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An Evaluation of Formulas for Estimating Clear-Sky Insolation Over the Ocean

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AN EVALUATION OF FORMULAS FOR ESTIMATING CLEAR-SKY INSOLATION OVER THE OCEAN

R. K. Reed

Recent oceanic data and observations from five coastal sites in the National Weather Service solar radiation network are compared with a formula for computing clear-sky insolation derived from the Smithsonian Meteorological Tables, using a transmission coefficient of 0.7. The results are generally in good agreement, and they suggest that this formula is suitable for computing insolation over the ocean for a wide range of latitudes. The comparison also indicates that a correction to the formula for middle latitudes is not warranted.

The one other formula in good agreement with that from the Smithsonian Tables is one derived by Lumb; Laevastu's formula is only acceptable at sun angles less than 50°, and Berliand's estimates are too high at all solar altitudes. The formula from the Smithsonian Tables can be used to compute insolation over the oceans with a random error of estimate probably not exceeding 5% for periods of a few days or longer.

1. INTRODUCTION

The insolation (direct solar and diffuse sky radiation) reaching the sea surface is a large and variable term in the heat budget of the upper ocean. In order to determine the relevant processes (surface exchange, advection, and diffusion) affecting the heat content of the ocean (and its changes over periods of a few days to a few months), it is imperative that one be able to specify the insolation with reasonable reliability. Since measurements over oceanic areas are normally lacking, the radiation is usually computed with formulas.

A number of formulas have been derived, both from theoretical and empirical studies, which allow estimates of insolation at the sea surface using inputs such as solar altitude, duration of daylight, and cloud cover. Unfortunately, many of the results show very poor agreement, presumably because of factors such as faulty instrument response or calibration, variations in atmospheric turbidity, and improper assumptions. The typical marine atmosphere in the absence of clouds has a fairly stable water vapor content and is less affected by industrial pollutants than air over land surfaces (Ainsworth and Monteith, 1972). Thus it should be possible to estimate insolation over the ocean, or at least over sub-areas, with reasonable confidence if reliable measurements were available to derive valid approximations.

This study is concerned with testing the various formulas with available data to find those suitable for estimating insolation under clear skies with a reasonable reliability (± 5-10%). It does not deal with the reduction of insolation caused by clouds or with radiation reflected from the sea surface. The methods to be used are as follows: (1) the various formulas that have been used to estimate insolation over the oceans are reviewed; (2) in order to obtain an adequate data base, observations at coastal sites in the National Weather Service network are compared with formulas derived from the Smithsonian Meteorological Tables; and (3) the various formulas are intercompared to assess their adequacy and to resolve a deficiency in those from the Smithsonian Meteorological Tables.

2. REVIEW OF PREVIOUS WORK

Many formulas have been derived from insolation data over land; because of large differences in attenuation through terrestrial and marine atmospheres, however, they will not be dealt with here unless they have been widely used for oceanographic studies. An early synthesis of oceanic data was that of Mosby (1936), who obtained measurements at high latitudes on the North Polar Expedition in 1918-19. Insolation was related to the mean solar altitude and a factor that was a function of turbidity of the air. Although this formula was apparently used in earlier heat budget studies (Dietrich, 1963), doubt exists about the validity of the factor used by Mosby and how it may vary seasonally or with latitude. An early work of considerable impact was that of Kimball (1928). He gave monthly values of insolation, based on theoretical concepts and the data then available from land and sea, at numerous locations in both hemispheres. Kimball's values were used extensively and were adopted for oceanic heat budget studies, for example, by Masuzawa (1954) and Tabata (1958). Laevastu (1960) derived the first formula based on oceanic measurements over a large area. He determined a relation between total daily insolation, duration of daylight, and noon solar altitude for angles up to 75°; a different relation was given for altitudes greater than 75°.

Perhaps the most widely used estimate of clear-sky insolation is that derived by T. G. Berliand (Budyko, 1974). It is in the form of a table giving values for each month at 5° intervals of latitude. According to Budyko, it was prepared by plotting the observed daily values at the available stations, which were presumably almost entirely over land. Since data on clouds were frequently not available, clear-sky insolation was estimated by drawing a curve based on the maximum values for each day; this frequently overestimates the insolation, however, because data obtained on days with the lowest, rather than the average, atmospheric turbidity tend to be selected. These data, however, have been applied to studies of oceanic regions (Wyrtki, 1965; Roden, 1974).

Lumb (1964) derived a formula from data at the British-manned Atlantic Ocean weather stations. He mainly used data at station J (52.5°N, 20°W) but also used data at stations A (62°N, 33°W), I (59°N, 19°W), and K (45°N, 16°W). Lumb's formula for clear-sky conditions is:

$$Q_0 = 1.94s\ (0.61 + 0.20s), \tag{1}$$

where Q_0 is clear-sky insolation (cal cm^{-2} min^{-1}) and s is the sine of the solar altitude. In deriving the formula, variations in earth-sun distance were not considered, and mean hourly values of sun angle were used to determine s. Hence to determine daily insolation it is necessary to sum the hourly computations. Lumb's (1964) formula was recommended for oceanic applications by James (1966).

Seckel and Beaudry (1973) used data obtained aboard the *RV Townsend Cromwell* over a sizeable area near the Hawaiian Islands. They found that these data were in good agreement with the data given in the Smithsonian Meteorological Tables (List, 1958), using an atmospheric transmission coefficient of 0.7. For higher latitudes they used some computed results at ocean weather station P (50°N, 145°W) given by Tabata (1964), which agreed fairly closely with Berliand's values. These results indicated that values derived from List (1958) with a transmission coefficient of 0.7 needed to be increased, and 30°N was chosen as the boundary to apply this mid-latitude correction. The computational methods given by Seckel and Beaudry are as follows:

$$Q_0 = A_0 + A_1 \cos\phi + B_1 \sin\phi + A_2 \cos 2\phi + B_2 \sin 2\phi \tag{2}$$

Latitude 20°S to 40°N	Latitude 40°N to 60°N
$A_0 = -32.65 + 674.76 \cos L$	$A_0 = 707.25 - 4.07\ L - 0.038\ L^2$
$A_1 = 19.88 + 397.26 \cos (L + 90)$	$A_1 = 107.50 - 12.09\ L + 0.088\ L^2$
$B_1 = -6.75 + 224.38 \sin L$	$B_1 = -9.90 + 5.08\ L - 0.035\ L^2$
$A_2 = -1.32 + 16.10 \sin 2\ (L - 45)$	$A_2 = 2.22 - 0.96\ L + 0.022\ L^2$
$B_2 = -1.04 + 29.76 \cos 2\ (L - 5)$	$B_2 = -80.08 + 5.02\ L - 0.070\ L^2$

Here Q_0 is the clear-sky insolation in cal cm^{-2} day^{-1}, ϕ is $(t-21)(360/365)$ where t is the time of year in days, and L is the latitude. The mid-latitude correction (north of 30°N) to Q_0 is $Q_0' = 33.2 + 1.011\ Q_0$. Formula (2) will generally be referred to as the Smithsonian formula or the Smithsonian formula with mid-latitude correction when this is applied.

Brief mention will be made of efforts in our laboratory to evaluate the formulas with measurements of insolation on selected cruises of the NOAA ship *Oceanographer*, on oceanographic buoys, and at shore stations near the ocean. A variety of recording techniques were used, but in all cases Eppley Model 8-48 pyranometers were used which had been calibrated by the manufacturer within less than a year of use. Reed and Halpern (1975) compared data from six clear days in 1973 off Oregon and found that the insolation was between 11 and 17% less (mean = 14%) than values computed with the Smithsonian formula with mid-latitude correction, and it was between 5 and 10% less (mean = 7%) than computed values without the mid-latitude correction. In addition, insolation during three clear days off Oregon in July 1975 was in each instance 14% less than computations by the formula with mid-latitude correction. On the other hand, data obtained in March and April 1974 in northwest Africa at 21°39'N, 16°59'W (on an open beach about 300 m from the water) were generally in good agreement with the Smithsonian formula. Data from 12 days when the analog traces indicated no significant cloud amounts were from 2% more to 7% less (mean = 2% less) than daily values calculated with the formula.

These limited oceanic data, however, do not really permit generalizations, and an effort was made to locate other sources of usable data. This led to investigating the feasibility of using data obtained at National Weather Service stations at coastal and insular locations. In following sections observations of insolation will be compared with the Smithsonian formulas because they are precise and convenient to use, and then the various formulas discussed above will be intercompared.

3. NATIONAL WEATHER SERVICE DATA

The National Weather Service has maintained a network of solar radiation stations in the United States and at other island stations for many years. A number of these stations are at coastal sites far removed from urban areas with large sources of aerosals so that the atmosphere there could be expected to be generally typical of that over the oceans. Also, at some sites visual observations of cloud cover are made every hour. Thus one should be able to use such data to derive daily insolation under clear skies, and the results could be compared with the various formulas.

Although data from other countries could also be used, this poses a number of problems. Data from the worldwide network are published (but without accompanying data on cloud cover) through sponsorship of the World Meteorological Organization; no detailed information on data quality is given, however, and it is known that this varies widely. Thus one would need to contact a large number of organizations in order to obtain the data and any information on data quality, which in many instances has not been fully investigated or documented. The data would also be in different formats, and computer processing of the data would be time-consuming and expensive. On the other hand, data from the United States and a number of island stations are all available from a single source (NOAA's National Climatic Center), in a single format for computer processing, and information is available on instrument calibrations and data quality. Finally, the United States data covers a major portion of the latitude range of the northern hemisphere so that one should be able to evaluate the applicability of various formulas to different latitudinal zones.

There are, however, difficulties in using the National Weather Service data. Flowers (1974) described a problem discovered in several Eppley pyranometers which were coated with Parson's black lacquer after early 1956. After several years of use, the coating on these instruments turned grey or green, and the sensitivity of the instruments decreased. The errors in some instances were as great as 20%, but the problem was not widespread in the data until about 1966 when a number of these instruments had been in use for several years. A different problem was discussed by Hanson (1974). The field instruments were calibrated in the Weather Service's integrating sphere with reference to working standards coated with lampblack and with Parson's black. The lampblack standards had equal sensitivity in the integrating sphere and in the sun, but the sensitivity of the Parson's black standards was approximately 7% too low in the sphere. Thus if the sensor surface of the field instrument and working standard were matched, there was no systematic error; if Parson's black field instruments were calibrated against lampblack standards, though, measurements of insolation with the field instrument were about 7% too high because of this "crossmatching" of sensor surfaces. Both of the sources of error just discussed (deterioration and crossmatching of sensor surfaces) are present in some of the archived data at the National Climatic Center, and only recently have efforts been started to correct the data base for these effects.

3.1 Methods of Data Analysis

Daily solar radiation (format 480) was obtained on magnetic tape from the National Climatic Center, Asheville, North Carolina. Average cloud cover during daylight hours is included in this format, except for a number of stations where the observations were not made. Originally a total of ten stations were selected for analysis on the basis of their location near coasts in a non-urban environment. Of these, only five were eventually used because three (Matanuska, Alaska; Hilo, Hawaii; and Canton Island) did not have cloud data on the tape, and two others (Swan Island and Wake Island) had very few data under clear skies. The data from the five stations used were listed for the period of record when the cloud cover was zero.

Information was then obtained from National Weather Service headquarters (Michael Riches, personal communication) on calibration factors of the instruments used and whether the sensor surfaces of instruments had been crossmatched during calibration. In using the data the following criteria were established: (1) data were not used for a period longer than two years after installation of recently calibrated instruments in the field; (2) if the instrument was not recalibrated after removal from the field so that changes in the factor could be assessed, data were not used for a period of longer than one year after instrument installation; (3) data were adjusted when significant changes (> 1%) occurred in the calibration factor, but they were not used if the changes exceeded 5%; and (4) data were reduced by 7% for those instruments that had crossmatched sensor surfaces during calibration. The stations used and their location are given in table 1, and the data periods used are listed with information on the instrument calibrations.

Table 1. Data used to obtain estimates of clear-sky insolation and information on calibration of the instruments.

Station	Location	Dates	Calibration Crossmatched	Check on Calibration Factor	Significant Change in Factor
Apalachicola, Florida	29°44'N, 84°59'W	22 Sept. 61- 11 May 63	Yes	Yes	1.000-1.019 times values
Santa Maria, California	34°54'N, 120°27'W	25 July 73- 28 June 74	No	No	-
Cape Hatteras, North Carolina	35°16'N, 75°33'W	17 Mar. 62- 24 Jan. 63	Yes	No	-
		24 Sept. 67- 15 Sept. 68	No	No	-
Astoria, Oregon	46°09'N, 123°53'W	18 Apr. 62- 5 Mar. 63	Yes	No	-
		16 Jan. 66- 4 Apr. 67	Yes	Yes	No
		30 June 67- 8 May 68	Yes	No	-
Annette Island, Alaska	55°02'N, 131°34'W	9 Jan. 68- 11 June 69	Yes	Yes	No

3.2 Presentation of Data

Clear-sky daily insolation for the periods used have been plotted against values computed with the Smithsonian formula. All values were used except a very few obviously erroneous values, the number of which are listed as excluded data in table 2. The mid-latitude correction was applied for all stations except for Apalachicola, Florida.

3.2.1 Apalachicola, Florida

The comparison for this station is shown in figure 1. In the mean, the observed values are 1% greater than the computed values. There is, however, appreciable "scatter" in the comparisons, with the standard deviation from the mean being ± 6%. There is also the suggestion of a trend in the deviations; in summer many of the observed values are lower than computed values while in winter the observed values tend to be higher. It is suspected that in winter the air over this site is mainly of continental origin (low moisture content and turbidity), whereas in summer it is of marine origin. Such a situation could plausibly alter the insolation as the data suggest.

3.2.2 Santa Maria, California

The data at Santa Maria are shown in figure 2. These data should be among the best in the Weather Service network because an Eppley precision spectral pyranometer was in use during the period of data used. This instrument generally has better cosine response and stability than the other Eppley pyranometers in the network (Hoyt, 1974). There is a small standard deviation from the mean difference, which implies that random errors in the data were small. It is strikingly evident also that the observed values are all less than the computed ones, with the mean difference being 8%.

3.2.3 Cape Hatteras, North Carolina

Data for two periods were used from this station and are presented in figures 3 and 4. The first group of data (1962-63) indicate that observed insolation was 8% less than the computed values, but the second group shows no mean difference between observed and computed values. Both sets of data have almost the same number of values, and both show approximately the same standard deviation from the mean (± 4%). In an effort to understand these differences, data from the upper-air soundings made at this site were examined. The mean vapor pressure from the surface to 600 mb (derived from the mean monthly data published in the Climatological Data National Summary) was 2 mb less for the second period than for the first; hence greater insolation did occur during the "drier" period. There are a number of uncertainties in making such inferences, however, and comparisons were not made for conditions above 600 mb.

Table 2. Comparison of clear-sky insolation at various sites obtained by the National Weather Service with that computed from the Smithsonian formula or the formula with mid-latitude correction.

Station	Dates	No. of Values	Mean Difference (formula—observed, %)	σ* (%)
Apalachicola	22 Sept. 61– 11 May 63	87 (1 excl.)	-1	±6.2
Santa Maria	25 July 73– 28 June 74	55	+8	±2.8
Cape Hatteras	17 Mar. 62– 24 Jan. 63	43	+8	±4.3
Cape Hatteras	24 Sept. 67– 15 Sept. 68	42 (3 excl.)	0	±4.2
Astoria	18 Apr. 62– 5 Mar. 63	13	+8	±3.8
Astoria	16 Jan. 66– 11 Apr. 67	16 (2 excl.)	+12	±2.8
Astoria	30 June 67– 8 May 68	24	+10	±2.1
Annette Island	9 Jan. 68– 11 June 69	42	+14	±11.0

*σ = standard deviation from the mean difference.

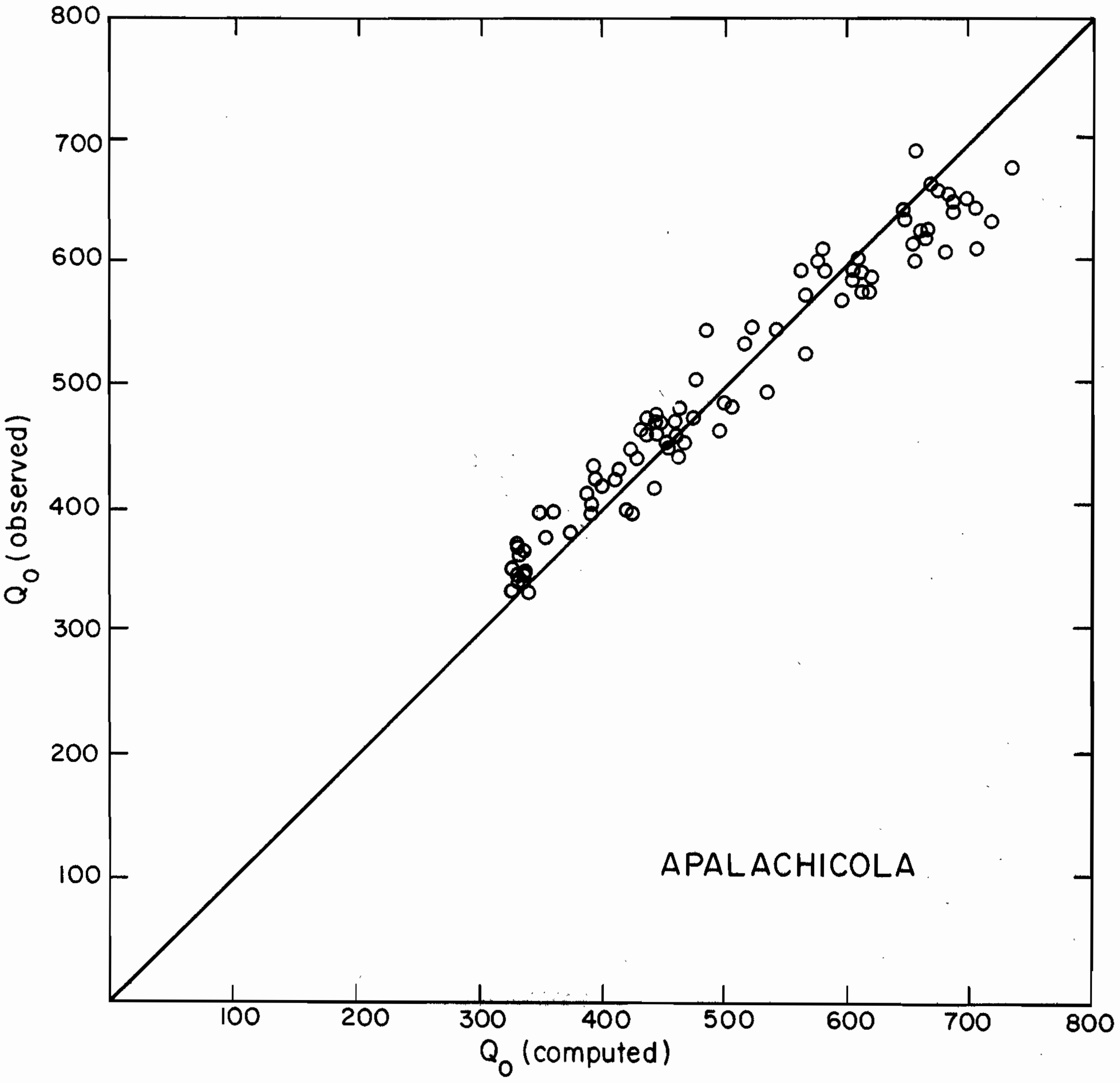

Figure 1. Comparison of observed clear-sky insolation (cal cm^{-2} day^{-1}) at Apalachicola, Florida (29°44'N, 84°59'W), with that computed from the Smithsonian formula for the period 22 September 1961 - 11 May 1963.

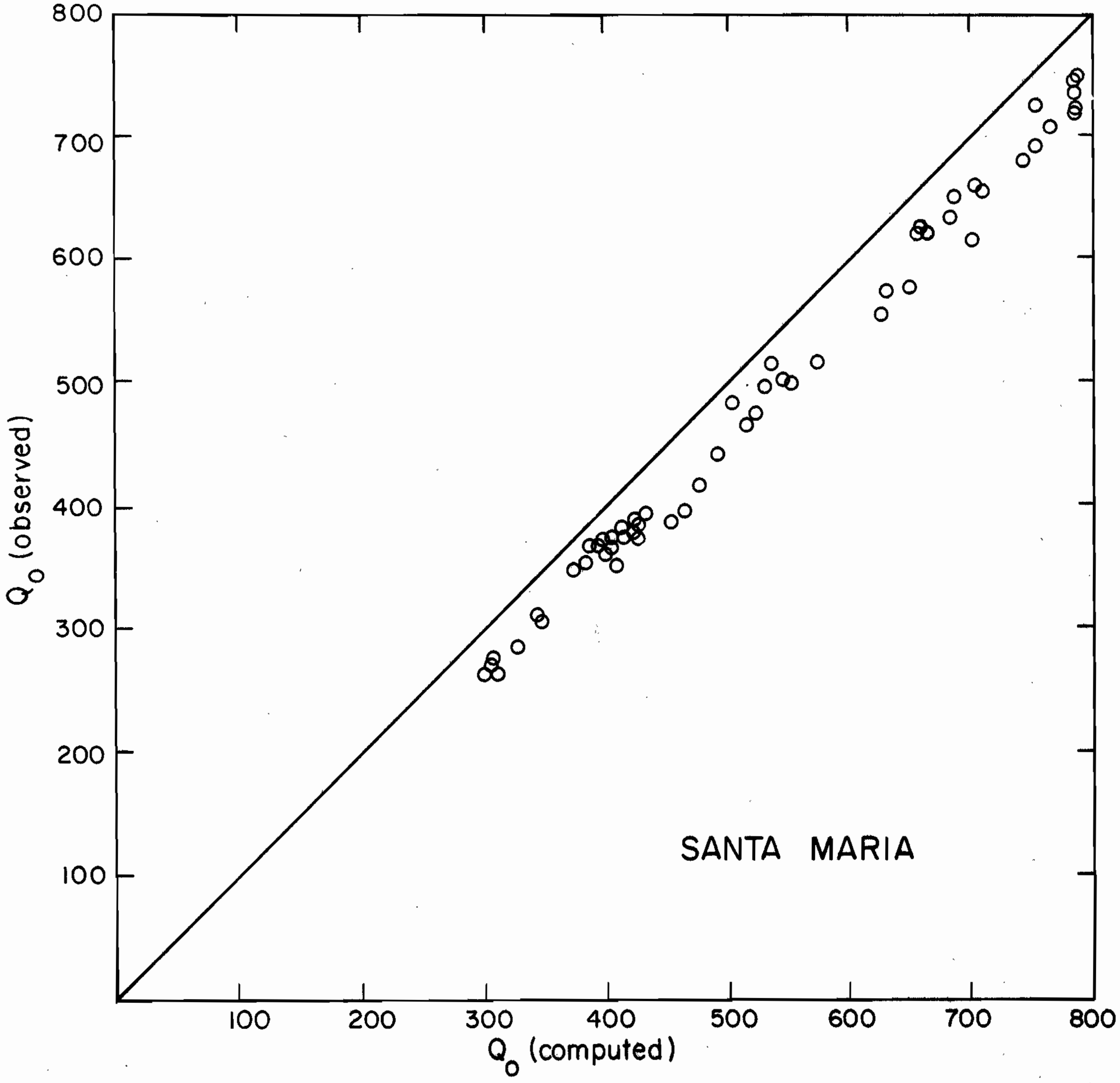

Figure 2. Comparison of observed clear-sky insolation (cal cm^{-2} day^{-1}) at Santa Maria, California (34°54'N, 120°27'W), with that computed from the Smithsonian formula with mid-latitude correction for the period 25 July 1973 - 28 June 1974.

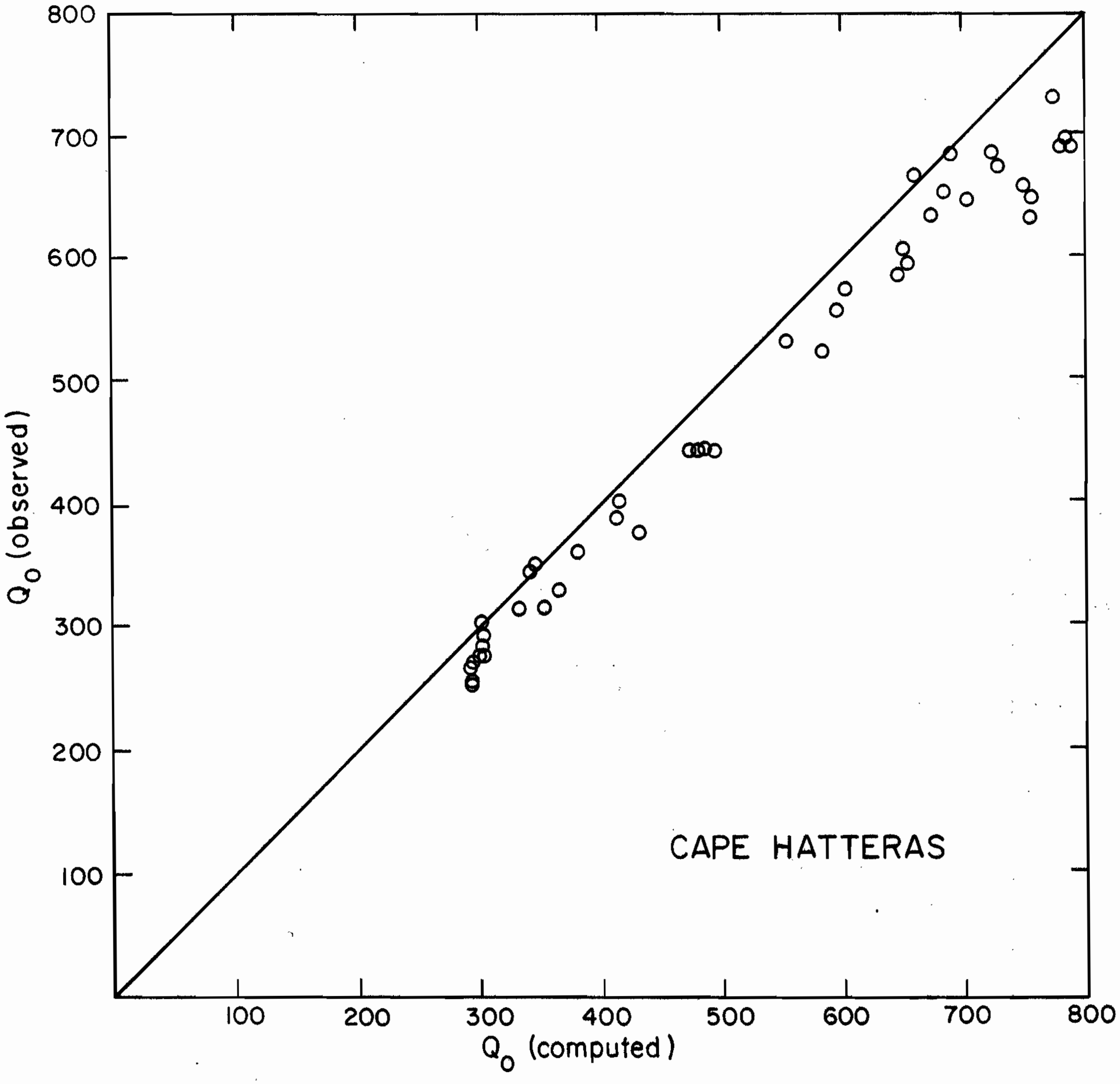

Figure 3. Comparison of observed clear-sky insolation (cal cm^{-2} day^{-1}) at Cape Hatteras, North Carolina (35°16'N, 75°33'W), with that computed from the Smithsonian formula with mid-latitude correction for the period 17 March 1962 - 24 January 1963.

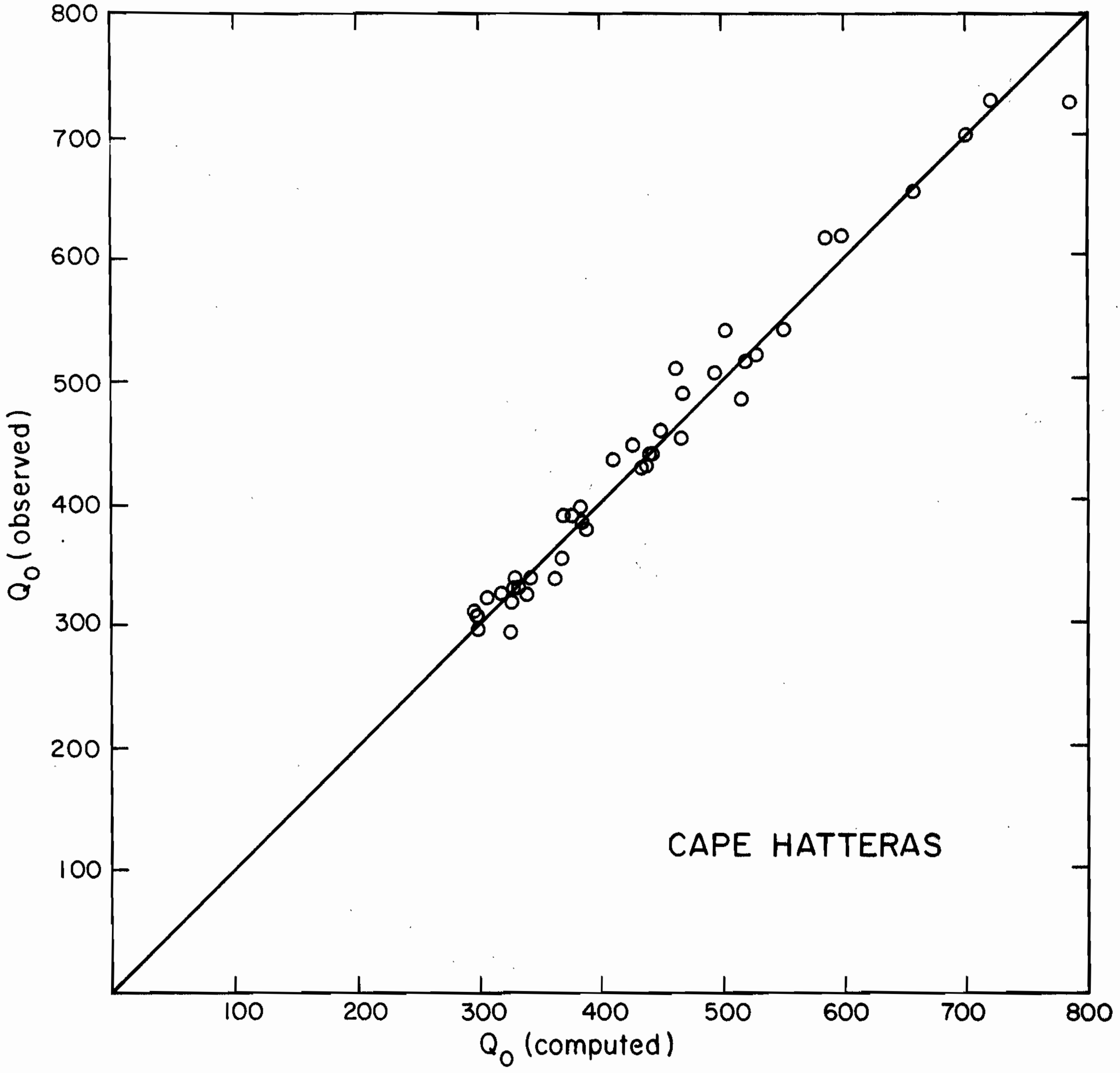

Figure 4. Comparison of observed clear-sky insolation (cal cm^{-2} day^{-1}) at Cape Hatteras, North Carolina (35°16'N, 75°33'W), with that computed from the Smithsonian formula with mid-latitude correction for the period 24 September 1967 - 15 September 1968.

3.2.4 Astoria, Oregon

Comparisons of observed and computed insolation for three periods at Astoria are shown in figures 5, 6, and 7. All of the periods reveal very similar differences between observed and computed values; that is, the observed values are appreciably less (between 8 and 12% in the mean) than those estimated by the formula. This condition is much like that found in the data discussed above that were observed off the coast of Oregon on buoys and aboard the NOAA ship *Oceanographer*.

3.2.5 Annette Island, Alaska

The data for this station are shown in figure 8. Here again, the observed values are appreciably less (mean = 14%) than the computed ones. This station has a very large standard deviation from the mean (± 11%), and this results at least in part from the seasonally varying effects of the mid-latitude correction. From figure 8 it is apparent that in summer (values > 500 cal cm^{-2} day^{-1}) the insolation is mainly between 5 and 10% less than computed values; in winter, however, the differences are frequently greater than 30%.

3.3 Summary of Data

The comparisons of the National Weather Service data with computations by the Smithsonian formula and the formula with mid-latitude correction are summarized in table 2. In general, the results indicate that the computed values are too high north of 30°N where the mid-latitude correction was applied. Except at Annette Island where wintertime insolation is very low, the computed insolation without the mid-latitude correction varies from about 6% to 12% less (in summer and winter, respectively) than that with the correction. This is about the magnitude of the differences indicated in table 2, which suggests that the mid-latitude correction should not be applied. (The exception to this trend at Cape Hatteras during 1967-68 was discussed previously, and it was suggested that the water vapor content of the air might have been relatively low. Other possible explanations are undetected errors in the calibration factor or crossmatched sensor surfaces, although Weather Service records indicated that they were not.) At Annette Island the percentage differences were much greater in winter than in summer, and one cannot reliably infer differences between the two formulas based on a single mean difference with data distributed unevenly by season. It was decided then to compare the observations at Annette Island directly with those of the Smithsonian formula without the mid-latitude correction. The comparisons were in closer agreement (mean difference = -7%) than the previous ones (mean difference = +14%), and these results are strongly influenced by a few winter data with small absolute differences which caused large percentage differences.

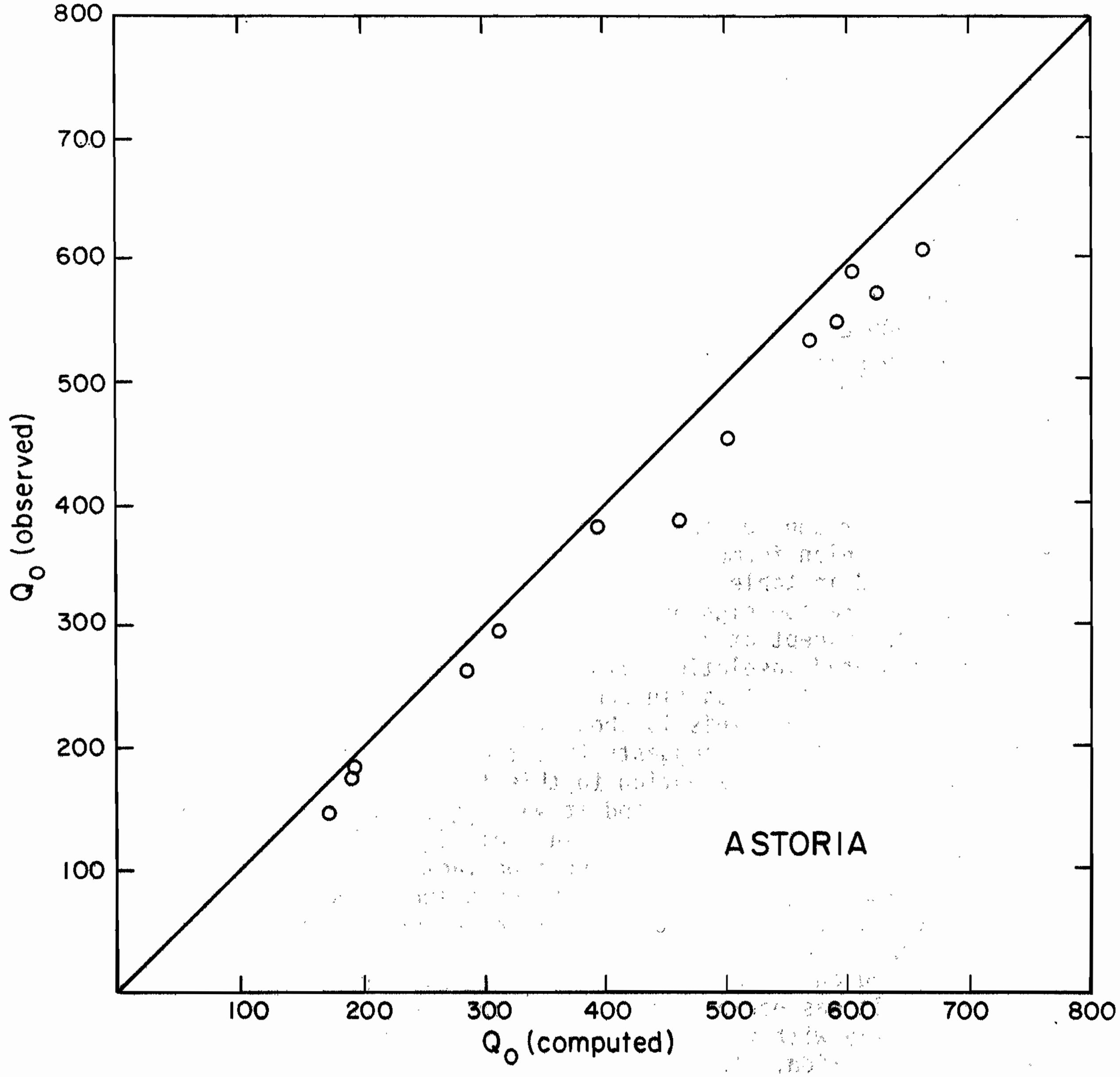

Figure 5. Comparison of observed clear-sky insolation (cal cm^{-2} day^{-1}) at Astoria, Oregon (46°09'N, 123°53'W), with that computed from the Smithsonian formula with mid-latitude correction for the period 18 April 1962 - 5 March 1963.

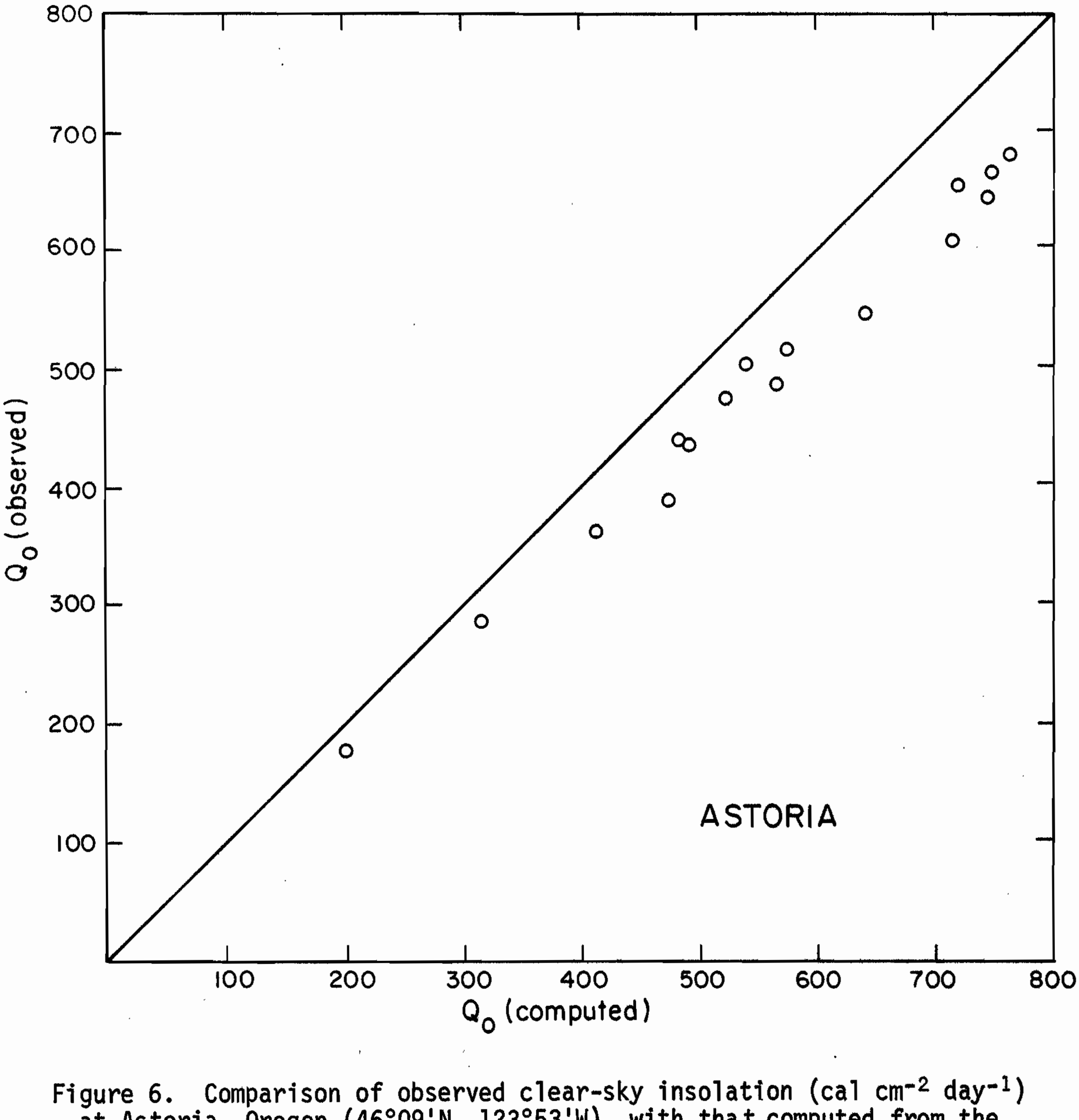

Figure 6. Comparison of observed clear-sky insolation (cal cm^{-2} day^{-1}) at Astoria, Oregon (46°09'N, 123°53'W), with that computed from the Smithsonian formula with mid-latitude correction for the period 16 January 1966 - 4 April 1967.

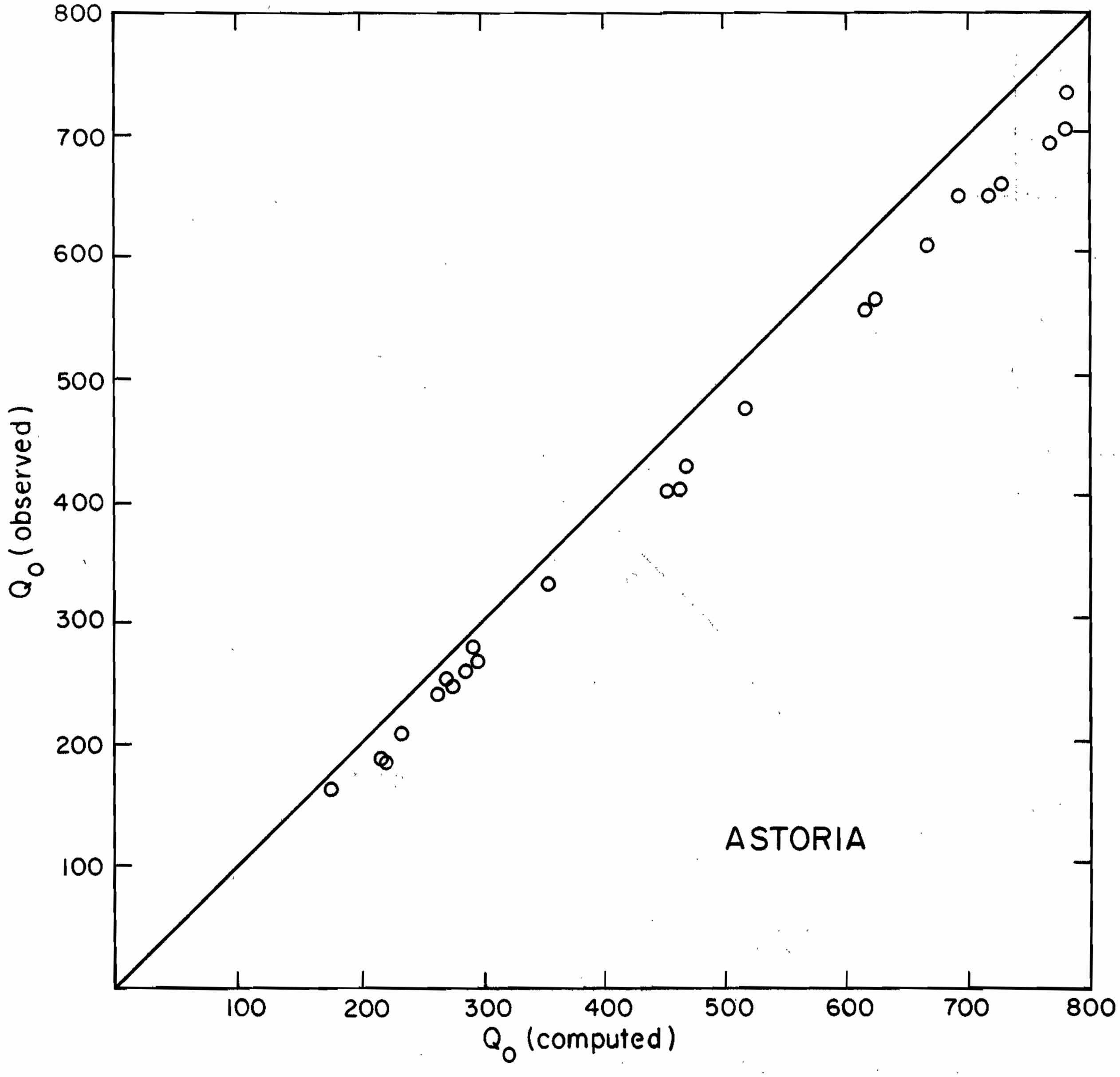

Figure 7. Comparison of observed clear-sky insolation (cal cm^{-2} day^{-1}) at Astoria, Oregon (46°09'N, 123°53'W), with that computed from the Smithsonian formula with mid-latitude correction for the period 30 June 1967 - 8 May 1968.

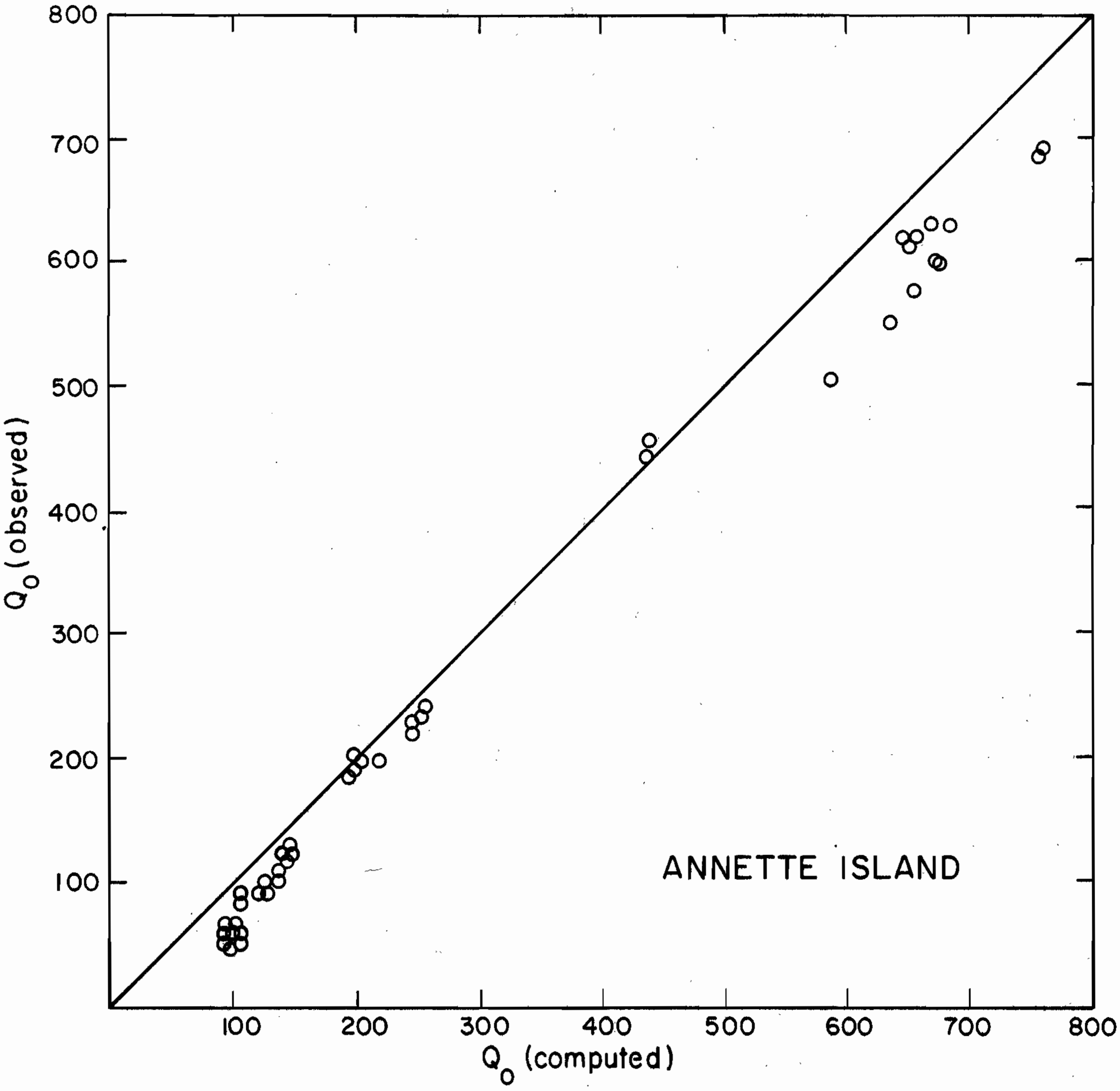

Figure 8. Comparison of observed clear-sky insolation (cal cm^{-2} day^{-1}) at Annette Island, Alaska (55°02'N, 131°34'W), with that computed from the Smithsonian formula with mid-latitude correction for the period 9 January 1968 - 1 June 1969.

3.4 Discussion of Errors

It is difficult to assess the reliability of estimates of clear-sky insolation with the Smithsonian formula. A crude estimate of the random error in an individual daily value can be obtained from the standard deviations of values from the mean differences between observed and computed insolation given in table 2. Most of these values are between 2 and 4% so that one could assume that the random error of estimate is 4-8% (two standard deviations at 95% confidence limits). The standard deviations at Apalachicola and Annette Island are larger than for the other stations; the data at Apalachicola, though, are believed to reflect the effects of varying continental and marine air while the large deviation at Annette Island is influenced appreciably, as noted above, by use of the mid-latitude correction. It is suggested then that an individual daily estimate of clear-sky insolation over the ocean should not generally have random errors greater than ± 8%. Typically, however, one makes estimates of insolation for periods of several days or longer so that the random error of estimate for even a few days should be less than 5%.

Systematic errors of estimate can also occur if the atmosphere becomes appreciably different than a typical marine atmosphere. This could happen as a result of outbreaks of continental air over the ocean in high latitudes or from large increases in water vapor caused by processes such as upwelling. The latter factor may have caused the low values off Oregon that were discussed above; two periods have had mean values 7% less than values computed with the Smithsonian formula without the mid-latitude correction.

4. INTERCOMPARISON OF VARIOUS FORMULAS

Although the data examined here suggest that the Smithsonian formula (with a transmission coefficient of 0.7) is valid over a wide range of latitudes (and that the mid-latitude correction should not be applied), some comparisons should be made of other formulas (or estimates) that have been widely used. This should permit determination of their suitability and may shed further light on the inapplicability of the mid-latitude correction.

Figure 9 compares the formulas or estimates discussed previously with the Smithsonian formula without the mid-latitude correction. The values were determined for mid-month at a latitude of 50°N. The observed values at ocean weather station P were derived from 16 clear-sky values during 1960-61 that were given by Ashburn (1963). Of the various estimates shown here, Kimball's (1928) are generally in poorest agreement with the Smithsonian formula. Both his values and those from Mosby's (1936) formula are appreciably larger than those from the Smithsonian formula. Berliand's values (Budyko, 1974), which have been widely used for ocean heat budget studies, are also appreciably greater than values computed with the Smithsonian formula except in summer. On the other hand, values from Laevastu's (1960) formula are close to those from the Smithsonian formula in winter,

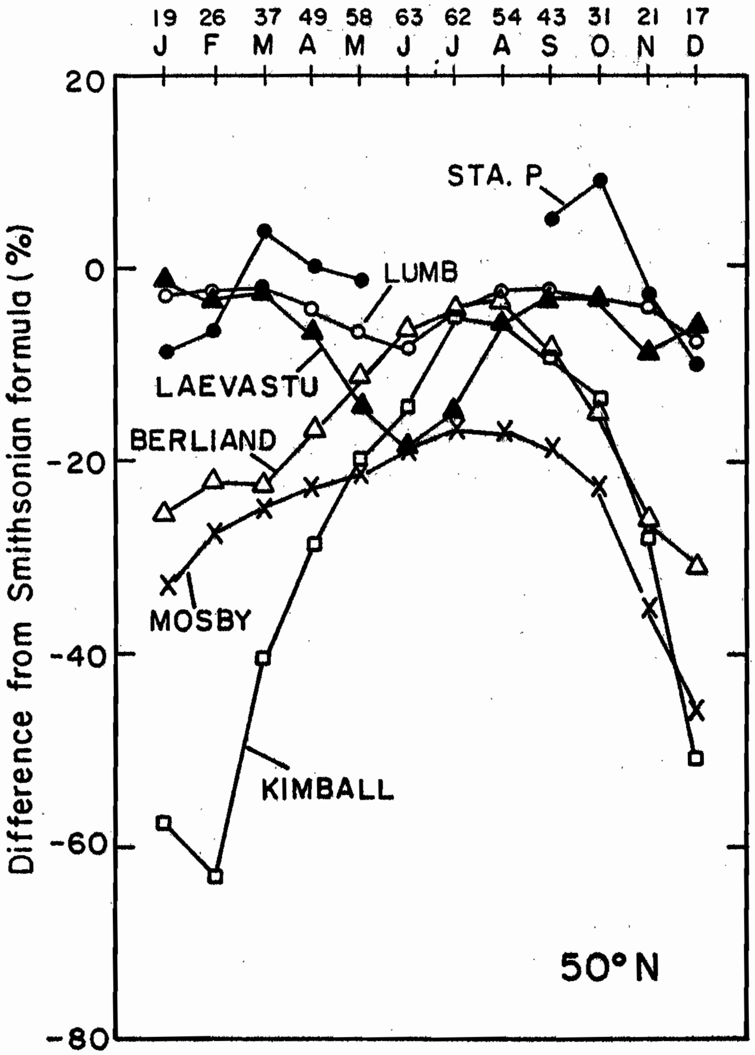

Figure 9. Comparison of clear-sky insolation formulas or estimates derived by Berliand, Kimball, Laevastu, Lumb, and Mosby with the Smithsonian formula (without the mid-latitude correction) for 50°N. Observed values at station P are also compared with the Smithsonian formula. Values were determined for mid-month, and the numbers shown over the months are noon solar altitude.

but the differences are large at the higher solar altitudes in summer. Of the various formulas, Lumb's (1964) is in best agreement with the Smithsonian formula at this latitude.

Although observed clear-sky values for ocean weather station P were not available for June, July, and August, during the rest of the year they are reasonably close on the whole to the computed values. There does, however, appear to be a tendency toward higher observed than computed insolation in winter, and rather similar behavior was observed in the data for Annette Island. If Lumb's (1964) formula (which was derived from oceanic data north of 45°N) were adjusted for the seasonally varying earth-sun distance, it would give results slightly greater than the Smithsonian formula in winter but within 5% of it at other times. The mid-latitude correction adopted by Seckel and Beaudry (1973) was based on computed data used at station P by Tabata (1964) and was supported by Berliand's results at 50°N. These data, though, give results that are higher than the observed clear-sky values at station P (or values computed with Lumb's formula) because they are based primarily on data over land where atmospheric attenuation of insolation was apparently less than through the moist marine air. Although it is suspected that the Smithsonian formula may slightly underestimate insolation at high latitudes in winter, use of the mid-latitude correction causes appreciable overestimates at all times.

Figures 10 and 11 present comparisons between the Smithsonian formula, Berliand's results, and Laevastu's and Lumb's formulas at 25°N and the equator respectively. As noted before, Kimball's (1928) values appear to appreciably overestimate the insolation, and Mosby's (1936) formula is not very satisfactory without further information on the turbidity factor for various latitudes; hence these estimates are not compared in figures 10 and 11. Berliand's results appear to generally be closer to the Smithsonian formula for higher solar altitudes than for lower ones (fig. 10), but just the opposite situation exists for Laevastu's (1960) formula. Laevastu's formula gives results that appear to be systematically high except at solar altitudes less than about 50°, and Berliand's values appear to be too high at all solar altitudes. On the other hand, Lumb's (1964) formula is in good agreement with the Smithsonian formula; the systematic seasonal differences shown in figures 10 and 11 are mainly the result of varying earth-sun distance which is not considered in Lumb's formula.

5. CONCLUSIONS

The various data examined here allow one to conclude that the Smithsonian formula (with a transmission coefficient of 0.7) provides a suitable estimate of clear-sky insolation through the marine atmosphere. It should be applicable from the equator to at least 60°N, but at the highest latitudes it may slightly underestimate the insolation in winter. One would presume that it should also be suitable for the southern hemisphere although it has not been tested against data there. Of the various other formulas and estimates examined, only Lumb's (1964) is in good agreement with the

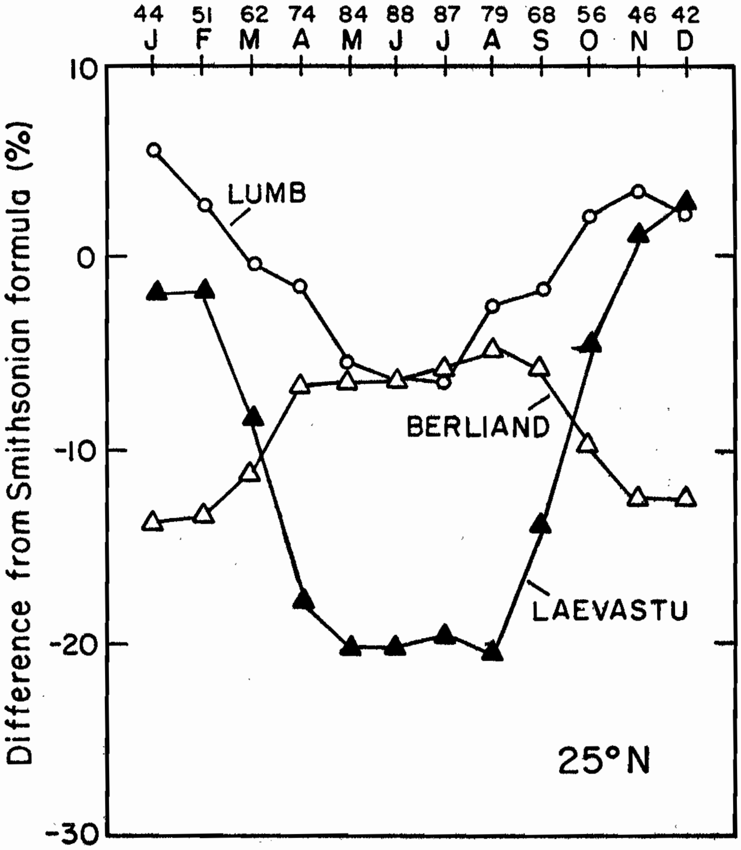

Figure 10. Comparison of clear-sky insolation formulas or estimates derived by Berliand, Laevastu, and Lumb with the Smithsonian formula for 25°N. Values were computed for mid-month, and the numbers shown over the months are noon solar altitude.

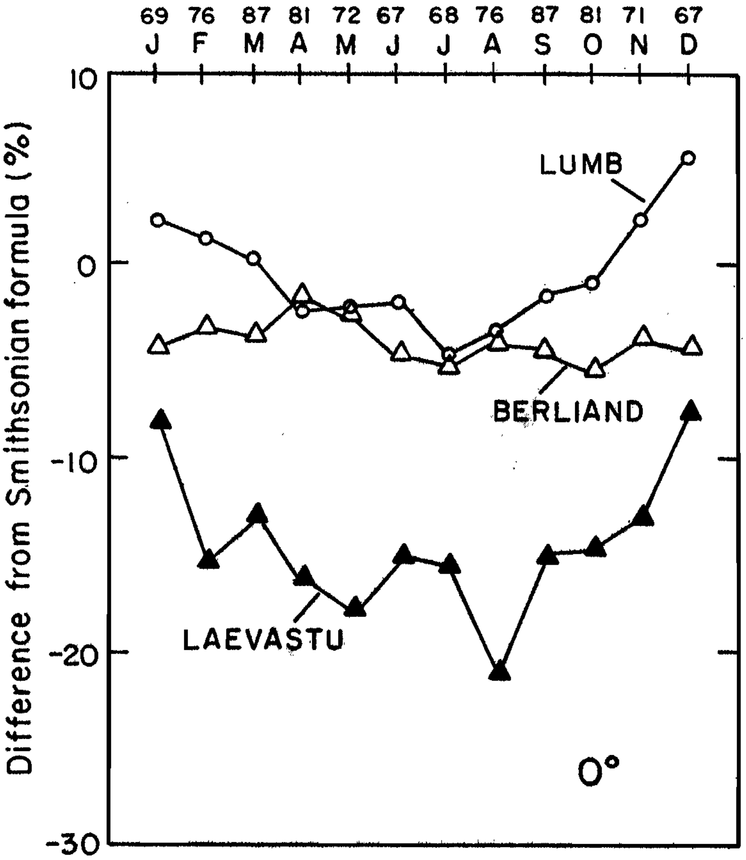

Figure 11. Comparison of clear-sky insolation formulas or estimates derived by Berliand, Laevastu, and Lumb with the Smithsonian formula for 0°. Values were computed for mid-month, and the numbers shown over the months are noon solar altitude.

Smithsonian formula; if Lumb's formula is used, it is recommended that corrections be applied for the variations in distance between the earth and sun. Berliand's values are systematically high by 5 to 25%, and Laevastu's are also too high except at sun angles less than about 50°.

In assessing short-wave radiation for heat budget studies of the ocean, one is concerned with the clear-sky insolation, the reduction in insolation caused by clouds, and the radiation reflected upward from the sea surface. This study deals with the first of these matters, and the methods of Payne (1972) are recommended for the computation of reflected radiation. The weakest link appears to be computation of the reduction of insolation by clouds. Research on this problem is underway, however; perhaps the best solution is relating insolation to cloudiness as determined from satellite data.

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