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A REVIEW OF METHODS FOR SOLAR RADIATION ESTIMATION USED IN OFF-SHORE APPLICATIONS

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Abstract: *The importance of knowing the contribution of solar radiation is vital for adapting and implementing novel solutions for converting solar energy into thermal or electrical energy. Currently, models have been developed to estimate the solar radiation, globally or locally, that take into account inter alia latitude, certain climatic parameters, temperature differences or clouds.*
This paper presents an overview of the main methods used to estimate solar radiation on large water surface (seas and oceans). A comparison is done between the measured solar radiation and empirical insolation formulas issued by Kimball, Laevastu, Reed and Tabata. Compared to the models used for land estimations, the main parameter taken into account in these empirical methods is cloud cover. The challenge consists in a good estimation of this parameter (in tenths or oktas), knowing that human error is about 10 – 12% relative to satellites measurements.
More precise determination of the amount of available solar radiation at sea comes in the context of refurbishment process and adoption of clean technologies shipping industry in order to reduce greenhouse gas emissions globally. Also, given the increasing need for energy, seas and oceans may become at some point due to large areas available, favorable space for installation of "green" systems.

Key-words: *solar radiation, modelling, sea, ocean, ship.*

Introduction

Incoming solar radiation in ocean and coastal waters is a crucial factor in air-sea interactions, in biogeochemical processes [1] and as prime source of energy for all physical and biological processes in the upper ocean. Its accurate estimation is needed in applications by considering the air-sea interaction, near- surface thermal structure, primary productivity etc. The amount of solar radiation incident on the oceanic surface at any instant depends on a number of factors such as the season, latitude, cloud characteristics (type, amount, thickness, number of layers etc.) and transmittance through atmosphere as a function of moisture, dust particles and other gases, which absorb and emit radiation [2].
According to Munoz [3], globally solar radiation peaks are slightly higher at sea than on land, the highest values being recorded in the tropics, moderate values at mid-latitudes, and, of course, the lowest values are found at the poles. Reports mention average solar radiation values of 83 Wm^{-2} for large areas of water, while the values recorded for land were about 45 Wm^{-2} as Table 1 shows.
However, in the absence of in situ data, one has to depend on empirical relationships to estimate radiation as a viable tool in projects and applications that require input parameters. Further, empirical formulas are presented; these were developed and evaluated especially for the Pacific and Atlantic Ocean [2, 6].

Table 1 Mean net radiation between 1980 and 2010 over different classes, [3]

Class	Mean net radiation $[Wm^{-2}]$
Land	45.2
Sea	82.6
Global	70.2
Evergreen Forests	137.2
Desert/Barren areas	86.7

Review of main empirical formulas

In the absence of clouds, the turbidity of the marine atmosphere generally varies over rather narrow limits as compared to air over land surfaces, which implies that a single formula might be suitable for computing insolation under clear skies over much of the world ocean [4].
From a primarily theoretical basis, Kimball [5] derived the following formula:

$$I = I_0(1 - 0.71C) \quad (1)$$

where: *I* is the average daily insolation at the surface when *C* is the fraction of the sky covered by clouds and I_0 is the average daily insolation at the surface in the absence of clouds.
Pyranometer measurements over a large area in the Atlantic, including low and middle latitude regions, Laevastu (1960) showed that insolation can be conveniently represented by:

$$I = 0.014h_0t_d(1 - 0.6C^3) \quad (2)$$

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where: h_0 is noon solar altitude for angles up to 75° and t_d is the duration of sunlight. Above 75°, h_0 is taken as a constant and the formula reads:

$$I = 1.06t_d(1 - 0.6C^3) \quad (3)$$

Tabata [9] and Lumb [10] formulas for real sky and clear-sky are presented in equations (4) and (5).

$$Q_s = Q_0(1 - 0{,}716C + 0{,}00252\alpha) \quad (4)$$

$$Q_0 = 1353s(0.61 + 0.20s) \quad (5)$$

where: Q_0 is clear-sky insolation (W/m^2), *C* cloud cover (in tenths), *α* is noon solar altitude and *s* the sine of solar altitude. Lumb's formula was derived for hourly computations and it is necessary to make the computations for each hour and average them to derive a daily mean.

Seckel and Beaudry [11] proposed a simple formula to calculate the clear-sky mean daily solar radiation (Q_0) as a function of latitude and date, using computed data listed in the Smithsonian Meteorological Tables (SMT). The SMT data are computed using a constant atmospheric transmissittance coefficient of 0.7.

These data have been widely used by oceanographers to calculate heat flux in relation to air-sea interactions because they provide simple and realistic estimates for a broad range of latitudes (20°S - 60°N), as shown in equation (6) and table 2.

$$Q_0 = A_0 + A_1 cos\varphi + B_1 sin\varphi + A_2 cos2\varphi + B_2 sin2\varphi \quad (6)$$

Here Q_0 is the clear-sky mean daily insolation in W/m^2, $\varphi = (t - 21)(360/365)$, *l* is time of year in days and L the latitude. Coefficients A_0,A_1,A_2,B_1 and B_2 depend on latitude, as presented in table 2 [4].

After noting considerable disagreement among the various factors that have been proposed, and considering that a cloud cover factor must be used to adjust the clear – sky insolation, Reed [7] examined 40 months of data at three coastal sites and computed the following empirical relation [4]:

$$Q_s = Q_0(1 - 0{,}62C + 0{,}0019\alpha) \quad (7)$$

where: Q_s is the insolation under cloudy conditions, Q_0 the insolation under clear skies from the Smithsonian formula, C cloud cover (in tenths) and α is the noon solar altitude.

Table 2 Values of coefficients by latitude, [11]

Coefficient	20°S - 40°N	40°N - 60°N
A_0	$-15{,}82 + 326{,}87 \cdot cosL$	$342{,}61 - 1{,}97L - 0{,}018L^2$
A_1	$9{,}63 + 192{,}44 \cdot \cos(L + 90)$	$52{,}08 - 5{,}86L + 0{,}043L^2$
B_1	$-3{,}27 + 108{,}70 \cdot sinL$	$-4{,}80 + 2{,}46L - 0{,}017L^2$
A_2	$-0{,}64 + 7{,}80 \cdot sin2(L - 45)$	$1{,}08 - 0{,}47L + 0{,}011L^2$
B_2	$-0{,}50 + 14{,}42 \cdot cos2(L - 5)$	$-38{,}79 + 2{,}43L - 0{,}034L^2$

The hourly incoming solar radiation *Q* at the surface of the ocean can be also computed following Dobson and Smith formula [8]:

$$Q_i = Q_0 sin\alpha(A_i + B_i sin\alpha) \quad (8)$$

and $sin\alpha = sin(\varphi)sin(d) + cos(\varphi)\ cos(d)\ cos(\omega)$

where: Qo is the solar constant (considered 1368 Wm^{-2}), α is the solar elevation and A_i, B_i are regression coefficients for different cloud amounts (Table 3).

Table 3 Regression coefficients A_i and B_i for different cloud amounts [4]

Cloud amount [oktas]	A_i	B_i
1	0,363	0,377
2	0,217	0,473
3	0,197	0,511
4	0,160	0,569
5	0,181	0,514
6	0,258	0,426
7	0,190	0,079
8	0,156	0,079

The α angle depends on latitude (φ), declination [$d = -22.45\ cos\ (t)$ where t is the Julian day] and hour angle of the sun [$\omega = 15(12 - t)$].

As stated above, cloud cover is expressed in tenths as unit of measure. In practice, records on board vessels and oceanographic studies are carried out in oktas. Conversion from oktas to tenths is being made considering $4/8 = 5/10$.

Case study: evaluation of four empirical formulas

Further, using values for observed insolation [6], a comparative analysis is done for the results obtained using main empirical formulas (Reed's - R, Kimball's - K, Laevastu's - K and Tabata's - T models).

Records were made between 26 October and 13 November 1983 onboard two vessels (R/P Flip and R/V Arcania) during MILDEX project [6]. At that time, results have been used for comparison between satellite and empirical formulas estimation of insolation over the oceans. Area covered by the two vessels was ranging from 33.4°N and 124.6°W at the beginning of the

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experiment and 34.1°N and 126.3°W at the end. In present paper latitude is considered to be constant at 34°N.

By using as variables the day of the year (corresponding to period specified above) and cloud cover and equations (1), (2), (4) and (7), there are calculated values of insolation derived from formulas of Kimball, Laevastu, Tabata and Reed (Table 4).

Table 4 Values of in situ observed insolation and computed one

Day	Observed insolation $[Wm^{-2}]$	Calculated insolation $[Wm^{-2}]$			
		R	K	L	T
299	171.2	178.7	158.8	191.3	179.1
300	156	146	122.0	176.1	141.6
301	141	151.5	128.9	179.0	148.2
302	175.6	169.8	150.3	185.1	169.5
303	137.4	157.6	137.0	180.2	155.7
304	92.2	127.5	103.0	157.7	121.2
305	149.8	143.1	121.4	170.9	139.4
306	177.9	176.3	160.0	180.1	178.0
307	133	106.9	81.0	129.8	98.1
308	126.2	123.5	100.3	152.9	117.3
309	172.6	178.6	164.2	175.3	181.4
310	152	150	131.8	169.6	148.4
311	124.8	144.1	125.7	166.4	142.0
311	121.4	117.5	95.1	146.3	111.2

Comparison between observed values and calculated ones gives a 0.80 correlation factor for Reed, Kimball and Tabata models and 0.66 for Laevastu model (of a maximum of 1).

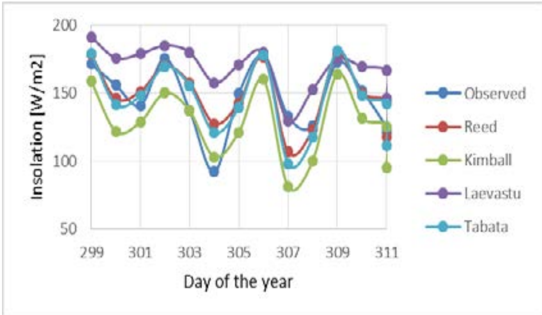

Fig. 1 Observed insolation versus calculated insolation

Figure 1 is a graphical interpretation for the values in Table 1. For a better understanding of disparities, deviations between observed and calculated values are presented in Table 5.

Table 5 Differences between calculated and observed insolation

Day	Cloud cover [tenths]	Difference [%]			
		R	K	L	T
299	0.25	-4.2	7.8	-10.5	-4.4
300	0.51	6.8	27.8	-11.4	10.1
301	0.45	-6.9	9.4	-21.2	-4.9
302	0.28	3.4	16.8	-5.1	3.6
303	0.37	-12.8	0.3	-23.7	-11.8
304	0.62	-27.7	-10.5	-41.5	-23.9
305	0.47	4.7	23.4	-12.3	7.5
306	0.16	0.9	11.2	-1.2	-0.1
307	0.77	24.4	64.2	2.5	35.6
308	0.61	2.2	25.8	-17.5	7.6
309	0.09	-3.4	5.1	-1.6	-4.9
310	0.34	1.3	15.4	-10.4	2.4
311	0.38	-13.4	-0.7	-25.0	-12.1
311	0.63	3.3	27.6	-17.0	9.2

As figure 2 shows, cloud cover (hereinafter referred as CC) is a key factor and has a significant influence when referring to final results.

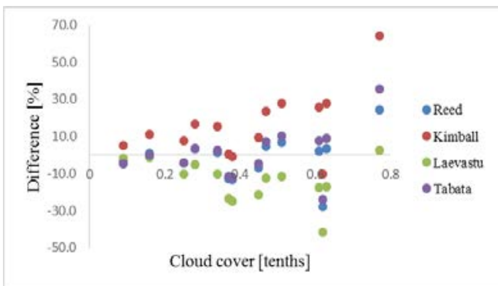

Fig. 2 Distribution of estimated insolation by cloud cover

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CONCLUSIONS

For clear - sky conditions (CC lower than 0.3) Reed, Laevastu and Tabata formulas generate the best results with a slight underestimation of maximum 5%, which is more than acceptable. Kimball's formula on the other hand overestimates insolation in all sky condition (for CC lower than 0.3 range between 5 and 17%, for 0.3<CC<0.6 range between 10 and 27% and for CC higher than 0.6 differences can be up to 65%). Laevastu's empirical formula constantly underestimates insolation and the worst prediction is for CC higher than 0.6. It can be noticed that Tabata's formula underestimates insolation for a CC lower than 0.6 but overestimate values for a CC than 0.6.
Considering results from present paper, as a recommendation, for all sky conditions, the best option it will be the use of Reed's formula, which generates satisfactory values of insolation.
A better understanding of results obtained for the long – term monitoring of radiation is still required. An alternative for retrieving data is represented by satellite records, solution which allow a more detailed spatial analysis. An analysis of the differences in contribution of solar radiation for land and sea is also a key topic which will be investigated. So far, due to relative constant water vapor and low influence of industrial pollutants, is considered that, globally, the amount of solar radiation is higher on sea than on land.

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