaled from 0 to 2.0 cal cm^{-2} min^{-1} and with a resolution of 0.1 cal cm^{-2} min^{-1}. The signal was damped to maintain chart readability during unsettled conditions.

[4/] Mention of products by name is for the convenience of the reader and does not constitute an endorsement or approval by the U.S. Department of Agriculture or Oregon State University to the exclusion of other products which may be suitable.

AIR TEMPERATURE

Temperature, measured by a thermistor, is continuously recorded on a separate 30-day RUSTRAK strip chart scaled from -10° to 40°C and with an accuracy and resolution of 1°C.

DEWPOINT TEMPERATURE

Water vapor concentration in the air is directly measured with a heated lithium-chloride dewpoint sensor. The sensor temperature, measured with a thermistor, is recorded continually on a separate 30-day RUSTRAK strip chart scaled from -5° to 20°C and with an accuracy and a resolution of 1°C.

WINDSPEED

A cup-type anemometer provides a contact closure for every 0.322 km of air movement. This signal is recorded by an event marker along the border of the same RUSTRAK strip chart used to record dewpoint temperatures. All the RUSTRAK strip charts are housed as an integral unit within the shelter at the primary meteorological station.

PRECIPITATION

Precipitation is recorded continuously by a universal weighing-type rain gage located 0.2 km from the meteorological station. This is the location of the U.S. Forest Service meteorological station still maintained by that agency.

The gages are serviced weekly and more frequently during storm periods. Periodic calibrations are made by weighing the precipitation caught in the 60-cm capacity storage gage. Oil is added to prevent evaporation during the warm seasons and ethylene glycol to prevent freezing during the winter. Daily precipitation recorded on the gage is keypunched onto data summary sheets.

Data Processing and Summarizing

The strip charts are collected at 30-day intervals and forwarded to Biome headquarters at Oregon State University for processing and summarizing. Hourly averages estimated from the strip charts are recorded for keypunching (fig. 4). The keypunched data are printed and checked by the senior author to assure that dewpoint temperatures never exceed air temperatures and that radiation and temperature follow normal patterns throughout the day. Extremes are checked and, if at all unusual, compared with data from secondary stations.

The decks of punched cards record hourly data except the precipitation data provided by the Forest Service, which are summarized for 24-hour periods starting at midnight. All cards are stored in the Biome data bank at the Forestry Sciences Laboratory of the U.S. Forest Service in Corvallis.

The input data for a day are contained on six sequential cards--4 hours of data per card. Each day's deck of hourly radiation, temperature, and dewpoint is analyzed by computer to yield daily averaged data. The computer program is listed in the appendix, and a flow chart is presented in figure 5.

CLIMATIC DATA
H. J. Andrews Experimental Forest
Rainfall 0.00

Year	Day	Hour	Radiation	Air temperature	Dewpoint	Windspeed
74	219	1	0	6	2	2
		2	0	5	2	3
		3	0	4	1	1
		4	0	4	1	2
		5	0	4	1	2
		6	1	5	2	0
		7	4	11	7	0
		8	7	14	10	3
		9	9	20	10	7
		10	10	23	10	7
		11	10	25	10	7
		12	10	26	11	8
		13	10	27	11	7
		14	9	27	8	5
		15	7	27	6	4
		16	1	25	6	5
		17	0	20	7	0
		18	0	16	7	1
		19	0	14	6	4
		20	0	13	6	3
		21	0	11	5	4
		22	0	9	5	3
		23	0	8	5	2
		24	0	8	5	2

Figure 4.--Example of digitized, hourly climatic data prepared for keypunching.

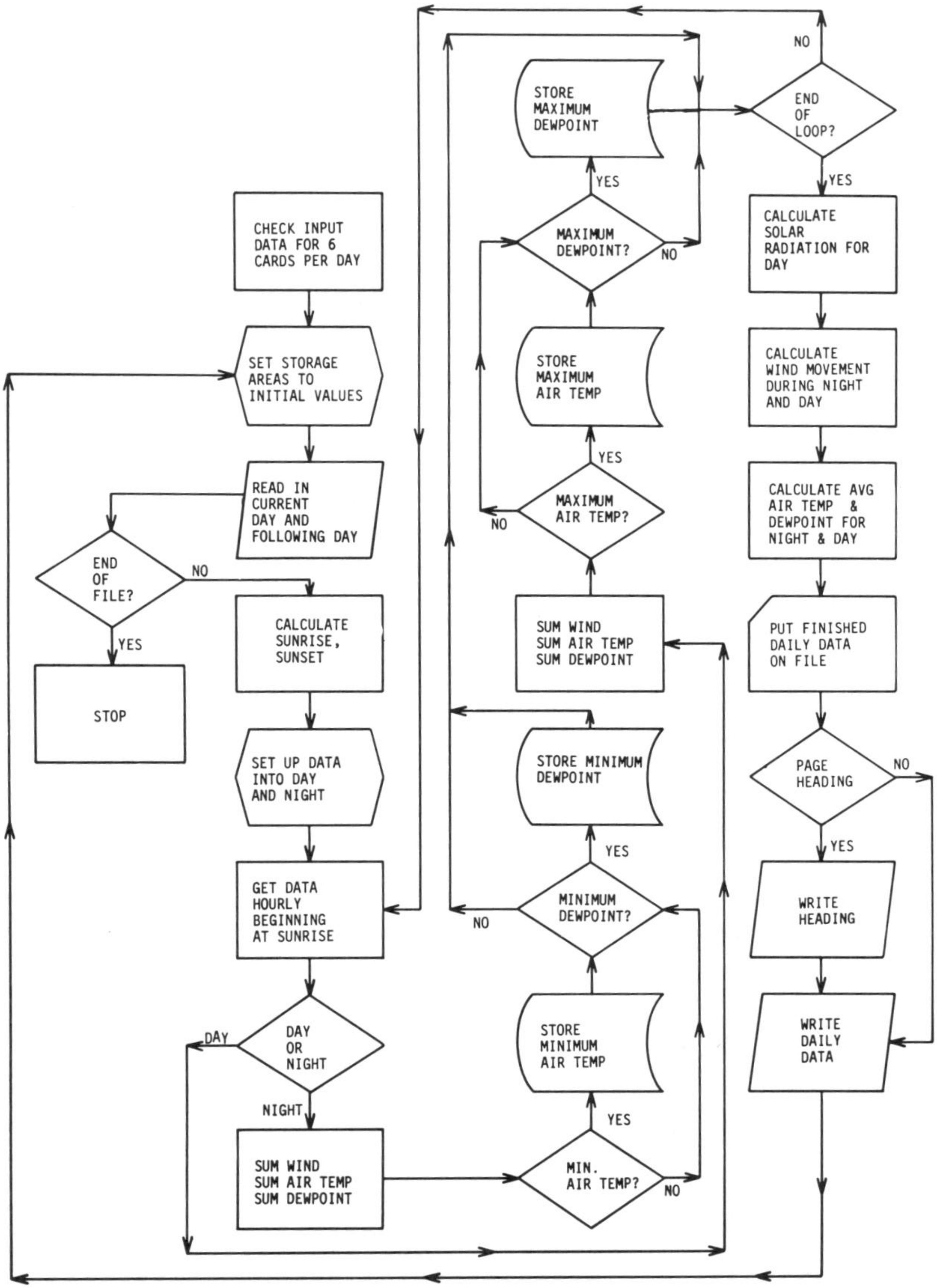

Figure 5.--Flow chart for reducing hourly data to daily summary.

Sunrise, sunset, and day length are calculated from sinusoidal functions listed in the program.

The computer program next separates the hourly data into diurnal and nocturnal segments, beginning with sunrise on the first Julian day and ending with sunrise the next day (table 3). During the two periods, the values for air temperature, dewpoint, and wind movement are summed for each hour in the respective period. The computer program keeps track of the maximum air and dewpoint temperatures during the day and of the minimum values during the night.

Air and dewpoint temperatures for each daytime or nighttime period are averaged by dividing the summed values by the number of hours in the period. Wind movement is summed for the period but not averaged. Solar radiation is also summed for the daylight hours.

The computer program compiles a file for a card-punched output and a

Table 3--*Calendar and Julian dates as used in data analysis*[1/]

Day of month	Jan. 1	Feb. 1	Mar. 3	Apr. 4	May 5	June 6	July 7	Aug. 8	Sept. 9	Oct. 10	Nov. 11	Dec. 12
1	1	32	60	91	121	152	182	213	244	274	305	335
2	2	33	61	92	122	153	183	214	245	275	306	336
3	3	34	62	93	123	154	184	215	246	276	307	337
4	4	35	63	94	124	155	185	216	247	277	308	338
5	5	36	64	95	125	156	186	217	248	278	309	339
6	6	37	65	96	126	157	187	218	249	279	310	340
7	7	38	66	97	127	158	188	219	250	280	311	341
8	8	39	67	98	128	159	189	220	251	281	312	342
9	9	40	68	99	129	160	190	221	252	282	313	343
10	10	41	69	100	130	161	191	222	253	283	314	344
11	11	42	70	101	131	162	192	223	254	284	315	345
12	12	43	71	102	132	163	193	224	255	285	316	346
13	13	44	72	103	133	164	194	225	256	286	317	347
14	14	45	73	104	134	165	195	226	257	287	318	348
15	15	46	74	105	135	166	196	227	258	288	319	349
16	16	47	75	106	136	167	197	228	259	289	320	350
17	17	48	76	107	137	168	198	229	260	290	321	351
18	18	49	77	108	138	169	199	230	261	291	322	352
19	19	50	78	109	139	170	200	231	262	292	323	353
20	20	51	79	110	140	171	201	232	263	293	324	354
21	21	52	80	111	141	172	202	233	264	294	325	355
22	22	53	81	112	142	173	203	234	265	295	326	356
23	23	54	82	113	143	174	204	235	266	296	327	357
24	24	55	83	114	144	175	205	236	267	297	328	358
25	25	56	84	115	145	176	206	237	268	298	329	359
26	26	57	85	116	146	177	207	238	269	299	330	360
27	27	58	86	117	147	178	208	239	270	300	331	361
28	28	59	87	118	148	179	209	240	271	301	332	362
29	29	60	88	119	149	180	210	241	272	302	333	363
30	30		89	120	150	181	211	242	273	303	334	364
31	31		90		151		212	243		304		365

[1/] For leap year, add 1 day to totals for days Mar. through Dec.

line printer file, then obtains more hourly data. The program will continue to process data until an end of file statement appears on the input file.

Daily Tabulation of Data

After hourly data are processed as daily summaries, the daily precipitation values are keypunched on cards, and the output is listed (table 4).

Table 4--*Example of daily climatic data summary*[1/][2/]

ID	YR JD	SOL RAD	AVG DAY TEMP	MAX DAY TEMP	AVG NGT TEMP	MIN NGT TEMP	AVG DAY DP	MAX DAY DP	AVG NGT DP	MIN NGT DP	WIND MOVEMENT DAY	WIND MOVEMENT NGT	DAY HRS	PRECIP
M07D	75306	131.9	10.7	12.0	11.4	10.0	3.7	6.0	3.6	3.0	1.6	2.3	10	1.30
M07D	75307	77.9	14.9	18.0	6.1	3.0	8.0	10.0	5.3	3.0	2.9	5.8	10	0.00
M07D	75308	209.9	12.9	19.0	6.6	4.0	9.1	13.0	1.9	0.0	3.5	4.8	10	0.00
M07D	75309	180.0	7.7	9.0	3.5	3.0	5.4	9.0	2.1	1.0	8.4	4.5	10	.56
M07D	75310	65.9	4.0	5.0	3.9	1.0	4.0	5.0	4.0	1.0	5.2	5.8	10	4.09
M07D	75311	30.0	4.9	6.0	1.9	1.0	4.9	6.0	1.9	1.0	2.9	3.2	10	1.72
M07D	75312	65.9	2.3	3.0	1.0	1.0	2.3	3.0	1.0	1.0	6.4	1.6	10	.96
M07D	75313	77.9	2.8	4.0	1.1	0.0	2.8	4.0	1.1	0.0	2.3	10.9	10	.56
M07D	75314	83.9	1.8	4.0	.9	0.0	1.8	4.0	.9	0.0	6.4	1.6	10	2.87
M07D	75315	71.9	3.3	5.0	-.6	-3.0	-1.5	0.0	-3.0	-3.0	3.9	7.1	10	.36
M07D	75316	173.9	2.4	7.0	-.9	-3.0	.8	3.0	-3.4	-6.0	4.5	6.8	10	
M07D	75317	155.9	3.6	10.0	2.1	0.0	-.6	4.0	-4.0	-5.0	3.5	6.8	10	
M07D	75318	119.9	6.5	8.0	7.2	6.0	6.5	8.0	7.2	6.0	2.9	8.1	10	2.82
M07D	75319	59.9	5.6	6.0	2.5	2.0	5.6	6.0	2.5	2.0	5.2	2.9	9	3.48
M07D	75320	47.9	2.9	4.0	.3	0.0	2.9	4.0	.3	0.0	10.3	8.7	9	1.32
M07D	75321	60.0	1.6	3.0	-1.9	-3.0	1.6	3.0	-1.9	-3.0	1.9	5.5	9	.74
M07D	75322	89.9	2.1	6.0	-3.7	-5.0	-1.7	-1.0	-5.2	-6.0	4.5	7.4	9	0.00
M07D	75323	131.9	.6	6.0	-.5	-1.0	-2.0	1.0	-1.2	-2.0	4.5	6.1	9	0.00
M07D	75324	65.9	2.7	5.0	.2	-2.0	-1.9	0.0	-3.6	-4.0	1.3	5.2	9	.33
M07D	75325	53.9	3.0	9.0	-.8	-3.0	-1.0	0.0	-3.6	-5.0	4.2	6.4	9	.05
M07D	75326	107.9	2.6	5.0	2.6	2.0	2.6	4.0	2.6	2.0	2.3	3.5	9	1.40
M07D	75327	59.9	6.3	10.0	1.4	-1.0	-1.0	1.0	-.7	-1.0	1.9	5.2	9	.03
M07D	75328	77.9	3.9	6.0	5.0	5.0	2.6	6.0	-2.2	-4.0	2.6	2.3	9	.20
M07D	75329	36.0	6.0	7.0	5.4	5.0	1.1	2.0	3.5	1.0	99.0	99.0	9	.10
M07D	75330	83.9	5.4	6.0	3.3	2.0	5.4	6.0	2.2	2.0	99.0	99.0	9	4.62
M07D	75331	47.9	3.4	4.0	0.0	-1.0	2.6	4.0	-.3	-1.0	99.0	99.0	9	.86

1/ ID is the data set identification code; YR JD are the last two digits of the year followed by the Julian day number; solar radiation is in units of calories per square centimeter per day; temperatures are in degree Celsius; DP is dewpoint; wind movement is in kilometers; DAY HRS is day length in hours; precipitation is in centimeters; 99.0 indicates missing data as listed on the last 4 days under wind movement.

2/ Complete data sets are available from Richard H. Waring, School of Forestry, Oregon State University, Corvallis, Oregon 97331, for $1.50 per year, upon request.

Editing of Data

Averages and totals for each day are essential when daily water, energy, and mineral transfer through forest ecosystems are estimated. To meet these requirements, the senior author edited the original daily summaries and flagged missing or suspicious data. In the editing procedures, radiation on apparently clear days without recorded precipitation was compared with previously compiled observed values (fig. 6). Radiation values more than 10 percent above or below the predicted values led to closer inspection of the preceding 30 to 50 days of data. Sometimes the radiometer output progressively decreased, probably the result of water shorting out the sensor. In such cases, a systematic reduction below the expected value (fig. 6) resulted in a correction applied to compensate for the decrease. Usually such corrections were less than 10 percent of the observed radiation in any given month.

In 1975 a more rugged radiometer with a lower output signal was installed, and a constant 75 langleys per day had to be added on clear days to correct for radiation below recordable levels at dawn and dusk periods. At other times when the radiometer became inoperative, correlations with temperature and precipitation patterns in the same month in previous years were used to estimate the missing values. Such periods are identified in table 2.

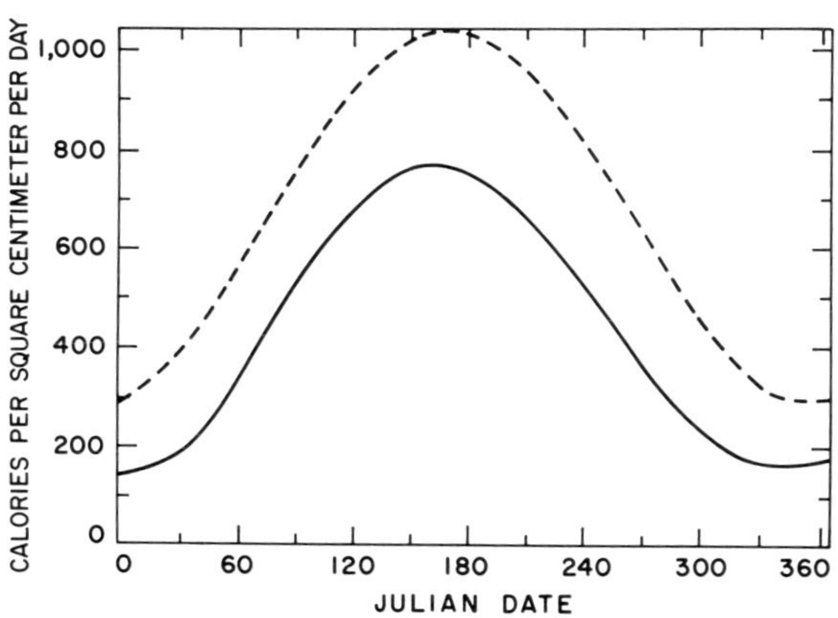

Figure 6.--Yearly variation in potential short-wave radiation reaching the earth's atmosphere (dotted line) and the maximum radiation reaching the earth's surface at 45°N. latitude (solid line).

Dewpoint was most difficult to measure accurately and continuously; as shown by the large amount of missing data (table 2). The importance of dewpoint data increases as evaporation and radiation increase, and fortunately, this corresponds with the dry season when instrument operation normally is satisfactory.

Only rarely did the air temperature recorder fail to operate. In these instances, a nearby thermograph provided data that agreed within 1°C. Periods when missing data were supplied from this source are also identified in table 2.

On the hourly summaries prepared before keypunching, the senior author assured that dewpoint temperatures never exceeded air temperatures. Because chart readings may err by 1°C, rainy days occasionally had dewpoint values listed a degree or so above air temperature. When that happened, they were made to equal air temperature.

Fortunately, failure of the dewpoint sensor generally occurs during cold wet weather when the air is nearly saturated with water vapor and the dewpoint and air temperatures are nearly equal anyway. The importance of this fact can be illustrated by comparing the evaporative demand in winter with evaporative demand in summer. To facilitate comparison, figure 7 illustrates the relationship between temperature and the water-holding capacity of air. To calculate the average evaporative demand, first determine the average day temperature and then read from the graph the corresponding vapor pressure: 760 mmHg = 1 013 mbar. The difference in vapor pressure at air temperature and at dewpoint indicates the evaporative demand.

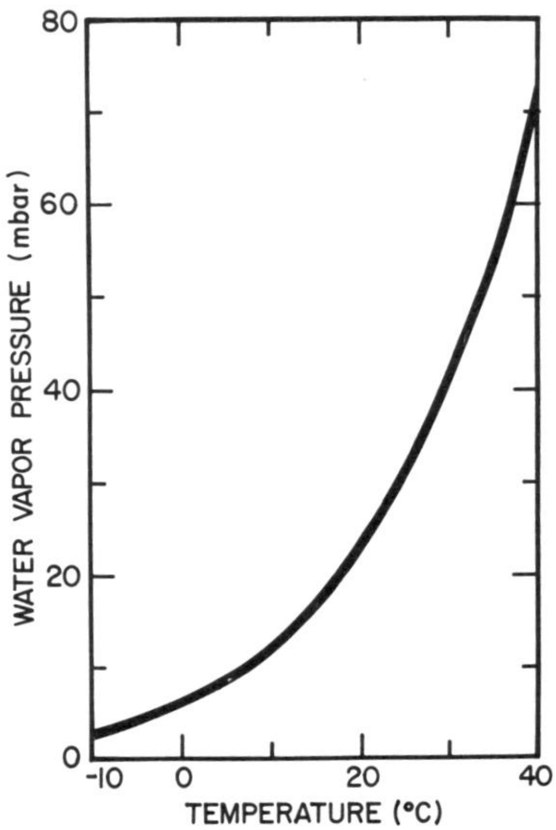

Figure 7.--Saturated vapor pressure (mbar) of water in relation to air temperature where vapor pressure = $6.1078 \exp\left(\frac{17.269T}{237 + T}\right)$.

On an unusual winter day (March 75073), the air temperature averaged 12°C and the dewpoint -1.5°C. Figure 7 shows that, if saturated, the water vapor concentration of air at 12°C would be 12.3 mbar. The amount actually in the air is equivalent to the saturation value at the dewpoint temperature, or only 5.5 mbar. The evaporative demand under these rather rare winter conditions is 6.8 mbar. Usually the demand in winter averages less than 2 mbar.

To fill in missing dewpoint temperature data during the dry season, we tried to define correlations between the night temperatures, which cooled the air and presumably condensed water vapor, and daytime dewpoint temperatures which might reflect the extent of cooling the previous night. Selecting days from April through September that were not preceded by rainfall for at least 5 days, we found general agreement between the average night temperature and the average-day dewpoint temperature (fig. 8). This relationship did not hold during extremely hot days in August when the night temperature did not approach dewpoint. Fortunately, the instrument did not fail in these periods. Most of the missing dewpoint data were estimated by assuming that average night temperature corresponds to average-day dewpoint temperature, unless precipitation occurs. Under the latter condition, more than 0.5 cm of precipitation was assumed to correspond to a saturated atmosphere, and dewpoint temperature was assumed to correspond with air temperature. With less precipitation, dewpoint temperature was estimated at an intermediate value above the average night temperature and below the average-day temperature.

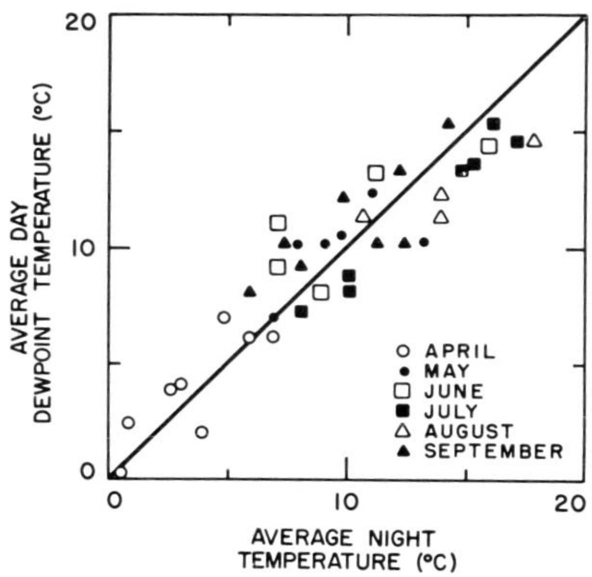

Figure 8.--Relationship between average night temperature and average daily dewpoint temperature. Data were selected for days that followed a 5-day period without precipitation.

English Equivalents

1 hectare = 2.47 acres
1 meter = 3.27 feet
1 kilometer = 0.625 mile

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Appendix

```
      PROGRAM M07DPRG(TAPE3,TAPE4,TAPE6,OUTPUT,TAPE61=OUTPUT)
C
C*********************************************************************
C****************** PROGRAMMER - RAY BUEB ***************************
C****************** DATE 5/25/75  CDC CYBER  KRONOS 2.1  FORTRAN EXT. 4.3
C****************** REVISED 8/1/75 ***********************************
C*********************************************************************
C
C*********************************************************************
C****************** DESCRIPTION **************************************
C*********************************************************************
C
C       PROGRAM TO CONVERT BCD CARD IMAGE M07H(HOURLY) DATA TO BCD CARD IMAGE
C       M07D(DAILY) DATA.  READ 6 CARDS WITH 4 HRS. DATA ON EACH CARD.
C       YOUR HOURLY INPUT DATA MUST CONTAIN SIX CARDS FOR EACH JULIAN DAY.
C       EACH CARD CONTAINS SOLAR RADIATION, AIR TEMPERATURE, DEW POINT
C       TEMPERATURE, AND WIND MOVEMENT, FOR EACH HOUR IN THE FOLLOWING
C       FORMAT:
C
C     CARD      HOURS
C
C       1         1-4
C       2         5-8
C       3         9-12
C       4        13-16
C       5        17-20
C       6        21-24
C
C  COLUMN     VARIABLE                                                  FORMAT
C
C  1- 4        IDENTIFIER OF DATASET                                    A4
C  5- 6        SEQUENCE NUMBER PERTAINING TO CARD POSITION (1-6)        I2
C  7- 9        YEAR OF DATA COLLECTION                                  I3
C 10-13        JULIAN DAY                                               I4
C 14-16        SOLAR RADIATION     * HOURS                              F3.1
C 17-20        AIR TEMPERATURE     * 1,5,9,13,17,21                     F4.0
C 21-24        DEW PT TEMPERATURE *                                     F4.0
C 25-29        WIND MOVEMENT       *                                    F5.0
C 30-32        SOLAR RADIATION             * HOURS                      F3.1
C 33-36        AIR TEMPERATURE             * 2,6,10,14,18,22            F4.0
C 37-40        DEW PT TEMPERATURE          *                            F4.0
C 41-45        WIND MOVEMENT               *                            F5.0
C 46-48        SOLAR RADIATION                     * HOURS              F3.1
C 49-52        AIR TEMPERATURE                     * 3,7,11,15,19,23    F4.0
C 53-56        DEW PT TEMPERATURE                  *                    F4.0
C 57-61        WIND MOVEMENT                       *                    F5.0
C 62-64        SOLAR RADIATION                             * HOURS      F3.1
C 65-68        AIR TEMPERATURE                             * 4,8,12,16,20,24  F4.0
C 69-72        DEW PT TEMPERATURE                          *            F4.0
C 73-77        WIND MOVEMENT                               *            F5.0
C
C
C*******************************************************************
C****************** INPUT, OUTPUT UNITS ****************************
C*******************************************************************
C
C       TAPE3= M07H. MUST HAVE 6 CARDS FOR EVERY JULIAN DAY (ERRORS WIL
C              DETECTED BY PROGRAM). IF YOU HAVE A COMPLETE YEARS DATA
C              MUST HAVE THE FIRST DAY OF THE NEXT YEAR AFTER THE LAST
C              ORDER TO GET DAILY AVERAGES FOR THE LAST DAY.
C       TAPE4= LINE PRINTER OUTPUT OF DAILY AVERAGES
C       TAPE6= CARD IMAGE M07D DATA (DAILY AVERAGES) TO BE PUNCHED
C       TAPE61= ERROR MESSAGES
```

```
C
C*********************************************************************
C***************** VARIABLES ****************************************
C*********************************************************************
C
C      A        IDENTIFIER FOR DATA SET M07D (DAILY AVERAGES OF M07H)
C      AT       AIR TEMPERATURE FROM TAPE3
C      DAY      ARRAY CONTAINING SUNRISE (OF CURRENT JD), DAYLENGTH (OF CU
C               CURRENT JD),SUNSET (OF CURRENT JD), AND SUNRISE (OF NEXT JD)
C      DP       DEW POINT FROM TAPE3
C      ICOUNT   NUMBER OF LINES OF PRINT PER PAGE
C      XID      COUNTER FOR NUMBER OF RECORDINGS OF SOLAR RADIATION
C      IDAY     INTEGER COUNTERPART OF VARIABLE DAY
C      IERRC    COUNTER OF ERRORS FOR TAPE3 IF NOT 6 CARDS PER DAY
C      ILOOP    TOTAL DAY LENGTH FOR DAILY AVERAGED DAY
C      IY       DAILY AVERAGED SOLAR RADIATION
C      IQ,IE    COUNTERS USED TO READ IN HOURLY DATA
C      ISEQ     SEQUENCE CHECK FOR 6 CARDS PER DAY
C      IYEAR    YEAR
C      JULCK    DAY SEQUENCING CHECK VARIABLE
C      JULDAY1  JULIAN DAY INDICATORS USED TO CHECK FOR MORE OR LESS THAN
C      JULDAY2     6 CARDS READ IN ON INPUT FILE TAPE3
C      JD       JULIAN DAY FROM INPUT FILE TAPE3
C      NA       COUNTER USED TO REORDER INPUT DATA INTO DAY AND NIGHT
C      NLGTH    NIGHT LENGTH FOR DAILY AVERAGED DAY
C      SOLAR    ERROR CHARACTER (/) FOR SOLAR RADIATION < 50 AND > 990
C      SR       SOLAR RADIATION FROM TAPE3
C      SSR      SUM OF SOLAR RADIATION
C      SWSD     SUM OF WIND MOVEMENT DURING THE DAY
C      SWSN     SUM OF WIND MOVEMENT DURING THE NIGHT
C      SNAT     SUM OF NIGHTIME AIR TEMP + AVG. NGT TEMP
C      SNDP     SUM OF NIGHTIME DEW POINT TEMP + AVG. NGT DEW TEMP
C      SDAT     SUM OF DAYTIME AIR TEMP + AVG. DAY TEMP
C      SDDP     SUM OF DAYTIME DEW POINT TEMP + AVG. DAY DEW TEMP
C      WS       WIND MOVEMENT FROM TAPE3
C      XDAT     MAX DAYTIME AIR TEMP
C      XDDP     MAX DAYTIME DEW POINT TEMP
C      XNAT     MIN NIGHTIME AIR TEMP
C      XNDP     MIN NIGHTIME DEW POINT TEMP
C      XAT      STORAGE ARRAY FOR AIR TEMPERATURE DIVIDED INTO NIGHT AND DAY
C      XDP      STORAGE ARRAY FOR DEW POINT TEMP  DIVIDED INTO NIGHT AND DAY
C      XSR      STORAGE ARRAY FOR SOLAR RADIATION DIVIDED INTO NIGHT AND DAY
C      XWS      STORAGE ARRAY FOR WIND MOVEMENT   DIVIDED INTO NIGHT AND DAY
C      Z        REAL FORMAT OF IY
C
      DIMENSION SR(2,24),AT(2,24),DP(2,24),WS(2,24),JD(2),DAY(4),IDAY(4)
     1  ,XSR(30),XAT(30),XWS(30),XDP(30)
      DATA (SOLAR=10H         /    )
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C         CHECK FOR 6 CARDS PER DAY IN ASCENDING SEQUENCING ORDER 1-6
C           AND THAT DAYS ARE CONSECUTIVE. CHECK FOR EACH HOUR, AIR TEMP >
C           DEW TEMP.
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
      READ(3,201) ISEQ,IYEAR,JULCK
      BACKSPACE 3
      JULCK=JULCK-1
      IERRC=0
  205 DO 200 J=1,6
      IF(J.NE.1) GO TO 202
      READ(3,201) ISEQ,IYEAR,JULDAY1,(XAT(N),XDP(N),N=1,4)
  201 FORMAT(4X,I2,I3,1X,I3,4(3X,2F4.0,5X))
      IF(EOF(3)) 250,209
  202 READ(3,201) ISEQ,IYEAR,JULDAY2,(XAT(N),XDP(N),N=1,4)
```

```
      IF(EOF(3)) 240,203
  240 WRITE(61,241)
  241 FORMAT(≠ CAN NOT HAVE LESS THAN 6 CARDS ON LAST DAY≠)
      STOP ≠PROBLEM WITH INPUT≠
  203 CALL ERRCK(XAT,XDP,IERRC,IYEAR,JULDAY2,ISEQ)
      IF(ISEQ.NE.J) WRITE(61,210) IYEAR,JULDAY1
      IF(ISEQ.NE.J) IERRC=IERRC+1
      IF(JULDAY1.EQ.JULDAY2) GO TO 200
      WRITE(61,204) IYEAR,JULDAY1,JULDAY2
  204 FORMAT(≠ PROBLEM ON INPUT FILE TAPE3 BETWEEN YEAR≠,I3,≠ JULIAN
     *DAYS≠,I4,≠ AND≠,I4)
      GO TO 206
  209 CALL ERRCK(XAT,XDP,IERRC,IYEAR,JULDAY1,ISEQ)
      IF(JULDAY1.EQ.366) GO TO 211
      IF(JULCK.GE.365) JULCK=0
  211 IF((JULCK+1).EQ.JULDAY1) GO TO 213
      WRITE(61,212) IYEAR,JULCK,JULDAY1
  212 FORMAT(≠ DAY MISSING BETWEEN YEAR≠,I3,≠ JULIAN DAYS≠,I4,≠ AND≠,I4)
      IERRC=IERRC+1
  213 IF(ISEQ.EQ.J) GO TO 200
      WRITE(61,210) IYEAR,JULDAY1
  210 FORMAT(≠ CARDS OUT OF SEQUENCE YEAR≠,I3,≠ JULIAN DAY ≠,I3)
      IERRC=IERRC+1
  200 CONTINUE
      JULCK=JULDAY1
      GO TO 205
  206 IERRC=IERRC+1
      BACKSPACE 3
      JULCK=JULDAY1
      GO TO 205
  250 IF(IERRC.NE.0) STOP ≠PROBLEM WITH INPUT≠
      REWIND 3
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C         SET INITIAL INDICATORS + ARRAYS
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
      ICOUNT=28
      A=4HM07D
    1 XID=0.
      ERRORS=10H
      XDAT=XDDP=XNAT=XNDP=SWSD=SSR=SNAT=SNDP=SDAT=SDDP=SWSN=0
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C         READ IN CURRENT DAY AND FOLLOWING DAY
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
      DO 155 IOI=1,2
      IQ=1
      IE=4
      DO 15 M=1,6
      READ (3,10)  IYEAR,JD(IOI),(SR(IOI,I),AT(IOI,I),DP(IOI,I),WS(IOI,I
     1  ),I=IQ,IE)
   10 FORMAT (6X,I3,X,I3,4(F3.1,2F4.0,F5.0))
      IF (EOF(3)) 30,31
   31 IQ=IQ+4
   15 IE=IE+4
  155 CONTINUE
      DO 989 J=1,6
  989 BACKSPACE 3
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C         CALCULATE SUNRISE, DAYLENGTH, AND SUNSET OF CURRENT JD AN
C           SUNRISE OF THE NEXT JD
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
      K = JD(1) - 86
      IF (K .LT. 0) K = K + 365
      DAY(1) = 6.06666 - 1.675*SIN(K*.017214)
```

```
      K = K + JD(2) - JD(1)
      DAY(4) = 6.06666 - 1.675*SIN(K*.017214)
      K = JD(1) - 81
      IF (K .LT. 0) K = K + 365
      DAY(2) = 12.23333 + 3.35*SIN(K*.017214)
      DO 6 K = 1,4
      IF(K.EQ.3) GO TO 6
      IDAY(K)=IFIX(DAY(K))
      X=(DAY(K)-FLOAT(IDAY(K)))*60.
      IF (X .GE. 30.) IDAY(K) = IDAY(K) + 1
      IF (K.NE.2) IDAY(K)=IDAY(K)+1
    6 CONTINUE
C**** ONE DAY IS ADDED TO SUNRISE CALCULATIONS BECAUSE OF
C**** METHOD OF DATA COLLECTION.
      IDAY(3) = IDAY(1) + IDAY(2)
      NLGTH=24-IDAY(3)+IDAY(4)
      ILOOP=NLGTH+IDAY(2)
      NA=IDAY(1)
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C        PUT INPUT DATA INTO DAY AND NIGHT OF CURRENT JULIAN DAY
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
      DO 818 J=1,30
  818 XAT(J)=XDP(J)=XWS(J)=XSR(J)=0
      DO 919 J=1,1000
      XAT(J)=AT(1,NA)
      XDP(J)=DP(1,NA)
      XSR(J)=SR(1,NA)
      XWS(J)=WS(1,NA)
      IF(NA.EQ.24) GO TO 918
  919 NA=NA+1
  918 K=IDAY(4)-1
      DO 917 NA=1,K
      J=J+1
      XAT(J)=AT(2,NA)
      XSR(J)=SR(2,NA)
      XWS(J)=WS(2,NA)
  917 XDP(J)=DP(2,NA)
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C        PROCESS 24 HOURS OF XSR, XAT, XDP, XWS TO GET DAILY AVERAGES
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
      DO 3 J=1,ILOOP
      IF(J.LE.IDAY(2)) GO TO 4
C
C              NIGHTTIME
C
      SWSN=SWSN+XWS(J)
      SNAT=SNAT+XAT(J)
      SNDP=SNDP+XDP(J)
      IF(J.GT.IDAY(2)+1) GO TO 5
      XNAT=XAT(J)
      XNDP=XDP(J)
      GO TO 3
    5 IF (XAT(J) .GE. XNAT) GO TO 8
      XNAT=XAT(J)
    8 IF (XDP(J) .GE. XNDP)  GO TO 3
      XNDP=XDP(J)
      GO TO 3
C
C              DAYTIME
C
    4 SWSD=SWSD+XWS(J)
      IF(XSR(J).LE.0) GO TO 60
      XID=XID+1.
```

```
      SSR=SSR+XSR(J)
      SSR=SSR+XSR(J)
   60 SDAT=SDAT+XAT(J)
      SDDP=SDDP+XDP(J)
      IF(J.GT.1) GO TO 11
      XDAT=XAT(J)
      XDDP=XDP(J)
      GO TO 3
   11 IF (XAT(J) .LE. XDAT) GO TO 13
      XDAT=XAT(J)
   13 IF (XDP(J) .LE. XDDP) GO TO 3
      XDDP=XDP(J)
    3 CONTINUE
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C         MAKE NEW DATA FILE M07D
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
       IF(XID.GT.0.) GO TO 75
      IY=0
      SSR=0.
      GO TO 76
   75 SSR=(SSR/XID)*(XID*60.)
      IY=IFIX(SSR*10.+.05)
   76 IF(SSR.LE.990.) GO TO 77
      SSR=990.
      IY=9900
   77 SWSD=.322*SWSD
      SWSN=.322*SWSN
      IF(SWSD.GE.99.) SWSD=99.
      IF(SWSN.GE.99.) SWSN=99.
      SDAT=SDAT/IDAY(2)
      SDDP=SDDP/IDAY(2)
      SNAT=SNAT/NLGTH
      SNDP=SNDP/NLGTH
C           CHECK ERRORS FOR RADIATION
      IF(SSR.GE.800..OR.SSR.LE.50.) ERRCRS=ERRORS.AND.SOLAR
      WRITE(6,70) A,IYEAR,JD(1),IY,SDAT,XDAT,SNAT,XNAT,SDDP,XDDP,SNDP,XN
     *DP,SWSD,SWSN,IDAY(2)
   70 FORMAT(A4,2I3,I5,10F5.1,I3)
C          IS HEADING NECESSARY
      IF (ICOUNT.LE.27) GO TO 80
      WRITE (4,20)
   20 FORMAT(≠1≠,//,17X,2(2X,≠AVG   MAX   AVG   MIN≠),6X,≠WIND≠,/,14X,
     *≠SOL≠,2(2X,≠DAY   DAY   NGT   NGT≠),≠   MOVEMENT DAY≠,/,
     *≠    ID YR JD    RAD≠,4(≠ TEMP≠),4(≠   DP≠),≠   DAY   NGT HRS≠)
      ICOUNT=0
   80 WRITE (4,16) A,IYEAR,JD(1),SSR,SDAT,XDAT,SNAT,XNAT,SDDP,XDDP,SNDP,
     1XNDP,SWSD,SWSN,IDAY(2),ERRORS
   16 FORMAT(≠0≠,A4,2I3,F6.1,10F5.1,I3,A10)
      ICOUNT=ICOUNT+1
      GO TO 1
   30 STOP ≠END OF RUN≠
      END
      SUBROUTINE ERRCK(XAT,XDP,IERRC,IYEAR,JULDAY,ISEQ)
C
C  CHECK TO SEE IF AIR TEMP, (XAT) IS > DEW TEMP (XDP) FOR
C  HOURS PASSED.
C
      DIMENSION XAT(30),XDP(30)
      DO 1 J=1,4
      IF(XAT(J).GE.XDP(J)) GO TO 1
      IERRC=IERRC+1
      IHOUR=(ISEQ-1)*4+J
      WRITE(61,2) IYEAR,JULDAY,IHOUR
```

```
2 FORMAT(≠ FOR YEAR≠,I3,≠ JULIAN DAY≠,I4,≠ HOUR≠,I3,≠ AIR TEMP≠,
 1≠ < DEW TEMP≠)
1 CONTINUE
  RETURN
  END
```

```
01.18.59.UCLP, 23,       0.352KLNS.
```

GPO 986-969