# Effective Cloudiness Derived from Ocean Buoy Data

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ABSTRACT

There is a need in the study of the dynamic aspects of radiation balance at the sea surface for cloud cover information on a finer scale than is presently available, especially for analyses of historic data. Although cloud cover is difficult to obtain without a human observer, or more recently without a satellite, insolation can be readily measured and recorded by an untended instrument. Cloud cover can then be estimated by using well-known formulas usually intended for calculating insolation from known cloud cover. An example of such a computation on a daily basis is presented here using insolation data from deep-moored instrument stations in the North Pacific Ocean. The effective cloudiness thus obtained is used to calculate the radiation balance at the sea surface.

## 1. Introduction

The investigation of oceanic thermal structure and its anomalous variations requires a detailed knowledge of the heat exchange between the ocean and the atmosphere. Accurate examination of this heat exchange depends in turn on careful determination of the incoming solar radiation and the outgoing long-wave radiation. Aside from astronomical factors, cloudiness is probably the most important parameter to be evaluated in the study of radiation balance at the sea surface. Clouds can reflect a large portion of the incoming radiation back to space and absorb and scatter a significant percentage of the remaining portion, thus greatly reducing the energy reaching the ocean surface. On the other hand, cloud cover also inhibits the escape of thermal energy from the ocean surface since water vapor is very opaque to infrared radiation. In a recent study, Schneider (1972) has pointed out that the effects of variation in cloud cover on the radiation balance and on the sea surface temperature may serve as a feedback mechanism in stabilizing the global climate. However, the dynamics of cloud physics and its coupled interrelationships with other meteorological factors such as wind, temperature and particulates are nonlinear and rather complicated. The amount of reduction in the incoming and outgoing radiations is a complex function of cloud characteristics. Three cloud characteristics are generally considered to be most influential in the radiation balance: cloud cover (fraction of the sky obscured by clouds), cloud type (thickness and moisture content of the cloud), and cloud height (height of top of cloud).

A few investigators (Lumb, 1964; Laevastu and Agres, 1966) have developed empirical formulas for solar radiation computations which take into account the above characteristics of clouds. Cloud data with these characteristics specified are difficult to obtain, however, so most of the commonly recognized empirical formulas are based on the single characteristic of cloud cover (Kimball, 1928; Black, 1956; Berliand, 1960; Laevastu, 1960; Tabata, 1964). Even this single characteristic has not generally been available over the open ocean except for large-scale spatial and temporal means, which are not very useful for investigating the dynamic aspects of the short-term energy balance (Laevastu, 1965). Daily cloud cover values from satellite composite pictures have recently become available, but there remains a need for determining cloudiness values that can be used for small-scale studies. This is especially true in analyzing historical data over the ocean where no reliable cloud cover data ever existed. One therefore has to rely on other means to evaluate cloudiness. One possible method would be to estimate the cloud cover from a comparison of observed solar radiation with the theoretical solar radiation for that time and place under cloudless conditions. In this paper, we present the results of such an estimate using insolation measured on board a cluster of buoys moored in the mid-latitude North Pacific Ocean. Three popular formulas for the calculation of insolation from cloud cover are used. The formulas are solved for cloud cover and applied to the insolation data; the results are compared to cloud cover derived from satellite data and are used in calculating radiation balance at the sea surface.

## 2. Estimated cloudiness formulas

Budyko (1956) and others (e.g., Wyrtki, 1965; Johnson *et al.*, 1965; Seckel, 1970) have used the formula of Berliand (1960) for the evaluation of insolation from sun and sky, i.e.,

$$Q_s = Q_0(1 - aC - bC^2), \tag{1}$$

where $Q_0$ is the total incoming solar radiation under cloudless conditions (hereafter called clear-sky insolation), $a$ and $b$ are empirical coefficients, and $C$ is the cloud cover in decimal fractions. The coefficients $a$ and $b$ are both approximately 0.38 for the latitude of buoy deployment.

Laevastu (1960) has proposed an empirical formula which was the best fit to his field data:

$$Q_s = Q_0(1 - 0.6C^3), \tag{2}$$

where $Q_0$ is obtained from the table presented by Berliand (1960). Laevastu also used another empirical formula for the calculation of short-term values of $Q_0$; the monthly means of these values agree with the values given in Berliand's table.

Based on direct radiation measurements from ocean station Papa (50N, 145W), Mateer (1963) derived a formula that relates insolation to the daytime cloud amount by a rectangular hyperbola, while Ashburn (1963) arrived at an exponential relationship. Tabata (1964) has analyzed the insolation data from the same station for a much longer period than Mateer or Ashburn and found the following formula to be the best regression fit:

$$Q_s = Q_0\,(1 - 0.756C + 0.00357h), \tag{3}$$

where $h$ is the noon sun's altitude which allows for the absorption and scattering of solar energy due to the variation of the path length of sun's rays through the atmosphere. Note that (3) has not been statistically verified by field data for days of cloud cover less than 0.5.

Eqs. (1), (2) and (3) for incoming solar radiation are plotted as a function of cloud cover in Fig. 1. Clearly, Laevastu's formula gives the highest insolation values and Tabata's the lowest with Berliand's in between except under complete overcast conditions when Berliand's values are slightly lower than those of Tabata. Note that insolation computed from Laevastu's formula varies little with cloudiness where sky cover is less than about one-third.

Solving the insolation formulas for estimated cloud cover yields

$$C = \{[a^2 + 4b(1-Q)]^{\frac{1}{2}} - a\}/2b \quad \text{(Berliand, 1960)} \tag{4}$$

$$C = [(1-Q)/0.6]^{\frac{1}{3}} \quad \text{(Laevastu, 1960)} \tag{5}$$

$$C = (1 - Q + 0.00357h)/0.756 \quad \text{(Tabata, 1964)} \tag{6}$$

where $Q$ has been substituted for the ratio $Q_s/Q_0$.

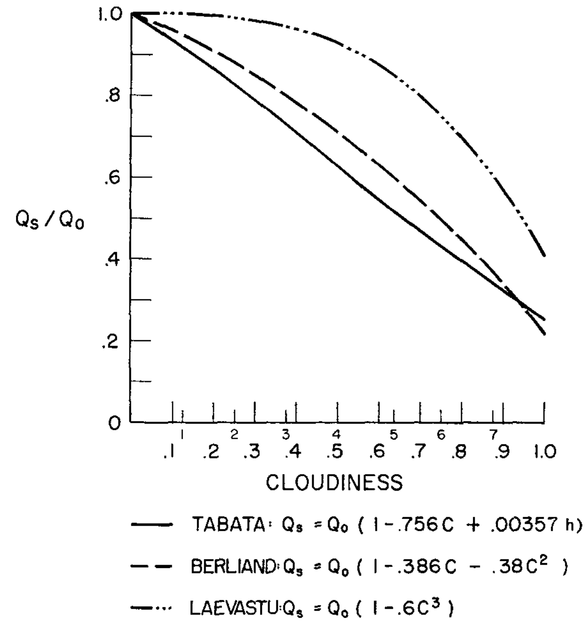


FIG. 1. $Q_s/Q_0$ vs cloudiness.

The original formulas are intended for use with time scales of a day to several days. The cloud cover calculations in this paper are done on a daily basis using a $Q_0$ obtained from the Milankovitch formula (List, 1958)

$$Q_0 = \frac{J_0}{D}\int_{\tau_1}^{\tau_2} \alpha^{\sec z} \cos z\, dt. \tag{7}$$

The formula was integrated from sunrise ($\tau_1$) to sunset ($\tau_2$) for each day of the study period to provide daily values of $Q_0$. $D$ is the radius vector of the earth (distance from center of the earth to the center of the sun expressed in terms of length of the semimajor axis of the earth's orbit), $z$ the solar zenith angle, and $J_0$ the solar constant for which a value of 1.94 cal cm$^{-2}$ min$^{-1}$ was used.

The atmospheric transmission coefficient $\alpha$ allows for the depletion of solar radiation from absorption and scattering; its value is unity in the absence of atmosphere. In this study, a value of 0.84 was chosen for $\alpha$ on the basis of clear-sky insolation data from Sable Island, which is at about the same latitude as the buoy cluster area. Fig. 2 shows the measured insolation (bars) together with the clear-sky insolation as calculated from the Milankovitch formula with $\alpha = 0.84$ (bell-shaped curve). The Sable Island data were provided by the meteorological branch of the Department of Transportation of Canada. This value of $\alpha$ gives almost exactly the same monthly insolation for this latitude as is given in Berliand's table.

## 3. Buoy insolation data

Deep-moored instrument stations have been deployed in the eastern North Pacific Ocean since 1968

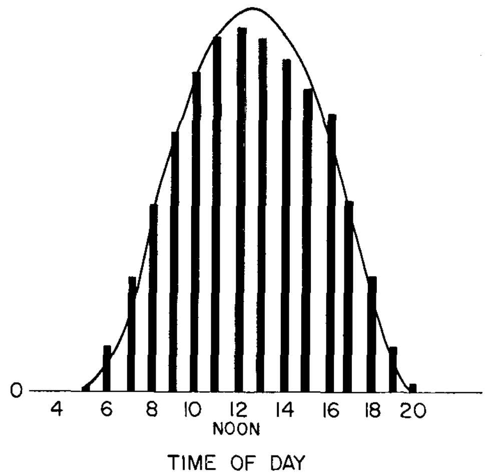


FIG. 2. Hourly insolation measured at Sable Island on a cloudless day (bars) and hourly clear-sky insolation computed from Malankovitch's formula with $\alpha=0.84$ (curve).

(Isaacs, 1968; Devereux *et al.*, 1969). A cluster of four of these buoys recorded hourly values of insolation during the period 1 October 1969–November 1969. The cluster was centered at approximately 43N, 158W and consisted of one large telemetering ocean data station (buoy *Alpha*) and three small taut-moored Scripps catamaran buoys as shown in Fig. 3. Eppley pyrheliometers were mounted on the buoy masts at 4 and 16 m above the sea surface on the small and large buoys respectively. The instruments measured total insolation from sun and sky through 180° with an essentially flat response between 0.375 and 2.5 $\mu$m with a slight drop of about 5% at 3.5 $\mu$m in the electromagnetic spectrum. This response curve results in the measurement being low but not by more than 1% of the total direct solar radiation (Hess, 1959). Buoy motions can cause measurement losses but these too are small except in very stormy weather. A constant rolling and pitching of 15° from the buoy upright position, for example, would introduce an error of less than 1%. Other sources of error are very difficult to determine (Ashburn, 1963). Calibrations made after application of sea water spray show that the measurement degradation may be as large as 9% of the total direct insolation when the sensor is heavily coated with salt.

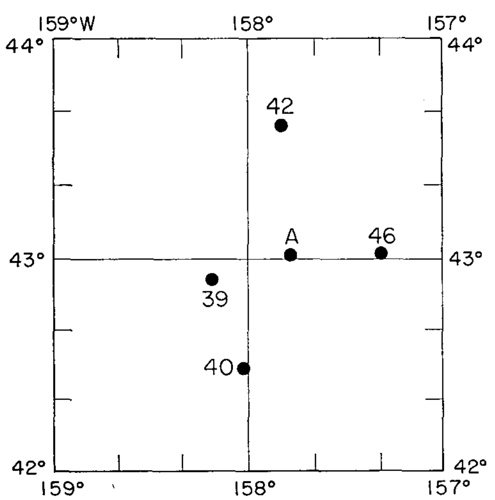


FIG. 3. Location of buoy cluster. (Buoy 39 was missing after a few days.)

In examining the hourly insolation data, it was observed that there were many daytime hours with zero insolation readings and that on the nearly cloudless days ($C=1$ okta, according to satellite data) $Q_s$ was much smaller than $Q_0$. There was no other direct *in-situ* solar radiation measurement available during that period of time for comparison. However, shipboard pyrheliometer data and cloud observations from the buoy servicing vessel were available for 1970. Comparison between shipboard measurements and those from the only surviving buoy at the same location (buoy 46) revealed that the buoy measurements were about 70 ly per day low in September and about 40 ly per day low in November. It was finally judged that cumulative errors had caused the buoy pyrheliometer readings to be low by more than 10%. On the assumption that the measured radiation should not be much less than that expected for a completely overcast sky and that $Q_s$ should be reasonably close to $Q_0$ for a clear day, it was decided to increase the buoy insolation data by an amount equal to the minimum insolation expected under total cloud cover conditions. This minimum insolation was computed using the Berliand formula with unity cloud cover. The adjustment values are approximately the same order as the differences observed between the shipboard measurements and the buoy measurements.

## 4. Computed cloudiness and satellite-measured cloudiness

Daily cloud cover values were calculated for each of the buoys using Eqs. (4), (5) and (6) with the adjusted daily insolation data. The results are compared with respective satellite-measured cloud covers. Two of such comparisons are shown in Fig. 4. The solid bars represent satellite cloud data; cloud cover calculated from the formulas of Laevastu, Berliand and Tabata are respectively shown by the solid, dashed and dotted lines.

The satellite cloud data were supplied in digitized form by the National Environmental Satellite Center, NOAA; they were derived from brightness data acquired by the AVCS (Advanced Vidicon Camera Systems) of the ESSA-9 meteorological satellite. The resolution of the AVCS unit is about 4 km. Although the satellite data are not daily means but daily synoptic measurements (1400–1600 LCT) they are regarded as fairly representative of the daily cloud cover, since diurnal variations are generally small over the open

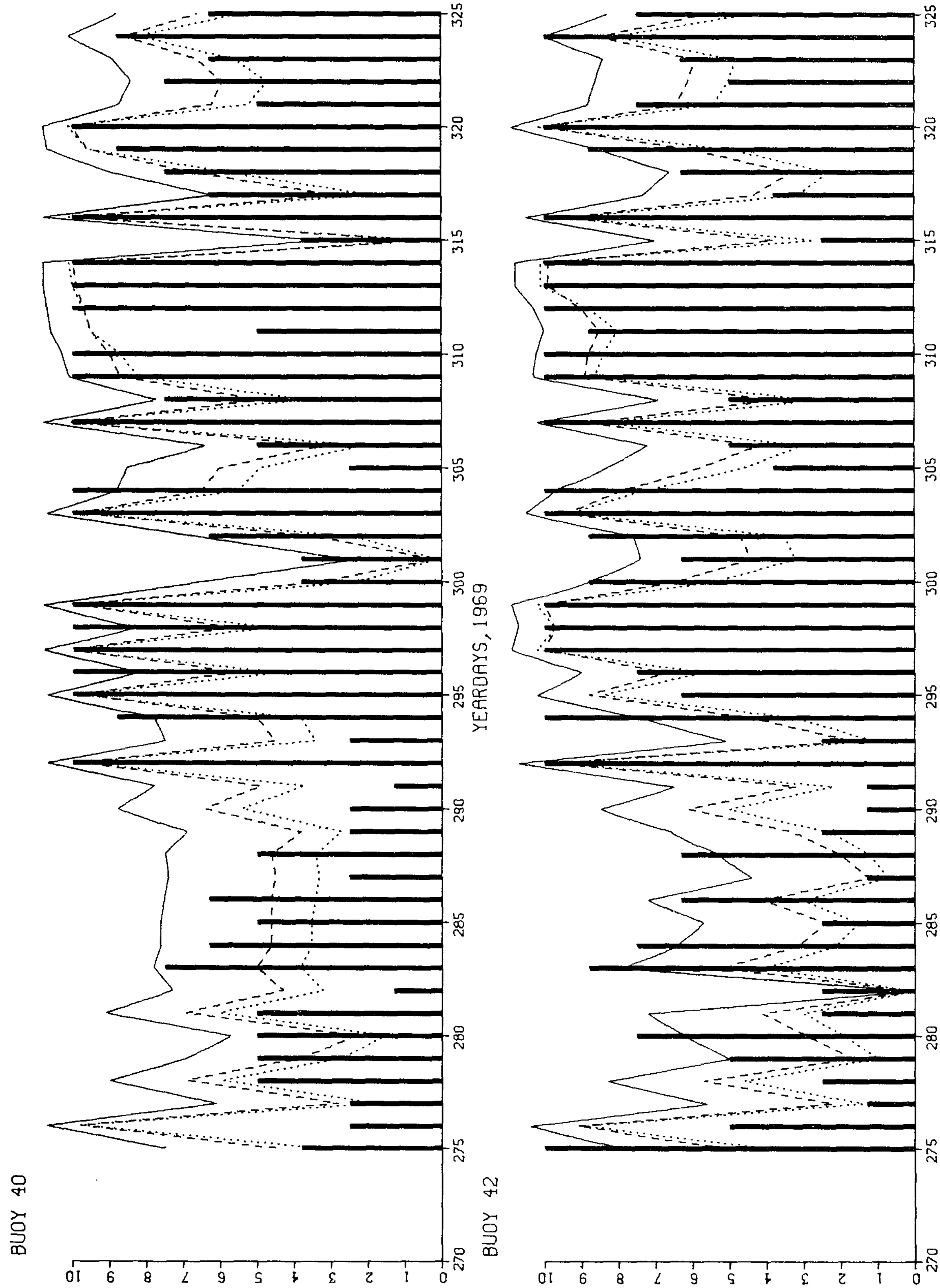


FIG. 4. Satellite-measure cloud cover (bars) and effective cloud cover computed from the formulas of Laevastu (solid line), Berliand (dashed line) and Tabata (dotted line).

TABLE 1. The correlation coefficients between computed effective cloudiness and the satellite cloud cover data.

| Buoy | Berliand | Laevastu | Tabata |
|---|---|---|---|
| 40 | 0.65 | 0.62 | 0.66 |
| 42 | 0.72 | 0.69 | 0.72 |
| 46 | 0.59 | 0.45 | 0.63 |
| *Alpha* | 0.54 | 0.52 | 0.56 |
| Mean | 0.62 | 0.57 | 0.65 |

ocean at the latitudes of interest (Tabata, 1964). More detailed information on satellite cloud cover can be obtained from Taylor and Winston (1968), Booth and Taylor (1969), Miller and Feddes (1971), and others (e.g., Young, 1967).

While there are problems with satellite cloud cover data and they are not regarded as ground truth, they do provide a means of comparison with our values. As seen in Fig. 4, the general pattern of the satellite data is matched quite reasonably by the effective cloudiness computed from all three formulas. Table 1 gives the correlations between each set of effective cloudiness values and the corresponding set of satellite cloud cover values.

Each set of cloud cover values was averaged over the period of interest (1 October 1969–20 November 1969) and these temporal means were then averaged over all four buoys to yield a single representative mean value for each of the three formulas and for the satellite cloud data. The results of this averaging are presented in Table 2. The mean satellite-measured cloud cover is 0.64±0.31; the mean effective cloudiness computed from the formulas of Berliand, Laevastu and Tabata are respectively 0.61, 0.84 and 0.54 with standard deviations of less than 0.27. The mean cloudiness computed from Berliand's formula agrees especially well with the mean of the satellite data.

## 5. Radiation balance

Radiation balance at the sea surface can be expressed by

$$R=Q_s(1-r)-Q_b, \tag{8}$$

where $Q_s$ is the incoming solar radiation (or insolation)

TABLE 2. Mean effective cloudiness and standard deviation (s.d.), obtained from the satellite data and computed from ocean buoy insolation data with the empirical formulas of Berliand, Laevastu and Tabata.

| | Satellite | | Berliand | | Laevastu | | Tabata | |
|---|---|---|---|---|---|---|---|---|
| Buoy | mean | s.d. | mean | s.d. | mean | s.d. | mean | s.d. |
| 40 | 0.65 | 0.29 | 0.63 | 0.28 | 0.85 | 0.20 | 0.56 | 0.31 |
| 42 | 0.67 | 0.31 | 0.59 | 0.29 | 0.82 | 0.22 | 0.52 | 0.32 |
| 46 | 0.63 | 0.32 | 0.59 | 0.28 | 0.81 | 0.26 | 0.52 | 0.30 |
| *Alpha* | 0.63 | 0.31 | 0.64 | 0.14 | 0.87 | 0.09 | 0.55 | 0.16 |
| Mean | 0.64 | 0.31 | 0.61 | 0.25 | 0.84 | 0.19 | 0.54 | 0.27 |

TABLE 3. Back radiation calculated from effective cloudiness and from Clark's (1967) chart: units ly per day.

| | B40 | B42 | B46 | *Alpha* | Clark |
|---|---|---|---|---|---|
| October mean | 109 | 104 | 116 | 116 | 113 |
| November mean | 87 | 88 | 90 | 90 | 112 |
| Total mean | 98 | 96 | 103 | 103 | 112 |

defined as before, $Q_b$ the back radiation, $r$ the albedo of the sea surface, and $R$ the residual radiation or net energy gained or lost through the air-sea interface. Albedo is a function of latitude and time and can be calculated from the formula of Cox and Munk (1955).

Back radiation can be calculated from the formula (Berliand and Berliand, 1952):

$$Q_b=s\sigma\theta^4(0.39-0.05\sqrt{e})(1-kC^2)+3s\sigma\theta^3(\theta_w-\theta), \tag{9}$$

where $s=0.97$ is the ratio of the radiation of sea surface to that of a blackbody, $\sigma$ is the Stefan-Boltzmann constant, $k$ is a function of latitude which increases from 0.5 near the equator to 0.8 at 70N, $\theta$ and $\theta_w$ are the absolute temperature of the air and of the surface water respectively, and $e$ is the vapor pressure of the air. The temperatures and vapor pressure were also monitored by the buoys.

The effective cloudiness obtained from Berliand's formula was used to calculate the back radiation from (9); the residual radiation was then calculated from (8). The mean values of $Q_b$ and $R$ over the period of study were respectively 100 ly per day and 64 ly per day. These values agree well with large-scale monthly mean values obtained by others (see Tables 3 and 4).

## 10. Conclusion

The computed effective cloudiness correlates significantly with the satellite-observed cloud cover on a daily basis. The two-month means of computed cloud cover also agree well with the satellite data, especially for the Berliand formula. The monthly means of back radiation and residual radiation calculated from effective cloudiness are comparable to monthly means obtained by other investigators. It is concluded that if the insolation measured by the pyrheliometer is reasonably accurate then the method presented here is an effective way of estimating cloud cover. This can facilitate oceanic data analyses related

TABLE 4. Residual radiation calculated from effective cloudiness and from Budyko's (1963) chart: units ly per day.

| | B40 | B42 | B46 | *Alpha* | Budyko |
|---|---|---|---|---|---|
| October mean | 92 | 101 | 77 | 69 | 100 |
| November mean | 34 | 41 | 53 | 47 | 35 |
| Total mean | 63 | 71 | 65 | 58 | 67 |

to heat balance, especially for cases in which satellite data are not available.

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## REFERENCES

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

Berliand, M. E., and T. G. Berliand, 1952: Determination of effective radiation of the earth as influenced by cloud cover. *Izv. Akad. Nauk SSR, Ser. Geofiz.*, No. 1.

Berliand, T. G., 1960: Climatological method of total radiation *Meteor. Gidrol.*, No. 6, 9–12.

Black, J. N., 1956: The distribution of solar radiation over the earth's surface. *Arch. Meteor. Geophys. Bioklim.*, **7**, 166–189.

Booth, A. L., and V. R. Taylor, 1969: Mesoscale archive and computer products of digitized video data from ESSA satellites. *Bull. Amer. Meteor. Soc.*, **50**, 431–438.

Budyko, M. I., 1956: *The Heat Balance of the Earth's Surface.* Leningrad, Gidrometizdat. Translated 1958 by N. Stepanova, issued by U. S. Weather Bureau, 259 pp.

——, 1963: *Atlas of the Heat Balance of the Earth.* Moscow, Akad. Nauk. SSR. Translated by I. A. Donehoo, issued by U. S. Weather Bureau.

Clark, N. E., 1967: An investigation of large-scale heat transfer processes and fluctuations of sea-surface temperature in the North Pacific Ocean. Ph.D. thesis, M.I.T.

Cox, C., and W. Munk., 1955: Some problems in optical oceanography. *J. Marine Res.*, **14**, 63–78.

Devereux, R. F., J. D. Isaacs, and F. O. Jennings, 1969: Long-distance telemetry of environmental data for the North Pacific study. *Proc. Intern. Ocean. Conf.*, England.

Hess, S. L., 1959: *Introduction to Theoretical Meteorology.* Holt, Rinehart and Winston.

Isaacs, J. D., 1968: Probing the birthplace of American weather. *Naval Res. Rev.*, Nov./Dec., 1–13.

Johnson, T. H., *et al.*, 1965: Automatic data processing program for marine synoptic radio weather reports. U. S. Fish and Wildlife Service, Spec. Rept. No. 503.

Kimball, H. H., 1928: Amount of solar radiation that reaches the surface of the earth on the land and on the sea, and methods by which it is measured. *Mon. Wea. Rev.*, **56**, 393–398.

Laevastu, T., 1960: Factors affecting the temperature of the surface layer of the sea. *Soc. Sci. Fennica, Comm. Phys. Math.*, **25**, No. 1, 1–136.

——, 1965: Daily heat exchange in the North Pacific, its relations to weather and oceanographic consequences. *Soc. Sci. Fennica, Comm. Phys. Math.*, **31**, No. 2, 1–53.

——, and E. Agres, 1966: Numerical synoptic analysis of heat exchange and their use in ocean thermal structure prediction. Fleet Numerical Weather Control/Monterey, Tech. Rept. No. 26.

List, R. T., 1958: *Smithsonian Meteorological Tables*, 6th ed. Smithsonian Inst., 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.*, 45–56.

Mateer, C. L., 1963: On the relationship between global radiation and cloudiness at Ocean Station 'P'. *Archiv. Meteor. Geophys. Bioklim*, **B12**, 482–490.

Miller, D. B., and R. G. Feddes., 1971: *Global Atlas of Relative Cloud Cover 1967–1970.* U. S. Dept. of Commerce and USAF, 237 pp.

Schneider, S. H., 1972: Cloudiness as a global climatic feedback mechanism: The effects on the radiation balance and surface temperature of variations in cloudiness. *J. Atmos. Sci.*, **29**, 1413–1422.

Seckel, G. R., 1970: The trade zone oceanography pilot study. Part VIII: Sea level meteorological properties and heat exchange processes, July 1963 to June 1965. Spec. Sci. Rept. No. 612, Bureau of Commercial Fisheries.

Tabata, S., 1964: Insolation in relation to cloud amount and sun's altitude. *Studies on Oceanography*, K. Yoshida., Ed., 202–210.

Taylor, V. R., and J. S. Winston, 1968: Monthly and seasonal global charts of brightness from ESSA 3 and ESSA 5 digitized pictures, February 1967–February 1968. ESSA Tech. Rept. NESC 46.

Wyrtki, K., 1965: The average annual heat balance of the North Pacific Ocean and its relation to ocean circulation. *J. Geophy. Res.*, **70**, 4547–4560.

——, 1966: Seasonal variation of heat exchange and surface temperature in the North Pacific Ocean. Institute of Geophysics Report, University of Hawaii.

Young, M. J., 1967: Variability in estimating total cloud cover from satellite pictures. *J. Appl. Meteor.*, **10**, 573–579.