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A SIMPLE RADIATION MODEL FOR THE TAR SANDS AREA

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ABSTRACT

Hourly data on net surface radiation (Q) on a horizontal surface are analyzed. An equation which computes the diurnal variation of Q from a knowledge of cloud cover and the sun's declination is presented for use in operational air quality models. The three constants in the model (characteristic frequency Ω, clear skies constant K_i and cloud cover constant K_c) are evaluated using radiation data collected in Alberta at $57^{o}1'$ latitude near the \$2.14 billion tar sands plant of Syncrude Canada Ltd. The numerical values of the cloud cover constant K_c (0.3 to 0.9) agree qualitatively with the values reported by Russian researchers Kondrat'yev and Doronin.

INTRODUCTION

In recent years air quality models have been used increasingly by industry in supplementary emission control systems (Noll and Davis)[1] a role which is a natural step from the basic assessment or prediction of air quality. Refinements have generally come through improvements in the physics of the models.

The mixing layer height h, the vertical distance which may limit the dispersion of pollutants can be quantified in one of two ways: either through use of historical data, or through use of predicted values refined with on-site observations. Predicting h requires an estimate of the changes in net surface heat flux Q with time (see Tennekes[2], Bettes[3], Carson[4], Kumar and Djurfors[5]). A simple model for Q is therefore essential for operational use.

The following approaches have been used for modelling the problems in the area of solar radiation:

1. Empirical formulae: These are simple and the calculations are easy (e.g.: Mateer[6], Glover and McCulloch[7]).
2. Theoretical models: Complex relationships are used to describe physical processes and relatively a large number of calculations are required to do the job. Such models generally provide detailed information with greater accuracy (e.g. Davies et al.[8]).
3. Hybrid approach: This approach uses the advantages of #1 and #2. The results are more accurate than Empirical formulae. This is achieved by accounting for some of the physical processes (e.g. Won[9]).

In this paper hourly values of Q^* are analyzed, and an equation for computing the variation of Q with the time of day and the time of year will be presented. The values are based on data collected in the Athabasca Tar Sands area during 1977.

The tar sands of Alberta are believed to be some 200 million years old and contain nearly 600 billion barrels of bitumen. The biggest and shallowest deposit occurs around the Syncrude plant and could yield approximately 29 billion barrels of synthetic crude oil with today's mining technology. Syncrude Canada Ltd. is a 2.14 billion dollar venture and will produce 129,000 barrels of synthetic crude oil per day at its design capacity.

FORMULAE:

The net radiation (Q) is defined as the net flux of downward and upward total (solar, terrestrial surface and atmospheric) radiation. The basic physical laws governing Q are determined by the same factors which influence its components. These include duration of sunshine, cloud amount, atmospheric transparency, the atmospheric temperature, the nature and condition of the boundary surface etc.

Q may be expressed in terms of time as

$$Q = Q_{max} \text{ Sin } \Omega t \tag{1}$$

This represents a periodic variation of Q in time with characteristic frequency Ω. Q_{max} is the maximum value of Q during the day.

In real life, the sky is nearly always covered by clouds. Therefore, one can obviously understand the importance of the effect of clouds upon net surface heat flux and the height of thermal boundary layer. In

* Note that the surface heat flux is assumed to be equal to the net radiation.

practice it is difficult to take into account all the variables which affect Q under cloudy conditions. Therefore, an empirical relationship is used in this study. For empirical equations this is usually done by introducing a cloud cover constant K_c such that

$$Q = Q_{max} \text{ (clear skies) } (1 - K_c . C) \ \text{Sin}\ \Omega\, t \qquad (2)$$

where C is the fractional cloud cover and K_c depends on the time of the year.

Q_{max} for clear skies may be approximated in terms of solar altitude κ, solar constant and the ratio of sensible heat flux from ground to the air to the incoming solar radiation. Therefore,

$$Q = K_i\ (1 - K_c c)\ (\text{Sin}\ \phi\ \text{Sin}\ \delta + \text{Cos}\ \phi\ \text{Cos}\ \delta)\ \text{Sin}\ \Omega\, t \qquad (3)$$

where, $\text{Sin}\ \kappa = \text{Sin}\ \phi\ \text{Sin}\ \delta + \text{Cos}\ \phi\ \text{Cos}\ \delta$ for maximum Q; K_i is a clear skies constant (numerical value depends on the time of the year) accounting for solar constant and the ratio of sensible heat flux from ground to the air to the incoming solar radiation. The angle ϕ is the latitude for the site and δ is the sun's declination.

δ is computed using the following relationship (Robertson and Russels[10]).

$$\begin{aligned}\delta = {} & 0.3964 + 3.631 \sin\alpha - 22.97 \cos\alpha + 0.03838 \sin 2\alpha - \\ & 0.3885 \cos 2\alpha + 0.07659 \sin 3\alpha - 0.1587 \cos 3\alpha - \\ & 0.01021 \cos 4\alpha\end{aligned} \qquad (4)$$

where, α the day angle is given by

$$\alpha = \frac{D}{365} \times 2\,\pi$$

D the day number; D = 1 for January 1.

A comparison of δ using the above formula and using the values given in Smithsonian Meteorological Tables[11] is given in Appendix A.

OBSERVATIONS

Measurements for Q were recorded using a CSIRO - pyr-radiometer*. Figure 1 to 4 shows diurnal variation of net surface heat flux (monthly mean values as functions of time of day) along with the standard deviation for winter, summer, autumn and spring seasons of 1977. Figure 5 and 6 depicts the contour plots of monthly mean values of Q and monthly mean values of Q for clear days observed in 1977. Note that 23 clear days were observed in 1977 (see Table 1 for a breakdown by month).

These observations further show that the highest positive values of net radiation usually occur around 12:00 MST (or 1 o'clock), while the maximum negative values occur during the night. The variations of Q during the night are small compared with those observed during the day. The curve of the diurnal variation of Q is sinusoidal in nature.

Figure 7 shows annual variation of positive component of average daily net heat flux. The numerical values were computed using the days for which data were recorded (some days were missing because of instrument breakdown). These range from 3.3 langleys (January) to 289.0 langleys (July). The negative average daily net heat flux is maximum for December (-11.8 langleys) and minimum for March (-47.2 langleys) (see Table 2).

Cloud cover, sunrise time and sunset time were also recorded for the purposes of this study.

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* This instrument was installed in late 1976 as a part of the Alberta Oil Sands Environmental Research Program.

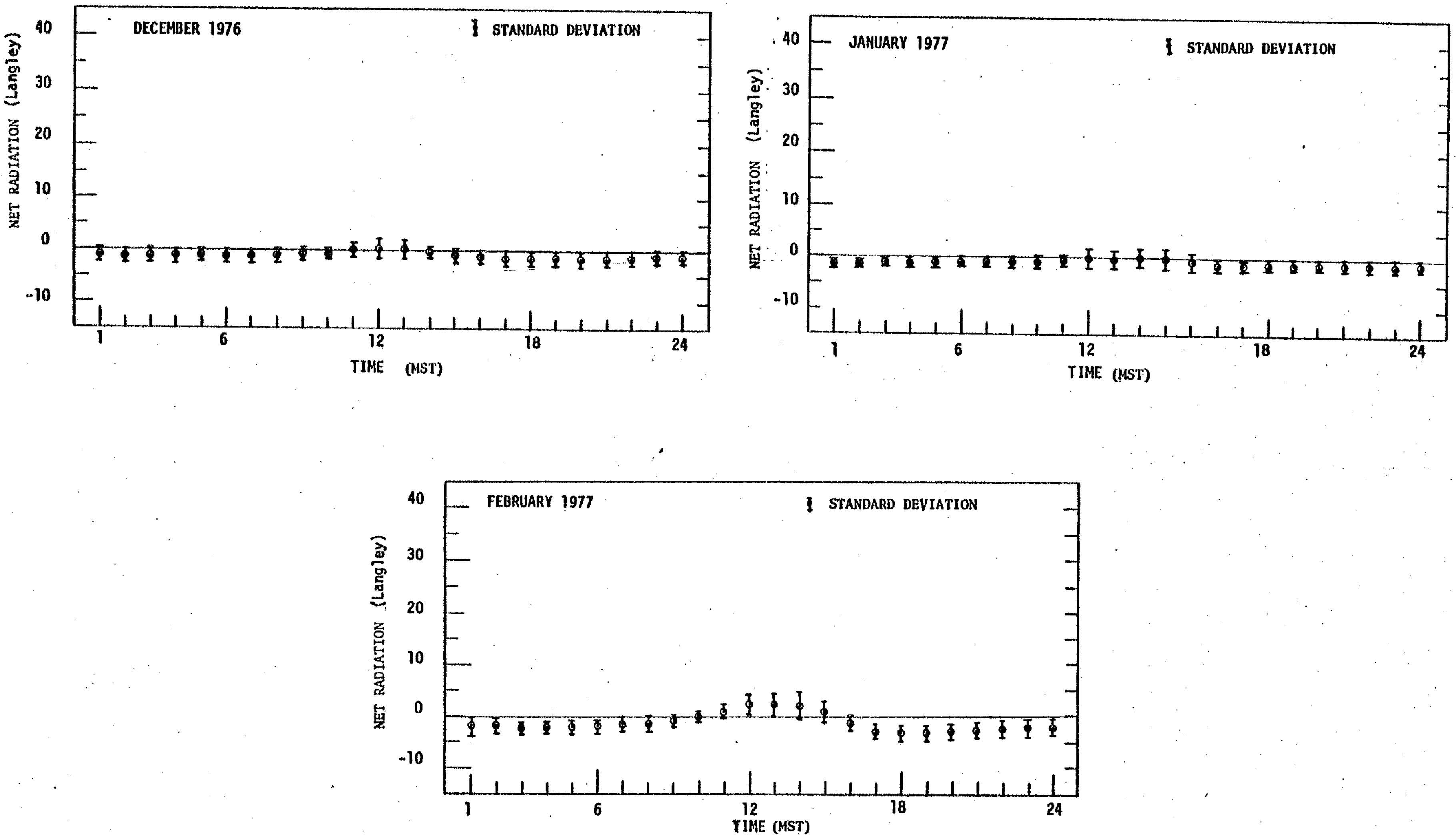

FIGURE 1: MEAN NET RADIATION AT THE SURFACE FOR WINTER 1976-77

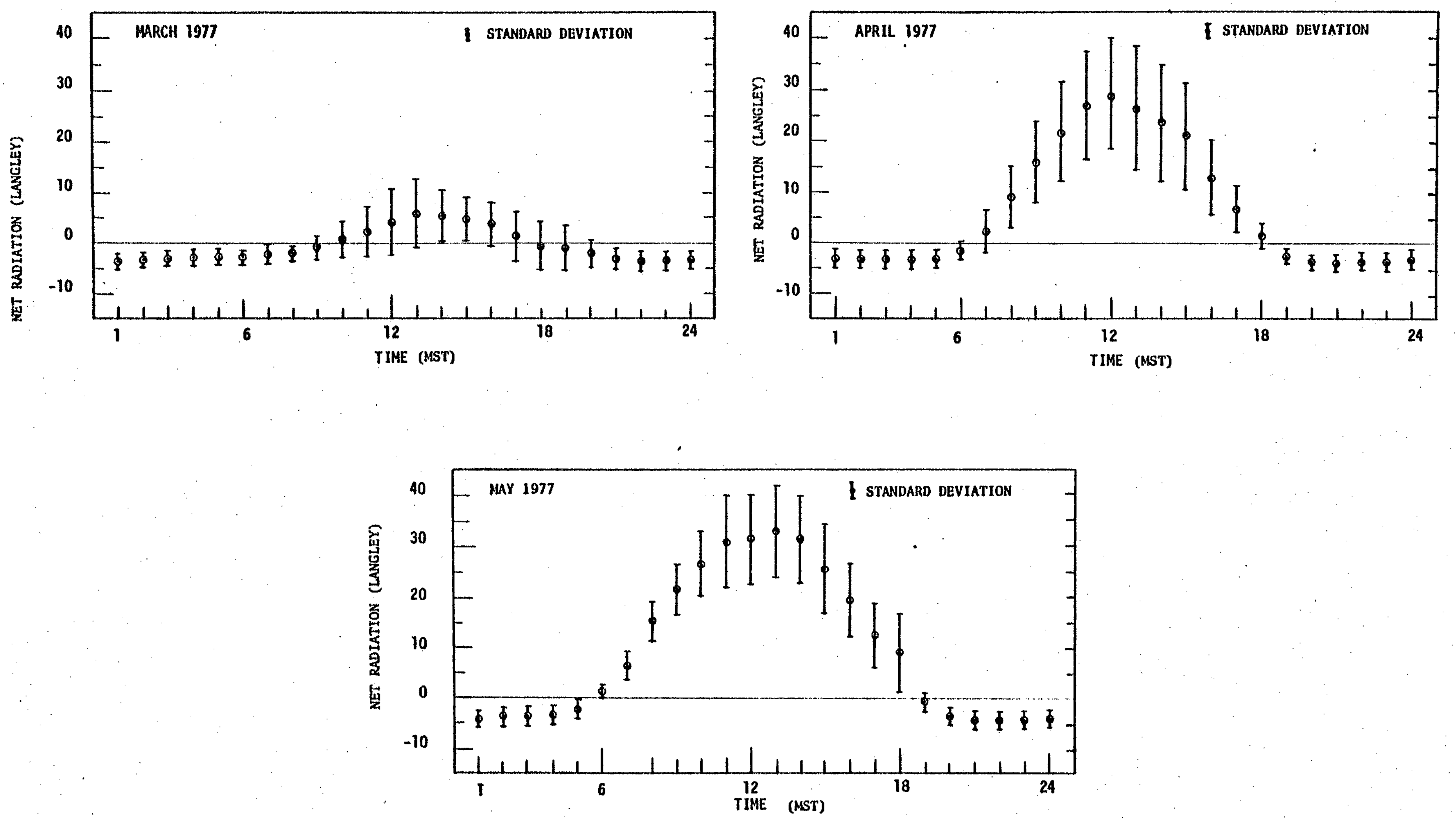

FIGURE 2: MEAN NET RADIATION AT THE SURFACE FOR SPRING 1977

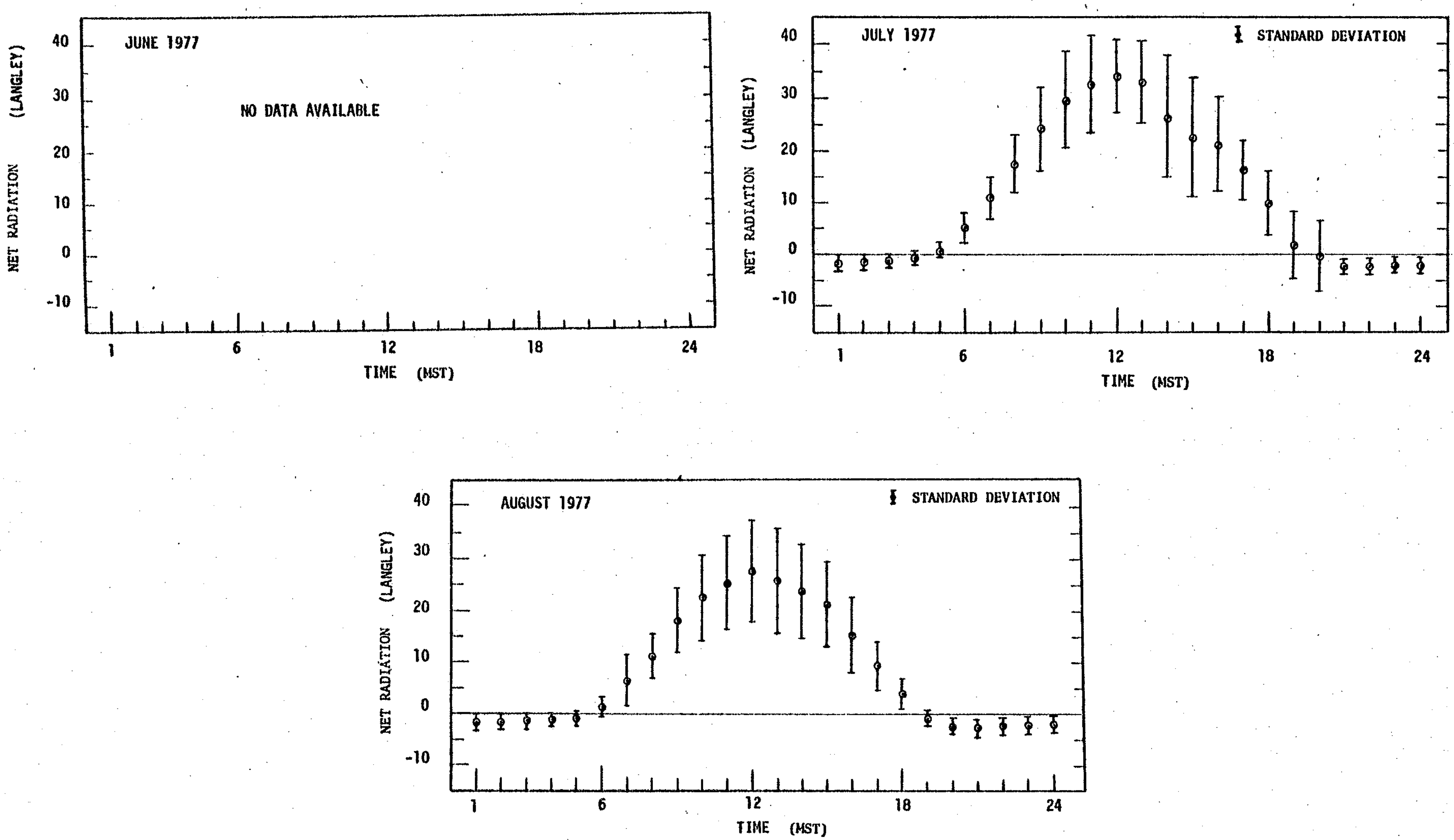

FIGURE 3: MEAN NET RADIATION AT THE SURFACE FOR SUMMER 1977

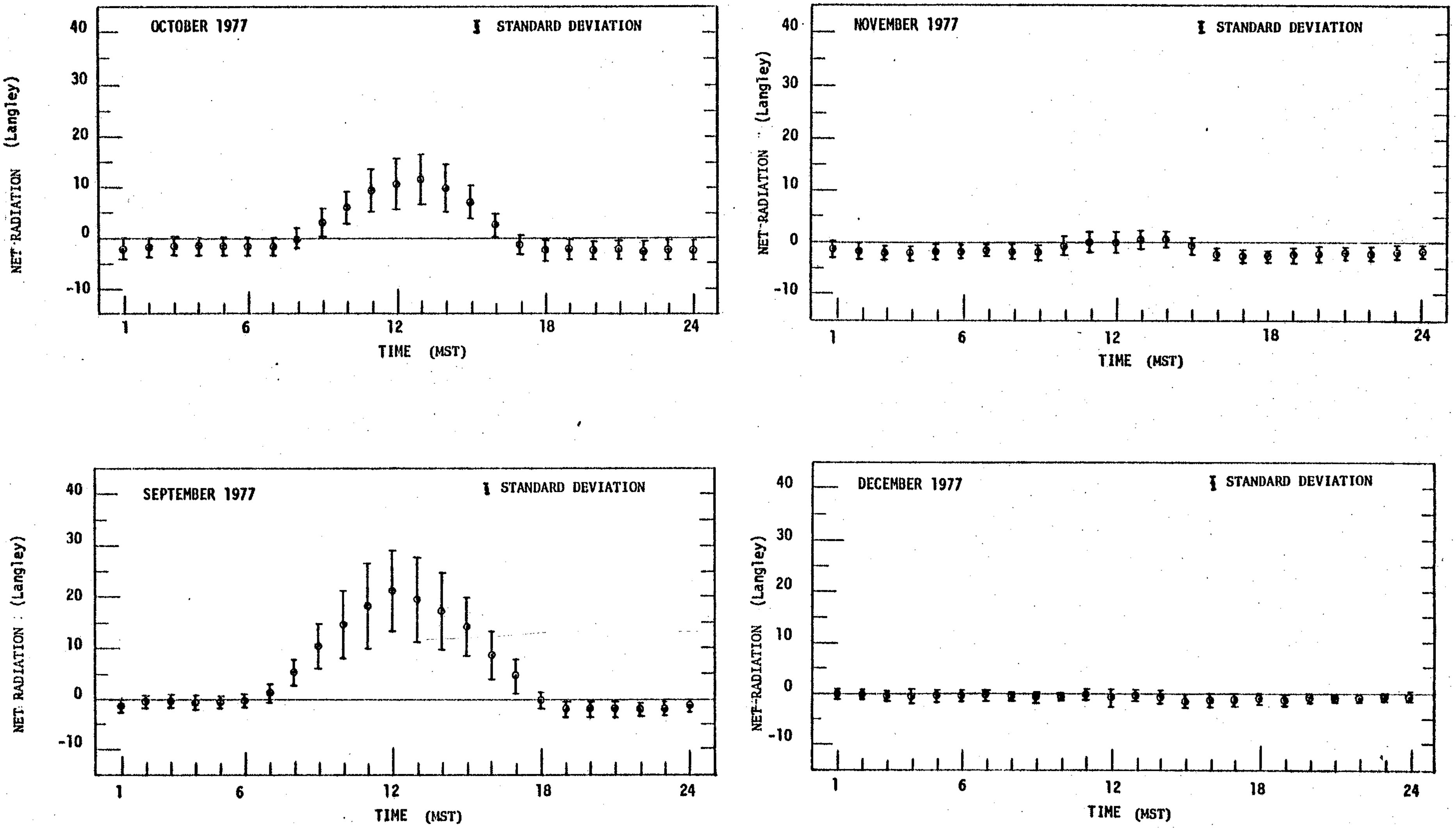

FIGURE 4: MEAN NET RADIATION AT THE SURFACE FOR SEPT. 1977 TO DEC. 1977.

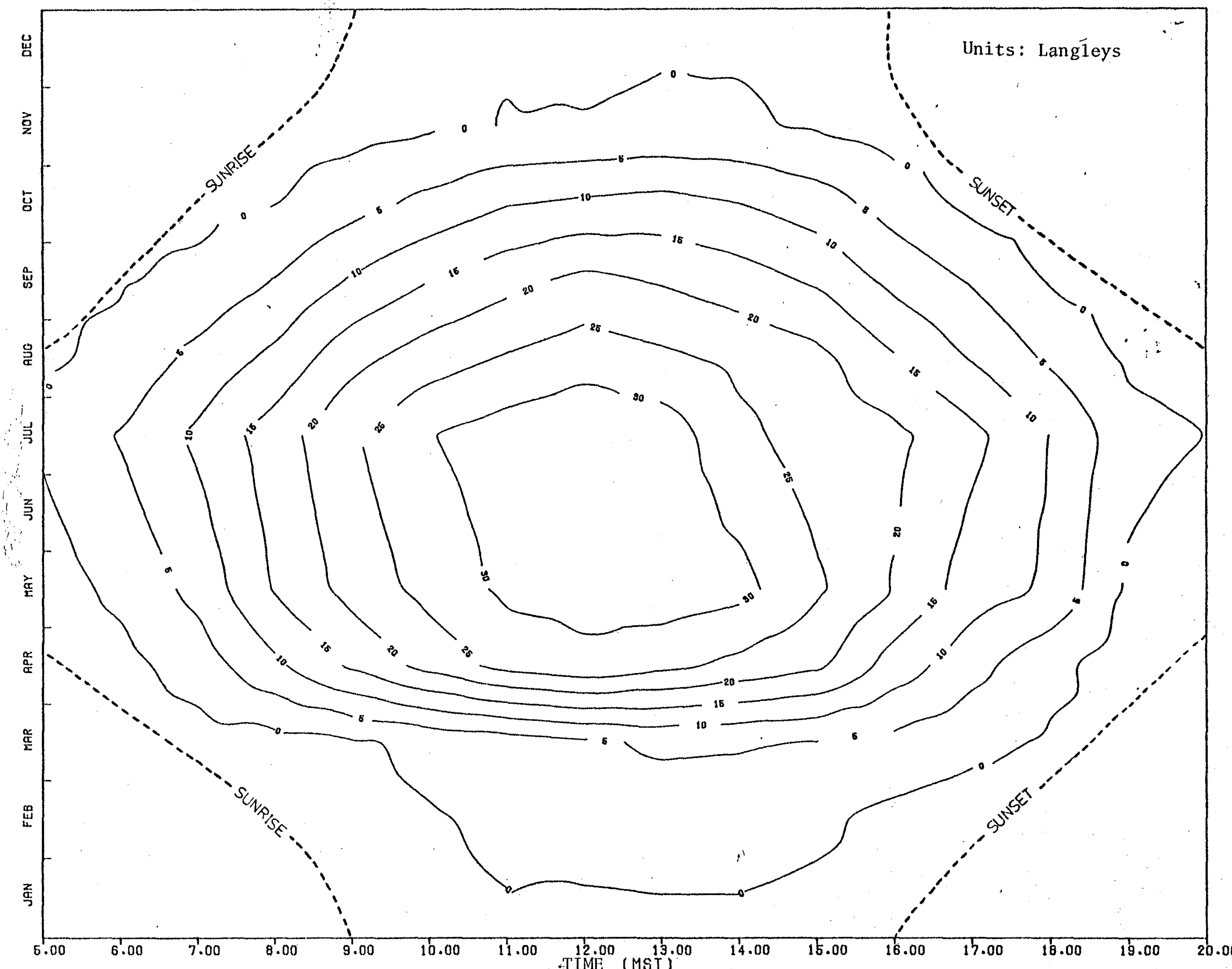

FIGURE 5: MONTHLY AVERAGES OF NET SURFACE HEAT FLUX FOR 1977.

[10] A

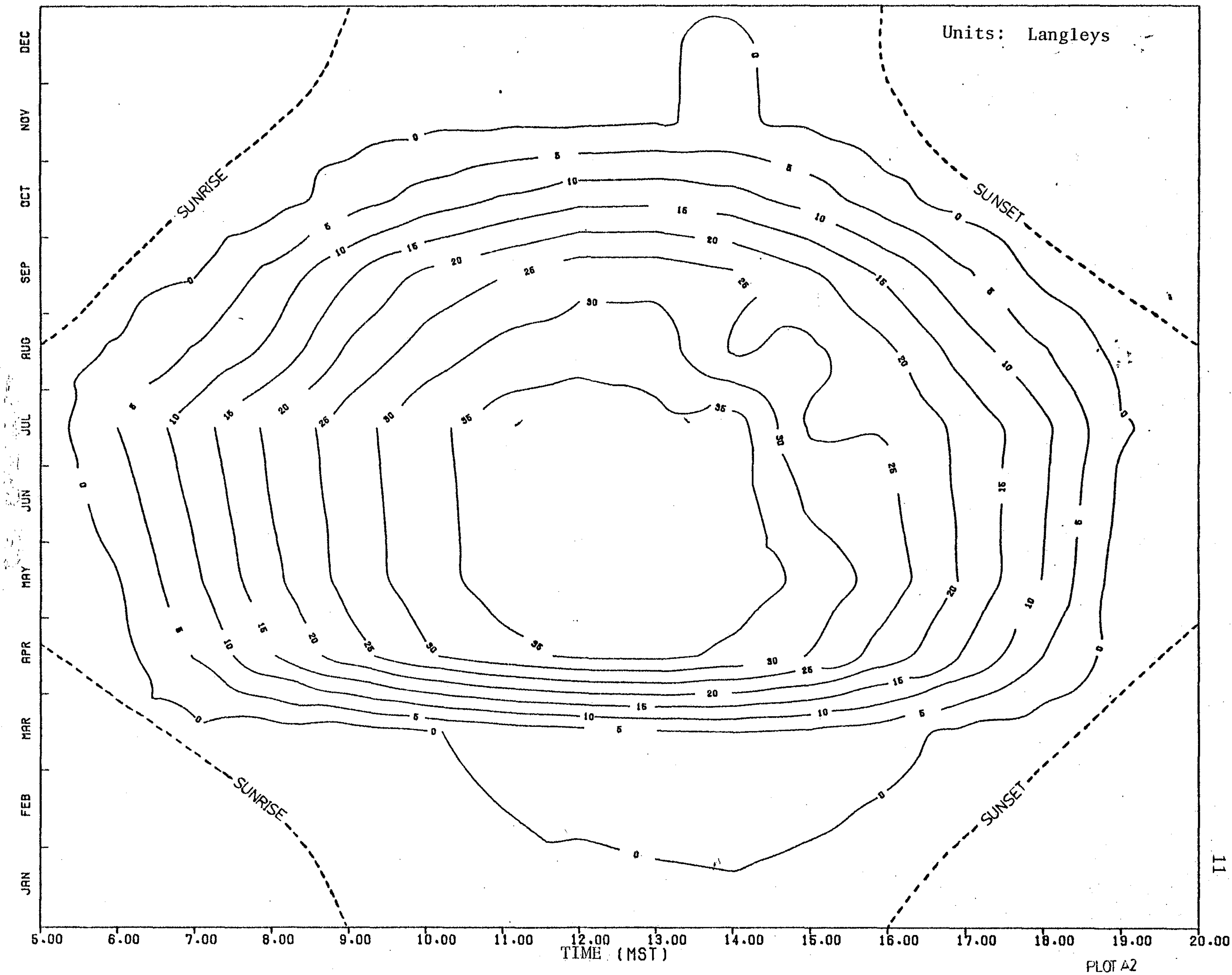

FIGURE 6: MONTHLY AVERAGES OF NET SURFACE HEAT FLUX FOR CLEAR DAYS IN 1977.

TABLE 1

CLEAR DAYS IN 1977

Month	No. of Days
January	3
February	2
March	2
April	1
May	2
June	1
July	1
August	1
September	2
October	3
November	2
December	3
Annual	23

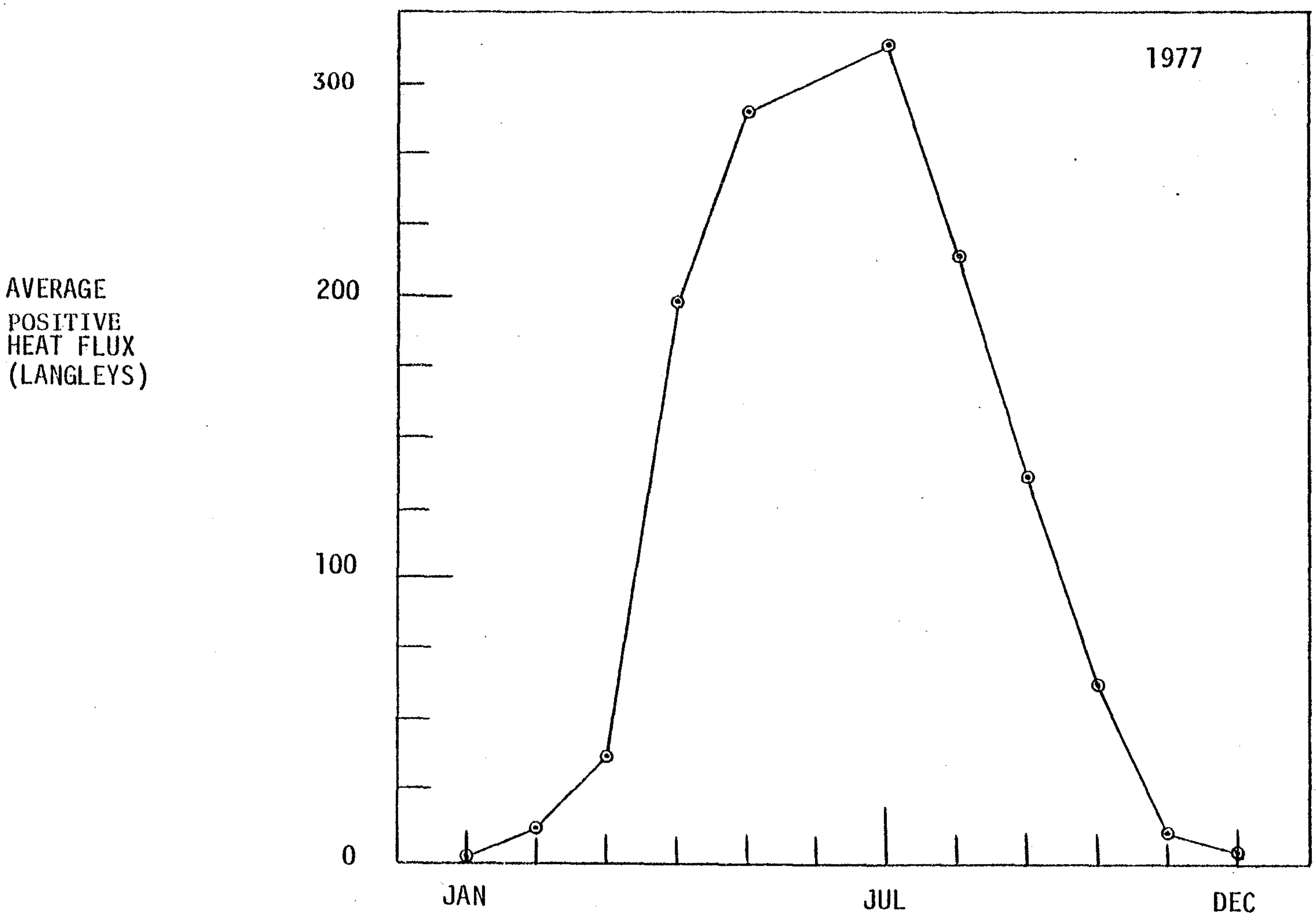

FIGURE 7: ANNUAL VARIATION OF AVERAGE DAILY NET HEAT FLUX (POSITIVE COMPONENT)

TABLE 2

AVERAGE DAILY NET HEAT FLUX IN 1977

MONTH	POSITIVE COMPONENT (Langleys)	NEGATIVE COMPONENT (Langleys)
January	3.3	-26.5
February	11.7	-41.8
March	37.3	-47.2
April	197.6	-40.6
May	265.0	-38.7
June	No Data	No Data
July	289.0	-15.3
August	214.2	-19.8
September	137.0	-17.6
October	62.9	-30.4
November	11.1	-23.0
December	6.2	-11.8

COMPUTATION OF Ω , K_i and K_c

(a) Characteristic Frequency (Ω): Ω depends upon the time of the year and may be expressed as

$$\Omega = \frac{\pi}{(\text{number of hours of positive heat flux } T_H)}$$

In order to assign a value to Ω , three different estimates of the number of hours of positive heat flux (T_H) were obtained:

(i) using monthly mean values of net heat flux

(ii) using mid month value of net heat flux

(iii) using daily values of net heat flux and then calculating the mean value

Table 3 shows a comparison of numerical values of T_H for each month and the number of hours of daylight based on 15th of each month. Mid-month values of T_H are consistently smaller than number of hours of daylight. This is due to the fact that (i) after sunrise it takes time for the downward total radiation to reach the same value as upward total radiation (i.e. from negative Q to positive Q) and (ii) in the evening hours net surface heat flux exceeds the heating component of the radiation balance some time before sunset.

The values of T_H chosen for calculating Ω are based on monthly means except for January. Monthly means were chosen as opposed to average of daily values because of wide scatter in raw data. Suggested values of Ω are shown in Table 4.

TABLE 3

A COMPARISON OF NUMBER OF POSITIVE HOURS OF HEAT FLUX AND NUMBER OF HOURS OF DAYLIGHT FOR 1977

Month	Hours of Positive Heat Flux			No. of Hours of Daylight (15th)
	Based on Monthly Means	Mid-Month	Average of Daily Values Over the Month	
January	0.0	2.8	3.0	7.5
February	5.4	4.8	5.2	9.6
March	8.5	6.3	7.2	11.8
April	12.0	11.4	11.6	14.3
May	13.2	13.6	13.5	16.5
June	No	Data	Available	17.8
July	15.2	15.9	15.8	17.2
August	13.5	14.1	13.7	15.2
September	11.7	16.1	13.1	12.8
October	8.7	8.6	9.1	10.5
November	4.9	5.7	2.9	8.2
December	4.0	4.4	2.8	6.8

TABLE 4

SUGGESTED VALUES OF CHARACTERISTIC FREQUENCY (Ω) FOR EQUATION (1)

Month	Hours of Positive Heat Flux Used for Calculation	$\Omega = \dfrac{\pi}{\text{Hours of Positive Heat Flux}}$ (radians/hr)
January	3.0	1.05
February	5.4	0.58
March	8.5	0.37
April	12.0	0.26
May	13.2	0.24
June*	14.2	0.22
July	15.2	0.21
August	13.5	0.23
September	11.7	0.27
October	8.7	0.36
November	4.9	0.64
December	4.0	0.79

* Mean value of May and July data (June data are not available).

(b) Clear Skies Constant (K_i):

For clear days (i.e. c = 0), Equations (2) and (3) may be written as

$$K_i = \frac{Q_{max}}{(\mathrm{Sin}\ \phi\ \mathrm{Sin}\ \delta + \mathrm{Cos}\ \phi\ \mathrm{Cos}\ \delta)} \qquad (6)$$

Thus, using the observed values of Q_{max} on a clear day, K_i can be evaluated. The results are shown in Figure 8.

(c) Cloud Cover Constant (K_c):

Equations (1) and (3) may be written as

$$K_c = \left[1 - K_i \frac{Q_{max}}{(\mathrm{Sin}\ \phi\ \mathrm{Sin}\ \delta + \mathrm{Cos}\ \phi\ \mathrm{Cos}\ \delta)}\right] \frac{1}{c} \qquad (7)$$

K_c is computed using (i) maximum heat flux during the day, (ii) average value of cloud cover during the day, and (iii) value of K_i (obtained above). Days with uniform cloud cover were favoured during computations of K_c.

K_c depends on the height and density of clouds and therefore a better way to compute K_c is based on the information of lower, middle and upper clouds

$$K_c = \frac{K_{c_1} \cdot c_1 + K_{c_m} \cdot c_m + K_{c_u} \cdot c_u}{c} \qquad (8)$$

Since this information is not available for our area, computations were carried out using average values of cloud cover. The results are given in Figure 9.

DISCUSSION

A summary of three constants (Ω, K_i and K_c) for computing net radiation is given in Table 5, while the annual variations (in graphical form) of K_i and K_c are shown in Figures 8 and 9.

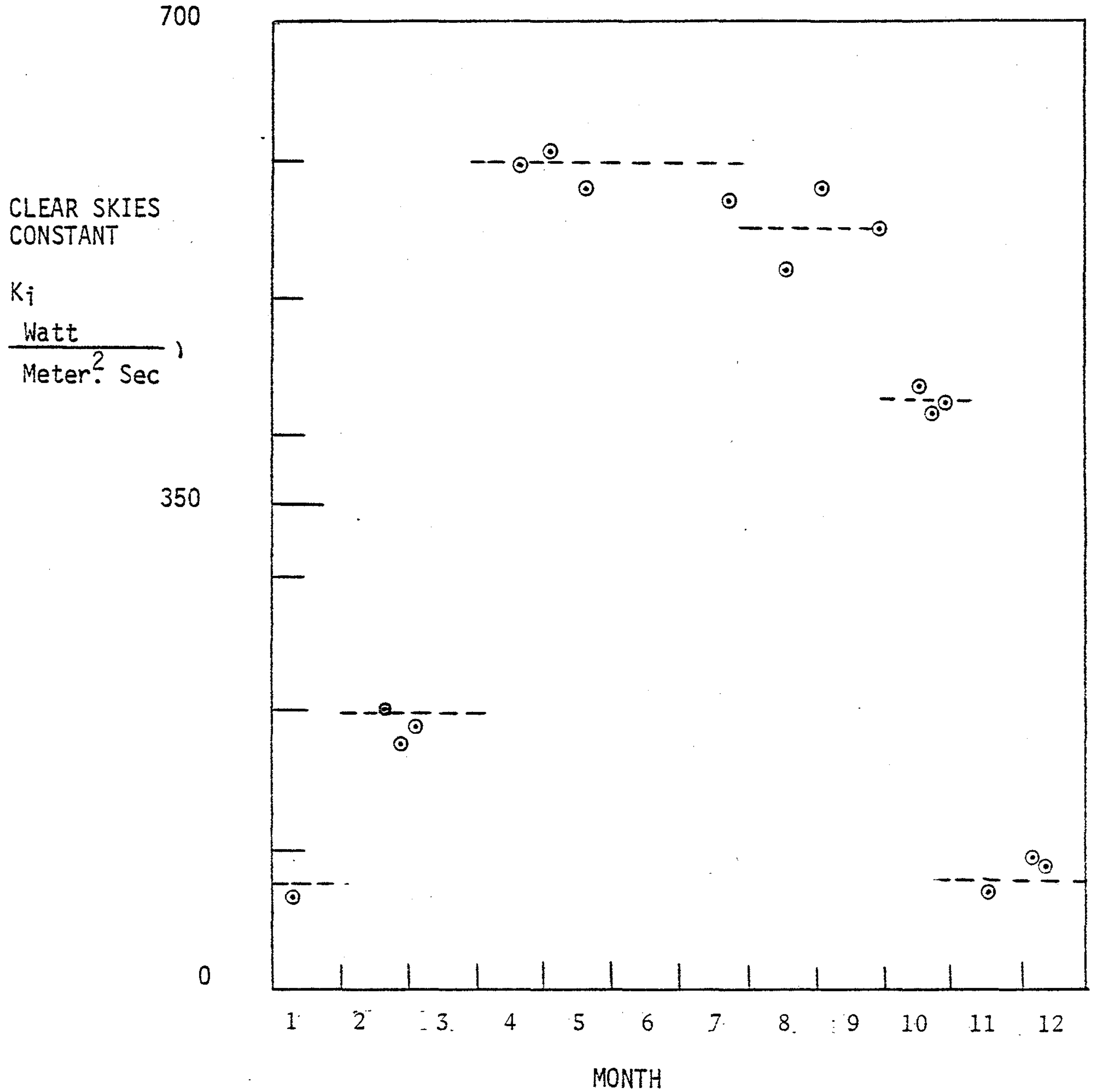

FIGURE 8: ANNUAL VARIATION OF CLEAR SKIES CONSTANT K_i.

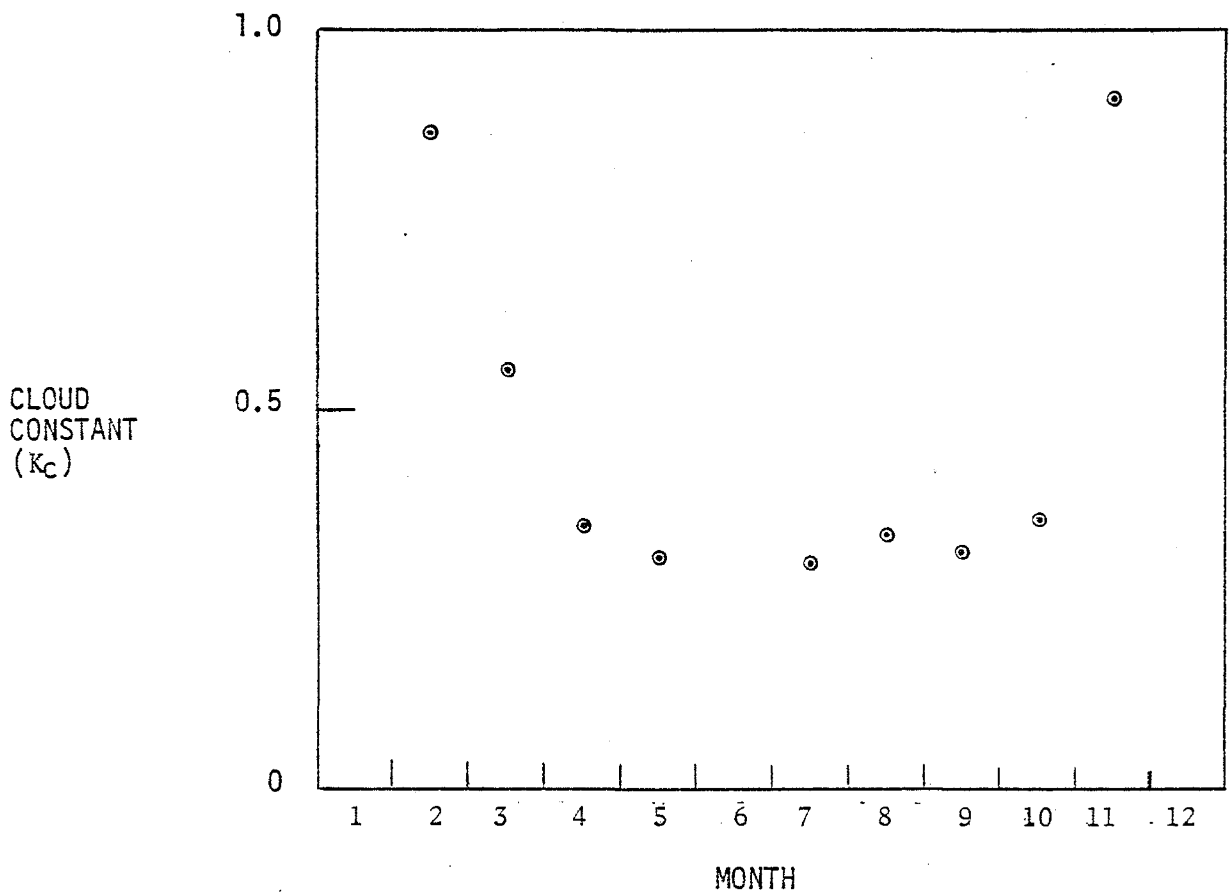

FIGURE 9: VARIATION OF CLOUD CONSTANT BY MONTH

TABLE 5

SUMMARY OF VARIOUS CONSTANTS USED IN THE RADIATION MODEL

Month	Ω (radians/hr)	K_i (Watt/m^2 sec)	K_c
January	1.05	75	0.87
February	0.58	200	0.87
March	0.37	200	0.55
April	0.26	600	0.35
May	0.24	600	0.30
June	0.22	600	0.30
July	0.21	600	0.30
August	0.23	550	0.33
September	0.27	550	0.31
October	0.36	425	0.36
November	0.64	75	0.91
December	0.79	75	0.91

The numerical values of clear skies constant K_i varies from 75 watt/m^{2}sec to 600 watt/m^{2}sec. The results indicate a lower value in winter months and a higher one in summer months. This trend is as expected and is also physically realistic.

Cloud cover constant K_c ranges from 0.30 to 0.91. Note that the value of K_c should be less than unity in order that Equation (2) is valid. A comparison between the results from the present study and the results of Russian work [12, 13] is given in Table 6. These results agree qualitatively.

One of the drawbacks in the use of a model of this type is the fact that net surface heat flux is underestimated for large zenith angles (first few hours after sunrise and before sunset). The "tails" of the sine curve in Equation (1) approach these areas and during these periods atmospheric transparency effects will give reduced values of Q.

This study is a part of the boundary layer program. The objective of this program is to develop an operational model for predicting the thermal boundary layer height for the use in Syncrude's dispersion model.

TABLE 6

COMPARISON OF CLOUD COVER CONSTANT

Source	K_c		Comments
Kondrat'yev	0.82	Cold	Latitude Over 60^o
	0.80	Warm	
	0.77	Cold	Latitude 60^o - 50^o
	0.70	Warm	
Doronin	0.80	(March	Tikhouya Bay (Recommended for computing total radiation.)
	0.35	(Aug.)	
	0.50	(Nov.)	
Present Study	0.87	(January)	Latitude $57^o1'$
	0.30	(June)	
	0.91	(Dec.)	

ACKNOWLEDGEMENTS

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NOMENCLATURE

c	Cloud cover (in tenth)
c_l	Cloud cover (in tenth) for lower clouds
c_m	Cloud cover (in tenth) for middle clouds
c_u	Cloud cover (in tenth) for upper clouds
D	Day number
h	Height of thermal boundary layer (mixing layer)
K_c	Cloud cover constant
K_{c_l}	Cloud cover constant for lower clouds
K_{c_m}	Cloud cover constant for middle clouds
K_{c_u}	Cloud cover constant for upper clouds
K_i	Clear skies constant
Q	Net radiation
Q_{max}	Maximum value of net radiation during the day
t	Time of day
T_H	Number of hours of positive heat flux

Greek Symbols

α	Day angle
κ	Solar altitude
Ω	Characteristic frequency
ϕ	Latitude
δ	Sun's declination

APPENDIX A

COMPARISON OF DECLINATION ANGLES

DATE	TABLE* degrees:minutes	CALCULATED** degrees:minutes	DIFFERENCE degrees:minutes	DATE	TABLE* degrees:minutes	CALCULATED** degrees:minutes	DIFFERENCE degrees:minutes
Jan 1	-23:04	-23:03	:01	Feb 1	-17:19	-17:19	:00
Jan 5	-22:42	-22:41	:01	Feb 5	-16:10	-16:09	:01
Jan 9	-22:13	-22:12	:01	Feb 9	-14:55	-14:55	:00
Jan 13	-21:37	-21:36	:01	Feb 13	-13:37	-13:36	:01
Jan 17	-20:54	-20:53	:01	Feb 17	-12:15	-12:14	:01
Jan 21	-20:05	-20:04	:01	Feb 21	-10:50	-10:49	:01
Jan 25	-19:09	-19:09	:00	Feb 25	- 9:23	- 9:22	:01
Jan 29	-18:08	-18:08	:00	Feb 29	-	-	
Mar 1	- 7:53	- 7:52	:01	Apr 1	+ 4:14	+ 4:13	:01
Mar 5	- 6:21	- 6:20	:01	Apr 5	+ 5:46	+ 5:45	:01
Mar 9	- 4:48	- 4:47	:01	Apr 9	+ 7:17	+ 7:16	:01
Mar 13	- 3:14	- 3:13	:01	Apr 13	+ 8:46	+ 8:44	:02
Mar 17	- 1:39	- 1:38	:01	Apr 17	+10:12	+10:11	:02
Mar 21	- 0:05	- 0:04	:01	Apr 21	+11:35	+11:34	:01
Mar 25	+ 1.30	+ 1:30	:00	Apr 25	+12:56	+12:55	:01
Mar 29	+ 3:04	+ 3:04	:00	Apr 29	+14:13	+14:12	:01
May 1	+14:50	+14:49	:01	Jun 1	+21:57	+21:56	:01
May 5	+16:02	+15:01	:01	Jun 5	+22:28	+22:27	:01
May 9	+17:09	+17:08	:01	Jun 9	+22:52	+22:51	:01
May 13	+18:11	+18:11	:00	Jun 13	+23:10	+23:09	:01
May 17	+19:09	+19;08	:01	Jun 17	+23:22	+23:21	:01
May 21	+20:02	+20:01	:01	Jun 21	+23:27	+23:26	:01
May 25	+20:49	+20:48	:01	Jun 25	+23:25	+23:24	:01
May 29	+21:30	+21:29	:01	Jun 29	+23:17	+23:16	:01
Jul 1	+23:10	+23:09	:01	Aug 1	+18:14	+18:13	:01
Jul 5	+22:52	+22:51	:01	Aug 5	+17:12	+17:11	:01
Jul 9	+22:28	+22:27	:01	Aug 9	+16:06	+16:05	:01
Jul 13	+21:57	+21:56	:01	Aug 13	+14:55	+14:54	:01
Jul 17	+21:21	+21:19	:02	Aug 17	+13:41	+13:40	:01
Jul 21	+20:38	+20:37	:01	Aug 21	+12:23	+12:22	:01
Jul 25	+19:50	+19:49	:01	Aug 25	+11:02	+11:02	:00
Jul 29	+18:57	+18:56	:01	Aug 29	+ 9:39	+ 9:38	:01
Sep 1	+ 8:35	+ 8:34	:01	Oct 1	- 2:53	- 2:52	:01
Sep 5	+ 7:07	+ 7:06	:01	Oct 5	- 4:26	- 4:25	:01
Sep 9	+ 5:37	+ 5:37	:00	Oct 9	- 5:58	- 5:57	:01
Sep 13	+ 4:06	+ 4:06	:00	Oct 13	- 7:29	- 7:28	:01
Sep 17	+ 2:34	+ 2:33	:01	Oct 17	- 8:58	- 8:57	:01
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Sep 25	- 0:32	- 0:32	:00	Oct 25	-11:50	-11:49	:01
Sep 29	- 2:06	- 2:05	:01	Oct 29	-13:12	-13:11	:01
Nov 1	-14:11	-14:10	:01	Dec 1	-21:41	-21:40	:01
Nov 5	-15:27	-15:26	:01	Dec 5	-22:16	-22:15	:01
Nov 9	-16:38	-16;38	:00	Dec 9	-22:45	-22:44	:01
Nov 13	-17:45	-17:45	:00	Dec 13	-23:06	-23:05	:01
Nov 17	-18:48	-18:47	:01	Dec 17	-23:20	-23:18	:02
Nov 21	-19:45	-19:44	:01	Dec 21	-23:26	-23:25	:01
Nov 25	-20:36	-20:35	:01	Dec 25	-23:25	-23:23	:02
Nov 29	-21:21	-21:20	:01	Dec 29	-23:17	-23:15	:02

* Data from Smithsonian Meteorological Tables

** Calculated from equations:

$$\delta = 0.3964 + 3.631 \sin A - 22.97 \cos A + 0.03838 \sin 2A - 0.3885 \cos 2A + 0.07659 \sin 3A - 0.1587 \cos 3A - 0.01021 \cos 4A$$

$$A = (2\pi/365)\ (\text{no. of days after Jan. 1})$$