Irradiance Measurements in the Upper Ocean

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ABSTRACT

Observations were made of downward solar radiation as a function of depth during an experiment in the North Pacific (35°N, 155°W). The irradiance meter employed was sensitive to solar radiation of wavelength 400–1000 nm arriving from above at a horizontal surface. Because of selective absorption of the short and long wavelengths, the irradiance decreases much faster than exponential in the upper few meters, falling to one-third of the incident value between 2 and 3 m depth. Below 10 m the decrease was exponential at a rate characteristic of moderately clear water of Type IA. Neglecting one case having low sun altitude, the observations are well represented by the expression $I/I_0 = Re^{z/\zeta_1} + (1-R)e^{z/\zeta_2}$, where I is the irradiance at depth $-z$, I_0 is the irradiance at the surface less reflected solar radiation, $R=0.62$, ζ_1 and ζ_2 are attenuation lengths equal to 1.5 and 20 m, respectively, and z is the vertical space coordinate, positive upward with the origin at mean sea level. The depth at which the irradiance falls to 10% of its surface value is nearly the same as observations of Secchi depth when cases with high wind speed or low solar altitude are neglected. Parameters R, ζ_1 and ζ_2 are computed for the entire range of oceanic water types.

1. Introduction

A knowledge of the distribution of solar radiation in the upper ocean is important for modeling physical, chemical and biological processes. The principal physical application is modeling the heating of the upper layers by absorption of solar radiation. The assump-

tion often used (e.g., Denman, 1973) is that the downward irradiance, and hence approximately the absorption, is an exponential function of depth given by

$$I = I_0 e^{z/\zeta}, \qquad (1)$$

where I, the downward irradiance, is the radiant flux density (energy per unit area per unit time) on a horizontal surface due to contributions from the entire upward hemisphere, I_0 the incident less reflected and emergent irradiance at the surface, z the vertical coordinate positive upward with origin at mean sea level and ζ the attenuation length. Upward irradiance, due to backscattering, ranges from about 0.3 to 3% of downward irradiance and is neglected in the present context. We assume that optical properties of the upper ocean are independent of depth—a reasonable approximation in the surface mixed layer.

The assumption of an exponential decay with depth is a poor approximation in the upper 5 m of the ocean because of the preferential absorption of the short- and long-wavelength components of sunlight. Below 10 m depth, however, the assumption of exponential decay is a good approximation because the preferential absorption above has left only blue-green light. These facts concerning the distribution of light in the upper ocean have long been known (Jerlov, 1968) but they have not always been completely taken into account when modeling the upper ocean (e.g., Denman, 1973). Even if one were only concerned about the distribution of light below 10 m where ζ is approximately constant, (1) is a poor approximation because I does not equal I_0 when extrapolating up to the surface (ζ varies in the upper 10 m).

Another aspect of modeling the distribution of solar radiation is the variation of optical characteristics with depth, geographical location and season. Jerlov (1968) has devised a system of classifications of surface water types based on spectral transmittance of downward irradiance at high solar altitude. Jerlov shows variations of water type with geographical location. Observations are lacking in many areas.

The purpose of this note is to describe measurements

of downward irradiance made in the upper 40 m of the North Pacific and to support a more accurate parameterization of irradiance than has often been used.

2. Observations

Observations were made from the R/P *FLIP* about 800 mi north of Hawaii in the vicinity of 35°N, 155°W during the POLE experiment, a component of the North Pacific Experiment (NORPAX).

The irradiance meter used for the measurement had a uniform spectral response within ±5% for wavelengths from 400 to 1000 nm. The sensing surface was flat and remained horizontal and facing upward while suspended from *FLIP* by an electrical conductor and strain member. The instrument was lowered by hand and measurements were recorded from a meter on deck. Values were recorded at selected levels both when lowering and raising the instrument. The values at each level were averaged to reduce errors caused by variations of I_0 over the period of the run (~10 min). Nevertheless, four out of a total of 10 runs were omitted because of variations in I_0 caused by variations in cloudiness. Observations of Secchi disc depth were usually made during each run.

Because of the characteristics of *FLIP* it was possible to make measurements of irradiance which were negligibly affected by platform motion or shading of the surface by the superstructure. Vertical motions of *FLIP* are only about 10 cm amplitude. The measurements were made from a deck extending well away from the hull. Care was taken to avoid measurements when the area below the deck was shaded by the superstructure. The variability in irradiance caused by waves was averaged by eye and the mean value recorded.

A summary of the conditions for each run is given in Table 1. The value of I_0 was determined by subtracting reflected and emergent radiation from the incident radiation measured by an Eppley pyranometer facing upward. Values of albedo according to Payne (1972) were used to estimate the reflected

TABLE 1. Irradiance measurements during the POLE experiment. ζ_2 is the attenuation length calculated between 10 and 40 m depth.

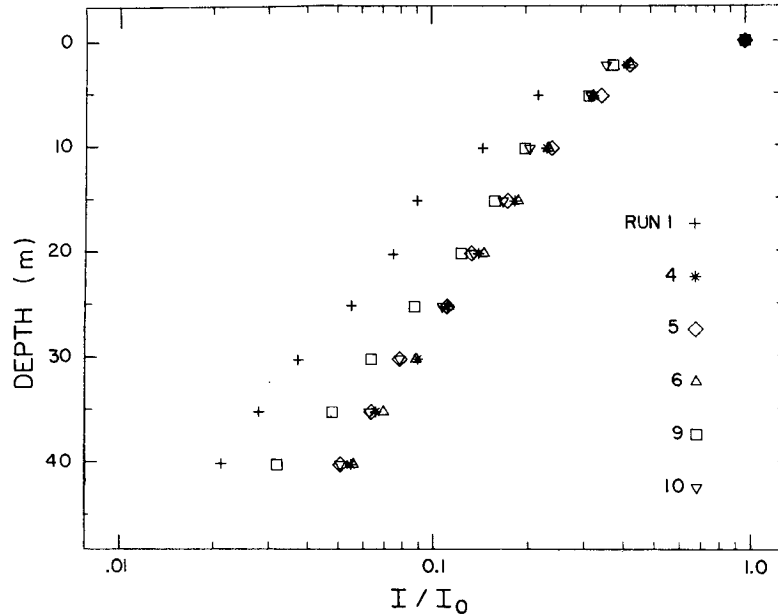| Run no.	Date (February)	Time (local)	Sun altitude (degrees)	I_0 (mW cm^{-2})	Cloud (tenths)	Wind (m s^{-1})	Secchi depth (m)	ζ_2 (m)
1	7	1625	16	32.7	0	3.5	23	16
4	10	1129	38	7.2	10	3	26	20
5	10	1501	30	18.3	10	5	24	19
6	11	1500	30	26.4	10	3	24	20
9	13	1112	38	23.3	10	12	—	16
10	13	1436	34	26.3	10	13	18	21
							Ave.	19

FIG. 1. Observations of irradiance normalized by surface values as a function
of depth. The conditions for each run are given in Table 1.

radiation. The estimated albedo was 0.06 for all runs except No. 1 which had a value of 0.15. Emergent radiation was assumed to be 0.5% of incoming (Payne, 1972).

The observations of irradiance in the water were corrected for the immersion effect (see, e.g., Westlake, 1965). The immersion effect is the difference in the response of the irradiance meter in water from that in air. Correction for the effect was determined from measurements in the laboratory and can be expressed as

$$I/I_0 = 1.18 I_m/I_{am},$$

where I_m and I_{am} are the measured downward irradiances in water and air, respectively. The dif-

ference in reflectivities of the plane water surface in the laboratory and the rough surface characteristics of the field observations was taken into account. The coefficient in the above expression for Run no. 1 is 1.31 rather than 1.18 because of the higher reflectivity of the water surface during that run. The uncertainty in the coefficients used in the correction is estimated to be ±0.02.

3. Analysis and discussion

The observations from each of the six runs are plotted in Fig. 1. As expected, there is strong attenuation near the surface because of the dependence on wavelength. Below 10 m depth, however, the decay is nearly exponential. Values of the attenuation length over 10–40 m depth were determined for each run by a least-squares fit of (1) to the observations below 10 m. These values (ζ_2) are given in Table 1.

The observations of Run no. 1 show a significantly larger attenuation with depth than the remaining runs, particularly near the surface. This can be explained by reference to Table 1 where it is seen that the sky was cloudless and the altitude of the sun was only 16° for Run no. 1 compared with overcast skys and a minimum solar altitude of 30° for the remaining runs. The combination of low sun angle and clear sky causes more rapid attenuation with depth because the path of the sun's rays is far from vertical.

A composite of the observations excepting Run no. 1 was formed by averaging I/I_0 for each depth. A plot of the composite is shown in Fig. 2 together with a plot of Run no. 1. A least-squares fit below
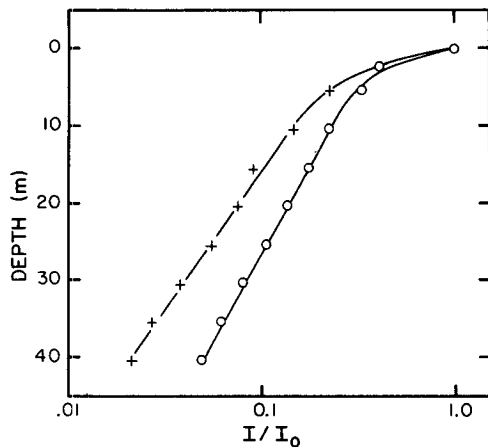

FIG. 2. Averaged observations of normalized irradiance (except Run no. 1) versus depth (circles) and a similar plot of Run no. 1 (crosses). The curves are from Eq. (4) with parameters given in Table 2.

10 m depth of

$$I/I_0 = (1-R)e^{z/\zeta_2} \tag{2}$$

to the composite observations and to Run no. 1 yielded values of R and ζ_2. I/I_0, computed from (2) with the determined values of R and ζ_2, was then subtracted from the observations above 6 m. A second least-squares fit of

$$I/I_0 - (1-R)e^{z/\zeta_2} = Re^{z/\zeta_1} \tag{3}$$

to the differenced observations [left side of (3)] over 0 to 6 m depth yielded an estimate of ζ_1 with R and ζ_2 specified from the previous fit. The combined expression obtained by rewriting (3) is

$$I/I_0 = Re^{z/\zeta_1} + (1-R)e^{z/\zeta_2}. \tag{4}$$

Values for R, ζ_1 and ζ_2 for Run no. 1 and the composite observations are given in Table 2. The curves plotted in Fig. 2 are computed from (4) with the best-fit parameters. The first exponential term of (4) characterizes the rapid attenuation in the upper 5 m due to absorption of the red end of the spectrum; the second exponential represents the attenuation of blue-green light below 10 m.

An expression identical in form to (4) was previously suggested by Kraus (1972, p. 92) as approximation to the irradiance field. Kraus suggested values of R, ζ_1 and ζ_2 of 0.4, 5 m and 40 m, respectively, for very clear ocean water based on observations in Crater Lake, which is among the clearest of natural water bodies. Comparison with the other estimates

TABLE 2. Values of parameters determined by fitting the sum of two exponentials to observations of downward irradiance based on Eq. (4).

	R	ζ_1 (m)	ζ_2 (m)
Run 1	0.74	1.7	16
Composite observations (Runs 4, 5, 6, 9, 10)	0.62	1.5	20
Kraus (1972)—very clear water	0.4	5	40
Jerlov (1968)—Type I	0.58	0.35	23
—Type 1 (upper 50 m)	0.68	1.2	28
—Type IA	0.62	0.60	20
—Type IB	0.67	1.0	17
—Type II	0.77	1.5	14
—Type III	0.78	1.4	7.9

of R in Table 2 suggests that $R=0.4$ may be too small.

Jerlov (1968) has proposed a scheme for classifying oceanic water according to its clarity. He defines five types: I, IA, IB, II and III, ranging from clear to increasingly dirtier water. We have determined best-fitting parameters by the method used above for each set of irradiance values (Jerlov, 1968, Table 21) corresponding to different water types. The parameters are given in Table 2 and are determined from a fit to the data in the upper 100 m (neglecting the 10 m value) except for Type I where a set of parameters was also determined for the upper 50 m because of a change in slope of $\ln I$ vs z below 50 m. A comparison of the parameters for the composite observations with the parameters for Type IA shows
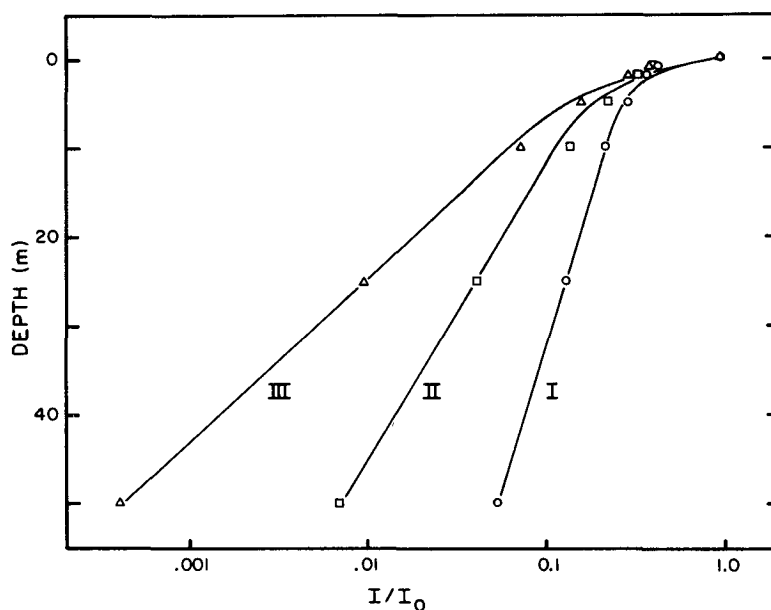

FIG. 3. Values of irradiance from Jerlov's (1968) Table XXI for water Types I, II and III. The curves are a plot of Eq. (4) with parameters given in Table 2. The parameters are from a fit to values in the table for the upper 100 m except Type I where parameters for the upper 50 m are used.
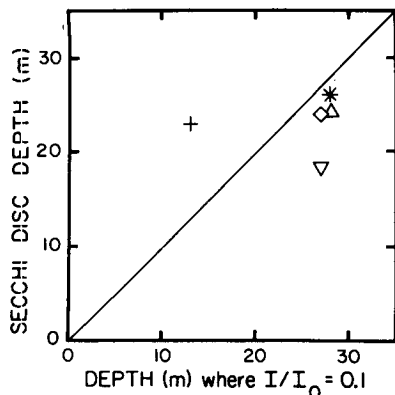
FIG. 4. Observations of Secchi disc depth versus depth at which $I/I_0=0.1$. The symbols correspond to run numbers identified in Fig. 1.

remarkable similarity, suggesting that the upper ocean during the POLE experiment can be classified IA. The lack of agreement between ζ_1 for the two cases is not critical because of inaccuracies in the representation (4) in the upper 5 m.

A comparison between the representation (4) and Jerlov's Table 21 is shown in Fig. 3. As would be expected, the fit is least accurate in the upper 10 m. The fit at 10 m could be improved by including the value at 10 m in the determination of R and ζ_2. The values of I vs depth z below mean sea level in the upper 5 m will be affected by the magnitude of the waves because of the nonlinear relation between I and z.

It is, of course, possible to devise more complicated and perhaps more realistic expressions than (4) for the irradiance as a function of depth by including additional exponential terms and explicitly accounting for solar altitude and refraction. This has been done in studies of lakes (e.g., Jassby and Powell, 1975). Even though crude, (4) is a significant improvement over (1) and is likely to be a satisfactory approximation for many applications.

Observations of Secchi disc depth (Table 1) were also made in all of the runs reported except one. The observations are remarkably consistent except for Run 10. The mean of the first four runs is 24±1 m, while Run 10 has a Secchi depth of 18 m. The reason for the lower value is likely because of the higher winds during Run 10, 13 m s^{-1} compared to a maximum of 5 m s^{-1} for the remaining runs. The higher winds increase the roughness and motion of the surface which tends to fragment the image of the disc and decrease its visibility. Neglecting Run 10, the Secchi disc depth appears to be a consistent indicator of optical characteristics, assuming the variation in characteristics over the series of observations was small.

The Secchi disc depths are plotted in Fig. 4 as a function of the depth at which the irradiance falls to 10% of its surface value. The drawing of a line in Fig. 4 with a slope of 1 is motivated by a relationship suggested by Tyler (1968), i.e.,

$$\frac{3.78K}{(\alpha+K)}=\frac{Z_{SD}}{I_{0.1}}, \tag{5}$$

where α and K are attenuation coefficients for collimated and diffuse light, respectively, Z_{SD} is the Secchi disc depth and $I_{0.1}$ is the depth at with I falls to 10% of the surface value. Eq. (5) is consistent with the line of unit slope in Fig. 4 if $\alpha=2.78K$, a value close to that observed in a clear lake (Smith et al., 1973). Caution should be exercised in the interpretation of Fig. 4. As pointed out by Tyler (1968), α is not necessarily a fixed multiple of K and other assumptions are made in the deviation of (5). The data presented in Fig. 4 are by themselves inadequate for a critical test of (5). More extensive observations over a wide range of optical properties are required. The scatter in a plot similar to Fig. 4 presented by Tyler (1968) encourages doubt in the validity of (5).

Although crude, observations of Secchi disc depth are economical and are often all that is available to characterize the optical properties of the upper ocean. The historical record of Secchi disc observations far outweighs that of less ambiguous optical measurements. Frederick (1970) has compiled an atlas of Secchi observations which shows variation in Secchi depth over the world oceans of remarkable detail. Atlases of this sort would be very useful to modelers if the relationships between Secchi depth and other optical properties could be improved.

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