Short-term Effects of Solar Storms in Phytoplankton Photosynthesis

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Abstract

It is investigated the potential short-term influence of a solar storm on micro-algal photosynthesis. From the secondary cosmic rays at sea level we focus on muons, given their high penetrating power, and it is considered that a "generic" solar storm would imply an increase of 10% in both muon fluxes and their average energy. It is then assumed an exponential decay of muon fluxes down the water column and a direct proportionality between their penetrating power and energy. This allows obtaining a function of ionizing radiation to be embedded in a physical-mathematical model for photosynthesis previously modified by some of us to include particulate ionizing radiation. It is finally shown that solar storms can cause a significant short-term depletion of photosynthesis in both ocean and coastal waters.

Introduction

Planetary bodies in the Milky Way receive considerable doses of ionizing radiation from astrophysical origin (Melott and Thomas 2011). For example, stellar explosions (supernovae, gamma-ray bursts), deliver high-energy cosmic rays which can hit the atmosphere and produce fluxes of atmospheric muons and other subatomic particles at ground level, underground and underwater, deplete the ozone layer, and radioactivate the environment. These phenomena could have caused some of the life extinctions found in the geological record of planet Earth. On another hand, biological mutations due to such ionizing radiations could have enhanced the fast appearance of new species after the extinctions.

In this paper we focus on a less energetic but more frequent situation: solar storms. Since they follow a cycle of approximately 22 years (11 years with a given polarity of the Sun's magnetic field, and the remaining 11 with the reverse polarity), several researchers have suggested consequent cyclical biological effects on Earth, mediated by several mechanisms: geomagnetic storms, perturbations of atmospheric chemistry, etc.

Secondary cosmic rays delivered at the planetary surface due to solar storms are a cocktail of particles (protons, neutrons, muons, neutrinos). The issue that neutrinos can cause biological effects is still very controversial, so in this work we investigate the potential effects on phytoplankton photosynthesis of the particles having the second place in penetrating power (after neutrinos): muons. In fact, several studies acknowledge the high penetration power of high-energy muons, quoting that they can travel through hundreds of meters in the ocean water column. In a former paper (Rodríguez-López et al 2018); several of us reported the first results on this, using a preliminary modification of a mathematical model for photosynthesis to include the effects of ionizing radiations. In this paper we report the short-term influence on phytoplankton photosynthesis that a flux of muons coming from a solar storm could do, but now using a more refined modification of the above above-mentioned model for photosynthesis (Rodríguez-López et al 2021).

Materials And Methods

To quantify the action of solar storms we used a modification, recently proposed by some of us, of the so-called E model of photosynthesis (Rodríguez-López et al 2021):

$$\frac{P(z)}{P_s} = \frac{1 - e^{-E_{PAR}(z)/E_s}}{1 + f_{ir}(z) + E^{*}_{UV}(z)}$$

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where P is the photosynthesis rate at depth z, P_S is the maximum possible photosynthesis rate, $E_{PAR}(z)$ is the irradiance of photosynthetically active radiation (PAR) at depth z, E_S is a parameter accounting how efficiently the species uses PAR, $E^*_{UV}(z)$ is the irradiance of ultraviolet radiation (UV), convolved with a biological action spectrum measuring how much each UV wavelength inhibits photosynthesis (the reason for the asterisk), and $f_{ir}(z)$ is the function formally introduced by some of us in (Rodríguez-López et al 2021) to represent the influence of ionizing radiation. To account for the effects of UV on photosynthesis we used a biological action spectrum typical of temperate phytoplankton (Neale 2014, personal communication).

The irradiances of PAR and UV at sea level were calculated with the radiative transfer code Tropospheric Ultraviolet and Visible, developed at the National Centre for Atmospheric Research of USA, free for download (https://www2.acom.ucar.edu/modeling/tropospheric-ultraviolet-and-visible-tuv-radiation-model). It was assumed a solar zenital angle of 45 degrees (moderate radiational regime), an ozone column of 300 Dobson units, an ocean albedo of 0,065; a cloud layer between 4 and 5 km above sea level with an optical depth of 0,00 (clear sky conditions); aerosols with an optical depth of 0,235 and a single scattering albedo of 0,990. The radiation transfer model in the atmosphere was pseudo-spherical with two streams. The radiation transfer model in the ocean included Lambert-Beer's law of Optics:

$$E(\lambda, z) = E\left(\lambda, 0^{-}\right)e^{-K(\lambda).z}$$

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where E(λ,z) are the spectral irradiances at depth z, $E(\lambda,0^-)$ are the spectral irradiances just below the ocean surface, and K(λ) are the (wavelength-dependent) attenuation coefficients, which were taken from Jerlov's reference tables (Jerlov 1976) and further interpolated according to (Peñate-Alvariño et al 2010). To get a wide range of potential responses, we used ocean optical types I and III, which are the clearest and darkest in Jerlov's classification. For the same reason, calculations were also made for coastal waters C1 and C9 of above-mentioned classification. In a further study, we intend to include freshwater ecosystems.

It was assumed that solar storms can increase at ocean surface both the muon flux and their average energy up to 10% respect to ordinary conditions. However, these increments were first treated separately, in order to weigh their relative importance, and then were considered together. As in (Rodríguez-López et al 2018), the penetration of muons in the ocean was modeled through:

$$I(z) = I_0 e^{-(\rho/l)z}$$

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where I_0 and $I(z)$ are the particle fluxes (m^{-2}) at ocean surface and at depth z, respectively; ρ is the density of water and l is a parameter measuring the penetrating efficiency of the particles of ionizing radiation (the bigger l, the more penetrating the particle). In this first modeling, it was not considered the disintegration of muons in their way down the water column, and it was assumed that the penetrating power depends linearly on their average energy < E>:

$$l = n\langle E \rangle$$

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The average energy < E_{SS}> of muons from solar storms can be written:

$$\langle E_{SS} \rangle = m\langle E \rangle$$

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where m is a proportionality constant. Thus, the penetrating power l_{SS} of "solar" muons can be stated as:

$$l_{SS} = n\langle E_{SS} \rangle = nm\langle E \rangle = ml$$

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Following an ansatz formally analogous to the one used in (Atri and Melott 2011; Rodríguez-López, Cárdenas-Ortiz and Rodríguez-Hoyos 2013), we propose as the function of ionizing radiation:

$$f_{ir} = \frac{I_{SS}(z)}{I(z)} = \frac{I_{0,SS} e^{-\left(\frac{\rho}{l_{SS}}\right)z}}{I_0 e^{-\left(\frac{\rho}{l}\right)z}}$$

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where the subscript ss means the scenario of the solar storm. Applying Eq. (6) to (7) we get:

$$f_{ir} = \frac{I_{0,SS}}{I_0} e^{\left\{-[(m-1)/m]\left(\frac{\rho}{l}\right)z\right\}}$$

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For our calculations we used $l = 10^4$ kg/m^2, a typical value for muons from ordinary cosmic rays. We used three particular cases of Eq. (8). If there is only an increase in muon flux and average energy remains constant, it means m = 1 in Eq. (5), which implies the following form for the function of ionizing radiation:

$$f_{ir} = \frac{I_{0,SS}}{I_0}$$

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Assuming a 10% of increase of the muon flux means $f_{ir}(z) = 1{,}1$. On another hand, if muon flux is constant and average energy increases in 10%, this means m = 1,1 in Eq. (5), so Eq. (8) results:

$$f_{ir} = e^{\left\{-0{,}09\left(\frac{\rho}{l}\right)z\right\}}$$

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The third case is an increase of 10% in both variables, implying:

$$f_{ir} = 1{,}1e^{\left\{-0{,}09\left(\frac{\rho}{l}\right)z\right\}}$$

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Results And Discussion

Photosynthesis rates were calculated using the equations of the former section for three above mentioned potential radiational situations:

a. the solar storm increments muon flux at sea level up to a 10%,
b. the solar storm increments average muon energy at sea level up to a 10% and,
c. the solar storm increments both muon flux and average muon energy at sea level up to a 10%.

For the sake of compactness, we only show the plots for the third situation (Fig. 1 to Fig. 4), but summarize results in Table I.

Table I presents relative photosynthesis reductions, considering depths between 0 and 100 meters (because in most situations photosynthesis rates beneath 100 meters were negligible). It can be seen that in general the darker waters will less affected. This is to be expected, as usually dark waters are more protected against radiational phenomena. On another hand, in most cases the increases in average muon energy and of muon flux will have relatively similar effects on photosynthesis (assuming the increases are similar, 10% each).

Table I Relative photosynthesis reductions

Effect of Increase of Muon Flux			
Water Type I		Water Type III	
$E_S = 1W/m^2$	$E_S = 100W/m^2$	$E_S = 1W/m^2$	$E_S = 100W/m^2$
49,3	46,9	50,3	40,6
Water Type C1		Water Type C9	
$E_S = 1W/m^2$	$E_S = 100W/m^2$	$E_S = 1W/m^2$	$E_S = 100W/m^2$
49,8	37,1	28,9	28,8
Effect of Increase of Average Muon Energy			
Water Type I		Water Type III	
$E_S = 1W/m^2$	$E_S = 100W/m^2$	$E_S = 1W/m^2$	$E_S = 100W/m^2$
59,0	53,6	54,2	41,0
Water Type C1		Water Type C9	
$E_S = 1W/m^2$	$E_S = 100W/m^2$	$E_S = 1W/m^2$	$E_S = 100W/m^2$
52,9	36,7	27,0	26,9
Combined Effects			
Water Type I		Water Type III	
$E_S = 1W/m^2$	$E_S = 100W/m^2$	$E_S = 1W/m^2$	$E_S = 100W/m^2$
61,2	55,8	56,5	43,1
Water Type C1		Water Type C9	
$E_S = 1W/m^2$	$E_S = 100W/m^2$	$E_S = 1W/m^2$	$E_S = 100W/m^2$
55,2	38,7	28,9	28,8

Conclusions

Using our mathematical model to account for the influence of ionizing radiations (such as muons), we found that solar storms can cause a significant short-term depletion of phytoplankton photosynthesis. In most cases the increases in average muon energy and of muon flux had similar effects (assuming both increases are similar, 10% each). It was also obtained that in general darker waters would be less affected. Our results especially apply for temperate phytoplankton, as the biological action spectrum used was obtained for this kind of microalgae. This study focused in ocean and coastal waters; in the near future we are considering including freshwater ecosystems.

Declarations

Author Contributions

Rolando Cardenas devised the general conception of the work, participated in the calculations and interpretation of results, and wrote the main manuscript text.

Madeleine López-Águila, Lien Rodríguez-López and Lisdelys González-Rodríguez participated in the calculations and interpretation of results, and reviewed the manuscript.

Competing Interests

The authors have no competing interests to declare that are relevant to the content of this article.

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Figures

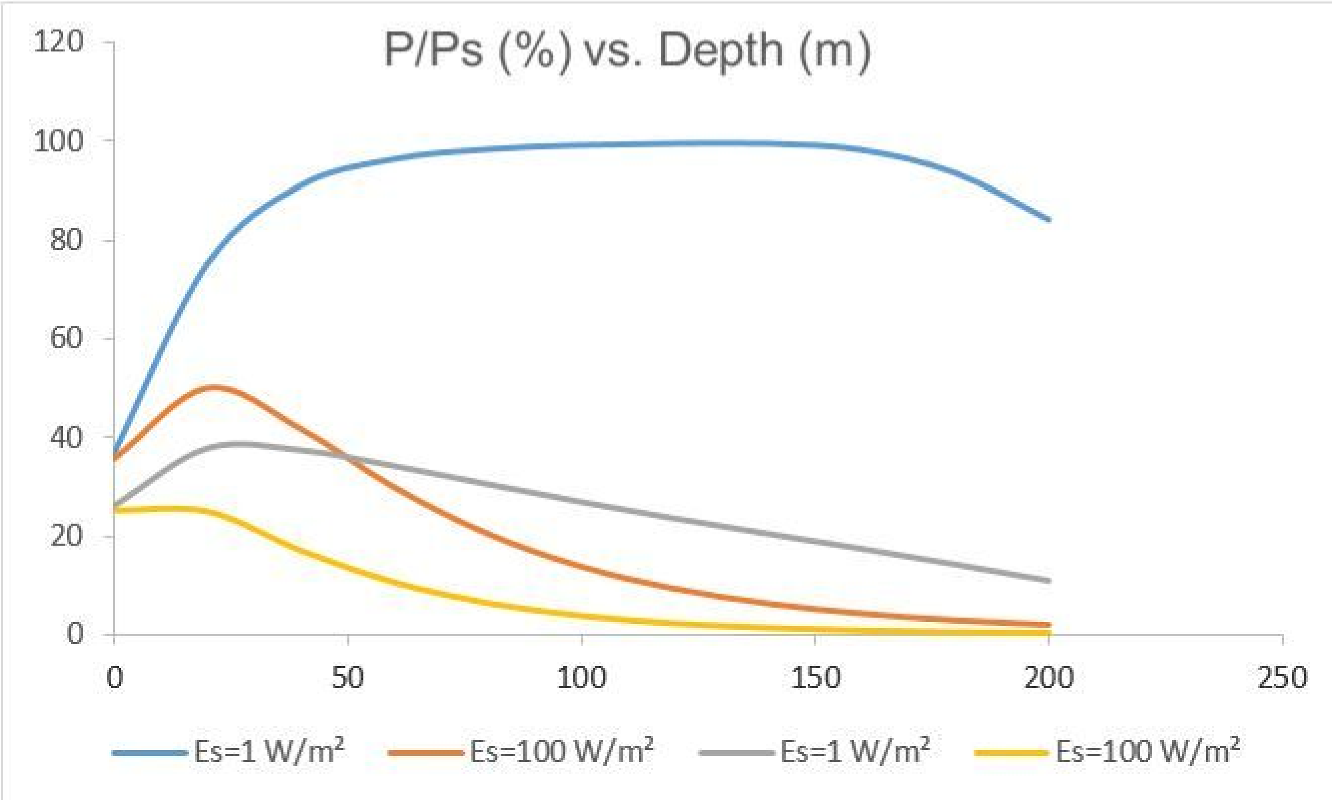

Figure 1

Photosynthesis rates (%) vs. depth (m) for ocean water type I. Blue and red lines: usual radiational scenario. Grey and orange lines: solar storm scenario

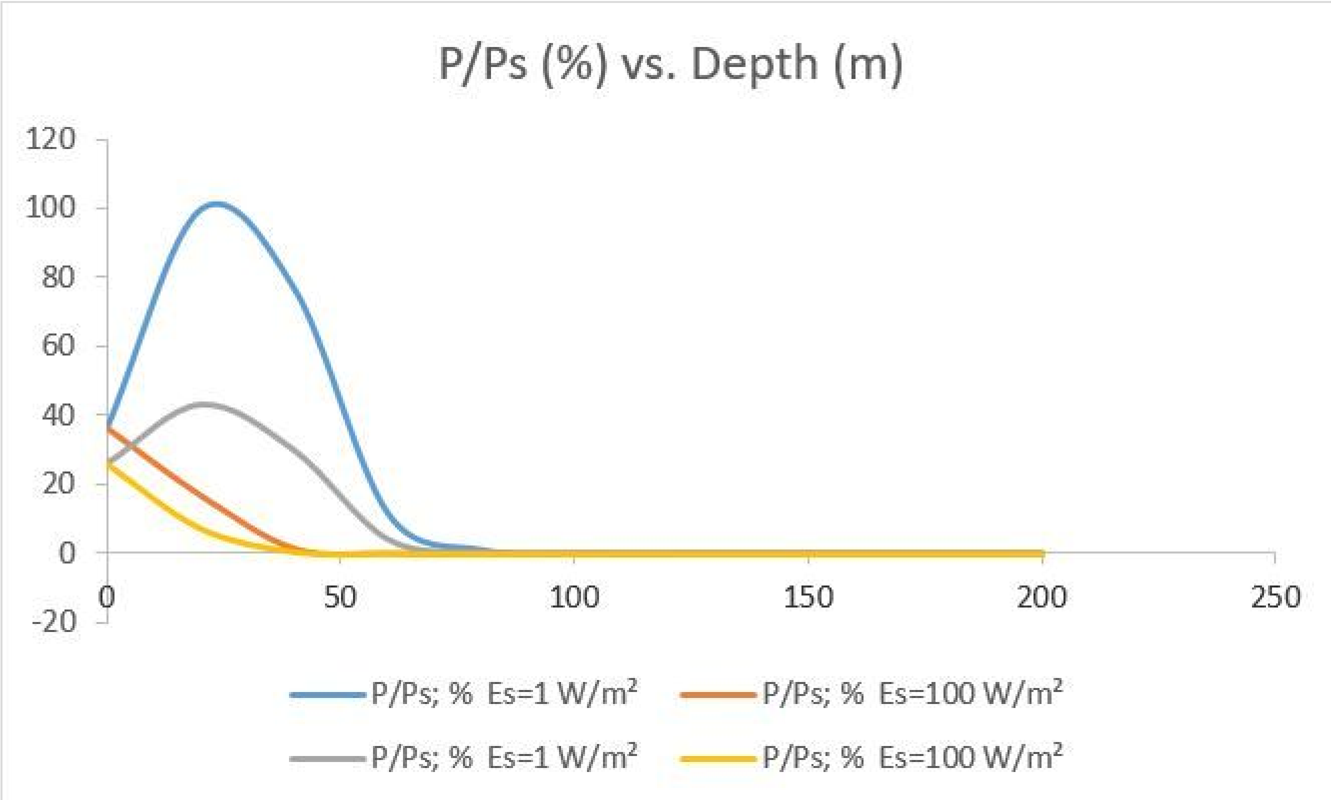

Figure 2

Photosynthesis rates (%) vs. depth (m) for ocean water type III. Blue and red lines: usual radiational scenario. Grey and orange lines: solar storm scenario.

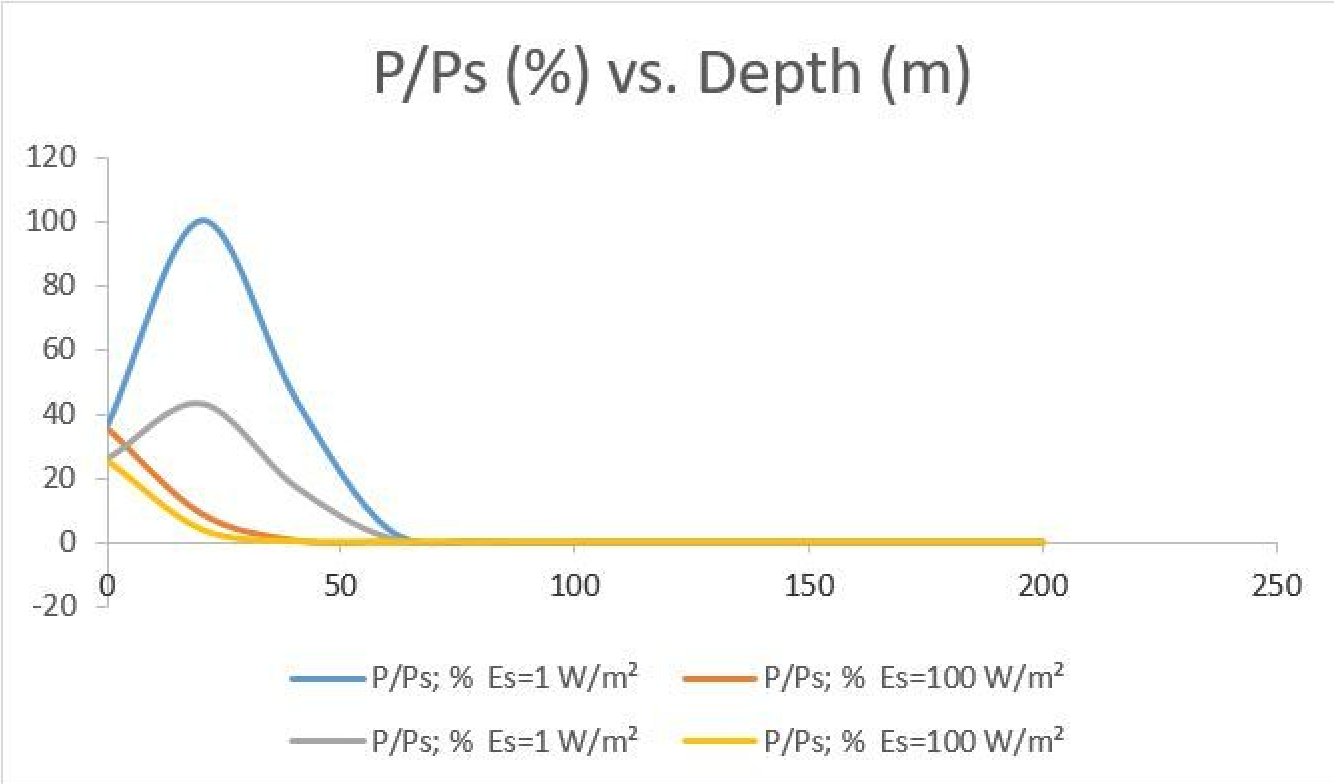

Figure 3

Photosynthesis rates (%) vs. depth (m) for coastal water type C1. Blue and red lines: usual radiational scenario. Grey and orange lines: solar storm scenario.

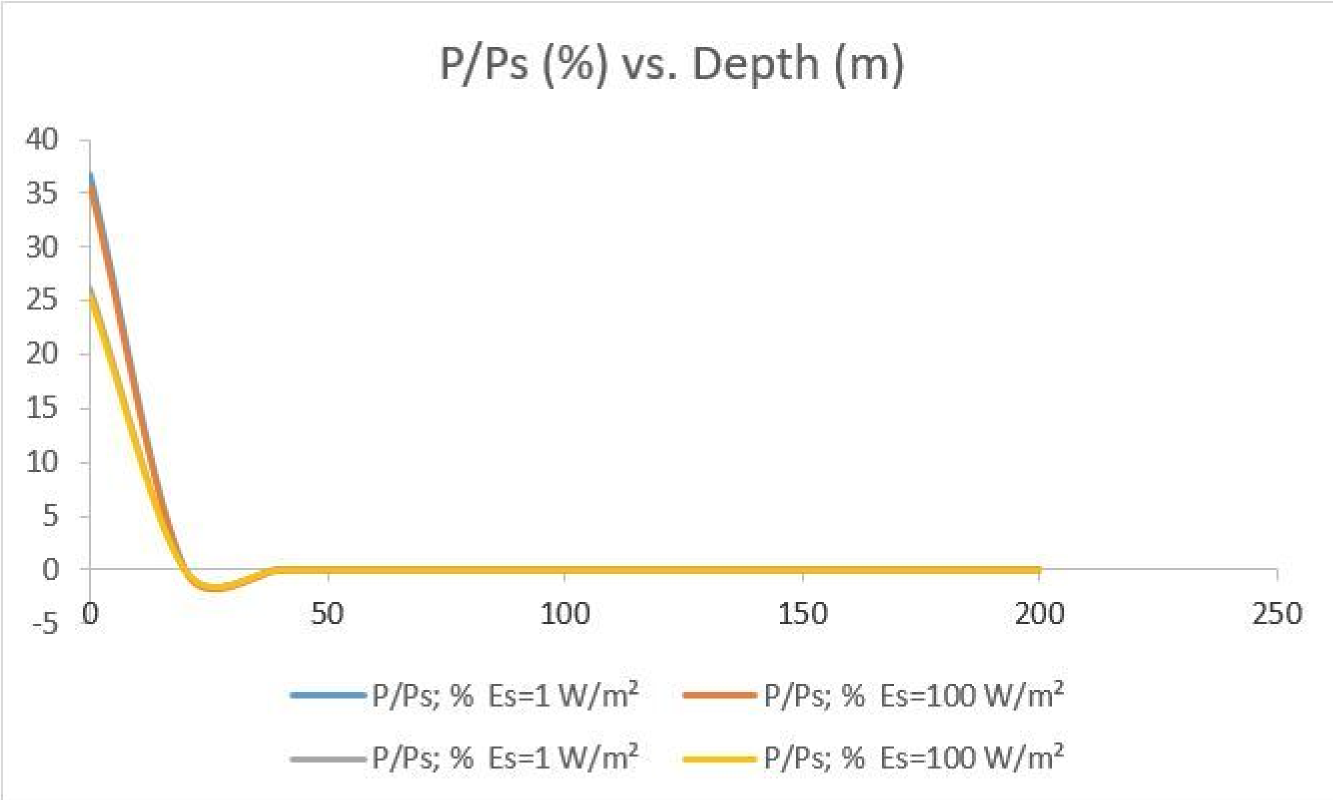

Figure 4

Photosynthesis rates vs. depth for coastal water type C9. Blue and red lines: usual radiational scenario. Grey and orange lines: solar storm scenario (apparent negative values due to interpolation procedure).