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A simple solar radiation model applicable in numerical hydrodynamical modeling on seasonal time-scale

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A solar radiation climatological data set is used to define a simple radiation model suitable for application in numerical hydrodynamical modeling. The model is based on the ÅNGSTRÖM empirical relation for albedo of the atmosphere and on a simplified function of sun height during the year. The model error is generally smaller than 20%. The results of the model are discussed in comparison with long time data series for clear sky conditions and actual measurements from the station at the Institute of Oceanography and Fisheries in Split.

Key words: solar radiation model, numerical hydrodynamic modeling, AMOS

INTRODUCTION

Knowledge of incoming solar and sky radiation is of great importance for more accurate weather forecast, in climatological studies, in study of conditions in the air above the sea, as well as in many fields of solar energy applications. In dynamical oceanography solar radiation is important because on the daily time scales it influences the sea surface layer dynamics and on the longer time scales the entire thermohaline circulation of the sea. The solar radiation can be directly measured with suitable instruments but, as these have not been employed, on a routine basis on most of the meteorological stations, it is often necessary to make predictions using various expressions. Several models for hourly solar radiation estimations were developed especially for solar energy design (for example: LIU and JORDAN, 1962; IQBAL, 1983; NEWELL, 1983; GUEYMARD, 2000). Some parts of the solar radiation are absorbed in the atmosphere and, due to scattering, other parts are reflected back into the space. Amount of attenuation of solar radiation throughout the atmosphere depends on conditions in atmosphere and sun height. That is, in the sea numerical hydrodynamical modeling the solar radiation should be defined at least as function of time. The results of the numerical experiments in the Middle Adriatic showed that higher values of the solar radiation have generated strongest surface currents (BEG PAKLAR and BONE, 1998). These and similar numerical experiments motivated us to pay more attention to the processes of heating of the surface sea layer by incoming solar energy fluxes.

A simple solar radiation model based on the ÅNGSTRÖM empirical relation for albedo of the atmosphere and a simplified function for sun height during the year is considered in this paper. It is sufficiently accurate to be applied in numerical modeling analyses of the Adriatic Sea dynamics and it is not computation time expensive. We started with the BOUGUER-LAMBERT low and ÅNGSTRÖM relation for sky albedo (e.g. HAURWITZ, 1941). The empirical constants in the model are calculated on the base of the PENZAR and BRATANIĆ (1979) solar radiation climatological data set for Split. The results were compared with experimental data obtained from the AANDERAA Automatic Metocean Station Split - Marjan Cape (AMOS) and with the values known from literature. Relative errors of maximum values for clear sky conditions during the year were also considered.

MATERIAL AND METHODS

A simple solar radiation model

Some parts of the incoming solar radiation at outer limit of the atmosphere are absorbed in the atmosphere (mainly by water vapor). Energy flux trough the unit horizontal surface at sea level, considering only the absorption, according the BOUGER-LAMBERT law (it is a form of the BEER low) may be written as follows (e.g., HAURWITZ, 1941):

$$I = \begin{cases} S_C \; T^{\frac{1}{sin(\xi)}} \; sin(\xi) \; , \; sin(\xi) > 0 \\ 0 \; , sin(\xi) \leq 0 \end{cases} , \; T = e^{-\int_0^\infty a dz}$$

where S_c is the solar constant, ξ is the solar height and T is the transmission coefficient with the absorption coefficient a depending on the vertical coordinate. Due to the scattering a diffusive light is generated. One part of it contributes to the total incoming solar radiative energy at sea level and the other part is lost back into the space. The significant part of the incoming solar radiative flux is also reflected from the clouds. ÅNGSTRÖM considered (e.g., HAURWITZ, 1941) the albedo of the atmosphere by simple linear relation to cloudiness:

$$A_C = A_0 + A_1 \; C \tag{2}$$

where C is cloudiness (from 0 to 1). In this case the total short wave energy flux trough the unit horizontal surface at sea level may be approximately described by simple formula:

$$G = \left[1 - (A_0 + A_1 \; C)\right] \; I \tag{3}$$

Sinus of the solar height calculated from the spherical triangle (sun, earth pole, zenith) with sufficient accuracy may be written as:

$$sin(\xi) = sin(\varphi) \; sin(\delta) + cos(\varphi) cos(\delta) \; cos\left[\frac{\pi}{12}(h - T_m)\right] \tag{4}$$

where φ is the latitude, δ is the sun declination, h is local time in hours and T_m is the mean time when the sun is in the upper meridian for the considered area (approximately the noon; for Split it is 12.1 h). The sinus of the sun declination calculated from the spherical triangle (ecliptic pole, earth pole, sun) assuming the angular earth velocity around the sun as constant (with sufficient accuracy) is:

$$sin(\delta) = sin(\frac{\pi}{180} \; 23.5) cos\left(\frac{2\pi}{365} \; (d - 172)\right) \tag{5}$$

where d is local time in days from the beginning of the year, and 172 is the day of the summer solstice.

The set of empirical constant (T, A_0, A_1) should be determined from the data. We used the mean hourly values of solar radiation for every 15[th] day in month for Split area according to PENZAR and BRATANIĆ (1979) data. For the cloudiness we used the mean monthly amount for the normal period 1961-1990 according to the State Hydro meteorological Institute - DHMZ data.

Statistical model for clear sky conditions

Available daily sums of solar radiation for the period 1965-1975 from meteorological station Split - Marjan were used to calculate daily sums of global radiation under clear sky conditions. A simple statistical model for estimating the daily radiation for clear sky conditions can be expressed as follows:

Step 1. → from available data set only those days for which the mean daily cloudiness reaches the zero value (C=0; clear sky) were extracted referring the particular day in year;

Step 2. → extracted values were least square fitted with the equation:

$$G(d)^{clear\,sky} = a + b\cos\left(\frac{2\ \pi\ d}{365} + c\right) \quad , \qquad (6)$$

where $G(d)^{clear\ sky}$ is the solar radiation energy received during day on the unit horizontal surface at sea level in the case of clear sky for particular day in year *(d=1, ... , 365)*, and *a*, *b*, and *c* are parameters. The cosine form of equation (6) is good approximation for equations (4) and (5). Although the equation is empirical it could be theoretically explained. First parameter is the daily solar radiation, *b* is amplitude and *c* is the phase constant, which should be set at a value corresponding to the longest day of the year (i.e., summer solstice, *d=172*).

Solar radiation obtained from AMOS

The description of AMOS was presented in detail in paper by GRBEC *et al.* (this issue). Among all 12-station parameters for air and sea, only solar radiation is of interest for our purpose. Incoming solar and sky radiation at AMOS are measured with AANDERAA Solar radiation Sensor 2770. This sensor has been developed to measure solar and sky radiation under all weather conditions. The sensor employs a high sensitivity thermistor bridge which measures the temperature rise of a black surface under a glass dome. To obtain a full reading, only a temperature rise of about 2.2 °C is needed due to the high sensitivity thermistor bridge. Because of this, a double dome, frequently used for radiation sensors, has been eliminated in AANDERAA solar radiation sensor. AANDERAA sensor is not affected by changes of ambient temperature. Therefore no radiation screen is needed around sensor. The solar radiation sensor is placed on the AANDERAA sensor arm 2700 situated 10 meters above sea level (Fig.1), and together with other sensor that Datalogger 3660, builds a monitoring station. Although the solar radiation sensor gives real time readings, it will give a sensible average of incoming radiation for each 10-min period. Solar radiation sensor is sensitive in the wavelength range between 0.3 to 2.5 mm, and measured radiation in range 0 - 2000 Wm^{-2} with resolution of 4 Wm^{-2}. Sensor accuracy is ± 20 Wm^{-2}.

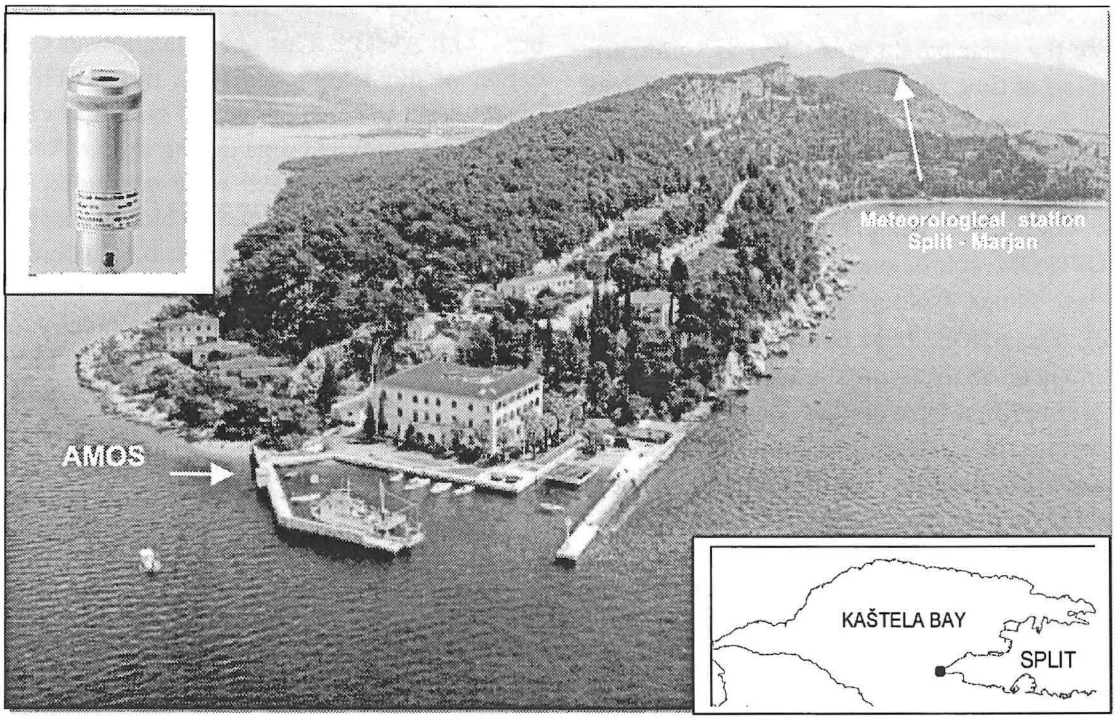


Fig.1. The map of Kaštela Bay and position of automatic weather station AMOS. Sensor for global radiation with Aanderaa arm was plotted in the corner

RESULTS AND DISCUSION

From the considered climatological data set for solar radiation, cloudiness is suitably considered as the monthly mean in equation (3). For statistical analysis of the equation (3) we used the following form

$$\frac{G_{h,m}}{S_C\, T^{\frac{1}{\sin(\xi_{h,m})}}\, \sin(\xi_{h,m})} = (1-A_0)-A_1\, C_m \qquad (7)$$

where index h denotes hour and index m month. The right hand part of equation (7) depends only on the mean monthly cloudiness and during day it is constant. It may be eliminated taking $G_{12,m}$ at 12^h as a reference and as subsequent values. In this case for the transmission coefficient may be written

$$T_{n,m} = \frac{\sin[\xi(12+n,m)]\,\sin[\xi(12,m)]}{\sin[\xi(12+n,m)]-\sin[\xi(12,m)]}\, \ln\left(\frac{\sin[\xi(12+n,m)]}{\frac{G_{12-n,m}+G_{12+n,m}}{2}}\,\frac{G_{12,m}}{\sin[\xi(12+n,m)]}\right), \qquad (8)$$

$$\begin{cases} n=1...3 \\ m=1...12 \end{cases}$$

where the solar height was taken as symmetric function of time around the midday. The annual mean for transmission coefficient was obtained as 0.986, with a relative error of less than 5%. Using the obtained mean value for the transmission coefficient from the equation (7) the ÅNGSTRÖM coefficients of albedo according the last square method are (A_0, A_1) = (0.144, 0.62). The ÅNGSTRÖM coefficients in the climatological analysis are frequently calculated using simplified form of equation (2) with $T=1$, neglecting the absorption. Compared values of equation (1) obtained for $T=0.986$ with those obtained for $T=1$ lead to the conclusion that during the whole sunshine interval the differences were about 10 Wm^{-2}. These differences for summer solstices ($d=172$) are shown in Fig. 2. The differences are small and are within the accuracy of the measurements. For purpose of numerical hydrodynamical modeling T may be set to one saving the computational time. Using the obtained values for A_0 and A_1 it is possible to define the clearness index for Split area. This index is defined as the ratio between hemispheric and extra terrestrial radiation. For clear sky conditions, the clearness index is set to be $1-A_0$= 0.856 and coincides with previously obtained values for the eastern Adriatic coast (KULIŠIĆ et al., 1987), and for some other locations (GUEYMARD, 2000).

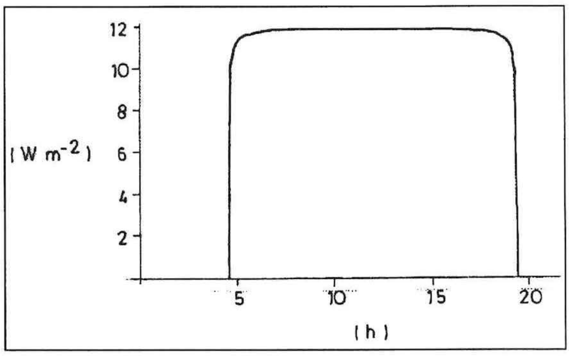


Fig. 2. Differences between hourly values of solar radiation for summer solstices (d=172) calculated from the equation (3) with T = 0.986 and T = 1

Using a set of estimated parameters (T, A_0, A_1), the few solar radiation values were calculated in order to compare the model results with climatological values and some values measured with AMOS. This analysis allowed verification of our simple radiation model. First, a model is set to calculate global radiation values at 12 h, i.e. daily maxima during a year. Results obtained from the model were compared with the climatological data set on which was applied bilinear interpolation in order to obtain continuous function of time. The noon values are shown in Fig.3a. The relative error is generally less than 20 %. The climatological values with the calculated ones during the day for summer solstices (21. June) and autumnal equinox (21. September) are compared in Fig. 4. The forms of the climatological and calculated functions agree with maximal error around the midday. This is steel better visible in the Fig. 5. where the differences between climatological and calculated data as function of hour and day are given. Annual variations of solar radiation are presented using various sources in Fig. 6. The figure shows similarity of results obtained from

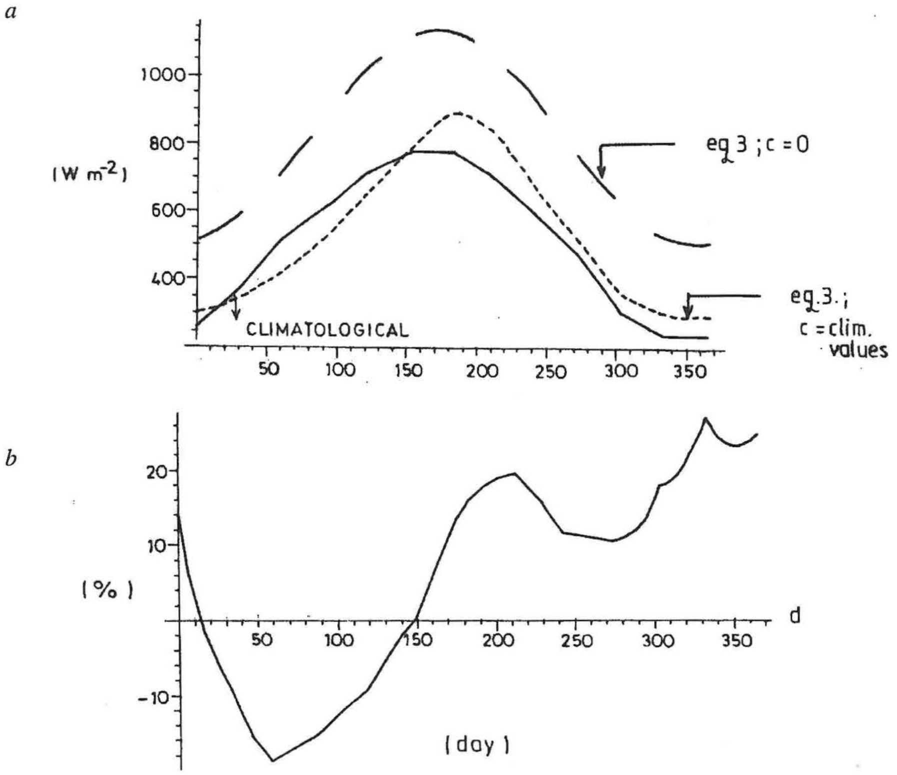


Fig. 3. Daily maximum values of solar radiation (at 12 h) predicted by the equation (3) and from the climatological data set (a), and the relative error between predicted and climatological data maximums during the year (b)

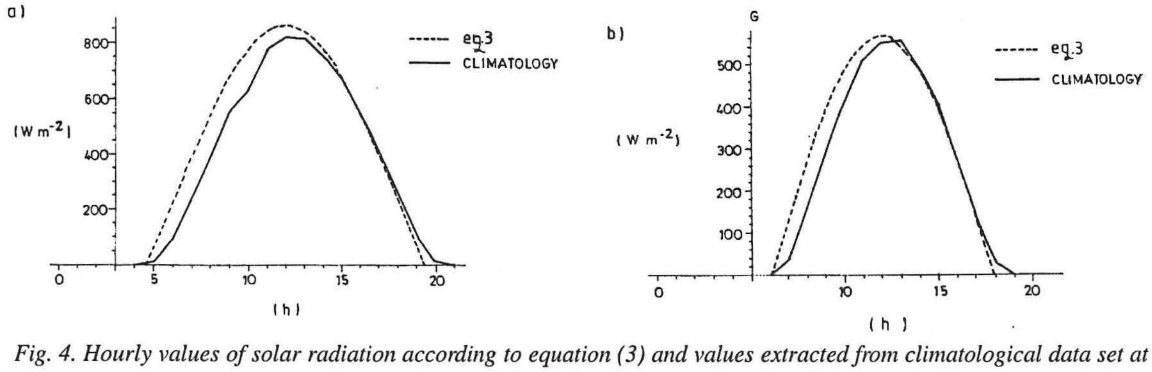
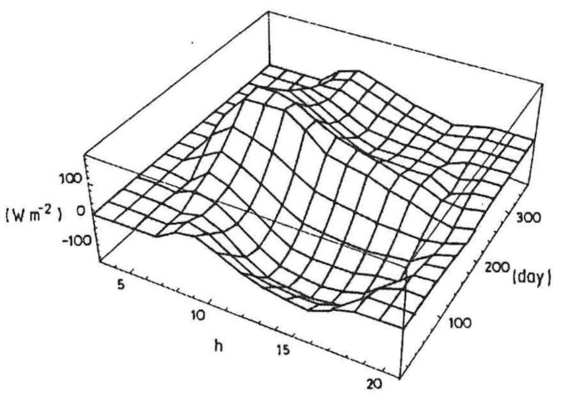


Fig. 4. Hourly values of solar radiation according to equation (3) and values extracted from climatological data set at summer solstices (a) and autumnal equinox (b)



climatological data set, measurement during period 1999 - 2000 with AMOS, and from our model.

Daily measured values during clear sky conditions throughout the year were analyzed as well. The parameters *a, b* and *c* in equation (6) according to the daily sum of solar radiation for

Fig. 5. Differences between predicted solar radiation according to equation (3) and climatological values during year

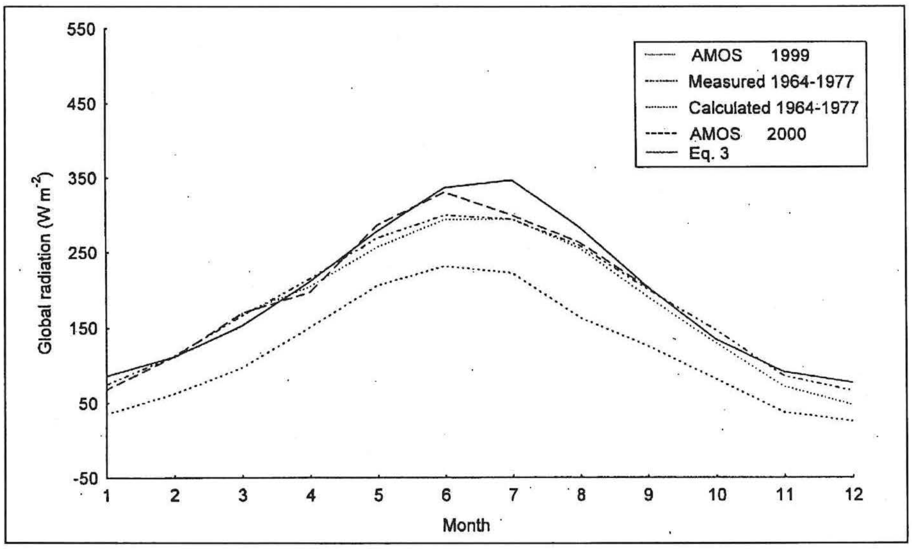


Fig. 6. Monthly solar radiation from climatological data sets, from proposed model, and hourly AMOS measured values

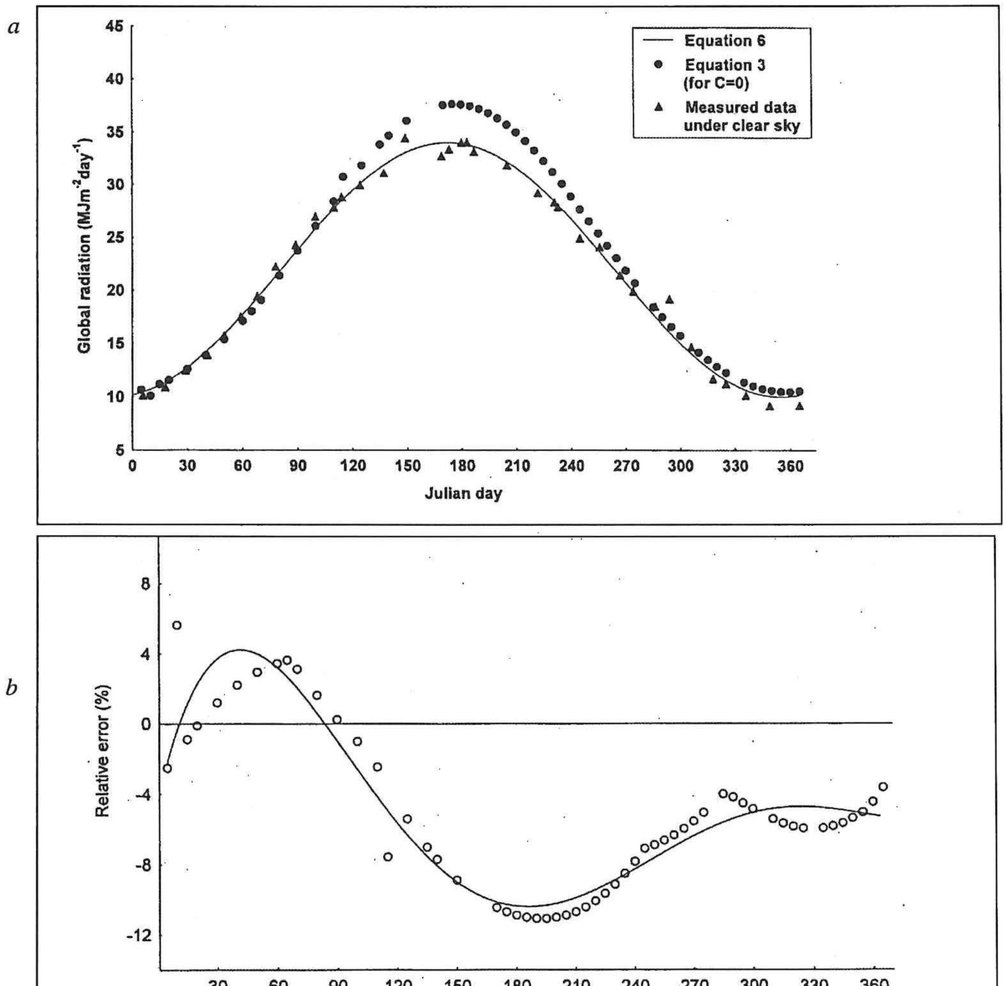


Fig. 7. Daily values of solar radiation for clear sky conditions according equation (3) and equation (6). Measured daily sums for clear sky are also plotted (a), and relative error between results from equations (3) and (6) (b)

clear sky conditions (GRBEC, 1989) are (*a, b, c*) = (21.98 ± 0.140 $MJm^{-2}day^{-1}$, -12.00 ± 0.202 $MJm^{-2}day^{-1}$, 12.74 ± 0.017 rad). The results of curve fitting are given in Fig. 7a together with the model output for clear sky conditions. Relative error between model results and results of equation (6) is about 5 % with absolute maximum of 12 % during warm period of the year (Fig.7.b). Station AMOS is in function from March 1999, so for the climatological analysis available period is too short.

CONCLUSION

A solar radiation model applicable in numerical hydrodynamical modeling is considered. It is demonstrated that solar radiation may be described with sufficient accuracy with the ÅNGSTRÖM empirical relation for albedo of the atmosphere and the simplified function of time for sun height during the year. There for the absorption of solar energy in atmosphere may be neglected. The empirical constants of this simple and not computational time expensive model of solar radiation are calculated from the climatological data set of solar radiation for Split (PENZAR and BRATANIĆ, 1979). The relative error of the model results compared with the climatological data is under 20%. The proposed model for solar radiation in the cloudless atmosphere is accurate with a relative error of less than 12 %. The solar radiation data that we started to collect at automatic station AMOS will be important to better understand the impact of solar radiation on the sea hydrodynamic processes in the Middle Adriatic.

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Jednostavan model za određivanje solarnog zračenja za primjenu u hidrodinamičkim modelima na sezonskoj skali

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SAŽETAK

Na dnevnim skalama zagrijavanje sunčevim zračenjem utječe na dinamiku površinskog turbulentnog sloja, dok je na dužim vremenskim skalama značajno za cijelu temohalinu cirkulaciju. U modelskim hidrodinamičkim studijama, unatoč nedostatku podataka, ovo zagrijavanje treba definirati. U cilju postavljanja jednostavnog modela iradijacije za svrhe numeričkog hidrodinamičkog modeliranja za srednji Jadran uzet je u ramatranje niz klimatoloških podataka. Pokazano je da ÅNGSTRÖM-ova empirijska relacija za albedo atmosfere, ovisno o oblačnosti i uz pojednostavljenu funkciju visine sunca za sat i dan u godini, može opisati iradijaciju jedinične površine mora s greškom općenito manjom od 20% ako je zadana oblačnost. Rezultati modela diskutirani su usporedbom s dugogodišnjim nizovima za vedro nebo i postojećim mjerenjima na stanici Instituta za oceanografiju i ribarstvo u Splitu.