NOTES

A Comparison of Computed and Observed Insolation under Clear Skies over the Pacific Ocean[1]

R. K. REED

Pacific Marine Environmental Laboratory, NOAA, ERL, Seattle, WA 98105

R. E. BRAINARD

NOAA Corps, Assigned to Air Resources Laboratories, NOAA, ERL, Boulder, CO 80303

28 October 1982 and 24 February 1983

ABSTRACT

In an effort to verify computational methods for ocean heat budgets, observations of insolation under clear skies for 26 days were compared with values computed by a formula previously derived from the *Smithsonian Tables.* The agreement between the observations and formula was within 2.0% for three groups of data over the Pacific between 10°S and 47°N. Random and systematic errors in the formula appear to be insignificant in these regions, but its validity is uncertain at higher latitudes.

1. Introduction

The insolation reaching the sea surface is typically a large portion of the exchange of energy between the ocean and atmosphere, and there is particular concern about the methods used for deriving this flux (Weare *et al.*, 1981). Gaining a better understanding of oceanic heat budgets is a major emphasis of investigations such as NOAA's EPOCS (Equatorial Pacific Ocean Climate Studies) and NSF's TROPIC HEAT. Hence, if these studies are to yield realistic results, insolation must be derived with reasonable accuracy.

Recently, Reed (1982) compared the results from six years of measurements of insolation at sea with empirical formulas. [These are the formulas recommended by Reed (1977) and used in the large-scale heat budget study by Weare *et al.* (1981).] The differences between computed and measured insolation in the data means (of three spatially averaged groups composed of subgroups of 5–27 days duration) were 1–3% (with standard deviations of 10–15%), and it was concluded that the cloud factor used is generally applicable over the oceans. This comparison does not provide independent evidence for the validity of the formula used for computing insolation under clear skies, however. Verification of this clear-sky formula, which was originally based on data in the *Smithsonian Meteorological Tables* (List, 1958) with a transmission coefficient of 0.7, is partially provided by observations over an area near the Hawaiian Islands (G. Seckel, NOAA, National Marine Fisheries Service, personal communication), by limited data at ocean weather station P (Ashburn, 1963), and by data from coastal sites in the National Weather Service network (Reed, 1977). It is important that verification of clear-sky formulas and cloud factors be obtained separately because it may become desirable to alter some, but not all, steps in a procedure. EPOCS observations aboard the NOAA Ship *Discoverer* in 1982, when combined with earlier, more limited data from the NOAA Ship *Oceanographer,* can provide a direct comparison with the clear-sky Smithsonian formula (Seckel and Beaudry, 1973).

The reason for concentrating on the Smithsonian formula here is that a previous comparison (Reed, 1977) suggests that it is the most realistic and easily useable one available for a wide range of oceanic conditions. Clear-sky values from the work of Kimball, Mosby, Berliand and Laevastu (see Reed, 1977) are appreciably greater for most solar altitudes than the Smithsonian formula, which is in good general agreement with the available measurements at coastal sites. The expression derived by Lumb (1964) from data at North Atlantic ocean weather stations, however, gives results quite close to the Smithsonian formula, except at latitudes poleward of about 45°. [A formula by Zillman (1972) was not compared, but its values at higher latitudes are close to Lumb's.] At present, it is unclear whether the values from the Smithsonian formula, which are lower by about 10%, or those from Lumb's or Zillman's expression are most realistic at

---

[1] Contribution No. 624 from the Pacific Marine Environmental Laboratory.

high latitudes, and the data here cannot answer this question.

2. Data and methods

The data used are 11 days of clear-sky insolation measurements taken on the *Oceanographer* from July 1975 to March 1981 in the area bounded by 3°S–46°N and 106–125°W, and 15 days on the *Discoverer* during February–May 1982 in the region from 10°S to 47°N and 79°W to 178°E. The criteria for the values chosen were mean cloud cover, based on hourly estimates, of 0.25 or less and smooth analog traces of insolation that are characteristic of clear skies. The individual observed daily values and those computed by the Smithsonian formula are contained in Table 1.

The Smithsonian formula (Seckel and Beaudry, 1973) is shown in (1) with the values of the coefficients for two latitude bands:

$$Q_0 = A_0 + A_1 \cos\phi + B_1 \sin\phi + A_2 \cos 2\phi + B_2 \sin 2\phi. \quad (1)$$

The coefficients have the following values for the latitude ranges shown.

Latitude 20°S–40°N	Latitude 40°N–60°N
$A_0 = -15.82 + 326.87 \times \cos L$	$A_0 = 342.61 - 1.97L - 0.018L^2$
$A_1 = 9.63 + 192.44 \times \cos(L + 90)$	$A_1 = 52.08 - 5.86L + 0.043L^2$
$B_1 = -3.27 + 108.70 \times \sin L$	$B_1 = -4.80 + 2.46L - 0.017L^2$
$A_2 = -0.64 + 7.80 \times \sin 2(L - 45)$	$A_2 = 1.08 - 0.47L + 0.011L^2$
$B_2 = -0.50 + 14.42 \times \cos 2(L - 5)$	$B_2 = -38{,}79 + 2.43L - 0.034L^2.$

Here Q_0 is the clear-sky mean daily insolation (W m^{-2}) and $\phi = (t - 21)(360/365)$, where t is time of year (days) and L the latitude.

On the *Oceanographer* an Eppley model 8-48 pyranometer was mounted on a leveled post on the forepeak of the ship; the installation on the *Discoverer* was identical to that on the *Oceanographer*, but an Eppley Precision Spectral Pyranometer was used. (The pyranometers were not kept perfectly level at sea, but high-frequency pitch or roll variations as great as 5° were rare in the relatively calm seas during

TABLE 1. Daily values of insolation under clear skies observed aboard the NOAA ships *Oceanographer* and *Discoverer* over the Pacific Ocean. Values computed from the Smithsonian formula are also shown, and the percent differences between computed and observed values are given.

Date	Position		Observed insolation (W m^{-2})	Computed insolation (W m^{-2})	Computed minus observed (%)
	Latitude	Longitude			
20 Jul 75	45.0°N	124.0°W	328*	345	+4.9
21 Jul 75	45.0°N	124.0°W	326*	344	+5.2
22 Jul 75	45.0–46.0°N	125.0°W	326*	342	+4.7
16 May 77	37.8–38.8°N	122.9–124.5°W	345*	341	−1.2
16 Nov 78	33.3–34.6°N	118.5–120.8°W	168	159	−5.7
26 Aug 79	32.3–32.6°N	120.4–120.5°W	293*	313	+6.4
26 Jan 81	28.0–30.7°N	116.2–116.8°W	188	186	−1.1
27 Jan 81	22.0–24.9°N	114.8–115.4°W	212	219	+3.2
04 Feb 81	0.0	110.2–110.3°W	308	319	+3.4
16 Feb 81	13.0–13.9°N	106.0–108.2°W	274	286	+4.2
15 Mar 81	0.3–2.7°S	109.9–110.0°W	314	331	+5.1
09 Feb 82	45.2–47.1°N	126.7–129.6°W	127	116	−9.5
20 Feb 82	27.5–29.4°N	115.6–116.3°W	239	231	−3.5
22 Feb 82	19.9–21.5°N	108.3–110.3°W	264	269	+1.9
23 Feb 82	17.0–18.4°N	104.0–105.9°W	272	281	+3.2
24 Feb 82	14.1–15.5°N	99.6–101.6°W	275	290	+5.2
26 Feb 82	8.7–9.9°N	91.9–93.5°W	305	308	+1.0
27 Feb 82	6.0–7.3°N	87.9–89.8°W	316	316	0.0
16 Mar 82	10.2–10.3°S	79.4–79.6°W	315	329	+4.3
26 Mar 82	2.0–4.4°S	81.9–82.5°W	313	328	+4.6
29 Mar 82	0.0–0.2°N	85.2–88.7°W	321	329	+2.4
01 Apr 82	1.0–2.0°N	94.9–95.1°W	321	328	+2.1
07 Apr 82	0.3–1.2°S	90.1–91.0°W	313	324	+3.4
12 May 82	0.0	148.0–150.7°W	318	303	−5.0
17 May 82	0.0	174.1–176.6°W	308	300	−2.7
18 May 82	0.0	179.5°W–178.3°E	307	300	−2.3

* Original values based on the IPS 56 Scale were adjusted to the Absolute Scale by increasing them by 2.5% (see Table 2).

TABLE 2. Information on pyranometers used aboard the NOAA ships *Oceanographer* and *Discoverer*, July 1975–May 1982.

Serial no.	Type	Calibration date	Source of calibration and scale	Calibration factor ($\times 10^{-6}$ V W^{-1} m^2)
12299	8-48	Dec 74	Eppley (IPS 56)	10.93
		Dec 75	Eppley (IPS 56)	10.97
		Jan 78	ERL (Absolute)	10.56
12536*	8-48	Dec 74	Eppley (IPS 56)	10.57
		Dec 79	ERL (Absolute)	10.30
13035F3**	PSP	Jan 82	ERL (Absolute)	6.98

* Used March 79–November 81. ** used during 1982.
Acronymns: PSP—Eppley Precision Spectral Pyranometer; IPS 56—International Pyroheliometric Scale of 1956; ERL—NOAA's Environmental Research Laboratories calibration facility.

the measurements reported here.) The instruments were calibrated on the international reference scale (Absolute Scale), or the values were later converted to that scale (by increasing them by 2.5%) for those pyranometers originally calibrated on the IPS 56 Scale (see Table 1 and Table 2 for detailed information on instruments). Daily total insolation was derived by accumulating the signal from sunrise to sunset with an electronic integrator, except that the analog traces were manually digitized during a period on the *Discoverer* when the integrator malfunctioned. On each vessel the system was carefully maintained: the analog record was annotated, the integrator output was recorded, and the pyranometer dome was cleaned frequently.

3. Results

A plot of the observed insolation and insolation under clear skies computed from the Smithsonian formula (Seckel and Beaudry, 1973; Reed, 1977) is presented in Fig. 1. Different symbols were used for the values in different latitude bands (grouped roughly as "tropical" and "mid-latitude") as indicated on the figure. Initially, we were concerned that the last three days of data on the *Discoverer* might have been affected by the dust cloud from the eruption of El Chichon volcano; the observed values (12, 17 and 18 May 1982; see Table 1) average slightly more than the computed values, however, and our observations were on the equator, whereas the volcanic plume at that time had remained mainly north of the equator.[2]

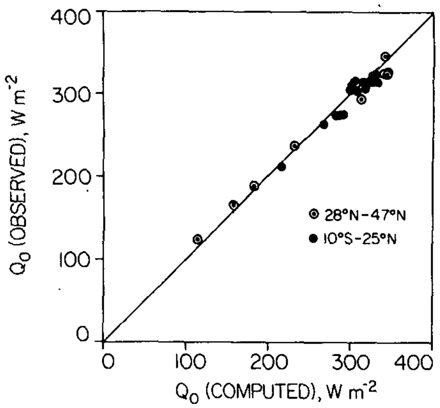

FIG. 1. Plot of clear-sky insolation (W m^{-2}) computed with the Smithsonian formula versus observations from the NOAA ships *Oceanographer* and *Discoverer* between 79°W and 178°E, July 1975–May 1982.

A comparison of computations with the Smithsonian formula and observed clear-sky values is shown in Table 3. The data are grouped by latitude ("tropical" and "mid-latitude") as in Fig. 1. All but four of the tropical values are from the *Discoverer* during February–May 1982. The mid-latitude group has a mean difference between computed and observed insolation of 0.0%, but the 95% confidence interval of the mean indicates that the sample and population means may differ by 4.3% because of the relatively large standard deviation and the small number of values. The relatively large standard deviation (5.6%) appears to result partially from systematic seasonal variations over this region near the west coast of North America; in summer (July 1975 and August 1979; see Table 1) observed values were about 5% less than those computed, but in fall and winter (November 1978, January 1981 and February 1982; see Table 1) observed values averaged 5% more than those from the Smithsonian formula. This behavior has been noted before (Reed, 1977) and appears to result from haze in marine air in summer and from relatively dry, continental air over the ocean during clear skies in winter.

TABLE 3. Comparison of computed and observed insolation under clear skies. The observed data are from the NOAA ships *Oceanographer* and *Discoverer*, July 1975–May 1982. The tropical data were located between 79°W and 178°E, and the mid-latitude observations were in the region 116–130°W.

		Insolation difference: Computed minus observed		
Sample	Days	Mean difference (%)	Standard deviation (%)	95% confidence interval of mean (%)
All data, 10°S–47°N	26	+1.3	4.1	1.7
Tropical, 10°S–25°N	17	+2.0	2.9	1.5
Mid-latitude, 28°N–47°N	9	0.0	5.6	4.3

---

[2] According to *Transactions American Geophysical Union*, 29 June 1982.

Of the tropical values, 11 were from south of the intertropical convergence zone near 8°N (Miller and Feddes, 1971). The variability of daily differences in insolation is less (standard deviation = 2.9%) for the tropics than for the mid-latitude group. The mean observed insolation is 2.0% less than the computed insolation, and this value is significant at the 95% confidence level. The fact that observed values are slightly less than those computed suggests that the marine air in this equatorial region has somewhat more water vapor than that accounted for by the transmission coefficient of 0.7 in the Smithsonian formula.

Use of the standard deviations in Table 3 would indicate that the standard error (at 95% confidence limits) in a computed monthly mean clear-sky insolation would vary between 1 and 2%. This error is insignificant compared to that in the monthly insolation computed with a cloud factor (see Reed, 1977, 1982). The small mean difference (2.0%) in the tropical data is only barely significant statistically (see Table 3). Adjustment of the Smithsonian formula to the Absolute Scale would decrease the disparity here but would increase it elsewhere; a larger source of variability is the constant transmission coefficient (0.7) used. The differences are quite small, though, and it appears that the Smithsonian formula (Seckel and Beaudry, 1973; Reed, 1977) provides a realistic estimate of insolation under cloudless skies in mid-latitudes and the tropics. Additional observations of insolation at sea under clear skies would provide a more comprehensive verification, however, especially at higher latitudes.

Acknowledgments. We thank the officers and crews of the NOAA ships *Oceanographer* and *Discoverer* for obtaining the data at sea. Thomas G. Jackson of the Pacific Marine Environmental Laboratory installed and maintained the equipment aboard the vessels. Gunter Seckel of the National Marine Fisheries Service provided information and advice. Carol H. Pease of the Pacific Marine Environmental Laboratory gave us useful ideas and comments. Data collection aboard the *Discoverer* was supported by NOAA's Equatorial Pacific Ocean Climate Studies program.

REFERENCES

Ashburn, E. V., 1963: The radiative heat budget at the ocean-atmosphere interface. *Deep-Sea Res.*, **10**, 597–606.

List, R. J., 1958: *Smithsonian Meteorological Tables,* 6th rev. ed. Smithsonian Institution, 527 pp.

Lumb, F. E., 1964: The influence of cloud on hourly amount of total solar radiation at the sea surface. *Quart. J. Roy. Meteor. Soc.*, **90,** 43–56.

Miller, D. B., and R. G. Feddes, 1971: *Global Atlas of Relative Cloud Cover, 1967–1970.* U.S. Department of Commerce and U.S. Air Force, Washington, DC, 237 pp.

Reed, R. K., 1977: On estimating insolation over the ocean. *J. Phys. Oceanogr.*, **7,** 482–485.

——, 1982: Comparison of measured and estimated insolation over the eastern Pacific Ocean. *J. Appl. Meteor.*, **21,** 339–341.

Seckel, G. R., and F. H. Beaudry, 1973: The radiation from sun and sky over the North Pacific Ocean (abstract). *Trans. Amer. Geophys. Union,* **54,** 1114.

Weare, B. C., P. T. Strub and M. D. Samuel, 1981: Annual mean surface heat fluxes in the tropical Pacific Ocean. *J. Phys. Oceanogr.*, **11,** 705–717.

Zillman, J. W., 1972: A study of some aspects of the radiation and heat budgets of the Southern Hemisphere ocean. Meteor. Study No. 26, Bureau of Meteorology, Department of the Interior, Canberra, 562 pp.