Effect of ship shadow on in-water irradiance measurements

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Abstract

Calculations of the effect of the ship's shadow on in-water irradiance measurement errors were performed with a Monte Carlo radiance transfer algorithm. The algorithm contained the Cox-Munk wave-slope probability function. A simple 3-D model of the rectangular underwater part of a ship was used. The effect was calculated as a function of sea-water absorption, surface roughness (depending on an assumed wind velocity of up to 15 m s^{-1}) with various wind velocities and directions, length and depth of the ship, distance of instrument from the ship, and bow-to-sun angle.

1. Introduction

The problems of the influence of instrumentation on in-water light fields have been studied with Monte Carlo methods for several years. Several shadow-related measurement artefacts for in-water optical instruments have been discussed: self-shading caused by the upwelling irradiance meter itself (Gordon & Ding 1992, Piskozub 1994, 1998, Aas & Korsbø 1997, Piskozub et al. 2000), self-shading caused by a buoyed instrument (Leathers & Downes 2001), the shadow effect of a measurement tower (Zibordi et al. 1999, Doyle & Zibordi 2002) and finally the shadow effect of

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

the research vessel (Gordon 1985). The problem of shadow is an inherent problem of in-water upwelling radiance and irradiance measurements. Since every photon of upwelling radiance (assuming no light sources in the water volume) must have passed the instrument depth on the way down to come back from beneath, it is obvious that some of them are blocked by the instrument's housing or other man-made objects (buoys, platforms, ships). The effect of ship shadow was first calculated by Gordon (1985). However, he did not consider sea-surface roughness in his paper. Owing to severe limitations of computing power, Gordon's simulations used no more than 10 000 photons. 400 times as many photons were used in the present study, thus allowing the statistical error to be reduced 20-fold (Lenoble 1985). A number of calculations for more turbid waters are also included in this study. This author used his own Monte Carlo algorithm for solving the radiance transfer equation in the sea. It included a numerical representation of a rough sea surface (Cox & Munk 1956) as well as light diffusion at a simulated bottom. The object of the calculations was to determine how surface waves influence the effect of ship shadow on the in-water light field.

2. Material and methods

The simulated ship is a completely black rectangular box. Consequently, it blocks photons out but does not reflect them. This simple model avoids problems due to the colour and shape of different parts of the ship, which influence reflection on the vessel much more than light blocking. The 3-D ship model consists only of its underwater part. In this way, problems arising out of the complicated shape of the vessel's superscructure are avoided, although this may be a problem if one considers the uppermost layers of the sea on the shadow side of the ship.

The photons in the Monte Carlo algorithm used in the calculations were traced in the natural forward direction. Absorption ended a photon's history, i.e. no partial photons were traced, so as to make the physical meaning of the algorithm easier to analyse (Kattawar & Plass 1972, Lenoble 1985). The price to be paid for that was the poorer time-efficiency of the program. The history of every photon that reached the assumed instrument's depth, either on its way down or back up again, was then traced back to see if it had passed through the simulated ship's outline. Each multiple pass of a given photon through the depth was counted, as each pass adds to the unperturbed downward (or upward) vector irradiance at the level of the instrument (henceforth simply called irradiation). The ratio of such photons to all photons downwelling (upwelling) through the instrument depth (again including multiple passes) is the sought-after ratio of irradiance blocked by the ship (i.e. the relative error of the irradiance measurement). Similarly, by counting not photons but the inverted cosines ($1/\cos(\theta)$) of their zenith angles, the effect of ship shadow on scalar downwelling (upwelling) irradiance can be calculated. If the photons are included only if they come to the instrument from a narrow solid angle, the analogous ratio represents the relative error of upwelling radiance coming from the centre of that angle. All three possibilities are incorporated in the computer code used. However, the results given in this paper are mostly obtained from irradiation simulations, as this is the most frequently measured parameter of the in-water light field.

The algorithm assumes a layered sea with different coefficients of absorption a and total backscattering b. Unless specifically stated, the values of a and b used in most calculation runs were typical of case 1 waters (Dera 1992). The water column was assumed homogeneous in order to make the simulations simpler to analyse. Similarly, only a point source of photons simulating the sun was used; light scattered in the atmosphere (skylight) was omitted from most calculations so that the dependence of self-shading on the solar zenith angle could be studied. The Petzold (1972) standard scattering phase function for turbid ocean sea-water was used. The roughness of the sea surface was introduced by using the Cox-Munk (1956) probability distribution of wave slopes. The parameters defining the distribution were the azimuth and velocity of the wind generating the sea-surface waves. Each time a photon reached zero depth (sea surface), including the moment it left the atmosphere, the inclination of the element of the wave surface was chosen randomly. Reflection or refraction was chosen according to Snell's law in the co-ordinates of the surface element. The effect of visibility of the wave element by the incident photon was accounted for by taking only slopes for which a random number (from the range 0.0 to 1.0) was smaller than the cosine of the surface element's normal to the photon direction.

There were some limitations to the method. Photons reflected or refracted into the wrong hemisphere, e.g. an upwelling photon reflected upwards on to a steeply sloped surface element, had to be rejected. All surface events were assumed to happen at zero depth, as the Cox-Munk distribution gives no information on the actual height of a surface element. No shading of the surface element by neighbouring waves could be taken into account, which distorted the calculations, especially at low sun angles. The Cox-Munk distribution is defined only for wind velocities up to 15 m s^{-1}. No effect of whitecap or in-water gas bubbles was taken into account. Moreover, the perturbing effect of the ship on the surface waves (and also on surface whitecap coverage and in-water gas bubble concentrations) could not be taken into account as at present there are no good models of the ship's effect on these phenomena.

The calculations presented in this paper were carried out on a 2.8 GHz Pentium 4 PC running Fedora Core Linux at the Institute of Oceanology. The results of all 147 Monte Carlo runs for the rough sea-surface model presented here were calculated using 40 million photons in each run. The calculations for each million photons took 30–40 seconds depending on the solar zenith angle and the degree of sea roughness.

3. Results and discussion

The calculations of the effect of the ship's shadow were done with the main axis of the ship (bows–stern) perpendicular to the sun's direction. Measurements of light field parameters are usually made on the sunny side of the research vessel lying in this position in drift. Unless explicitly stated, the calculations were done for oceanic water at the summer midday solar zenith angle for mid-latitudes. The following values were used as default: solar zenith angle $\theta = 30°$, wind velocity $v = 5$ m s^{-1}, wind direction to solar azimuth $\Psi = 45°$, absorption coefficient $a = 0.1$ m^{-1}, scattering coefficient $b = 0.025$ m^{-1}, ship length $l = 60$ m, ship width $d_w = 10$ m, ship draught $d_s = 9$ m; distance from ship side to measurement instrument $d_x = 2$ m. Unless marked otherwise, all measurement errors are for an instrument depth $z = 10$.

Fig. 1 shows the results of the shadow effect calculations as a function of distance from the ship's sides at a depth just below the ship's draught. The relative error of irradiance on the shadow side of the ship is overwhelming, as expected. For downwelling irradiance almost 100% of downwelling photons are blocked by the ship's contour close to its side. The shadow line is clearly visible. The relative error in the upwelling irradiation is smaller but extends much farther from the ship. It approaches 60% close to the ship and is still important 30 m from the shadow source. However, more significant are the results for the sunny side, where measuring instruments would be placed. The effect for downwelling irradiation is not great (an error of a few per cent) but the error of upwelling irradiation cannot be neglected. It is $> 10\%$ even 5 m from the ship and still $> 5\%$ 20 m away from it.

Fig. 2 shows the effect of the simulated ship's draught on the shadow effect. The error of upwelling radiation increases as the draught does so (as expected) and is especially marked at depths lower than realistic draught values. (The figure presents the results up to 40 m draught, which is well

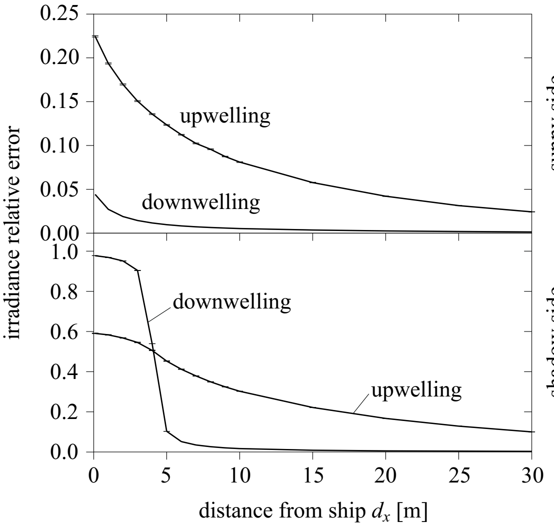

Fig. 1. Relative error of irradiance as a function of distance from ship d_x (z = 10 m, $\theta = 30°$, v = 5 m s^{-1}, Ψ = 45°, a = 0.1 m^{-1}, b = 0.025 m^{-1}, l = 60 m, d_w = 10 m, d_s = 9 m)

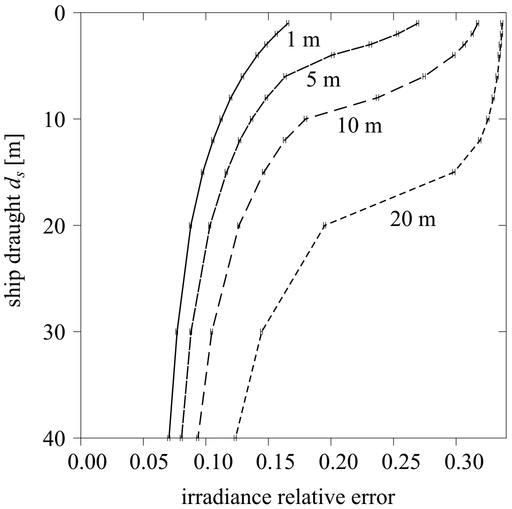

Fig. 2. Relative error of upwelling irradiance measured at 1, 5, 10 and 20 m depth as a function of ship draught d_s ($\theta = 30°$, v = 5 m s^{-1}, Ψ = 45°, a = 0.1 m^{-1}, b = 0.025 m^{-1}, l = 60 m, d_w = 10 m, d_x = 2 m, sunny side)

over the range of realistic values, but my intention is to show the whole range of measurement error variability). However, at even greater depths, it is over 10% for typical ship sizes and water conditions. Fig. 3 presents the effect of ship length on the results. The results show that with measurements done amidships, the error for downwelling radiation ceases to grow with ship size at about 20 m and for upwelling irradiation at about 40 m for an instrument placed at 10 m depth, which means that the quality of (especially) upwelling irradiance measurement can be improved simply by using a smaller vessel.

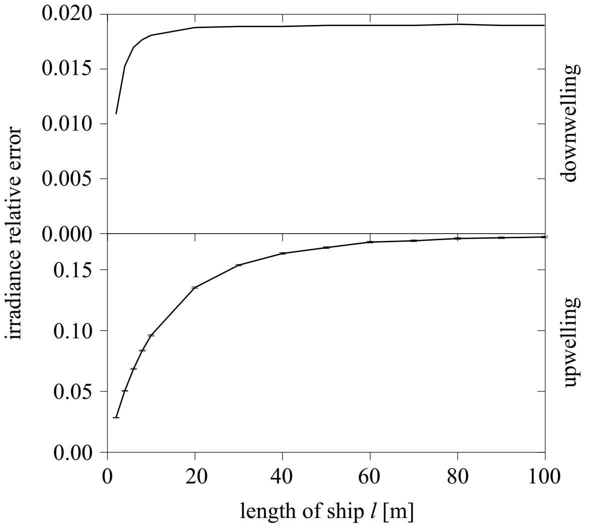

Fig. 3. Relative error of irradiance as a function of ship length l (z = 10 m, $\theta = 30°$, v = 5 m s^{-1}, Ψ = 45°, a = 0.1 m^{-1}, b = 0.025 m^{-1}, d_s = 9 m, d_w = 10 m, d_x = 2 m, sunny side)

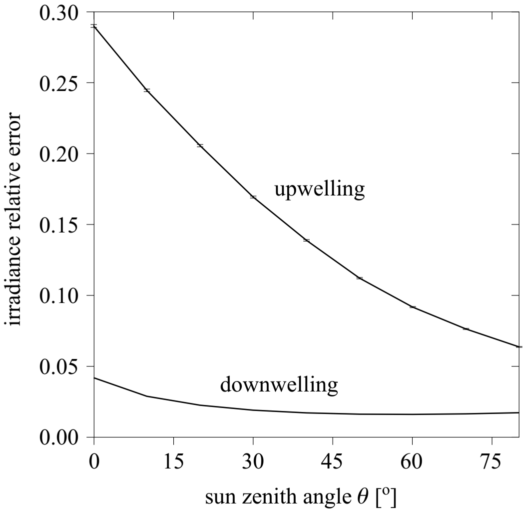

Fig. 4. Relative error of irradiance as a function of sun zenith angle θ (z = 10 m, v = 5 m s^{-1}, Ψ = 45°, a = 0.1 m^{-1}, b = 0.025 m^{-1}, d_s = 9 m, d_x = 2 m, d_w = 10 m, l = 60 m, sunny side)

An important factor influencing this phenomenon is the solar zenith angle (Fig. 4). One would expect the error to grow with the sun high over the horizon (on the sunny side of the ship). However, at a distance of 2 m from the ship's side, the effect with respect to downwelling irradiation is not significant even with the sun at the zenith. On the other hand, the error for upwelling irradiance measurements depends strongly on the solar zenith angle, reaching over 25% for vertical sunshine at a depth of 10 m.

All these results were calculated for light attenuation typical of clear oceanic water in the blue range of the visible spectrum. However, in many

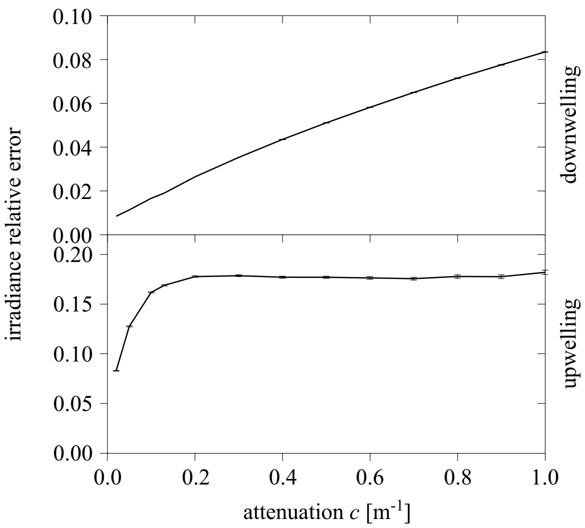

Fig. 5. Relative error of irradiance as a function of light attenuation c. Photon survival ratio $\omega_o = 0.8$ ($z = 10$ m, $\theta = 30°$, $v = 5$ m s^{-1}, $\Psi = 45°$, $d_s = 9$ m, $d_x = 2$ m, $d_w = 10$ m, $l = 60$ m, sunny side)

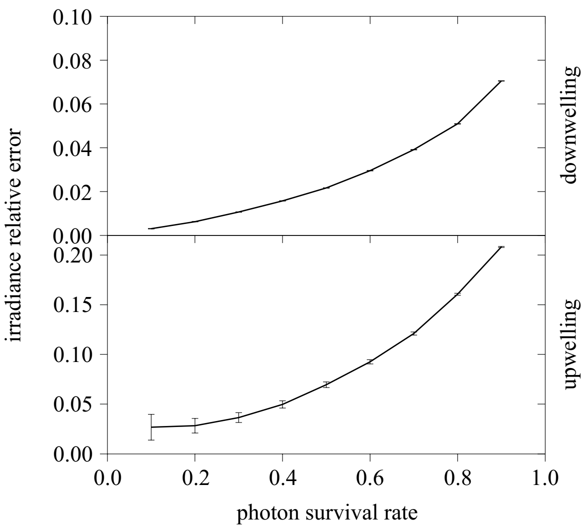

Fig. 6. Relative irradiance error as a function of photon survival ratio ω_o with attenuation coefficient $c = 0.5$ m^{-1} ($z = 10$ m, $\theta = 30°$, $v = 5$ m s^{-1}, $\Psi = 45°$, $d_s = 9$ m, $d_x = 2$ m, $d_w = 10$ m, $l = 60$ m, sunny side)

basins (including the Baltic, of especial interest to the author's organization – the Institute of Oceanology, Polish Academy of Sciences), the values are usually much greater. Therefore, the effect of the value of c (attenuation) on ship-shadow induced error was investigated (Fig. 5). The downwelling irradiance error depends almost linearly on attenuation up to $c = 1.0$ m^{-1} (calculations for greater values of c would need much more computation time owing to the high photon loss ratio). Surprisingly, the effect for upwelling irradiance reaches a plateau at about $c = 0.2$ m^{-1}. This means that errors for irradiance in both directions may be comparable in case 2 waters.

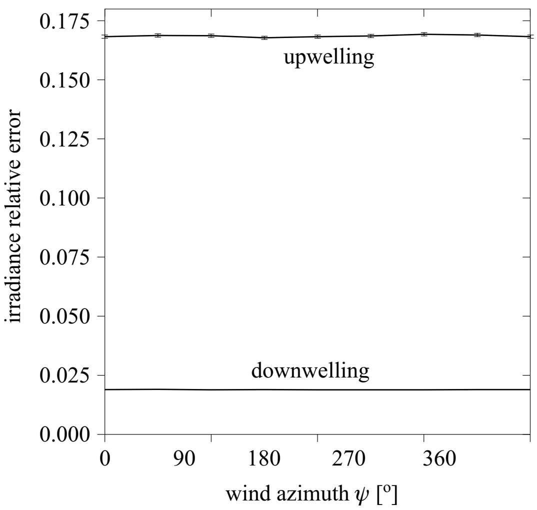

Fig. 7. Relative error of irradiance as a function of wind-to-sun azimuth Ψ (z = 10 m, $\theta = 30°$, v = 15 m s^{-1}, a = 0.1 m^{-1}, b = 0.025 m^{-1}, d_s = 9 m, d_x = 2 m, d_w = 10 m, l = 60 m, sunny side)

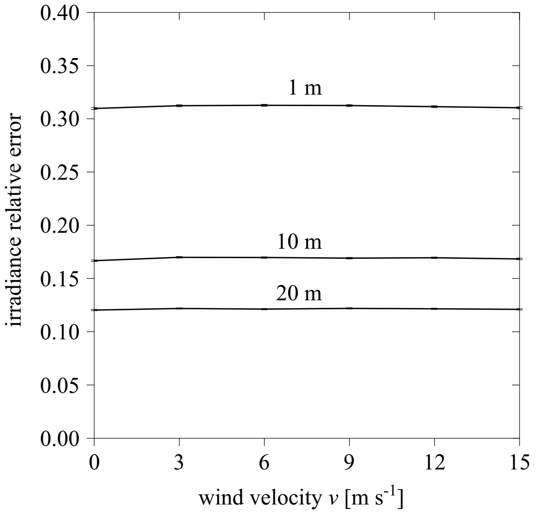

Fig. 8. Relative error of upwelling irradiance as a function of wind velocity v (z = 10 m, $\theta = 30°$, $\Psi = 45°$, v = 15 m s^{-1}, a = 0.1 m^{-1}, b = 0.025 m^{-1}, d_s = 9 m, d_x = 2 m, d_w = 10 m, l = 60 m, sunny side)

Because attenuation consists of two independent phenomena – absorption a and scattering b – the influence of the photon survival ratio $\omega_o = b/(a + b)$ was studied (Fig. 6). The downwelling irradiance error increases with an increase in scattering (with $c \equiv a + b$ = const). The relative error for the upwelling irradiance increases in a similar fashion. However, the high values of the statistical error for the Monte Carlo results presented (marked on the figure) for low ω_o values due to the low number of water-leaving photons with in a highly absorbing sea should be noted.

One of the main aims of this paper was to investigate how the ship affects the light field in conjunction with surface waves. Fig. 7 shows the results of calculations for various azimuths of wind generating the Cox-Munk model waves. All the calculated errors lie within one standard deviation of their average for 40-million-photon computation runs. The results for different wind velocities (Fig. 8) display a similar outcome. However, there is a slight decrease in the calculated error with increasing surface roughness.

4. Conclusions

The effect of ship shadow cannot be neglected, even on the sunny side of the ship, especially as regards upwelling irradiation. It seems that all accurate measurements of this parameter should be done from, say, buoys drifting a few hundred metres from the ship. The error is important even on small research vessels; indeed, it is practically as important on a ship the size of s/y 'Oceania' (the research ship of the Polish Academy of Sciences used in most measurements by the author) as on the largest vessels used in oceanography. As the relative errors increase with increasing light attenuation, especially with respect to downwelling irradiation, it is especially important in case 2 water basins such as the Baltic. The effect for upwelling irradiation is important even a long way from the ship's sides (about 5% at 20 m for ocean waters, more in case 2 waters).

The results of numerical Monte Carlo simulations of the ship's effect on in-water instruments measuring downwelling and upwelling irradiance show that introducing a rough sea-surface does not lead to radical changes in the ship-induced error. In particular, the influence of the direction of the wave-inducing wind can be disregarded. A separate study of the ship shadow effect on upwelling radiance is planned. Moreover, the investigation of phenomena such as the ship's effect on sea surface roughness, whitecap coverage and bubble cloud production is worth pursuing, as they all influence optical measurements performed from research vessels.

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