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Comparison of Marine Insolation Estimating Methods in the Adriatic Sea

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Abstract – We compare insolation results calculated from two well-known empirical formulas (Seckel and Beaudry's SB73 formula and the original Smithsonian (SMS) formula) and a radiative transfer model using input data predicted from meteorological weather-forecast models, and review the accuracy of each method. Comparison of annual mean daily irradiance values for clear-sky conditions between the two formulas shows that, relative to the SMS, the SB73 underestimates spring values by 9 W m^{-2} in the northern Adriatic Sea, although overall there is a good agreement between the annual results calculated with the two formulas. We also elucidate the effect on SMS of changing the 'Sun-Earth distance factor (f)', a parameter which is commonly assumed to be constant in the oceanographic context. Results show that the mean daily solar radiation for clear-sky conditions in the northern Adriatic Sea can be reduced as much as 12 W m^{-2} during summer due to a decrease in the f value. Lastly, surface irradiance values calculated from a simple radiative transfer model (GM02) for clear-sky conditions are compared to those from SB73 and SMS. Comparison with *in situ* data in the northern Adriatic Sea shows that the GM02 estimate gives more realistic surface irradiance values than SMS, particularly during summer. Additionally, irradiance values calculated by GM02 using the buoy meteorological fields and ECMWF (The European Centre for Medium Range Weather Forecasts) meteorological data show the suitability of the ECMWF data usage. Through tests of GM02 sensitivity to key regional meteorological factors, we explore the main factors contributing significantly to a reduction in summertime solar irradiance in the Adriatic Sea.

Key words – insolation formula, radiative transfer model, heat-flux, irradiance, Adriatic Sea

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1. Introduction

Incoming solar radiation in ocean and coastal waters is a crucial factor in air-sea interactions and biogeochemical processes. Consequently, much of our understanding of ocean dynamics hinges on the quantification of solar radiation reaching surface waters. Accurate estimates of photosynthetically-active radiation (PAR), for example, are central to calculating phytoplankton photosynthesis rates (Liu *et al*. 2002).

Insolation at the sea-surface under clear-sky conditions depends on astronomical, and meteorological parameters, and on geographic location. Clear-sky radiative transfer models (RTMs) consider variation in all of these parameters and thus have the potential to estimate solar radiation more accurately than empirical formulae with constant atmospheric transmission coefficients.

Use of RTMs is particularly important for calculating phytoplankton photosynthesis in marine ecosystem models (Liu *et al*. 2002). However, most of the weather forecasting models used to generate the meteorological inputs for RTMs do not spectrally-resolve solar-irradiance, nor do they produce the conversion factors for PAR needed to calculate phytoplankton production. Where conversion factors are considered, PAR irradiance is conventionally assumed to equal half the total irradiance (*e.g*. Parsons *et al*. 1984; Colijn and Cadée *et al*. 2003). This is despite the fact that this ratio varies between 0.42 and 0.5 both daily and seasonally, depending on solar zenith angle, cloud effects, aerosol optical thickness, and water vapor (Jacovides *et al*. 2003; Byun and Cho 2006).

Table 1. The clear-sky mean daily solar radiation formula (SB73) derived from data in the Smithsonian Meteorological Tables and the original solar radiation formula (SMS) used in calculating values in the Smithsonian Meteorological Tables

SB73 (Seckel and Beaudry 1973)		SMS (Rosati and Miyakoda 1988)
$Q_0 = A_0 + A_1\cos\phi + B_1\sin\phi + A_2\cos 2\phi + B_2\sin 2\phi$		$Q_0 = Q_{Dir} + Q_{Dif}$
Latitude 20°S – 40°N	Latitude 40°S – 60°N	$Q_{Dir} = S_E\tau^{\sec\theta}$
$A_0 = -15.82 + 326.87\cos L$	$A_0 = 342.61 + 1.97L - 0.018L^2$	$Q_{Dif} = \frac{1}{2}S_E[(1-A_a) - \tau^{\sec\theta}]$
$A_1 = 9.63 + 192.44\cos(L+90)$	$A_1 = 52.08 - 5.86L + 0.43L^2$	where $S_E = f\,S_0\cos\theta$ and
$B_1 = -3.27 + 108.70\sin L$	$B_1 = -4.80 + 2.46L - 0.017L^2$	$\cos\theta = \sin L\sin\delta + \cos L\cos\delta\cos h$
$A_2 = -0.64 + 7.80\sin 2(L - 45)$	$A_2 = 1.08 - 0.47L + 0.011L^2$	
$B_2 = -0.50 + 14.42\cos 2(L - 5)$	$B_2 = -38.79 + 2.43L - 0.034L^2$	

Here, $\phi = (D - 21)(2\pi/365)$, D is the day of year, L is the latitude (in degrees), τ (=0.7) is the atmospheric transmission coefficient, θ is the solar zenith angle, A_a (= 0.09) is the water vapor and ozone absorption, S_0 (= 1367 W m^{-2}) is the total mean solar irradiance at the top of the atmosphere, f is the Sun-Earth distance factor, ä is the solar declination angle and h is the solar hour angle.

Since RTMs require several types of meteorological input data which, in the past, have not been available for ocean and coastal waters, simple, latitude- and date-dependent empirical insolation formulas have conventionally been used by the oceanographic modeling community (*e.g.* Castellari *et al*. 1998, 2000), including in several models of the Mediterranean and Adriatic Seas (*e.g.* Schiano, 1996; Chiggiato *et al*. 2005). One such formula is Seckel and Beaudry's (1973) mean daily clear-sky insolation parameterization (herein referred to as SB73), which was derived from data in the Smithsonian Meteorological Tables (Table 1). Similarly, Reed's (1977) cloudy-sky insolation formula was based on the SB73 insolation formula. In their general oceanic circulation model, however, Rosati and Miyakoda (1988) used the more-accurate, original Smithsonian insolation formula (herein referred to as SMS) alongside Reed's cloud formula, as illustrated in Table 1. Note that the SMS calculates instantaneous insolation values, whereas the SB73 estimates mean daily insolation.

These empirical insolation formulas have been used in many studies of the Mediterranean Sea: the SB73 formula was used by Garrett *et al*. (1993) and Gilman and Garrett (1994), while the SMS formula was used by Schiano (1996), Maggiore *et al*. (1998), Angelucci *et al*. (1998), Castellari *et al*. (1998), Tragou and Lascaratos (2003), Cardin and Gačić (2003), Wang (2005) and Chiggiato et al. (2005). In studies using the SMS formula, the sun-Earth distance factor is often assumed to be constant, or is not considered, or is mentioned without clear explanation. Few studies have assessed the effect of such approximations in an oceanographic context. This is despite reports that calculations based on SB73 or SMS overestimate summertime solar radiation in the Mediterranean and Adriatic Seas (Garrett *et al*. 1993; Gilman and Garrett 1994; Schiano 1996; Tragou and Lascaratos 2003; Chiggiato *et al*. 2005).

This study is a preliminary part of a larger program aiming to correctly-parameterize solar irradiance in marine ecosystem models. That is, our ultimate aim is to establish an appropriate Adriatic Sea RTM capable of being used in not only ocean circulation models to estimate heating but also biogeochemical models to estimate phytoplankton photosynthesis. One example of an ecosystem model, the coupled hydrodynamic-biogeochemical model, is the 3-D European Regional Sea Ecosystem Model, ERSEM (Vichi *et al.* 2003). The biogeochemical model of ERSEM is composed of >90 state variables for the pelagic and benthic models that already require significant computing overheads. Thus, we selected a simple, spectrally-coarse but -sufficient, maritime RTM, even though more-accurate, spectrally-higher-resolution maritime radiative transfer models are available (*e.g.* Gueymard 2001; Ricchiazzi *et al.* 1998).

In this study we compare results of the two well-known clear-sky insolation empirical formulas (SB73 and SMS) with those of the simple RTM using the predicted meteorological input data, as well as *in situ* insolation data from Barbara Station in the Adriatic Sea, in order to understand their characteristics and ability to accurately estimate insolation. To our knowledge these important comparisons have not been made before. Our results assess the validity of using simple RTM models, with input data predicted from meteorological weather-forecast models, in future ecosystem modeling research. Lastly, we use the RTM to explore the main meteorological factors affecting seasonal variability in irradiance at Barbara Station in the Adriatic Sea, a research problem which has not yet been thoroughly explored.

2. Description of Clear Sky Insolation Formulas and a RTM

Empirical solar radiation formulas

Seckel and Beaudry (1973) proposed a simple formula for clear-sky mean daily solar radiation (Q_0) as a function of latitude and date using the computed data listed in the Smithsonian Meteorological Tables (SMT) (List 1958). The SMT data are computed using a constant atmospheric transmission coefficient of 0.7. These data have been widely used by oceanographers to calculate heat flux in relation to air-sea interactions (*e.g*. Simpson and Paulson, 1979; Gilman and Garrett 1994) because they provide simple and realistic estimates for a broad range of latitudes (20°S - 60°N), as shown in Table 1.

Since the 1990s, rapid improvements in computational capabilities have tended to allow more widespread use of the original Smithsonian SMS formula, which estimates instantaneous insolation for clear-sky conditions. This formula is expressed as the sum of direct solar radiation (Q_{Dir}) and diffuse sky radiation (Q_{Dif}) (Table 1).

In SMS, S_E or the extraterrestrial solar radiation on a horizontal surface, corrected for the Sun-Earth distance, can be expressed (Almorox *et al*. 2005):

$$S_E = \frac{S_0}{r^2}\cos\theta = fS_0\cos\theta \tag{1}$$

where θ is the solar zenith angle (in degrees) and S_0 is the mean total solar irradiance at the top of the atmosphere (in 1367 W m^{-2}). Satellite observations reveal that S_0 fluctuates between 1363 and 1368 W m^{-2} over 27-day and 11-year cycles due to the sun's rotation and sunspot activity. As such, S_0 is referred to as the 'total solar irradiance', and not the 'solar constant' (Wen *et al.* 2003; Gueymard 2004). The formulas for the inverse of the square of the 'Sun-Earth radius vector' *r*, the so-called 'Sun-Earth distance factor', f ($=1/r^2$), are listed in Table A1. In this work, we use Michalsky's (1988) algorithm.

The radiative transfer model (RTM)

The RTM used in this study is based on Gregg and Carder (1990)'s clear-sky maritime spectral-irradiance model, as extended to include the entire solar spectra (200-4000 nm) by Gregg (2002). This model (hereafter the GM02) has the relatively-fine spectral resolution of 25 nm in the 350-700 nm range, the PAR for phytoplankton photosynthesis. The resolution with which other spectral ranges are represented varies from 50 to 800 nm according to spectral importance; the total set of spectral resolutions used is thought be reasonable considering the necessary computation time after coupling with a 3-D marine ecosystem model.

Global downwelling solar irradiance (E_d (λ, 0^+)) above the sea-surface consists of the sum of two components, the spectral direct (E_{dd} (λ, 0^+)) and diffuse downwelling irradiances (E_{ds}(λ, 0^+)), which may be expressed by:

$$E_d(\lambda, 0^+) = E_{dd}(\lambda, 0^+) + E_{ds}(\lambda, 0^+) \tag{2}$$

where λ is wavelength (nm) and 0^+ represents a level above the sea-surface. The direct downwelling irradiance arriving at the sea surface is determined through the primary attenuation processes by the following spectral transmittance components in a cloud-free maritime atmosphere: $T_r(\lambda)$ after aerosol scattering, $T_a(\lambda)$ after aerosol scattering and absorption and $T_{oz}(\lambda)$, $T_{o_2}(\lambda)$, $T_{co_2}(\lambda)$ and $T_w(\lambda)$ after ozone, oxygen and carbon dioxide, and water-vapor absorptions, respectively. This may be expressed as (Gregg and Carder, 1990; Gregg, 2002):

$$\begin{aligned} &E_{dd}(\lambda, 0^+) \\ &= fH_0(\lambda)\cos\theta T_r(\lambda)T_a(\lambda)T_{oz}(\lambda)T_{o_2}(\lambda)T_{co_2}(\lambda)T_w(\lambda) \end{aligned} \tag{3}$$

where $H_0(\lambda)$ is the mean extraterrestrial solar irradiance as a function of light wavelength (W m^{-2} nm^{-1}).

The diffuse downwelling irradiance is calculated from the two spectral diffuse components induced by Rayleigh scattering ($I_r(\lambda)$) and aerosol scattering ($I_a(\lambda)$), given by (Gregg and Carder, 1990; Gregg, 2002):

$$E_{ds}(\lambda, 0^+) = I_r(\lambda) + I_a(\lambda) \tag{4a}$$

$$\begin{aligned} I_r(\lambda) &= \frac{1}{2} fH_0(\lambda)\cos\theta T_{oz}(\lambda)T_{o_2}(\lambda)T_{co_2}(\lambda)T_w(\lambda) \\ &T_{aa}(\lambda)(1 - T(\lambda)_r^{0.95}) \end{aligned} \tag{4b}$$

and

$$\begin{aligned} I_a(\lambda) &= fH_0(\lambda)\cos\theta T_{oz}(\lambda)T_{o_2}(\lambda)T_{co_2}(\lambda)T_w(\lambda) \\ &T_{aa}(\lambda)T_r^{1.5}(1 - T_{as}(\lambda))F_a(\theta) \end{aligned} \tag{4c}$$

where $T_{aa}(\lambda)$ and $T_{as}(\lambda)$ are transmittances after aerosol absorption alone and aerosol scattering alone respectively, and $F_a(\theta)$ is the forward scattering probability of the aerosol. As presented in Table 2, the atmospheric transmittances

Table 2. Maritime atmospheric transmittance after absorption or scattering used in the spectral cloudless atmospheric radiative transfer model

Transmittance	Attenuation coefficient	Reference
$T_r = f\,(\tau_r(\lambda), M(\theta), p)$		Gregg and Carder (1990)
	$\tau_r(\lambda)$: Rayleigh scattering	Gueymard (2001)
	$M(\theta)$: atmospheric path length	Kasten and Young (1989)
$T_{oz} = f\,(a_{oz}(\lambda), M_{oz}(\theta), H_{oz})$		Gregg and Carder (1990)
	$a_{oz}(\lambda)$: ozone absorption	Gregg (2002)
	$M_{oz}(\theta)$: ozone path length	Paltridge and Platt (1976)
	H_{oz}: ozone scale height	Van Heuklon (1979)
$T_{o2} = f\,(a_{o2}(\lambda), M(\theta), p)$		Bird and Riordan (1986)
	$a_{o2}(\lambda)$: oxygen absorption	Gregg (2002)
$T_{co2} = f\,(a_{co2}(\lambda), M(\theta), p)$	$a_{co2}(\lambda)$: carbon dioxide absorption	Gregg (2002)
$T_w = f\,(a_w(\lambda), M(\theta), W_v)$		Leckner (1978)
	a_w(ë): water vapor absorption	Gregg (2002)
	W_v: precipitable water vapor	Gueymard (1994)
$T_a = f\,(\tau_a(\lambda), M(\theta))$		Gregg and Carder (1990)
	$\tau_a(\lambda)$: aerosol optical thickness	Venice platform
$T_{aa} = f\,(\tau_a(\lambda), M(\theta), \omega_a(\lambda))$		Justus and Paris (1985)
$T_{as} = f\,(\tau_a(\lambda), M(\theta), \omega_a(\lambda))$		Justus and Paris (1985)
	$\omega_a(\lambda) = f\,(\mathrm{AM}, R_H)$: single-scattering aerosol albedo	Gregg (2002)

(*i.e.* T_r, T_a, T_{aa}, T_{as}, T_{o_2}, T_{co2}, and T_w) except for T_{oz} are a function of atmospheric path length ($M(\theta)$) at sea level. T_{oz} uses the ozone path length ($M_{oz}(\theta)$). Moreover, $T_{aa}(\lambda)$ and $T_{as}(\lambda)$ are a function of the aerosol optical thickness (τ_a) and of the single-scattering aerosol albedo (ω_a).

In order to compare the results estimated from the RTM with those of empirical models, the output spectral irradiance (*i.e.* $E_{dd}(\lambda, 0^+)$ and $E_{ds}(\lambda, 0^+)$ in equations (3) and (4)) are integrated over the entire spectral domain (200-4000 nm). It should be noted that the integrated PAR (350-700 nm) irradiance in this model accounts for 43% of the total extraterrestrial solar irradiance integrated over the entire solar spectra.

The solar irradiance in Equations (3) and (4) depend on several meteorological variables as listed in Table 3. We have used the 6-hourly (*i.e.* 00/06/12/18 in UTC) ECMWF (The European Centre for Medium Range Weather Forecasts) analysis fields (i.e. wind speed, atmospheric pressure, air temperature and dew point temperature) with 0.5° horizontal resolution. Hereafter, this is referred to as the 'standard run' associated with the GM02 sensitivity experiments in Section 4. Our test site is a station called Barbara located in the northern Adriatic Sea, where an ocean buoy is moored and meteorological data are available for the entire of 2001 period. *In situ* irradiance data are compared with the results of the formulas in Section 3.

3. Results

The hourly insolation values at the Barbara station

Table 3. Meteorological input parameters and data sources used for the radiative transport model simulation (standard run)

Input variables	Data source	Note / Reference
10 m wind speed (WS, m s^{-1})	6-hourly ECMWF data	
Atmospheric Pressure (AP, hPa)	6-hourly ECMWF data (mean sea level pressure)	
Relative humidity (R_H, %)	Based on 6-hourly ECMWF data (2 m air temperature, 2 m dewpoint temperature, mean sea level pressure)	See Appendix A
Total precipitable water vapor (PWV, cm)		PWV formula by Gueymard (1994) See Appendix A
Aerosol optical thickness, τ_a(500 nm)	0.2	Calculated from the Venice platform
Ångström exponent (α)	0.0	Assuming purely marine aerosol
Air-mass type (AM)	1	For open-ocean aerosols

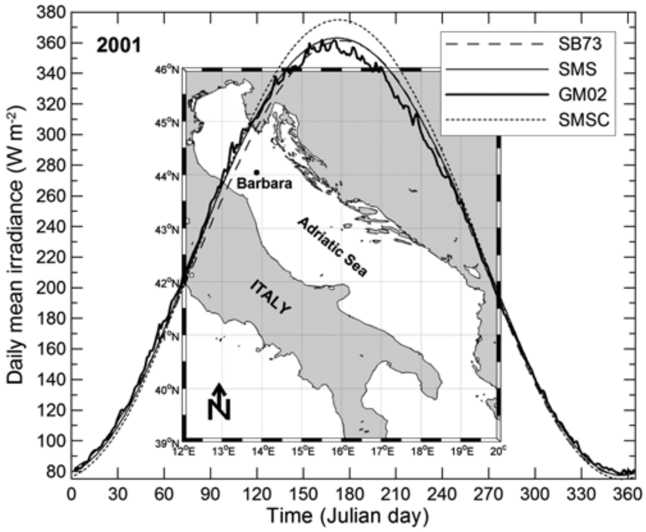

Fig. 1. Annual daily mean surface irradiances for clear-sky conditions at Barbara in the northern Adriatic Sea, 2001, calculated from the SMS, SB73 and SMSC ($f = 1$) formulas, and from the GM02 model.

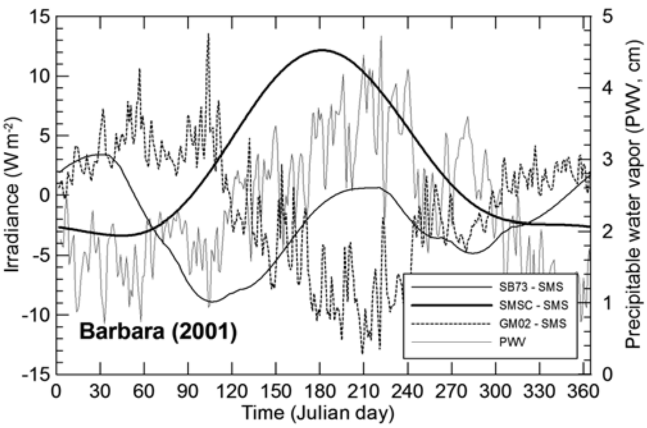

Fig. 2. Differences in mean daily surface irradiances for clear-sky conditions (shown in Fig. 1) between the SMS and the SB73, SMSC ($f = 1$) and GM02, and mean daily total precipitable water vapor at the Barbara station location.

computed from the SMS in were averaged to derive a mean daily value for comparison with that from the SB73. As shown in Fig. 1, the SB73 and SMS formulas produced similar results in terms of general seasonal variation in clear-sky mean daily insolation. However, in comparison with SMS, SB73 underestimated insolation by up to approximately 9 W m^{-2} for the period from March to June (Fig. 2). That is, this result reveals that the SB73 parameterized from the SMS results tends to underestimate insolation during the period from March to June.

When the effect of seasonal variation in the Sun-Earth distance factor is not considered in the SMS (*i.e*. $f = 1$, hereafter called the SMSC formula), mean daily insolation is markedly-overestimated during summer (by up to 12 W m^{-2}) but only slightly underestimated during winter (3 W m^{-2}). The order of magnitude difference in insolation is produced as a result of the combination of higher solar zenith angle and relatively-short day length in the Northern-Hemisphere winter. As expected, seasonal variation in the Sun-Earth distance factor, which ranges from 0.967 in summer to 1.035 in winter, affects the solar irradiance. This is why the hourly insolation results calculated from SMSC and SMS show maximum differences of –13 W m^{-2} and 33 W m^{-2} during winter (January) and summer (June), respectively (Fig. 3). This result clearly demonstrates the importance of including the effects of the Sun-Earth distance factor when computing insolation values.

We compared the mean daily irradiance calculated from SMS with that derived and integrated from the spectral radiative transfer model, GM02 (Figs. 1 and 2). In general, the results of GM02 and SMS show similar seasonal patterns of variation, although with slightly-different magnitudes of change (Fig. 1). Relatively large differences, of 13 W m^{-2}, occur frequently during summer. Note that the difference between GM02 and SMS, which is as high as 13 W m^{-2} in spring, is related to the low precipitable water vapor values (Fig. 2). Notably, as shown in Fig. 3 in hourly values at noon, the maximum differences between GM02 and SMS (SMSC) are 28.4 (15.6) W m^{-2} in January (winter), whereas there are marked differences, by 46.6 (77.8) W m^{-2} in June (summer). These differences are likely to be because of use of a constant atmospheric transmission coefficient (0.7) in SMS or SMSC despite the existing temporal variation. From the results of GM02-SMS and GM02-SMSC it may

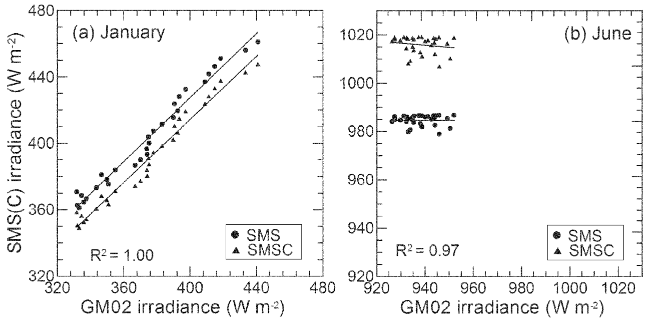

Fig. 3. Comparisons in noon irradiance (Italian standard time) calculated for clear-sky conditions at Barbara station in January (a) and in June (b) 2001 between GM02 and SMS (SMSC).

be inferred that wintertime has a slightly higher transmission coefficient (> 0.7) while summertime has a slightly lower one (< 0.7).

Finally, summertime and wintertime surface irradiances observed at the Barbara station in the northern Adriatic Sea are compared with the results computed from the empirical formulas and the GM02. The clear sky data (cloud cover < 0.3) at 12:00 UTC are initially determined from cloud cover information from ECMWF re-analysis 12:00 data. Further, for the relatively rare occasions when the observed value is unexpectedly 150 W m^{-2} (which is the subjective value) lower than the calculated value, the value is excluded from the comparison. These large differences may be due primarily to incorrect input data in our GM02 (e.g. aerosol and precipitable water vapor) or to inaccurate irradiance measurements.

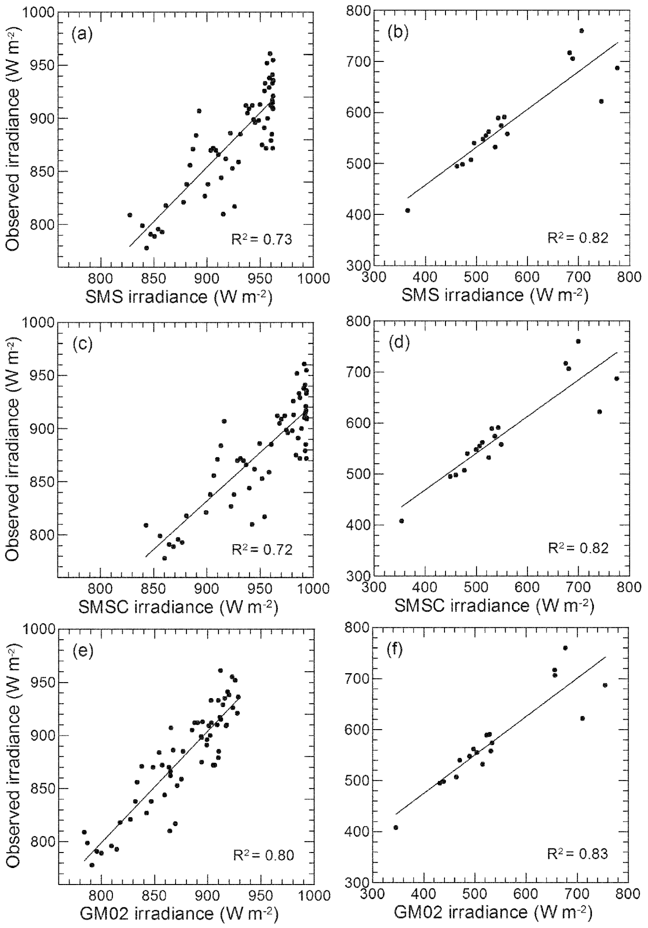

Fig. 4. Comparisons between surface irradiance at 12:00 UTC for clear days at Barbara from June to August and from January to March 2001 (which are determined from ECMWF cloud cover fraction of <0.3) forthe observed irradiance and estimated values from SMS (a, b), SMSC (c, d) and GM02 (e, f). The regression coefficients are: for SMS/observed: R^2 = 0.73, (b_1, b_0) = (1.026, -69.6) for (a) and R^2 = 0.82, (b_1, b_0) = (0.742, 161.1) for (b) for SMSC/ observed: R^2 = 0.72, (b_1, b_0) = (0.911, 11.8) for (c) and R^2 = 0.82, (b_1, b_0) = (0.718, 181.8) for (d); R^2 = 0.80, (b_1, b_0) = (1.051, -41.6) for (e) and R^2 = 0.83, (b_1, b_0) = (0.751, 174.7) for (f).

As illustrated in Figs. 4(a, c, e), the slope values (b_1), regression-line intercepts (b_0), and correlations of determination (R^2) clearly show that GM02 reproduces the observed values more closely than do the empirical formulas. As expected, without the effect of the Sun-Earth distance factor, the SMSC overestimates irradiance values even more than in the SMS in summertime. However, there is no significant difference between SMS and SMSC in winter with respect to the effect of the Sun-Earth distance (Figs. 4(b,d)). In reality, we know that the winter solar zenith angle is higher than in summer, so that the irradiance reaching the wintertime sea-surface is lower. Since the amount of the winter irradiance is relatively small, they (unclear what 'they' refers to) do not clearly show the expected underestimation of SMSC in winter. In addition, the winter case of the GM02 (Fig. 4(f)) does not show improved results relative to the summer case (Fig. 4(e)). This may be related to the more changeable meteorological conditions and greater sea surface instability in winter versus summer. Thus, RMS differences between the observed and calculated results in winter are larger than those in summer: for winter 49.4 W m^{-1} (b), 56.0 W m^{-1} (d) and 61.9 W m^{-1} (f) and for summer 16.2 W m^{-1} (a) , 16.4 W m^{-1} (c) and 10.8 W m^{-1} (e).

Another issue is how appropriate is the usage of meteorological surface field data for GM02. Fig. 5(a, b) reveals that there is a strong correlation (R^2 = 0.98, 1.00), similar slope (b_1 = 1.012, 0.987) and small intercept value (b_0 = -9.9, 15.8) between irradiance values calculated by

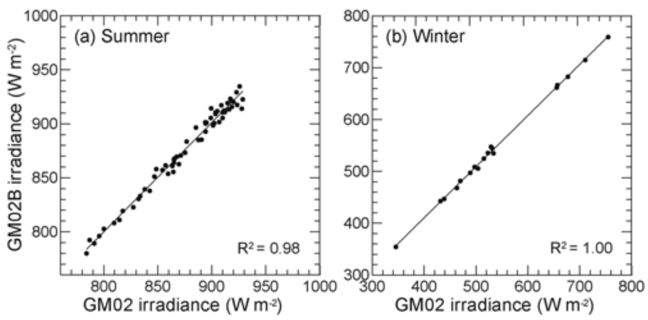

Fig. 5. Comparisons in surface irradiances at 12:00 UTC calculated from GM02 with the ECMWF analysis meteorological surface fields and computed from GM02 with in situ data of the Barbara station (GM02B) for cases of summer (June-August) (a) and winter (January-March) (b).

GM02 from the buoy meteorological fields (called GM02B) and ECMWF analysis meteorological data; this shows the suitability of ECMWF data as ancillary data in these formulas.

These results indicate that use of a constant atmospheric transmission coefficient (0.7) in the empirical model leads to significant overestimation of irradiance in the clear-sky limit and in the Adriatic Sea, particularly in summer, and to underestimation when low water vapor content conditions are present.

4. Discussion

In the previous section, we identified the relatively large differences that result from using an empirical formula (SMS) versus a radiative transfer model (GM02) to calculate late spring and, in particular, summer irradiance values (from May to August) (Figs. 1 and 2). Unlike the empirical insolation formula, which uses a constant value (t = 0.7) for globally-averaged atmospheric transmission, the RTM can estimate atmospheric transmittance from input data based on variability in meteorological conditions. Thus, the RTM offers clues as to the cause of the empirical formula overestimation of insolation in the Mediterranean Sea and Adriatic Sea during summer. The tendency for SMS to overestimate summertime insolation has been identified by Schiano (1996), Tragou and Lascaratos (2003) and Chiggiato *et al*. (2005). In this paper, we clarify for the first time that this is due not only to the variable atmospheric transmittance but, in part, to the usage of a constant Sun-Earth distance factor.

We are now able to investigate the main meteorological factors affecting the summertime irradiance in the Adriatic Sea through the RTM. This is achieved by exploring differences in the mean daily-irradiance values calculated using SMS and GM02 (hereafter SSDGM) in relation to each mean-daily meteorological parameter (total precipitable water vapor, relative humidity and atmospheric pressure) for July 2001 (Fig. 6). R^2 results show that SSDGM exhibits a strong correlation (0.96) with total precipitable water vapor but a relatively weak correlation with relative humidity (0.70) and no correlation with atmospheric pressure (0.01). These results indicate that summertime irradiance estimates produced by the GM02 are lower than those produced by SMS because the former model takes into account the significant attenuation of radiation which arises from the increased water vapor content in the atmosphere. This result conforms to the argument of Schiano (1996), who pointed out that use of a constant transmission coefficient (0.7) results in the overestimation of irradiance as it does not take into account increases in water vapor and high concentrations of aerosols. Garrett *et al.* (1993) and Gilman and Garrett (1994) proposed that the attenuation of solar irradiance in the Mediterranean is markedly affected by Saharan dust particles and anthropogenic aerosols; that is, the combined effect of these aerosols with the increased humidity during summer leads to a continuous upper layer of haze in the Mediterranean. Similarly, Tragou and Lascaratos (2003) used satellite data to observe the importance of a summertime decrease in the aerosol transmission coefficient for the index of optical thickness.

RTM sensitivity tests were conducted for each meteorological

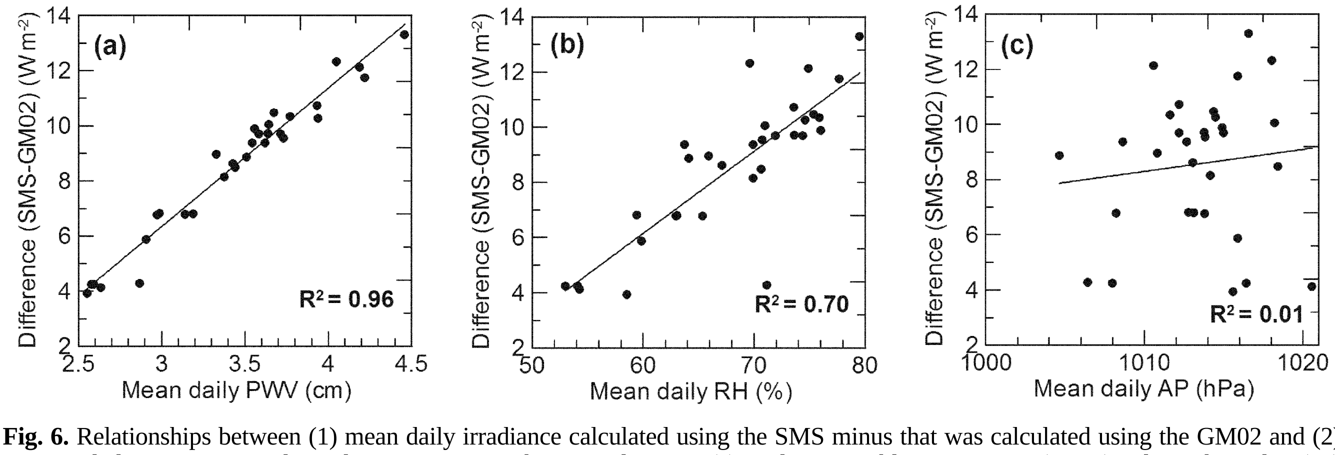

Fig. 6. Relationships between (1) mean daily irradiance calculated using the SMS minus that was calculated using the GM02 and (2) daily mean meteorological parametersat Barbara in July 2001: (a) total precipitable water vapor (PWV), relative humidity (R_H) and (c) atmospheric pressure (AP).

input parameter listed in Table 3 in order to discern the key variables affecting solar attenuation under clear-sky conditions. In addition, the effect of the single-scattering aerosol albedo variable (ω_a) was tested using the constant 0.95 value suggested for dust by Fouquart *et al.* (1987) from flux divergence measurements of Saharan aerosols. The effects of direct and diffuse sea-surface reflectance induced by sea-surface roughness and whitecaps were included in Equation 2 for the sensitivity experiments. Thus, the RTM estimates the direct and diffuse downwelling irradiances just below the sea-surface. Equations (3) and (4a) are written by:

$$E_{dd}(\lambda, 0^+) = E_{dd}(\lambda, 0^+)(1-\rho_d) \qquad (5a)$$

and

$$E_{ds}(\lambda, 0^-) = [I_r(\lambda) + I_a(\lambda)](1-\rho_s) \qquad (5b)$$

where ρ_d and ρ_s are the direct and diffuse sea-surface reflectances respectively, and 0^- represents a level below the sea-surface. Reflectance is formulated as a function of seawater absorption, total scattering and wind speed by Gregg (2002), based on Frouin's data (Frouin *et al.* 1996).

Table 4 compares the results of the sensitivity tests to those of the standard run, including reflectance terms. These results clearly show that variability in solar irradiance is significantly influenced by the following three meteorological parameters: precipitable water vapor (PWV), aerosol optical thickness (τ_a), and single-scattering aerosol albedo (ω_a). For

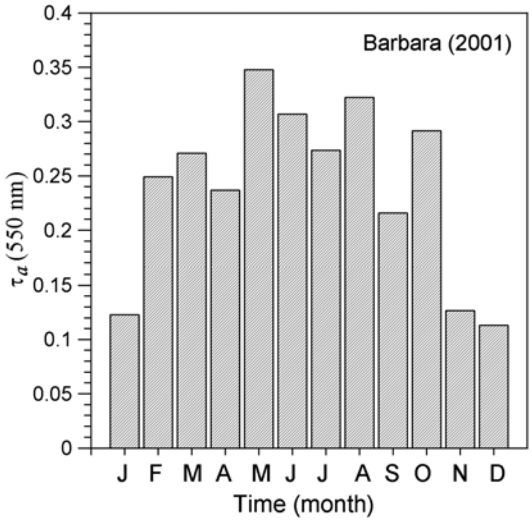

Fig. 7. Monthly averaged values of aerosol optical thickness τ_a (550 nm) at Barbara 2001 obtained from a level-3 MODIS (the Moderate Resolution Imaging Spectroradiometer) (http://g0dup05u.ecs.nasa.gov/Giovanni//modis.MOD08_M3.shtml).

example, when the RTM is simulated with a 40% decrease/increase in PWV, the RMSD (root mean square difference) between the test case and standard run is >5 W m^{-2} / >3.5 W m^{-2}. In addition, use of the 50% increased value of τ_a leads to a reduction in irradiance from –5.3 to –1.3 W m^{-2}. Monthly averaged values of τ_a at 550 nm observed through MODIS (the Moderate Resolution Imaging Spectroradiometer) (Fig. 7) indicate that the value of 0.2 at 500 nm used in the

Table 4. Sensitivity analysis of the GM02 with respect to the meteorological input parameters presented in Table 3 (unit in W m^{-2})

Parameter (x)	Modification to x	RanD	RMSD	MeanD	StdD
WS (m s^{-1})	-20%	-1.1 ~ 2.1	0.4	0	0.1
	20%	-3.5 ~ 1.6	0.4	-0.1	-0.0
AP (hPa)	-10%	0.7 ~ 2.4	1.7	1.6	0.6
	10%	-2.3 ~ -0.6	1.7	-1.6	-0.6
R_H(%)	-40%	-1.0 ~ -0.2	0.6	-0.6	-0.1
	40%	0.2 ~ 1.0	0.6	0.6	0.1
PWV (cm)	-40%	1.6 ~ 8.1	5.5	5.0	2.2
	40%	-5.4 ~ -1.1	3.7	-3.3	-1.5
τ_a(500 nm)	-50%	1.7 ~ 6.0	4.3	4.1	1.2
	50%	-5.3 ~ -1.3	3.6	-3.4	-1.2
α	0.1	-0.4 ~ -0.2	0.3	-0.3	0.0
	0.2	-0.7 ~ -0.4	0.5	-0.6	0.0
AM	5	-1.3 ~ -0.6	1.0	-1.0	-0.2
	10	-2.8 ~ -1.4	2.2	-2.1	-0.5
ω_a	0.95	-4.1 ~ -1.5	2.9	-2.9	-0.6

RanD is the range of annual maximum and minimum irradiance differences between the test case and standard run. RMSD, MeanD and StdD indicate root-mean-square, mean and standard-deviation differences, respectively. The annual mean and standard deviation of the standard run are 209.7 W m^{-2} and 95.8 W m^{-2}, respectively.

standard run may be underestimated by >50% during summer and overestimated by >30% during winter. Thus, the use of the variable τ_a also results in improved-irradiance estimates. Note that since the ω_a formula used in the RTM is a function of air-mass type and relative humidity, with a mean value of 0.990 and range of 0.987-0.991 over 2001, the use of the lower-constant value of 1 for air-mass type also contributes to the overestimation of surface irradiance during summer.

Overall, the results shown in Table 4 indicate that the reduction of irradiance in the Adriatic Sea during summer is due primarily to increases in water vapor and aerosols, which, in turn, lead to an increase in the attenuation of solar radiation. This finding is consistent with studies by Garrett *et al*. (1993), Gilman and Garrett (1994), Schiano (1996) and Tragou and Lascaratos (2003), all of which employed empirical insolation formulas.

5. Conclusions

This paper constitutes a preliminary study in preparation for the adaptation of a spectral solar radiation model for a marine ecosystem modeling. We detail, for the first time, comparisons between solar irradiance values calculated using simple empirical models versus those from an RTM for the Adriatic Sea region. We show that seasonal variability in the Sun-Earth distance significantly reduces the summertime incoming solar radiation reaching the top of atmosphere in the Northern Hemisphere (vice versa in the Southern Hemisphere). Thus, this distance-factor effect should be considered in solar irradiance formulas or numerical models concerned with air-sea interactions.

Comparisons between mean-daily solar surface-irradiance values calculated using an empirical insolation formula (SMS) and a radiative transfer model (GM02) under clear-sky conditions show that the SMS overestimates surface insolation over the Adriatic Sea, particularly during summer, due to the use of the constant atmospheric transmission coefficient 0.7. Examination of the relationship between the mean-daily irradiance results of SMS minus those of GM02 and each mean-daily meteorological parameter (*i.e*. total precipitable water vapor, relative humidity and atmospheric pressure), reveal that GM02 is capable of modifying (reducing) the summer surface irradiance values due to the increased total-precipitable water vapor. Analysis of the sensitivity of the RTM to variation in the meteorological parameters shows that variability in solar irradiance is markedly affected by key meteorological parameters including precipitable water vapor, aerosol optical thickness and single-scattering aerosol albedo. Thus, the summertime reduction in solar radiation in the Adriatic Sea occurs because of an increase in atmospheric attenuation induced by an increase in water vapor and high aerosol concentrations (via an increase in aerosol optical thickness and a decrease in the single-scattering aerosol albedo).

In conclusion, we show that a simple radiative transfer model for clear-sky conditions can provide realistic estimates of solar radiation using ancillary information from a Numerical Weather Prediction (NWP) model such as the ECMWF. In future studies we will now be able to confidently decompose the total solar irradiance available from NWP models with the RTM and ancillary field estimates. Accordingly, we advise that a simple but accurate spectral radiative transfer model should be used in preference to empirical insolation formulas, even if the model uses field-state variables from NWP models that are not calibrated for such a purpose.

Beyond these findings there remains a problem with cloud effects: our RTM does not consider cloud effects while the empirical formulas do (*e.g*. Reed 1977). Further studies are needed in appropriate spectral parameterizations of cloud effects and in the use of more meteorological input data from satellite observations.

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Appendix A: Calculation of precipitable water vapor

The 6-hourly ECMWF analysis data of air temperature and dew point temperature are used to calculate relative humidity and the total amount of precipitable water vapor (shortly, precipitable water). Relative humidity (R_H, %), defined as the percent ratio of vapor pressure (e_a) to vapor pressure (e_s) saturated at the air temperature T_a (°C) is given by:

$$R_H(\%) = \frac{e_a}{e_s(T_a)} \times 100 \tag{A1}$$

Since the vapor pressure is the saturated vapor pressure at the dew point temperature (T_d, °C), that is, $e_a = e_s(T_d)$, Eq. (A1) can be rewritten as:

$$R_H(\%) = \frac{e_s(T_d)}{e_s(T_a)} \times 100 \tag{A2}$$

The saturated vapor pressure at T (T_d or T_a) was calculated from Tetens (1930)' formula, expressed as:

$$e_s(T) = 0.61078 \exp\left(\frac{17.269T}{T+237.29}\right) \tag{A3}$$

Total precipitable water vapor (W_v, g cm^{-2} or cm), expressed as the vertical integration of water vapor density, can be estimated from the Okulov *et al.*'s (2002) empirical formula, with humidity and surface air temperature functions:

$$W_v = \int_{z_0}^{z} \rho_v(z)dz \tag{A4}$$

where $\rho_v(z)$(g m^{-3}) is the water vapor at z above sea level (z_0), $\rho_v(z_0) = \frac{217R_H(z_0)e_a(T_d)}{T_d+273.15}$ and $H = \int_{z_0}^{z} \frac{\rho_v(z)}{\rho_v(z_0)}dz$. The water vapor scale height, H (km), was estimated from the Gueymard (1994)'s empirical formula:

$$H = 0.4976 + 1.5265T_\theta + \exp(13.6897T_\theta - 14.9188T_\theta^3) \tag{A5}$$

where $T_\theta = 1+\frac{T_a}{273.15}$. Note that precipitable water vapor can also be directly obtained from the ECMWF product.

Appendix B: The Sun-Earth distance factor formulas

The Sun-Earth distance factor, also referred to as the eccentricity correction factor, is defined as the amount by which extraterrestrial irradiance varies as the Earth orbits the Sun due to changes in the distance between them. This can be estimated simply using Cooper's (1969) formula, and more accurately using Spencer's (1971), Gordon et al.'s (1983) or Michalsky's (1988) algorithm. Here we chose Michalsky's (1988) algorithm as a reference formula. In Table A1, each formula mentioned above is presented and the associated results are compared with that of Michalsky's

Table A1. Algorithms of the Sun-Earth distance factor (f) and the root-mean-square difference (RMSD) in comparison with Michalsky's formula (1988)

Formula	RMSD	Reference
$f = 1+0.033 \cos(2\pi D/365)$	0.0010	Cooper (1969)
$f = 1.00011+0.034221 \cos\tau + 0.00128 \sin\tau + 0.000719 \cos 2\tau + 0.000077 \sin 2\tau$ where $\tau = 2\pi(D-1)/365$	0.0008	Spencer (1971)
$f = \{1+0.0167 \cos[2\pi(D-3)/365]\}^2$	0.0006	Gordon *et al*. (1983)
$f = 1.00014 - 0.01671 \cos g - 0.00014 \cos 2g$ where $g = [357.528 + 0.9856003(JD-241545.0)](\pi/180)$	-	Michalsky (1988)

Here D is the day of year and JD is the Julian Day, given by (Blanco-Muriel *et al*. 2001): JD(y, m, d, hr) = {1461[y+4800+(m-14)/12]}/4+{367[m-2-12[(m-14)/12]]}/12-{3[[y+4900+(m-14)/12]/100]}/4+d-32075-0.5+hr/24 where y is the year, m is the month, d is the day of the month and hr is the hour of the day (Universal Time).

formula for interested readers. It should be noted that the Sun-Earth distance factor can be calculated to a high degree of accuracy by Bretagnon and Francou's (1988) formula but this is beyond the purpose of our study.