

Comments on GMD-2024-94: *Sunburned plankton: Ultraviolet radiation inhibition of phytoplankton photosynthesis in the Community Earth System Model version 2*
Authors: Coupe et al.

General Comments – The authors have implemented for the first time an earth system model that includes the effect of solar UV irradiance on the photosynthesis of marine phytoplankton. Although there have been several modeling exercises that address the effect of UV inhibition of photosynthesis on, e.g., daily areal productivity for global or regional (e.g. Southern Ocean) basis, this is the first time those responses have been integrated into a full ecosystem model with the provision of feedback effects and shifts in taxonomic composition. This new model is potentially useful in inferring what effects UV currently has on the marine pelagic ecosystem as well as how these effects may change in response to various extreme events or climate manipulations. An additional use case would be to compare the model output for scenarios with and without the controls on ozone depleting substances imposed by the Montreal Protocol. Such global assessments of the “world avoided” have thus far only been conducted for carbon cycling in terrestrial ecosystems (Young et al. 2021).

While I applaud the work of the authors in structuring the model, the implementation of the biological weighting functions and penetration of weighted UV radiation has several deficiencies. I expect that the model can be corrected to address these problems (detail provided below), so that the modeling and assessment community can have a CESM2-UVphyto that is consistent with our current understanding of UV effects on phytoplankton.

Specific Comments

- 1) A general point that should be made clear to any user of the model is that sensitivity to inhibition by UV irradiance is a physiological characteristic that is as variable as any other parameter of phytoplankton photosynthesis. Sensitivity is variable mainly because net inhibition reflects that balance between damage and repair processes (e.g. Neale and Kieber 2000). Variability on the damage side primarily derives from physical characteristics – e.g. the optical characteristics and cell dimension – these most often vary in a narrow range for any one taxa. However, repair processes can vary considerable depending on growth conditions. In this version of CESM2-UVphyto, Biological Weighting Functions (BWFs) are fixed irrespective of growth conditions (except for CO₂ – see below). This is an inconsistency in the code since the MARBL model does incorporate photoadaptation of photosynthesis in general through the C:Chl ratio, responding to growth irradiance, temperature and nutrients. It shouldn't be surprising that sensitivity to UV inhibition is also affected by these factors and there are many studies that confirm this beyond the studies cited for the model (see bibliography below). Where variation is known, e.g. for temperature and growth irradiance (cf. Neale and Thomas 2016), the code should account for it. If UV inhibition response is known only for one growth condition, the model should warn of increased uncertainty for predictions beyond the experimental conditions used for determination.

2) The one condition for which the model varies sensitivity to UV is in relation to atmospheric CO₂, which changes the pCO₂ and pH of ocean water. Ironically, the BWFs for the microalga chosen to simulate the effect of changing CO₂ show no evidence that they are affected by elevated CO₂. Lorenzo et al. (2019) compared the BWFs of *E. huxleyi* grown at equilibrium with atmospheric CO₂ of 400 and 800 ppm and found no difference even though there were changes in the coccoliths. Xu et al (2016) observed somewhat contrasting results in that a calcified strain was more resistant to UV than a naked strain. They concluded that coccoliths have an effect protecting against UV, however the experiment was not controlled in the sense that there were several differences between the + and – UV treatments, besides UV (including strain, PAR level, variability of exposure). These differences don't exclude that coccoliths perform a screening function, however the study of Lorenzo et al was performed under controlled conditions so that CO₂ was the only factor that varied. In this case, the changes in coccoliths were insufficient to affect sensitivity to UV or if the change in coccoliths did allow more damaging UV to reach the cell, the effects were compensated by enhanced repair capabilities (this is discussed by Lorenzo et al). In summary, it would be inappropriate to vary the E_{inh} (* omitted for convenience) computed from the Lorenzo et al BWF according to the PIC/POC ratio when Lorenzo et al did not observe an effect. As an aside, other taxa do show increased sensitivity to UV under CO₂ enhancement and it would be interesting to evaluate their responses in the context of the model (see Sobrino et al 2008).

In principle, I expect that the model code can be changed to accommodate this variability, which I encourage the authors to do. But I also recognize that the BWFs used in the case studies shown could be regarded as a “proof of concept” choices. This is defensible as long as it is made clear that results could be quite different for other choices, even for taxa within the same PFT group. However, independent of the choice of BWF, there are several steps described in the calculation of inhibition of photosynthesis section that are incorrect and lead to results that are inconsistent with current understanding of UV effects.

3) The propagation of E_{inh} through the water column cannot be approximated with the attenuation of a single wavelength (Eqs 2 and 3). Although it is often used as a proxy for the attenuation of DNA damaging UV-B, the attenuation coefficient at 305 nm is inappropriate for propagating $E_{inh}(z)$ because most of the weight derives from UV-A. As a result, $E_{inh}z$ propagated with K_d305 , declines with depth much faster than that calculated with a fully spectral resolved $K_d(\lambda)$, as shown in this example for clear oceanic water :

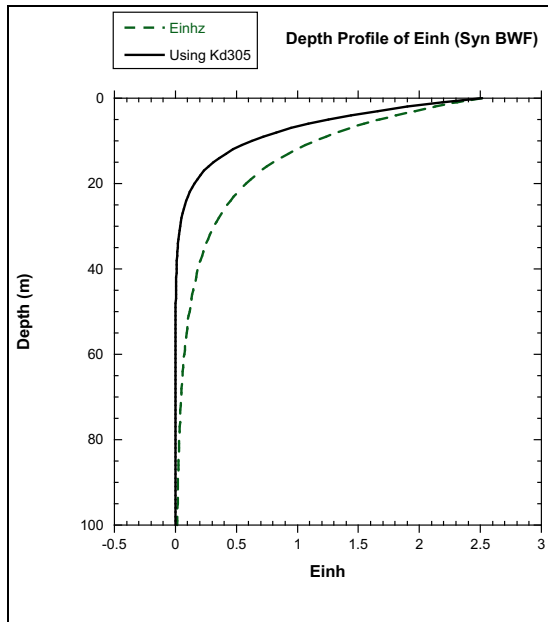
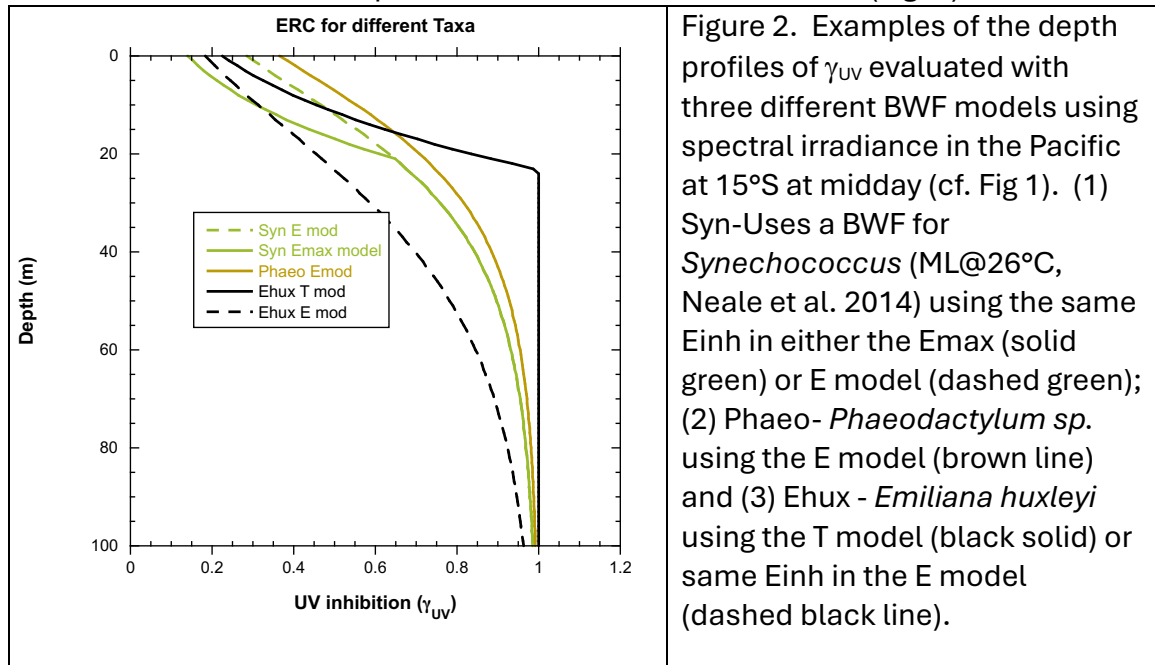


Figure 1: Depth profiles of Einh estimated using either a single attenuation coefficient ($K_d(305)$) applied to weighted irradiance at the surface (solid line) or using spectral attenuation coefficients (dashed line). Spectral irradiance and attenuation coefficients in the Pacific at 15°S at midday were estimated as described by Neale and Thomas (2016) and Einh calculated using a BWF for *Synechococcus* (ML@ 26°C , Neale et al. 2014). For this profile, $K_d(305)$ was 0.139 m^{-1} .

The depth to which UV inhibition affects photosynthesis in clear ocean waters is much deeper than 16 m (see also Fig. 2 in Neale and Thomas 2016). The effective $K_d(z)$ ($= -\ln(\text{Einh}(z+1)/\text{Einh}(z))$) in this example is similar to that of $K_d(\lambda=327\text{ nm})$ at the top of profile but changes (decreases) progressively to be similar to $K_d(\lambda=388\text{ nm})$ at 100 m, with about 2.4x change in apparent K_d over the profile.

- 4) Therefore, a more wavelength resolved approach is needed to propagate Einh. The values of Overmans and Agusti (2020) for coral reef areas in the Red Sea are inappropriate to apply over the whole ocean (Eq 2). Many areas of the ocean have more UV transparency than the Red Sea. Tedetti and Sempéré (2007, Table 2) reviewed global measurements of UV penetration and report that most open ocean waters have, e.g., 10%UV-B depths $> 8\text{ m}$. The maximum 10%UV-B depth possible from the Overmans and Agusti equation is $2.3/.29 = 7.9\text{ m}$. UV penetration is higher in the open ocean because it is further from land and has lower concentrations of colored dissolved organic matter (CDOM) than the Red Sea. CDOM is more important in determining UV transparency than Chl. One possible approach to a more representative spectral K_d is to use the equation of Lee et al (2013) (see their Eq. 5), estimating the IOPs of absorption and backscattering based on MARBL parameters – mainly Chl, POC and DOC.
- 5) BWFs in the literature are part of specific integrated photosynthesis-irradiance relationships (BWF/P-I models), and only correctly estimate UV inhibition if implemented using the relationship for which they were defined. There are three BWF/P-I models : E, T and E_{max} (see comparative discussion in Lorenzo et al. (2019), and each BWF used in the CESM2-UVphyto case studies uses a different linked model. Particularly important is the difference between the E model used for the Diatom (*Phaeodactylum*) BWF ($1/[1+\text{Einh}]$ dependence) and the T model used for the Coccolithophore (*E. huxleyi*) BWF ($1/\text{Einh}$

dependence). Evaluating UV inhibition by substituting the *E. huxleyi* Einh into the E model predicts more inhibition than if implemented with the correct T model (Fig. 2)



For the T model prediction of *E. huxleyi* inhibition (Fig. 2), there is a sharp decline in inhibition with depth as this model was optimized to best predict responses at high exposure. The same Einh evaluated with the E model has lower γ_{UV} (more inhibition) and penetrates deeper. Lorenzo et al acknowledged that there probably is some inhibition at lower exposures (and deeper in the water column), but this could not be resolved given the variability of the laboratory measurements, so below a certain depth (23 m in the above) there is no effect. In the example, the overall inhibition of midday productivity over the upper 100 m, given the P-I parameters in Lorenzo et al, is only 11% with the T model, but increases to 30% if the T model Einh is used to predict γ_{UV} using Equation 4 (E model). This directly impacts conclusions drawn from the reported case studies that coccolithophores are the most sensitive to inhibition by UVR. Higher Einh, per se, doesn't mean more inhibition if the models are different.

- 6) On the other hand, for the small prokaryotes, *Prochlorococcus* and *Synechococcus*, response at low exposure (which varies as $1/[1+Einh]$) could be resolved and distinguished from that at high exposure ($1/Einh$ dependence), the two responses are combined in the Emax model (Neale et al 2014). The BWF/PI for both Pro and Syn use the Emax model, which in this case leads to more inhibition for the Einh(PI) case compared to using the $1/[1+Einh]$ form over the whole water column (Fig. 2). Use of the correct model combined with more accurate Einh propagation should result in much higher relative effect of UV on ocean productivity for Einh(PI) than the ~1% effect in the reported case studies. The cited range of 7-28% inhibition reported by Neale and Thomas 2016 is the inhibition of integrated midday production by UV (vs only PAR) in their simulations of the Pacific for current conditions, not what was observed in the laboratory. Similarly, estimates of around 7%

inhibition of daily integrated production by UVR have been obtained by other approaches, e.g. Cullen et al. (2012) and Moreau et al. (2015).

- 7) The BWF function chosen for small phytoplankton is for *Prochlorococcus*, which is much more sensitive to inhibition by UV radiation than other picophytoplankton (Neale and Thomas 2016). It is better consider Pro a separate case. The BWFs for *Synechococcus* is probably more representative of picophytoplankton overall as well as diazotrophs.
- 8) Equation 1 should include a term for inhibition by PAR ($\epsilon_{PAR} * E_{PAR}$ cf. Eq. 3 in Neale and Thomas 2016). PAR inhibition is significant for the cases of *E. huxleyi*, *Prochlorococcus* and *Synechococcus*, and other published BWFs. No PAR inhibition was defined for *Phaeodactylum*, that is partly related to the lower E_{PAR} exposures used in this first experimental determination of the BWF.
- 9) Elevated UV radiation. Because most inhibition is caused by UV-A radiation, E_{inh} at the surface for known BWFs will never be increased by a factor of 20 vs $E_{inh}(PI)$, even if 95% of stratospheric ozone is destroyed (total ozone column would be reduced by a lower fraction as the increased penetration of UV-C will form ozone at lower altitudes). Thomas et al (2015) treated the case of a gamma-ray burst resulting, briefly (months), in a strong depletion of column ozone by 70% in the region of the strike. At most, this increased the $E_{inh}(0)$ by a factor of 2.63, based on the Phaeo BWF which has probably the largest ratio of sensitivity to UV-B vs UV-A. The multiplier will be less for almost all other phytoplankton especially when PAR inhibition is included. The effect of a gamma-ray burst on Integrated production at midday was also evaluated for *Synechococcus* and *Prochlorococcus* (Neale and Thomas 2016b) and ozone depletion of 70% resulted in at most 3% additional inhibition (vs normal ozone) to the 1% depth of PAR and 7% additional inhibition of productivity integrated over the mixed layer.
- 10) Yet another approach is needed for polar phytoplankton, for which low light and temperature can result in very low repair rates such that in some cases (mainly deeply mixed zones), inhibition is time dependent (see Neale et al 1998, Smyth et al 2012). Probably polar oceans, especially S. Ocean inside ice-limit, should be treated as a special case.
- 11) Finally, the CESM2-UVphyto model assumes that the only effect of UV on phytoplankton is through inhibition of photosynthesis. However, UV (more specifically UV-B) also directly damages DNA, inhibiting growth. Too little is known to quantify the importance of this mode of UV effect on a global basis, still it should be recognized that it could be important (see Andreasson and Wangberg 2007).

Summary – The model needs extensive revision after which the case studies can be re-run. At that point the results and conclusions can be re-examined and re-written as needed. Detailed reviews of those sections will be provided then.

Minor and Technical Comments

Line 95 Although stratification has intensified, surface mixed layer depths are not increasing, contrary to the expectations of Gao et al. (2019). See discussion in Neale et al. (2023)

Figure 1 The text in several places states limits to UV-B as 280-315 nm, but this plot has the division between the bands at 320 nm

Line 230 Supplemental Table 1 only lists weights up to 327 nm

Line 230 Relative to the originally published BWFs, weights have been both interpolated and extrapolated.

Line 265 As mentioned above, Lorenzo et al. 2019 did not find an effect of PIC/POC ratio on the BWF. In any case, the treatment effect found by Xu et al (which could be UV as well as other factors) is more accurately defined as $3.5/2=1.75$, since the calcified strain grew twice as fast as the naked strain under PAR-only incubator conditions.

Line 520 Arrigo 1994 – journal name missing

Line 620 Neale and Thomas GCB, publication year is 2016

Respectfully submitted,

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