Proceedings, 13th National Annual Passive Solar Conf., American Solar Energy Society (ASES), Cambridge, Massachusetts, June 20-24, 1988, p. 301-306.

EVALUATION OF SOLAR ANGLES AND INCIDENT SOLAR ENERGY AT MACHU PICCHU, PERU

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ABSTRACT

The results of solar angles and incident solar energy of eight slope orientations and ten angles are presented for summer and winter days under clear sky conditions. The study incorporates results from field measurements and a computer program. It is shown that the Incas had an understanding of the solar-terrestrial relationships at the site during the construction of Machu Picchu.

1. INTRODUCTION

This research paper is the first of a forthcoming series on the quantitative evaluation of the solar-terrestrial-building relationships found by the author at the Machu Picchu Ruins, Peru since 1978. A qualitative report on the above relationships is given in a separate paper (1).

The present report consists of an evaluation of solar angles and incident solar energy at Machu Picchu Ruins, Peru. The results of the following are discussed: azimuth and zenith solar angles, and incident solar energy of slopes. The slopes are oriented due south, southwest, west, northwest, north, northeast, east, and southeast. Moreover, these slopes have angles ranging from 0.0 to 90.0 degrees. The incident solar energy is calculated at ten degree increments for the above-cited slope orientations under clear sky condition during the summer and winter. The result for partially clear and overcast skies are not presented here due to format requirements, but are being prepared for publication.

The Machu Picchu Ruins are of interest due to the reverence of the Incas to "Inti," or the Sun God in Quechua(2, 3). This research is part of the author's interdiciplinary graduate research in archaeology, geography, and urban design at the University of California, Los Angeles. The data presented here is going to be used in a study of energy budgets of building facets and the natural environment at Machu Picchu. The ultimate goal of this research is to translate the design principles of utilization of natural resources found at Machu Picchu to be used by architects and urban designers of the present.

2. SITE OF STUDY

The Machu Picchu Ruins were found in the most preserved state among all archaeological sites of Peru. It was discovered for the Western World by Hiram Bingham in 1911 (4). There was a recovery of most of the archaeological material, and the site has been explored as a major touristic attraction of Peru since the 1950s.

The Machu Picchu Ruins are located in the Vilcabamba Cordillera and along the Urubamba River on the eastern slopes of the Andes of Southern Peru. More specificaly, its coordinates are latitude 13° 09' South, longitude 72° 32' West, and an altitude of about 2,170 meters (7,161 feet).

The ruins are situated on the boundary of the sub-tropical and tropical latitudinal zones (5) and in the "Tierra Templada" altitudinal zone (6). Moreover, the climate of the region where the ruins are located is broadly classified as Cw (7). That is, a mild-humid climate with a dry winter (June - September) and a wet summer (December - March) having about ten times the amount of precipitation of the dry season (8).

3. METHODOLOGY

This research employed a combination of results from field measurements of total solar energy at Machu Picchu and a computer program. The measurements of solar energy were conducted by the author on various occasions since 1978. The instrument used was a Kipp-Zonen pyranometer with a recording device. The computer program SOLAR (9) was utilized to calculate the solar angles and the incident solar energy of all ten angles of the eight slope orientations for every hour of the day.

The computer program SOLAR uses well known equations to determine the position of the sun and the CEM model, which was developed and validated by Atwater and coworkers (10, 11, 12). Further discussion of the CEM model and the SOLAR program is outside the scope of this report.

A sensitivity analysis was conducted prior to computing the values of solar energy in order to determine the applicability of the CEM model in the present study. This analysis was carried out to evaluate the model's sensitivity to changes in hourly dew point temperature and atmospheric turbidity.

It was necessary to determine the accuracy of the model with respect to changes in hourly dew point temperature because such temperatures were obtained for Machu Picchu based on the sinusoidal approach. The maximum and minimum air temperatures and relative humidity from a ten-years climatic record collected by the Peruvian Weather Bureau (SENAMHI) at Machu Picchu, were used as the input in the sinusoidal approach. Also, this analysis was conducted to account for possible errors from readings during the observation period. The study of changes in turbidity was useful in determining a turbidity factor for Machu Picchu, since no turbidity was established for the site during previous field work.

The dew point temperature for every hour of the day was changed by ± 5.0 °C at 1.0 °C increments. Therefore, a full range of 10.0 °C was considered as the possible error. The atmospheric turbidity was increased from 0.1 to 0.5 at 0.1 intervals. These turbidity factors represent background and polluted urban environment (9).

The results of the sensitivity analysis show that the model is not sensitive to changes in dew point temperature, while highly sensitive to different turbidity. There is a decrease in the total solar energy of about 1.6% (14.37 W/m^2 = 0.02 ly/min) and of approximately 3.6% (33.36 W/m^2 = 0.05 ly/min) with an increase and decrease of 5.0 C at noon, respectively. A total decrease of 1.6% (17.0 W/m^2 = 0.024 ly.min) is determined for the entire data set.

However, there is a decreease of 23.3% (218.62 W/m^2 = 23.7 ly/min) with an increase in turbidity from 0.1 to 0.5 at noon. The results of the sensitivity analysis is presented in Figure 1A and 1B, respectively.

The turbidity factor for Machu Picchu was determined by analysing the correlation between measured and computed values with turbidity factor increase of 0.025. The turbidity that gave the highest correlation (r= 0.997) between measured and computed total solar energy on a horizontal surface was equal to 0.175. Therefore, this value was employed in the computation of the incident solar energy of the aforementioned slopes. The correlation between measured and computed total solar energy for a typical clear day at Machu Picchu is shown in Figure 1C.

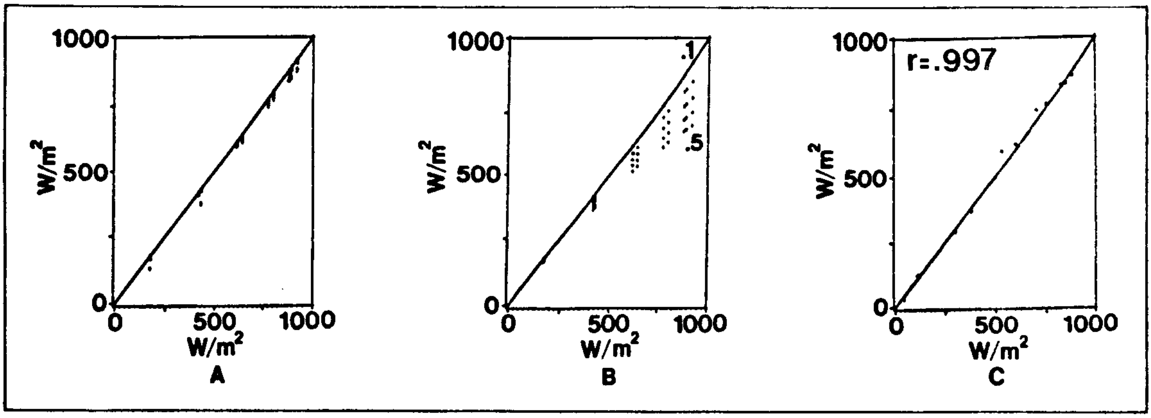


Fig. 1. Sensitivity analysis of dew point temperature (A) and turbidity (B), and correlation between measured and computed total solar energy (C).

The errors accrued from the usage of inadequate dew point temperatures were disregarded. It is worthwhile to note that the model used performed very well under the environmental conditions of Machu Picchu.

4. RESULTS

This section is divided into two parts which are presented bellow.

4.1 Solar Angles

The sun rises at 5:24 and 6:34 on the summer and winter solstices, respectively. The results of the zenith and azimuth solar angles are shown in Figure 2A and 2B for the before-mentioned solstices. The solar zenith angles are 10.35 and 36.65 degrees during the summer and winter, respectively. Therefore, the solar altitude is 79.65 degrees in the summer and 53.35 degrees in the winter. That is the sun is higher in the summer and lower in the winter.

Sunrise occurs at 23.0 South of East and 26.0 degrees North of East during the summer and winter solstices, respectively. Sunset takes place at 23.0 degrees South of West and 26.0 degrees North of West during the summer and winter solstices, respectively. Furthermore, the sun is in the southern sky in the summer and in the northern sky in the winter at noon. The apparent path of the sun at Machu Picchu is portrayed in Figure 2C.

4.2 Incident Solar Energy

Figures 3 to 18 show the incident solar energy for the before-mentioned eight slope orientations with angles ranging from 0.0 to 90.0 degrees for every hour of a typical summer and winter day with clear sky. The summer and winter graphs of slopes with the same orientation are side-by-side for easy seasonal comparisson.

The total solar radiation arriving on a horizontal surface ranges from 77.90 to 1,037.20 W/m^2 (0.11 to 1.48 ly/min) at 06:00 and 12:00, respectively, on a summer day. On the other hand, it ranges from 127.63 to 800.30 W/m^2 (0.18 to 1.15 ly/min) at 07:00 and 12:00, respectively, during a winter day.

The amount of incident solar energy of each slope orientation and angle is obviously a function of the position of the sun in the sky, which was described in the above section. Therefore, the slope orientations of south, east, and southeast receive the greatest amount of solar energy during the summer. On the contrary, the north, east, and northeast are collecting the highest amount of solar energy during the winter. Moreover, the slopes that receive the highest hourly values of solar energy are southeast at 30.0 degrees (1,061.08 W/m^2 at 11:00) and northeast at 50 degrees (1,007.74 W/m^2 at 10:00), during the summer and winter, respectively. A detailed discussion of the incident solar energy of each slope orientation for every hour of a summer and winter day would be lengthy and tedious, and it is avoided here. Further comparisson of can be easely carried out by visually inspection of the solar energy graphs.

However, it is of interest to analyze the daily total amounts of incident solar energy of each slope. These values are shown in Figures 19 and 20 for summer and winter conditions. The horizontal surface receives a daily amount of 8,421.96 W/m^2 (12.08 ly/nim) during the summer and 5,773.73 W/m^2

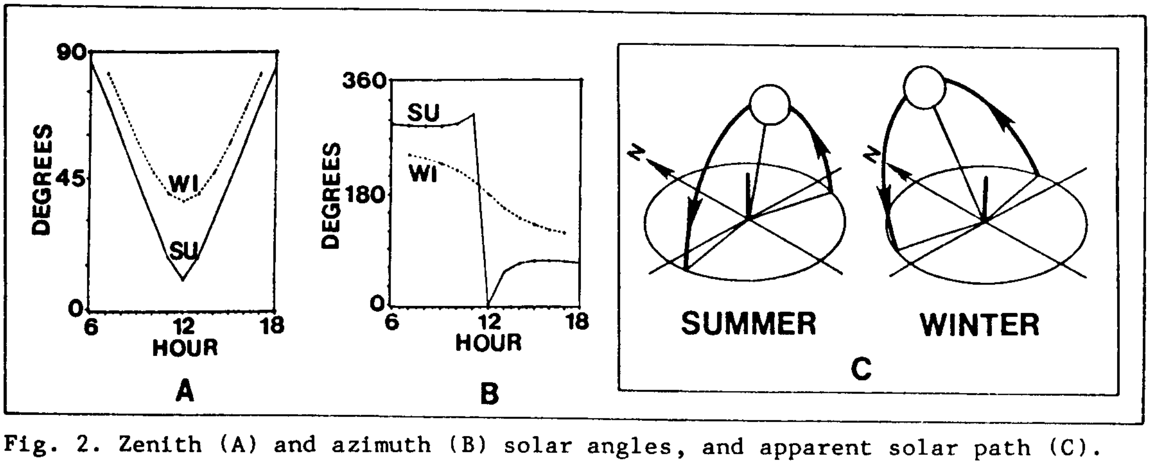


Fig. 2. Zenith (A) and azimuth (B) solar angles, and apparent solar path (C).

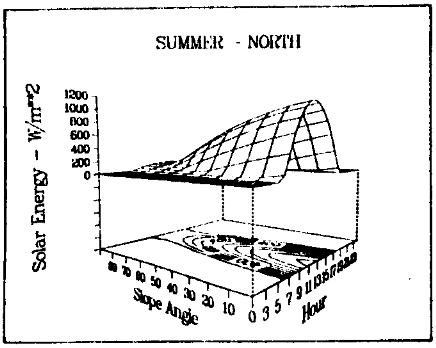
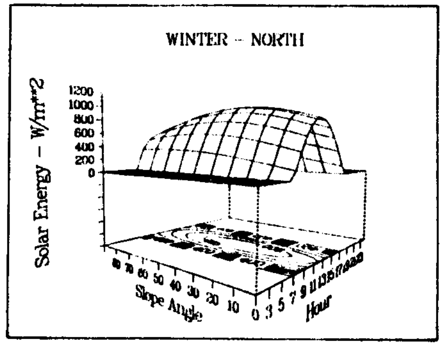


FIG. 11



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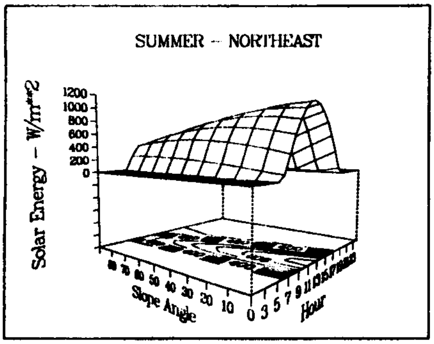

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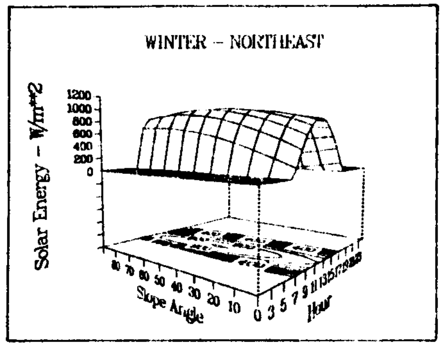

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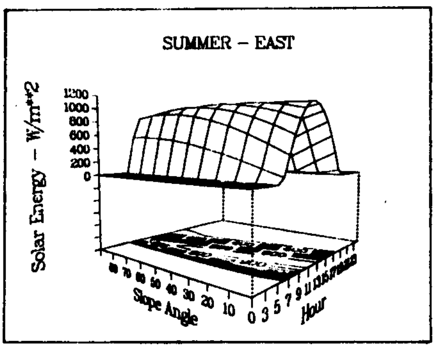

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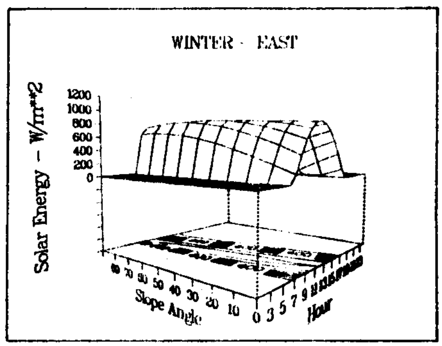

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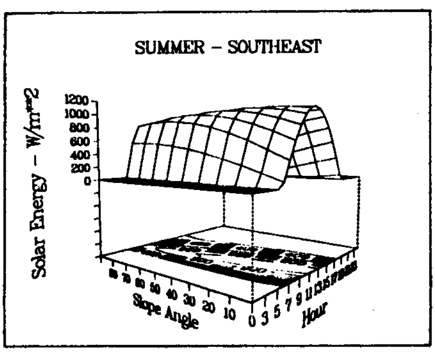

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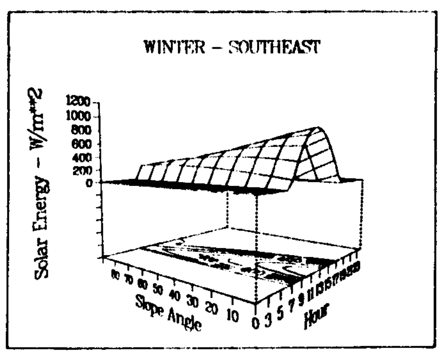

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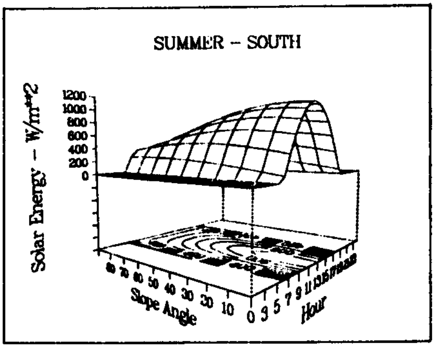

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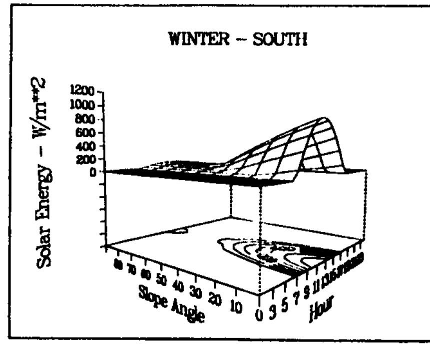

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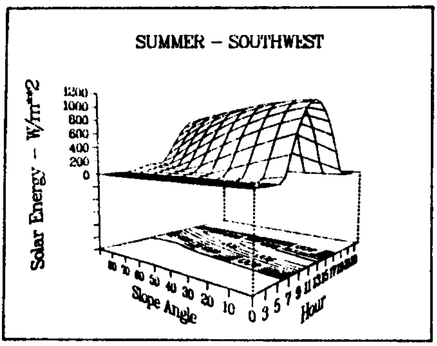

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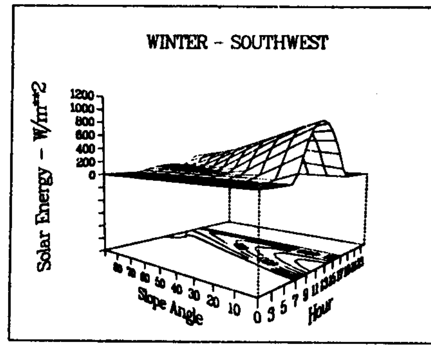

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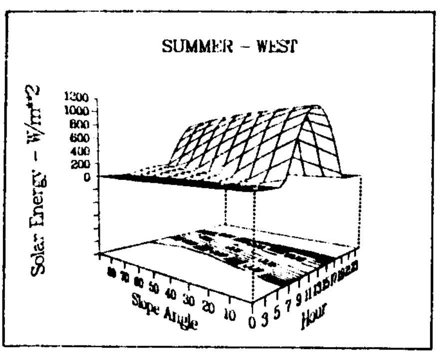

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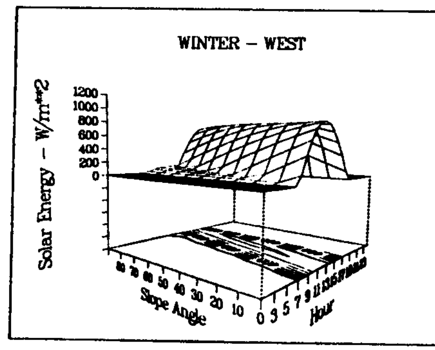

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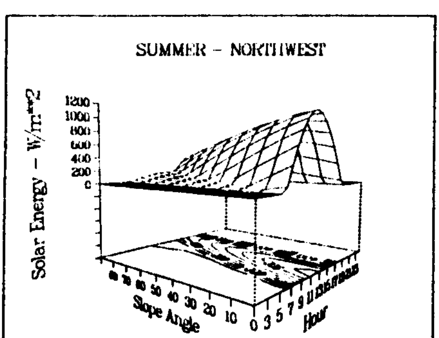

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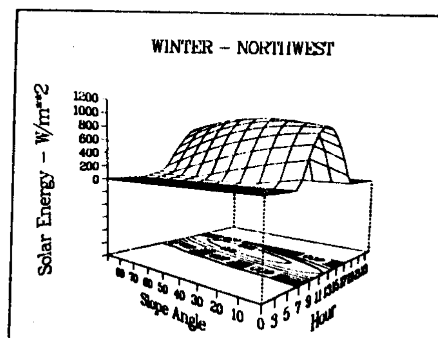
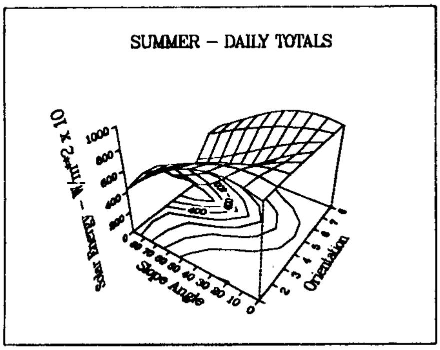


FIG. 10

(8.28 ly/min) during the winter. Moreover, the same slopes that collect the highest hourly values also have the greatest daily amounts. During summer, the south, east, and southeast slopes at 30 degrees receive 8,984.55, 7,855.34, and 8,619.99 W/m^2 (12.88, 11.26, and 12.36 ly/min), respectively. During the winter, the north, east, and northeast slopes at 50 degrees receive 7,978.77, 6,962.65, and 6,882.86 W/m^2 (11.44, 9.98, and 9.87 ly/min), respectively. The daily values for other slopes can be read from the figures. The orientation numbers 1 to 8 refer to south to southeast in a clockwise faction.



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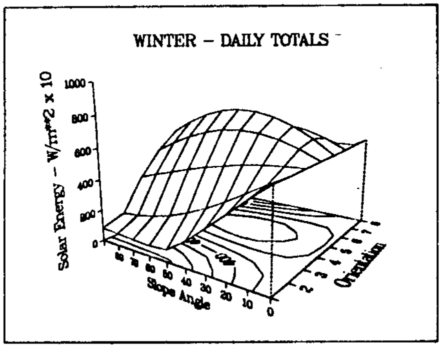

FIG. 20

5. CONCLUSIONS

The results presented in this study show that the builders of Machu Picchu had an understanding of the solar-terrestrial relationships at the site. The ruins are oriented Northeast, which maximizes winter solar gain when it is most needed. The results support the author's observations at Machu Picchu (1). A report on the solar-building associations is underway.

The computer program used gave fairly accurate results when compared with the measured values. The type of analysis conducted here can be very useful in contemporary building design.

6. ACKNOWLEDGEMENTS

The author is grateful to Prof. Werner Terjung, Geography Department, UCLA, for his guidance, comments, and encouragement which made this study possible. I would like to thank Dr. Jean Lanat, Peruvian Geophysical Institute, who provided me with a pyranometer. I am obliged to the UCLA Fellowship and Financial Aid Offices for financial support and the Office of Academic Computing for computer time and consulting. This research had the logistic support of the following institutes in Peru: IGP, INC, SENAMHI.

7. REFERENCES

(1) Chohfi, R. Identification of passive solar principles at Machu Picchu, Peru, PROCEEDINGS, 12th Annual Passive Solar Conf., 510 (1987).

(2) Pease, F. Dios creador andino, Mosca Azul Ed., Lima (1973).

(3) Demarest, A. The nature and antiquity of the Andean high god, Peabody Mus. Monogr., Harvard Univ., (1981).

(4) Bingham, H. Machu Picchu, a citadel of the Incas, Yale Univ. Press, New Haven (1930).

(5) Bowman, I. Andes of Southern Peru, Henry Holt and Co., New York (1916).

(6) Humboldt, A. von. Essai politique sur le royaume de la Nouvelle-Espagne, Bey F. Schoell (1811).

(7) Köppen, W. Klima der Erd, Justus Prestes, Darmstadt (1954).

(8) Strahler, A. Elements of physical Geography, John Wiley & Sons, New York (1979).

(9) Terjung, W. An outline of boundary layer climatology, UCLA Academic Publ. Services, Westwood (1980).

(10) Atwater, M./P. Brown. Numerical computations of latitudinal variation of solar radiation for an atmosphere of varying opacity, J. APPL. MET., 23, 289 (1974).

(11) Atwater, M./J. Ball. A numerical solar radiation model based on standard meteorological observations, SOLAR ENERGY, 21, 163 (1978).

(12) Atwater, M./P. Lunde. A cloud-cover model producing results equivalent to measured radiation data, PROCEEDINGS, Int. Cong. of Int. Solar Energy Soc., Atlanta, GA, 2203 (1979).