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Estimating Monthly Means of Daily Totals of Direct Normal Solar Radiation and of Total Solar Radiation on a South-Facing, 45°, Tilted Surface

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Estimating Monthly Means of Daily Totals of Direct Normal Solar Radiation and of Total Solar Radiation on a South Facing, 45°, Tilted Surface

E. C. Boes and I. J. Hall

Abstract

Direct Normal, DN, radiation data is presently available for only a few sites in the country while total horizontal, TH, radiation is available for many locations. If a mathematical function relating DN and TH were established, solar engineers could estimate DN for any site for which TH data is available. Total radiated energy on a tilted surface, TT, is also of interest to solar engineers. A recently completed report [2] includes TT values for a surface tilted at 45° for 26 sites. A function relating TT and TH would permit one to estimate TT for sites where only TH data is available. This paper gives empirically derived functions relating DN and TH and TT and TH.

* This work sponsored by U.S. ERDA.

Introduction

Reference [1] contains tables which give mean monthly values of DN (Direct Normal) and TH (Total Horizontal) radiation in $kW \cdot h/m^2$·Per day for 26 weather stations. The DN values were generated from total-horizontal radiation data using an empirically derived formula based on hourly data. In Section III, of [1] the idea of trying to establish an empirical relationship with a simple adjustment for latitude between the mean daily totals of DN and TH is discussed. Such a relationship would permit one to estimate the mean daily totals of DN for all those additional sites which have only daily TH data available. In this report another model is developed and applied to predict DN from TH. The model involves adjusting TH by the average monthly zenith angle.

Solar engineers are often interested in estimating the radiant energy on a tilted surface. Presently good data for making such estimates do not exist. In a recently completed report [2] estimates of TT(t) - Total radiation on a flat surface at a tilt angle of t - were obtained. Mean daily totals of TT(t) for each month for each of the 26 weather stations mentioned above were calculated. A function relating TT(t) and TH would permit one to estimate TT(t) for sites where only TH data is available. In the second part of this report we give the results of fitting a function of TH to the TT(t) (with $t = 45°$) data.

Model for DN versus TH

The DN-TH data is listed in Table 1; this table also lists the total number of days, N, used in computing these mean daily DN and TH values. Figures 1 and 2 are scatter plots of the January and July data. Examination of the data indicated that a substantial amount of the scatter in DN about a straight line could be explained by latitude and time of the year. In an

TABLE 1

MEAN DAILY TOTALS OF DIRECT-NORMAL
AND TOTAL-HORIZONTAL RADIATION FOR JANUARY - JUNE

	Jan			Feb			March			April			May			June		
	DN	TH	N	DN	TH	N	DN	TH	N	DN	TH	N	DN	TH	N	DN	TH	N
Albuquerque	6.6	3.6	152	6.9	4.5	139	7.8	5.9	155	8.9	7.3	148	9.9	8.3	155	10.0	8.6	150
Appalachicola	4.7	3.3	142	5.2	4.2	139	5.5	4.9	155	6.6	6.2	150	7.1	6.9	155	6.9	6.8	140
Bismark	4.3	1.8	153	5.4	2.9	141	5.9	4.0	155	7.1	5.4	150	7.3	6.3	155	8.8	7.1	150
Blue Hill	3.6	1.9	134	3.9	2.6	141	4.8	3.8	150	4.9	4.5	113	5.7	5.6	155	5.6	5.7	146
Boston	3.2	1.8	155	3.6	2.5	141	4.8	3.8	149	4.8	4.5	149	5.9	5.6	155	5.9	5.9	150
Brownsville	3.3	2.9	155	4.0	3.7	141	3.9	4.3	155	4.8	5.3	142	6.1	6.3	124	6.4	6.5	119
Cape Hatteras	5.0	3.1	155	5.0	3.7	141	5.9	4.9	155	7.4	6.6	150	8.4	7.6	155	7.5	7.2	135
Caribou	3.9	1.7	155	4.8	2.7	141	6.2	4.2	155	5.6	4.8	150	5.8	5.5	155	6.0	5.7	150
Charleston	3.9	2.7	155	4.3	3.4	141	4.8	4.4	155	6.5	6.0	142	6.4	6.5	155	5.7	6.1	150
Columbia	3.9	2.3	151	4.2	3.0	141	4.3	3.7	155	5.4	5.0	150	6.8	6.4	155	6.8	6.6	150
Dodge City	6.0	3.1	135	4.8	3.3	81	5.9	4.6	115	6.8	5.9	112	7.5	6.8	124	7.9	7.2	108
El Paso	6.6	3.8	155	7.5	5.0	141	8.6	6.4	155	9.6	7.8	150	10.2	8.5	155	9.8	8.5	150
Ely	5.5	2.9	155	5.4	3.6	141	7.2	5.3	155	8.5	6.9	150	8.8	7.5	155	10.1	8.4	150
Fort Worth	4.8	3.0	155	4.8	3.6	140	5.5	4.7	150	5.8	5.5	150	6.8	6.6	155	7.2	6.9	150
Great Falls	2.8	1.5	152	4.2	2.5	141	5.6	4.0	154	5.7	4.9	150	6.7	6.0	155	8.3	6.9	150
Lake Charles	3.7	2.8	155	3.6	3.2	139	4.7	4.4	155	5.2	5.4	148	6.3	6.4	153	5.9	6.1	121
Madison	4.0	2.0	121	4.9	3.1	78	5.9	4.4	88	6.1	5.3	88	6.8	6.2	91	8.0	7.3	90
Medford	1.6	1.4	155	2.6	2.3	141	4.1	3.7	155	6.0	5.5	148	6.8	6.4	155	8.7	7.6	150
Miami	5.1	3.8	151	6.4	4.9	131	5.8	5.3	155	6.6	6.4	147	6.3	6.3	154	5.8	6.1	128
Nashville	3.1	2.1	155	3.6	2.9	142	4.0	3.6	153	5.6	5.3	146	6.3	6.3	125	6.1	6.3	150
New York	2.8	1.8	124	3.3	2.5	105	4.6	3.7	96	4.6	4.5	120	4.9	5.2	124	5.6	5.9	92
Omaha	4.6	2.4	155	5.1	3.2	131	5.4	4.2	117	6.3	5.4	127	6.5	5.9	149	7.0	6.6	107
Phoenix	5.8	3.6	155	6.5	4.5	141	7.9	6.0	137	9.3	7.5	143	10.0	8.4	153	9.3	8.1	150
Santa Maria	5.3	3.2	155	5.0	3.7	141	7.1	5.6	146	8.5	7.3	116	9.1	7.9	151	9.2	8.4	150
Seattle	1.5	1.0	155	2.0	1.7	141	3.7	3.1	155	4.8	4.4	150	6.0	5.8	155	7.6	6.6	150
Washington, DC	3.8	2.2	136	4.1	2.9	140	5.0	4.2	155	5.7	5.2	150	5.6	5.7	155	6.4	6.4	150

TABLE 1

MEAN DAILY TOTALS OF DIRECT-NORMAL
AND TOTAL-HORIZONTAL SOLAR RADIATION FOR JULY - DECEMBER

	July			August			Sept			Oct			Nov			Dec		
	DN	TH	N	DN	TH	N	DN	TH	N	DN	TH	N	DN	TH	N	DN	TH	N
Albuquerque	9.2	8.1	153	9.2	7.6	127	7.9	6.2	147	7.8	5.1	153	6.6	3.8	150	6.1	3.2	155
Appalachicola	6.5	6.5	138	5.9	5.9	148	6.1	5.5	150	6.1	4.8	155	5.4	3.8	150	4.6	3.1	155
Bismark	8.7	7.0	155	8.1	6.3	146	6.7	4.6	150	5.7	3.2	155	3.9	1.9	150	3.5	1.5	155
Blue Hill	5.0	5.4	155	5.4	5.1	155	4.9	4.2	150	4.2	2.9	155	3.1	1.9	150	3.3	1.7	147
Boston	5.6	5.7	155	5.5	5.2	153	5.0	4.2	150	3.9	2.8	155	2.8	1.8	150	2.9	1.6	155
Brownsville	7.4	7.2	124	6.6	6.3	155	5.3	5.2	150	4.9	4.3	153	3.8	3.3	150	3.0	2.6	154
Cape Hatteras	8.2	7.5	137	7.1	6.5	155	7.1	5.8	132	5.7	4.2	133	4.9	3.2	150	4.5	2.7	155
Caribou	6.1	5.8	155	5.9	5.1	155	4.6	3.7	150	3.4	2.3	155	2.3	1.3	150	3.1	1.4	155
Charleston	5.4	5.9	153	5.4	5.6	154	5.2	4.9	150	5.3	4.2	146	4.3	3.1	145	4.0	2.7	153
Columbia	6.7	6.4	154	7.4	6.4	155	5.7	4.7	147	5.2	3.7	154	4.1	2.5	149	3.4	2.0	155
Dodge City	8.0	7.1	126	7.9	6.7	155	6.8	5.4	146	6.9	4.4	155	5.8	3.2	150	5.0	2.5	155
El Paso	8.7	7.8	155	8.7	7.4	155	7.7	6.2	150	7.7	5.3	155	6.4	4.0	150	6.1	3.5	155
Ely	8.8	7.6	155	8.6	7.0	155	8.4	6.1	150	7.4	4.6	155	6.0	3.2	150	5.6	2.7	150
Fort Worth	7.4	6.9	155	7.4	6.6	155	6.1	5.3	150	5.6	4.2	154	4.7	3.2	150	4.1	2.6	155
Great Falls	8.2	7.0	149	7.2	5.9	155	5.9	4.4	137	4.5	2.9	152	3.0	1.7	150	2.4	1.2	155
Lake Charles	5.6	5.8	151	5.1	5.3	152	5.0	4.9	150	4.7	4.0	154	4.0	3.1	142	3.3	2.5	155
Madison	7.8	7.0	93	7.4	6.3	93	5.8	4.5	83	4.7	3.1	93	3.4	1.9	90	3.8	1.8	93
Medford	9.8	8.1	155	8.4	6.8	155	6.6	5.1	150	4.4	3.2	153	2.4	1.8	150	1.4	1.1	155
Miami	6.0	6.3	155	5.8	5.8	155	5.2	5.1	150	5.8	4.8	155	5.2	4.0	150	5.2	3.7	155
Nashville	5.8	6.1	155	5.6	5.6	153	5.2	4.7	150	4.7	3.7	155	3.6	2.5	144	2.9	1.9	124
New York	4.7	5.3	91	4.3	4.6	116	5.3	4.5	95	4.0	3.0	93	2.6	1.8	88	2.8	1.6	91
Omaha	7.2	6.6	119	7.3	6.0	141	5.8	4.6	150	5.4	3.5	155	4.1	2.4	141	3.8	1.9	155
Phoenix	8.6	7.7	155	7.7	6.9	155	7.4	6.1	150	6.9	4.9	155	5.8	3.8	150	5.1	3.1	155
Santa Maria	8.5	7.9	155	7.9	7.0	155	7.2	6.0	147	7.0	4.9	155	5.7	3.6	150	5.1	3.0	155
Seattle	8.6	7.1	155	6.1	5.4	155	4.6	3.8	143	3.0	2.2	155	2.0	1.3	150	1.2	0.8	155
Washington, DC	5.5	5.9	155	5.5	5.4	155	5.2	4.6	150	4.7	3.5	153	3.6	2.3	150	3.6	2.0	155

Scatter Plots of DN versus TH

Figure 1

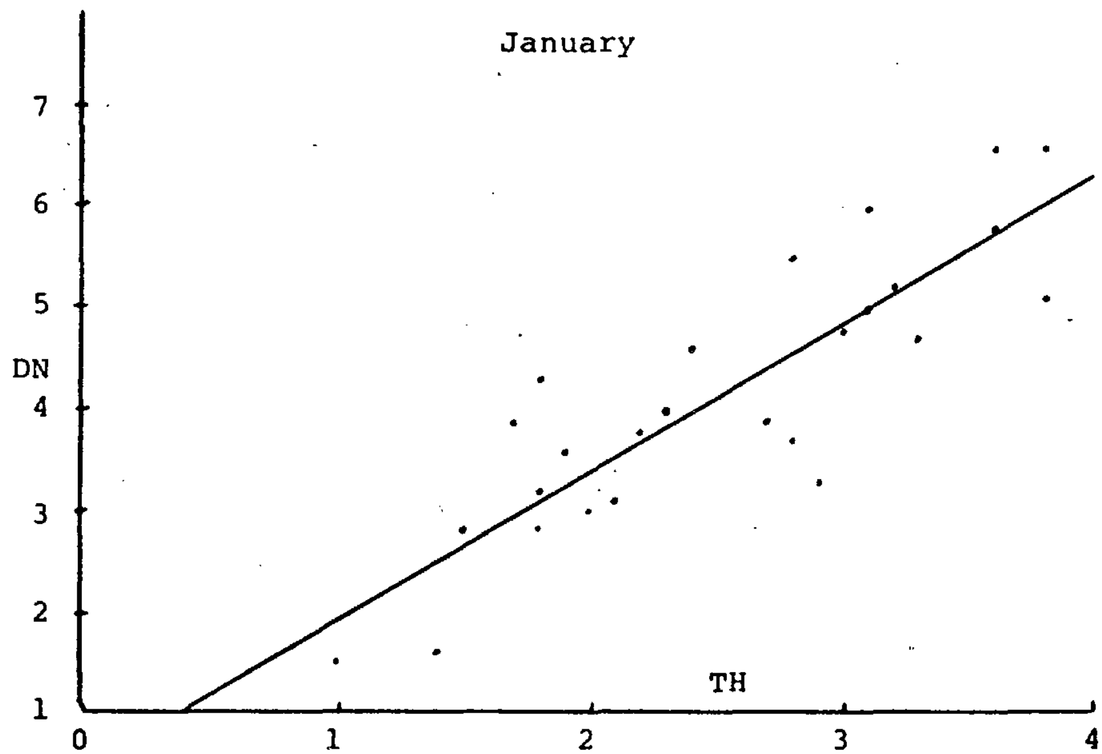

Figure 2

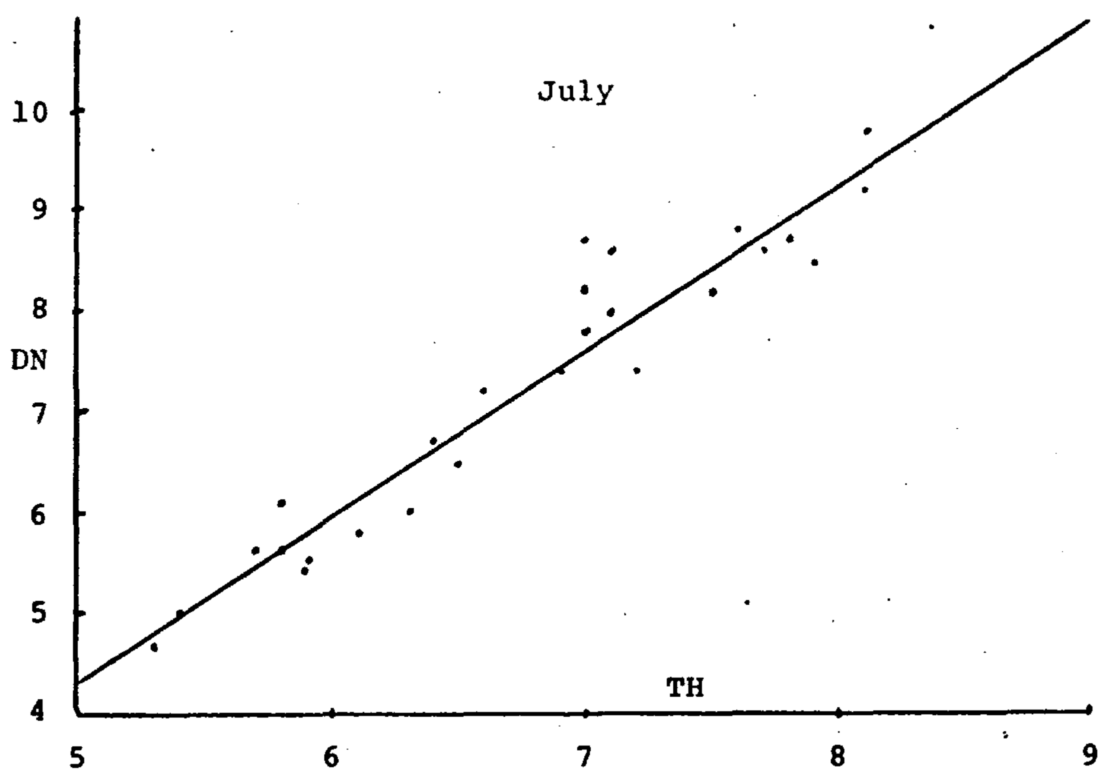

Table 2

Regression Coefficients for the Model, $\hat{DN} = a + b * TH/\cos\theta$

	a	b	R^2	s	Extreme Error	Location of Extreme Error
Jan.	-2.41	1.27	.979	.06	-17.9%	Medford
Feb.	-2.91	1.35	.983	.05	-13.7	Medford
Mar.	-3.12	1.36	.976	.06	-10.7	Medford
April	-3.49	1.40	.982	.06	- 8.0	Medford
May	-4.48	1.52	.983	.06	- 8.3	Seattle
June	-4.17	1.48	.983	.06	- 4.9	Santa Maria
July	-4.31	1.49	.984	.06	6.8	Lake Charles
Aug.	-3.87	1.46	.980	.06	- 6.6	Seattle
Sept.	-3.55	1.42	.982	.05	- 5.1	Seattle
Oct.	-3.00	1.37	.982	.06	- 9.55	Great Falls
Nov.	-2.30	1.24	.980	.06	14.4	Caribou
Dec.	-2.14	1.22	.984	.05	13.1	Seattle

R^2 = Regression sum of squares/Total Sum of Squares

error = $100(DN - \hat{DN})/DN$ where $\hat{DN}$ = predicted value from (1) and DN is data value

s = standard error

(If the intensity of TH followed a perfect sine wave through the day, the average hour angle with respect to energy would occur at SSH/3. However, possibly because of increasing air mass for larger zenith angles, we found that using a mean hour angle of SSH/4 gave a better data fit).

In addition to fitting the DN-TH/cos θ data with a straight line on a monthly basis the data were combined over months and fitted with a single line. The equation is

$$(5) \qquad \hat{DN} = -2.62 + 1.29\ TH/\cos\theta$$

$$\text{with } R^2 = .983 \qquad s = .23.$$

The extreme errors between predicted direct normal, $\hat{DN}$, and the data DN values by month are given in Table 3.

Mean daily totals by month for DN and TH for three locations - Raleigh, Livermore, and Fort Hood - have recently become available from Aerospace Research Corp. These data are given in Table 4. The DN-TH/cos θ data for these three locations are plotted in Figure 5. The data points are not as tightly clustered about a straight line as the data for the other locations. Equation (5) as well as the line obtained from the least squares fit to the data are plotted on Figure 5.

Equations (1) and (5) were used to predict DN from the TH values and the predicted values were then compared to the measured DN values. The results are given in Table 5.

Models for TT(45) versus TH

The TT(45) - TH data are listed in Table 6. The TT(45) data (total radiation on a flat surface tilted up 45° from horizontal toward south)

Table 3

Monthly Extreme Errors of $\hat{DN}$ when Single Model (Eq. (5)) is Used.

	Extreme Error	Location
Jan.	22.1%	Seattle
Feb.	-15.2	Medford
Mar.	-12.9	Medford
April	- 8.9	Medford
May	-11.4	Seattle
June	- 8.8	New York
July	-12.7	New York
Aug.	- 8.4	New York
Sept.	- 8.4	Seattle
Oct.	- 7.6	Great Falls
Nov.	20.4	Caribou
Dec.	37.3	Seattle

Table 4

Mean Daily Totals of Direct-Normal and Total-Horizontal Solar Radiation

	Raleigh				Livermore				Fort Hood			
	DN	TH	N days	H hours	DN	TH	N days	H hours	DN	TH	N days	H hou
Jan.	4.064	2.578	31	310	5.317	2.978	8	80	4.442	2.947	28	2[illegible]
Feb.	4.657	3.599	29	304	3.797	3.201	15	160	4.561	3.716	27	2[illegible]
Mar.	4.117	4.062	28	336	2.578	3.323	19	228	4.596	4.307	27	3[illegible]
April	4.340	5.056	26	334	5.370	5.769	14	186	3.957	4.994	19	2[illegible]
May	3.665	5.165	15	210	8.496	7.777	10	140	*	*	*	*
June	5.497	6.537	17	238	10.82	8.442	5	70	5.743	6.733	20	2[illegible]
July	*	*	*	*	9.522	8.001	26	364	5.567	6.545	25	3[illegible]
Aug.	6.288	6.099	5	60	7.992	6.987	14	192	5.309	6.411	23	3[illegible]
Sept.	2.574	3.831	30	360	6.582	5.363	10	120	5.499	5.459	28	3[illegible]
Oct.	4.251	3.661	31	348	4.081	3.932	9	104	5.894	4.743	22	2[illegible]
Nov.	4.081	2.739	30	300	*	*	*	*	5.752	3.642	27	2[illegible]
Dec.	3.706	2.091	27	270	*	*	*	*	4.387	2.827	26	2[illegible]

* Data not available

Figure 5

Scatter Plot of DN versus TH/cos θ
for Raleigh, Livermore, and Ft. Hood Data

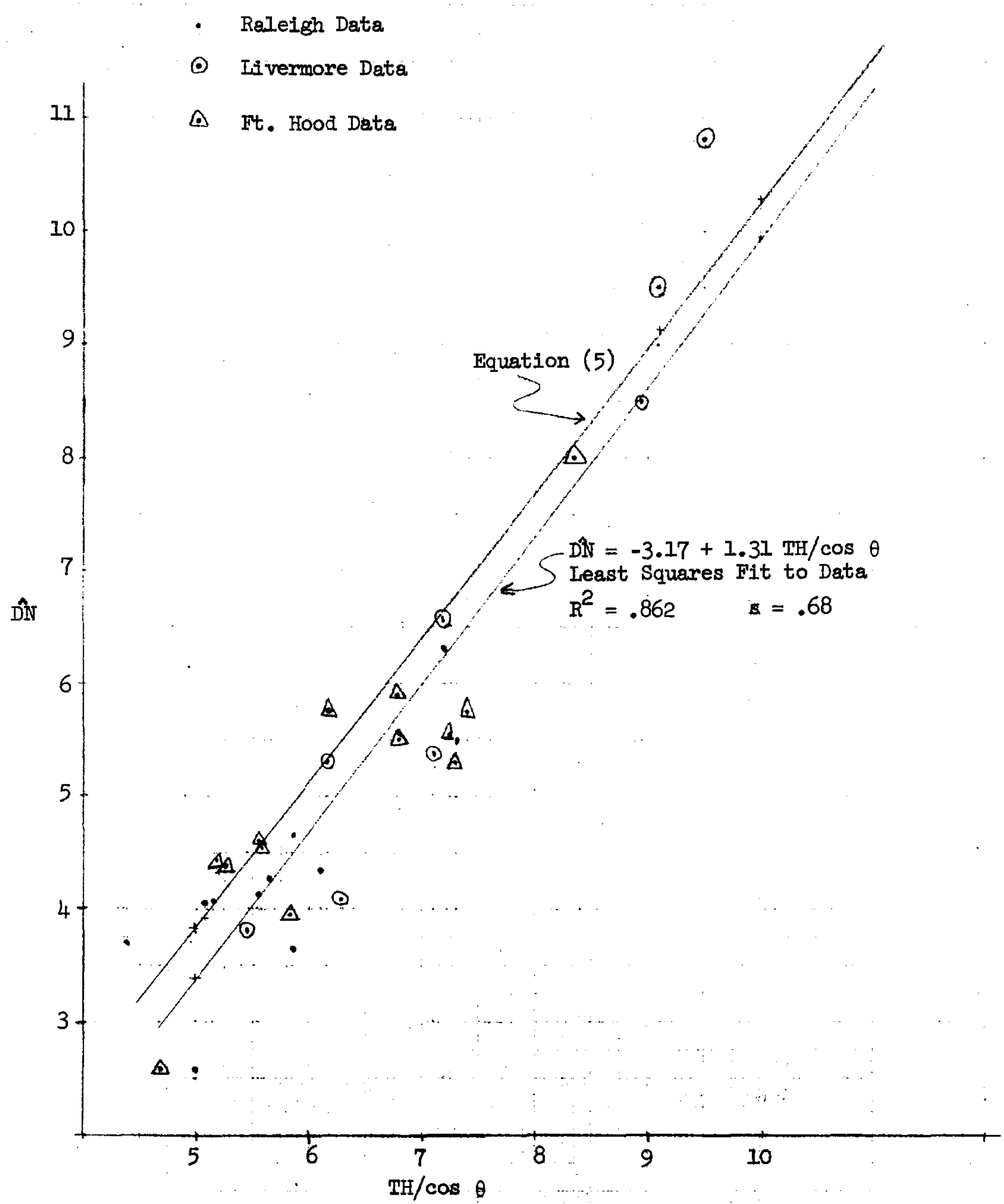

Table 5

	Raleigh		Livermore		Fort Hood	
	Error 1	Error 2	Error 1	Error 2	Error 1	Error 2
Jan.	- .1%	3.15%	- 2.9%	- .8%	5.4%	8.4%
Feb.	- 7.7	- 6.8	-16.4	-15.9	- 1.1	- .5
Mar.	- 8.7	-11.2	-26.6	-32.9	2.5	.4
April	-17.3	-21.4	-20.5	-21.7	-18.4	-23.6
May	-21.7	-35.4	- 7.4	- 5.1	*	*
June	-20.6	-23.7	8.6	10.9	-17.9	-20.7
July	*	*	2.7	4.2	-16.3	-20.6
Aug.	- 4.8	- 5.7	- 3.7	- 2.0	-27.9	-28.6
Sept.	-38.8	-49.4	- 1.1	- .9	-10.9	-11.6
Oct.	-11.5	- 9.8	-37.4	-34.4	- 6.7	- 4.1
Nov.	.3	1.5	*	*	7.6	7.5
Dec.	13.6	17.8	*	*	3.3	5.5

* Data not available. Error = $100(DN - \hat{DN})/DN$. Negative errors indicate over prediction.

Error 1: Errors using equations in Table 2 (Different equations for each month)

Error 2: Errors using equation in (5) - (Same equation for all months) was obtained from [2] and the TH data from [1]. The TH values are the same as those in Table 1. (Both sets of data are derived from the same data base discussed in [1]). In the sequel TT = TT(45).

Scatter plots of TT versus TH similar to those of Figures 1 and 2 indicated that latitude and time of year should be incorporated into a model for predicting TT from TH. The model used is

$$(6) \qquad TT = c + d * (\tan\theta \cos\beta \sin 45 + \cos 45)TH$$
$$= c + d * f(\theta)TH$$

where

c and d are constants to be determined,

θ = solar zenith angle,

β = solar azimuth angle, and

$f(\theta) = \tan\theta \cos\beta \sin 45 + \cos 45$.

The motivation for the model is as follows: The major component of TT is probably the direct component, DT

On an instantaneous basis it is given by

$$(7) \qquad DT = DN * \cos\theta\,[\tan\theta \cos\beta \sin 45 + \cos 45]$$

Now assume DN can be expressed as DN = a + b(TH/cos θ). Thus, we looked for a model of the form

$$(8) \qquad TT = (a + b\frac{TH}{\cos\theta}\cos\theta)[\tan\theta\cos\beta\sin 45 + \cos 45]$$
$$= c + d * (\tan\theta\cos\beta\sin 45 + \cos 45)TH.$$

An "average" value of θ defined in (3) was used in (6).

Table 6

Mean Daily Totals of Total at 45° Tilt
and Total-Horizontal Radiation for January-June

	Jan.		Feb.		Mar.		April		May		June	
	TT	TH	TT	TH	TT	TH	TT	TH	TT	TH	TT	TH
Albuquerque	6.1	3.6	6.4	4.5	6.9	5.9	7.0	7.3	6.8	8.3	6.6	8.6
Appalachicola	4.8	3.3	5.4	4.2	5.3	4.9	5.7	6.2	5.5	6.9	5.0	6.8
Bismark	3.9	1.8	5.0	2.9	5.5	4.0	5.9	5.4	5.9	6.3	6.2	7.1
Blue Hill	3.5	1.9	4.0	2.6	4.7	3.8	4.6	4.5	5.1	5.6	4.9	5.7
Boston	3.2	1.8	3.7	2.5	4.7	3.8	4.6	4.5	5.1	5.6	5.0	5.9
Brownsville	3.8	2.9	4.4	3.7	4.3	4.3	4.7	5.3	4.9	6.3	4.7	6.5
Cape Hatteras	5.0	3.1	5.8	3.7	5.7	4.9	6.4	6.6	6.4	7.6	5.6	7.2
Caribou	3.6	1.7	4.6	2.7	5.6	4.2	5.1	4.8	5.1	5.5	5.0	5.7
Charleston	4.1	2.7	4.5	3.4	4.9	4.4	5.7	6.0	5.4	6.5	4.8	6.1
Columbia	3.9	2.3	4.3	3.0	4.4	3.7	5.0	5.0	5.6	6.4	5.4	6.6
Dodge City	5.5	3.1	4.7	3.3	5.5	4.6	5.9	5.9	5.9	6.8	5.8	7.2
El Paso	6.1	3.8	6.9	5.0	7.3	6.4	7.2	7.8	6.8	8.5	6.3	8.5
Ely	5.2	2.9	5.3	3.6	6.5	5.3	6.9	6.9	6.5	7.5	6.7	8.4
Fort Worth	4.8	3.0	4.9	3.6	5.3	4.7	5.2	5.5	5.4	6.6	5.3	6.9
Great Falls	2.8	1.5	4.1	2.5	5.3	4.0	5.3	4.9	5.6	6.0	6.1	6.9
Lake Charles	4.0	2.8	4.0	3.2	4.7	4.4	5.0	5.4	5.1	6.4	4.6	6.1
Madison	3.8	2.0	4.8	3.1	5.5	4.4	5.5	5.3	5.7	6.2	6.2	7.3
Medford	2.0	1.4	3.1	2.3	4.4	3.7	5.7	5.5	5.8	6.4	6.4	7.6
Miami	5.2	3.8	6.0	4.9	5.5	5.3	5.6	6.4	4.9	6.3	4.5	6.1
Nashville	3.2	2.1	3.9	2.9	4.1	3.6	5.1	5.3	5.3	6.3	5.1	6.3
New York	3.0	1.8	3.6	2.5	4.6	3.7	4.6	4.5	4.6	5.2	5.0	5.9
Omaha	4.4	2.4	4.9	3.2	5.2	4.2	5.5	5.4	5.3	5.9	5.5	6.6
Phoenix	5.7	3.6	6.2	4.5	6.9	6.0	7.1	7.5	6.8	8.4	6.1	8.1
Santa Maria	5.2	3.2	5.0	3.7	6.5	5.6	7.0	7.3	6.6	7.9	6.5	8.4
Seattle	1.7	1.0	2.4	1.7	3.9	3.1	4.7	4.4	5.5	5.8	5.8	6.6
Washington, DC	3.7	2.2	4.2	2.9	5.0	4.2	5.3	5.2	5.0	5.7	5.4	6.4

Table 6

Mean Daily Totals of Total at 45° Tilt
and Total-Horizontal Radiation for July-December

	July		August		Sept.		Oct.		Nov.		Dec.	
	TT	TH	TT	TH	TT	TH	TT	TH	TT	TH	TT	TH
Albuquerque	6.6	8.1	6.9	7.6	6.8	6.2	6.8	5.1	6.2	3.8	5.7	3.2
Appalachicola	5.1	6.5	5.1	5.9	5.6	5.5	5.9	4.8	5.4	3.8	4.7	3.1
Bismark	6.4	7.0	6.5	6.3	5.7	4.6	5.1	3.2	3.6	1.9	3.2	1.5
Blue Hill	4.8	5.4	5.0	5.1	4.8	4.2	4.0	2.9	3.2	1.9	3.2	1.7
Boston	5.0	5.7	5.0	5.2	4.8	4.2	3.9	2.8	3.0	1.8	2.9	1.6
Brownsville	5.2	7.2	5.2	6.3	5.0	5.2	5.0	4.3	4.3	3.3	3.5	2.6
Cape Hatteras	6.1	7.5	5.9	6.5	6.2	5.8	5.6	4.2	4.9	3.2	4.5	2.7
Caribou	5.3	5.8	5.3	5.1	4.5	3.7	3.4	2.3	2.4	1.3	2.9	1.4
Charleston	4.8	5.9	5.0	5.6	5.2	4.9	5.2	4.2	4.5	3.1	4.2	2.7
Columbia	5.5	6.4	6.1	6.4	5.3	4.7	5.0	3.7	4.0	2.5	3.5	2.0
Dodge City	5.9	7.1	6.3	6.7	6.0	5.4	6.1	4.4	5.4	3.2	4.7	2.5
El Paso	6.0	7.8	6.5	7.4	6.5	5.2	6.8	5.3	6.1	4.0	5.8	3.5
Ely	6.3	7.6	6.6	7.0	6.9	6.1	6.6	4.6	5.6	3.2	5.2	2.7
Fort Worth	5.5	6.9	5.9	6.6	5.6	5.3	5.4	4.2	4.7	3.2	4.1	2.6
Great Falls	6.4	7.0	6.1	5.9	5.5	4.4	4.4	2.9	3.0	1.7	2.4	1.2
Lake Charles	4.5	5.8	4.6	5.3	5.0	4.9	4.8	4.0	4.3	3.1	3.6	2.5
Madison	6.2	7.0	6.2	6.3	5.3	4.5	4.5	3.1	3.3	1.9	3.5	1.8
Medford	7.0	8.1	6.7	6.8	6.0	5.1	4.5	3.2	2.7	1.8	1.7	1.1
Miami	4.7	6.3	4.9	5.8	5.0	5.1	5.5	4.8	5.3	4.0	5.3	3.7
Nashville	5.1	6.1	5.2	5.6	5.1	4.7	4.8	3.7	3.7	2.5	3.1	1.9
New York	4.6	5.3	4.5	4.6	5.1	4.5	4.1	3.0	2.9	1.8	2.8	1.6
Omaha	5.7	6.6	5.9	6.0	5.3	4.5	5.0	3.5	4.0	2.4	3.7	1.9
Phoenix	6.1	7.7	6.2	6.9	6.4	6.1	6.3	4.9	5.7	3.8	5.1	3.1
Santa Maria	6.5	7.9	6.5	7.0	6.5	6.0	6.5	4.9	5.6	3.6	5.0	3.0
Seattle	6.5	7.1	5.5	5.4	4.6	3.8	3.2	2.2	2.2	1.3	1.4	.8
Washington, D.C.	5.1	5.9	5.2	5.4	5.1	4.6	4.7	3.5	3.7	2.3	3.6	2.0

Figures 6 and 7 are scatter plots of the TT - $f(\theta)$TH data for January and July. The plots indicate that a straight line will fit the data quite well. A straight line, equation (6), using a least squares procedure was fitted to each month's data. The values of c, d, s, R^2, and extreme error are given in Table 7. The high values of R^2 indicate that the least squares line fits the data quite well. A negative error indicates our model over predicts TT. The largest errors occur at the northern locations. Of course the northern locations have small TT values in the winter and hence a rather small difference between $\hat{TT}$ (predicted value) and TT(data value) will give a large percentage error. For example $\hat{TT}$ - TT = 3.35 - 3.00 = 0.35 for the November Great Falls location. This difference leads to a -11.8% error in the predicted value.

Besides fitting the TT - $f(\theta)$ TH data with a straight line on a monthly basis all the data were combined and fitted with a single straight line as was done with the DN - TH/cos θ data. The derived equation is

$$\hat{TT} = -.79 + 1.05\, f(\theta)\, TH \tag{11}$$

with R^2 = .964 and s = .212

$f(\theta)$ is the same as in (6).

The extreme errors in $\hat{TT}$ for each month using this model are given in Table 8. As would be expected the magnitudes of these extreme errors are somewhat larger than those listed in Table 6.

Unfortunately TT data similar to the DN data from the locations of Raleigh, Livermore, and Fort Hood was unavailable for checking the $\hat{TT}$ model. This data will become available at a later time.

Scatter Plots of TT versus f(θ) TH

Figure 6

January

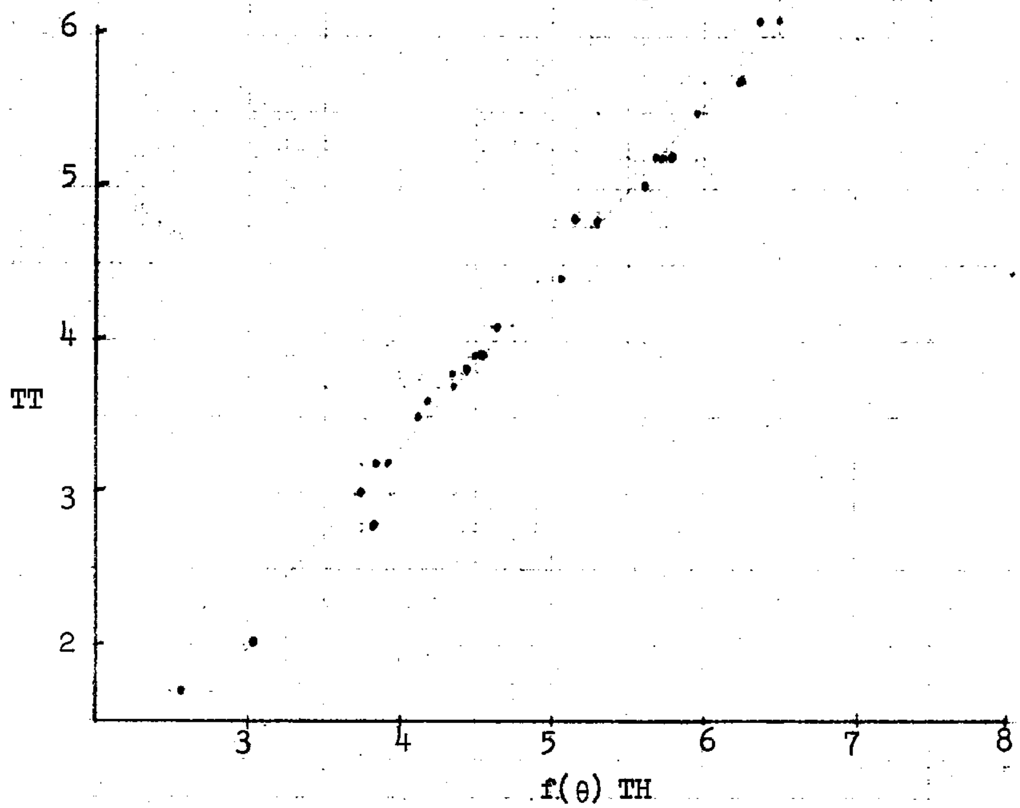

Figure 7

July

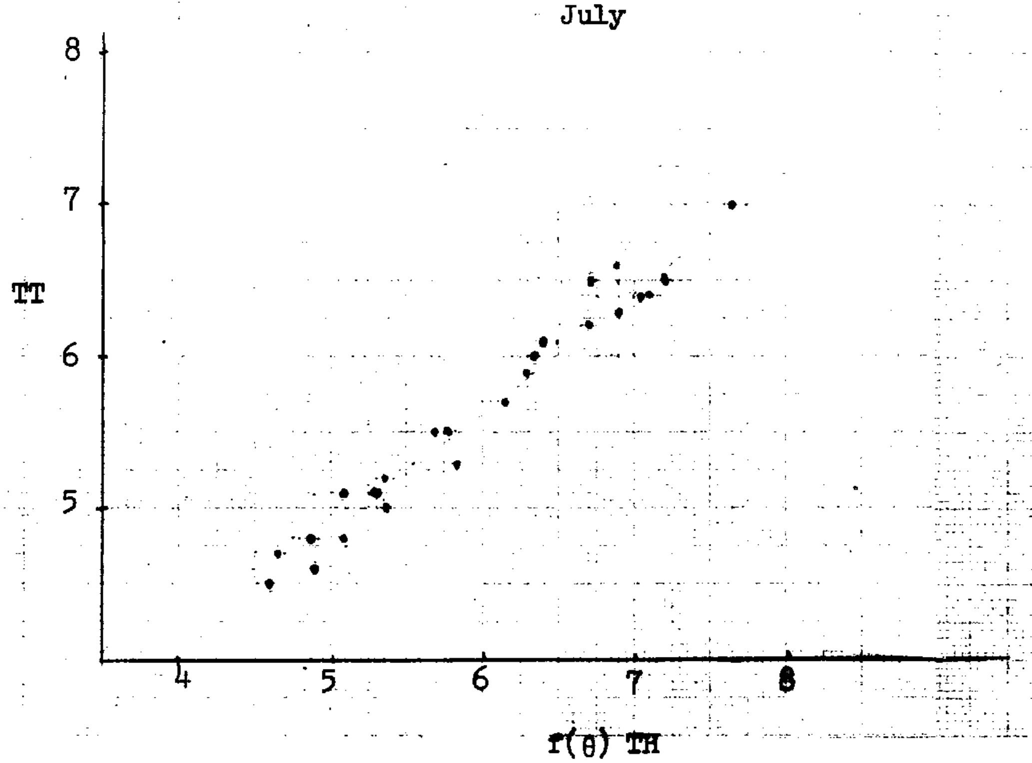

Table 7

Regression Coefficients for the Model, $\hat{TT} = c + d * f(\theta) * TH$

	c	d	R^2	s	Extreme Error	Location of Extreme Error
Jan.	-1.29	1.14	.990	.12	-11.62%	Great Falls
Feb.	-1.24	1.13	.980	.15	- 6.94	Medford
Mar.	- .67	1.02	.961	.18	- 8.32	Seattle
April	- .08	.94	.952	.19	- 6.65	Seattle
May	.53	.85	.940	.16	- 5.37	Great Falls
June	1.00	.77	.970	.12	- 5.62	Caribou
July	.83	.81	.969	.13	- 4.39	Caribou
Aug.	.51	.84	.954	.15	- 5.78	Seattle
Sept.	- .30	.96	.940	.17	- 6.44	Seattle
Oct.	-1.21	1.11	.984	.13	- 6.91	Great Falls
Nov.	-1.24	1.12	.987	.14	-11.81	Great Falls
Dec.	-1.25	1.13	.990	.12	- 7.61	Great Falls

R^2 = Regression sum of squares/total sum of squares

error = $100(TT - \hat{TT})/TT$ where $\hat{TT}$ = Predicted value from (6) and TT is data value.

s = standard error

Table 8

Monthly Extreme Errors of $\hat{TT}(45)$ when Single Model (Eq. (11)) is Used.

	Extreme Error	Location of Extreme Error
Jan.	-20.6%	Medford
Feb.	-14.6	Seattle
Mar.	- 8.5	Seattle
April	10.2	Brownsville
May	12.2	Miami
June	16.6	Miami
July	12.9	Miami
Aug.	10.5	Medford
Sept.	- 6.7	Seattle
Oct.	- 8.8	Lake Charles
Nov.	-17.2	Lake Charles
Dec.	-15.8	Lake Charles

Conclusions

The DN - TH/cos θ data can be fitted quite well with a straight line. It is interesting that the model fits the original data, in which the DN values were generated by summing the hourly TH data, significantly better than it fits the recently acquired data from Raleigh, Fort Hood, and Livermore where both DN and TH were measured. This suggests that there may be more real variations in monthly mean values of daily totals of DN and TH than a linear equation can adequately model. The data plotted in Figure 5 also indicates considerable scatter about a straight line. The predicted values, $\hat{DN}$, obtained from the straight line prediction equation for the Raleigh, Livermore, and Fort Hood locations are usually somewhat higher than the data values of DN. In one case $\hat{DN}$ is almost 50% higher than DN. The prediction equations seem to do somewhat better for the winter months. The results of Table 5 and the data plotted in Figure 5 show that caution must be used in using an empirically derived linear equation to predict DN values.

The TT - f(θ) TH data can also be fitted quite well with a straight line. The predicted values of TT for the northern latitude locations seem to have the largest errors. Perhaps some modification in f(θ) would improve the model. The data from Livermore, Raleigh, and Fort Hood should be used to verify our empirical models for TT when it becomes available.

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