Algorithm to estimate daily Photo-synthetically Available Radiation at the Ocean surface (OTSK14)

A. Algorithm Outline

(1) Algorithm name: daily Photo-synthetically Available Radiation at the Ocean surface

(2) Product Code: PAR

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B. Theoretical Description

1.1 Algorithm Description (revised for version 2.2 –includes diurnal variability of clouds and modified parameterization of surface albedo)

The algorithm estimates daily (i.e., 24-hour averaged) Photosynthetically Active Radiation (PAR) reaching the ocean surface from GLI data. PAR is defined as the quantum energy flux from the Sun in the spectral range 400-700 nm. It is expressed in Einstein/m^2/day.

The PAR model uses plane-parallel theory and assumes that the effects of clouds and clear atmosphere can be de-coupled. The planetary atmosphere is therefore modeled as a clear sky atmosphere positioned above a cloud layer. This approach was shown to be valid by Dedieu et al. (1987) and Frouin and Chertock (1992). The great strength of such a de-coupled model is its simplicity. It is unnecessary to distinguish between clear and cloudy regions within a pixel, and this dismisses the need for often-arbitrary assumptions about cloudiness distribution.

Under solar incidence θ_s, the incoming solar flux at the top of the atmosphere, $E_0 \cos(\theta_s)$ is diminished by a factor $T_d T_g/(1-S_a A)$ by the time it enters the cloud/surface layer. In this expression, T_d is the clear sky diffuse transmittance, T_g is the gaseous transmittance, S_a is the spherical albedo, and A is the cloud/surface layer albedo. As the flux, $E_0 \cos(\theta_s) T_d T_g/(1-S_a A)$, passes through the cloud/surface layer, it is further reduced by a factor A. The solar flux reaching the ocean surface is then given by

$$E = E_{clear}(1 - A)(1 - A_s)^{-1}(1-S_a A)^{-1} \qquad (1)$$

where A_s is the albedo of the ocean surface and $E_{clear} = E_0 \cos(\theta_s) T_d T_g$ is the solar flux that would reach the surface if the cloud/surface layer were non reflecting and non-absorbing. In clear sky conditions, A reduces to A_s.

In order to compute E, A is expressed as a function of the radiance measured by GLI in the PAR spectral range. The algorithm works pixel by pixel and proceeds as follows.

First, for each pixel not contaminated by glitter the GLI radiance L_i^* in band i $(i = 1, 2, \ldots, 6)$, where 1 is 0.412 µm, 2 is 0.443µm, 3 is 0.490 µm, 4 is 0.519 µm, 5 is 0.544 µm, and 6 is 0.679 µm, expressed in mW/cm^2/µm/sr, is transformed into reflectance, R_i^*:

$$R_i^* = \pi L_i^*/[E_{0i}(d_0/d)^2 \cos(\theta_s^*)] \qquad (2)$$

where E_{0i} is the extra-terrestrial solar irradiance in band i, θ_s^* is the sun zenith angle at the GLI observation time, and d_0/d is the ratio of mean and actual Earth-Sun distance. The glint areas are not selected because they would be interpreted as cloudy in the PAR algorithm.

Second, R_i^* is corrected for gaseous absorption, essentially due to ozone:

$$R_i' = R_i^*/T_{gi} \qquad (3)$$

with

$$T_{gi} = exp[-k_{oi}U_o/cos(\theta_s^*)] \quad (4)$$

where k_{oi} is the ozone absorption coefficient in band i and U_o the ozone amount.
Third, the reflectance of the cloud/surface layer, R_i, is obtained from R_i' following Tanré et al. (1979) and assuming isotropy of the cloud/surface layer system. That is:

$$R_i = (R_i' – R_{ai})[T_{di}(\theta_s^*)T_{di}(\theta_v) + S_{ai}(R_i' – R_{ai})]^{-1} \quad (5)$$

where θ_v is the viewing zenith angle and R_{ai} is the intrinsic atmospheric reflectance in band i (corresponds to photons that have not interacted with the cloud/surface layer). The assumption of isotropy is made because no information on pixel composition is available.

In Eq. (5), R_a is modeled using the quasi single-scattering approximation:

$$R_a = (\tau_{mol}P_{mol} + \omega_{aer}\tau_{aer}P_{aer})[4cos(\theta_s^*)cos(\theta_v)]^{-1} \quad (6)$$

where τ_{mol} and τ_{aer} are the optical thicknesses of molecules and aerosols, P_{mol} and P_{aer} are their respective phase functions, and ω_{aer} is the single scattering albedo of aerosols. Subscript i has been dropped for clarity. The diffuse transmittance T_d and spherical albedo S_a are computed using analytical formulas developed by Tanré et al. (1979):

$$T_d(\theta) = exp[-(\tau_{mol} +\tau_{aer})/cos(\theta)]exp[(0.52\tau_{mol} + 0.83\tau_{aer})/cos(\theta)] \quad (7)$$

$$S_a = (0.92\tau_{mol} + 0.33\tau_{aer})exp[-(\tau_{mol} + \tau_{aer})] \quad (8)$$

where τ_{mol} is the optical thickness of molecules, τ_{aer} that of aerosols, and θ is either θ_s^* or θ_v.
The optical thickness of aerosols in band i, τ_{aeri}, is obtained from the optical thickness in band 18 centered at 0.866 µm, τ_{aer8}, and the Angström coefficient, α:

$$\tau_{aeri} = \tau_{aer18}(\lambda_{18}/\lambda_i)^{\alpha} \quad (9)$$

where λ_i and λ_{18} are equivalent wavelengths in GLI bands i and 18, respectively. A monthly climatology may be used for τ_{aer} and α, since aerosol properties cannot be determined when the pixel is cloudy. This procedure is also justified because, in general, aerosol effects on E are secondary compared to cloud or θ_s effects.
To estimate ω_{aer} and P_{aer}, the two closest of 12 aerosol models, k and l, that verify $\alpha(l)< \alpha< \alpha(k)$ are selected, and a distance $d_{aer} = [\alpha(l) – \alpha]/[\alpha(l) – \alpha(k)]$ is computed. Using this distance, ω_{aer} and P_{aer} are obtained as follows:

$$\omega_{aer} = d_{aer}\omega_{aer}(k) + (1 – d_{aer})\ \omega_{aer}(l) \quad (10)$$

$$P_{aer} = d_{aer}P_{aer}(k) + (1 – d_{aer})P_{aer}(l) \quad (11)$$

where $\omega_{aer}(l)$ and $\omega_{aer}(k)$ are the single scattering albedos of aerosol models l and k, and $P_{aer}(l)$ and $P_{aer}(k)$ their respective phase functions.
Next, an estimate of daily PAR, $<E>_{day}$, is obtained by integrating Eq. (1) over the length of the day:

$$<E>_{day} = <E_0>\int_{day}\{cos(\theta_s)<T_g><T_d>[1 – <A>]\ [1 – <A_s>]^{-1}[1 – <S_a><A>]^{-1}\}\ dt \quad (12)$$

with

$$<T_g> = exp[-<k_o>U_o/cos(\theta_s)]exp[-<k_v>U_v /cos(\theta_s)] \quad (13)$$

$$<T_d> = \sum_i(T_{di}E_{oi})/\sum_iE_{0i} \quad (14)$$

$$<S_a> = \sum_i(S_{ai}E_{oi})/\sum_iE_{0i} \quad (15)$$

$$\langle A_s \rangle = \langle T_{dir} \rangle \langle T_d \rangle^{-1} [0.05/(1.1[\cos(\theta_s)]^{1.4} + 0.15] + 0.08 \langle T_{dif} \rangle \langle T_d \rangle^{-1} \quad (16)$$

$$\langle T_{dir} \rangle = \sum_i T_{diri} E_{oi} / \sum_i E_{0i} \quad (17)$$

$$\langle T_{dif} \rangle = \langle T_d \rangle - \langle T_{dir} \rangle \quad (18)$$

$$T_{diri} = \exp[-(\tau_{moli} + \tau_{aeri})/\cos(\theta_s)] \quad (19)$$

$$\langle A \rangle = F(t^*) \langle R(t^*) \rangle A'/A'(t^*) \quad (20)$$

$$\langle R \rangle = \sum_i R_i(t^*) / \sum_i E_{0i} \quad (21)$$

where t^* is the GLI observation time, T_{diri} is the direct component of T_{di} in band i, A' is a climatological albedo, and <> symbolizes average value over the PAR range. Note that because of saturation at low radiance in some of the GLI spectral bands, the algorithm only takes into account, for each pixel, the spectral bands that do not saturate. It is possible, as an option, however, to use only the band centered at 0.544 µm (does not saturate over clouds) to estimate cloud effects on PAR. In the code, this option is activated when the flag “flag544” is on.

In Eq. (12), absorption by water vapor in the PAR spectral range, occurring weakly between 690 and 700 nm, is included. The ozone and water vapor absorption coefficients $\langle k_o \rangle$ and $\langle k_v \rangle$ in Eq. (13) are taken from Frouin et al. (1989). Surface albedo is parameterized as a function of sun zenith angle and fractions of direct and diffuse incoming sunlight. The formula of Briegleb and Ramanathan (1982), developed for the total spectrum, is adapted to the PAR range via a simple multiplication factor (1.13). This parameterization, which takes into account Fresnel reflection and diffuse under-light, is sufficient since the influence of $\langle A_s \rangle$ on surface PAR is small. In some cases, however, the retrieved $\langle A \rangle$ might be less than $\langle A_s \rangle$. When this happens, $\langle A \rangle$ is fixed to $\langle A_s \rangle$.

Even though the cloud/surface layer is assumed to be isotropic in the correction of clear atmosphere effects (Eq. 5), $R(t^*)$ is corrected by the angular factor $F(t^*)$ (Eq. 20). Analytical formulas proposed by Zege (1991) for non-absorbing, optically thick scattering layers are applied.

Diurnal changes in the cloud/surface layer are taken into account by introducing the factor $A'/A'(t^*)$ in Eq. (20). A regional diurnal albedo climatology (Standfuss et al. (2001) (see also Viollier et al., 2001) is used. This climatology (monthly, 2.5 degree resolution, 16 local times from 05:30 to 20:30) was obtained from 5 years of ERBS scanner data (1985-1990). Note that using Eq. (12) the algorithm yields a daily PAR estimate for each instantaneous GLI pixel.

Finally, the individual daily PAR estimates, obtained in units of mW/cm^2/µm, are converted into units of Einstein/m^2/day. The factor required to convert units of mW/cm^2/µm to units of Einstein/m^2/day is equal to 1.193 to an inaccuracy of a few percent regardless of meteorological conditions (Kirk, 1994, pp. 4-8.). In middle and high latitudes, several daily estimates may be obtained over the same target during the same day, increasing product accuracy.

Test results of the PAR code, version 2.2 are displayed in Figures 1 and 2 for input radiance of 10 and 20 mW/cm^2/µm/sr, respectively. Flag554 is equal to zero (i.e., all the wavelengths are taken into account in the computations). Differences between the results of version 2.2 (diurnal variability of clouds included) and version 2.0 (diurnal variability of clouds neglected) are displayed in Figures 3 and 4, respectively.

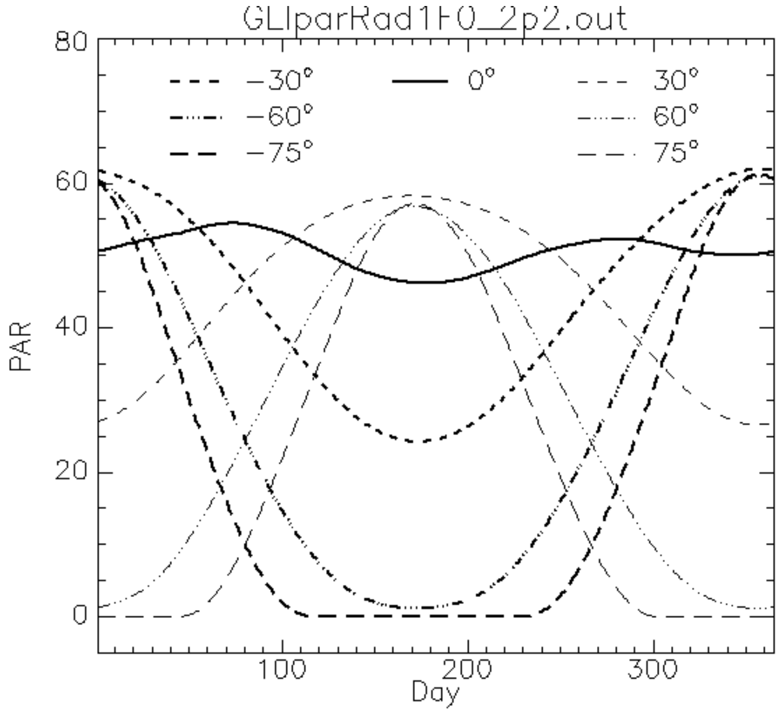

Figure 1. PAR as a function of Julian Day and latitude for input radiance of 10 mW/cm^2/μm/sr. Units are Einstein/m^2/day.

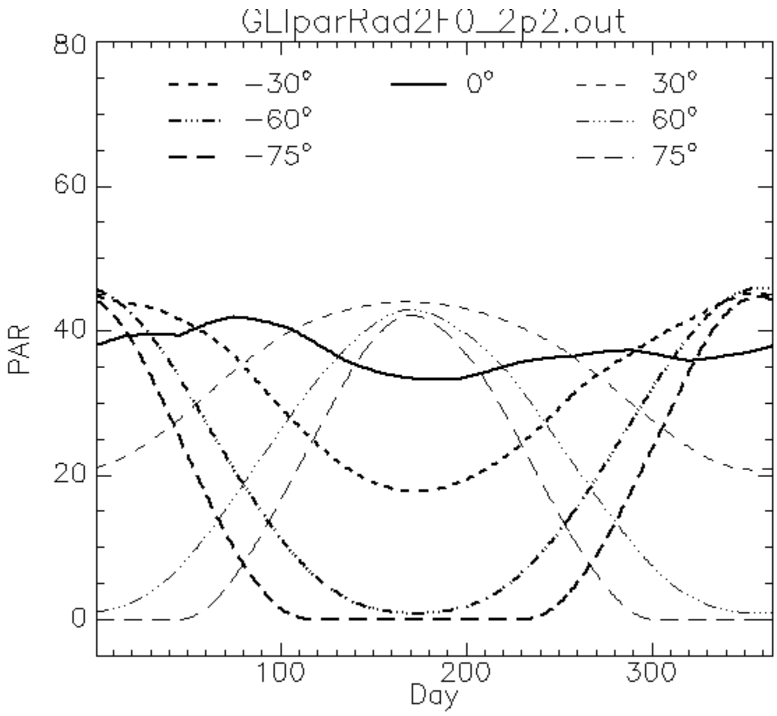

Figure 2. Same as Figure 1, but for input radiance of 20 mW/cm^2/μm/sr. Units are Einstein/m^2/day.

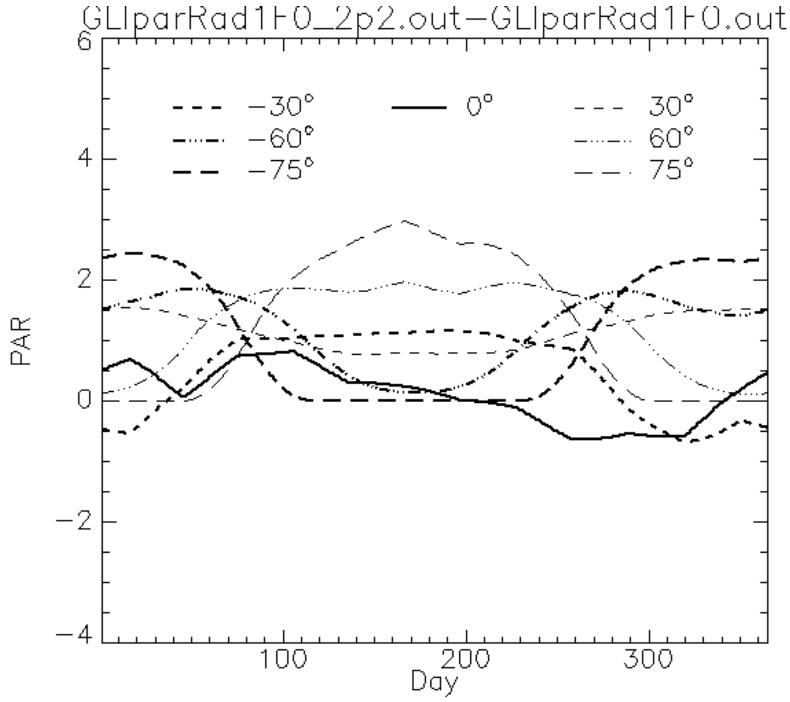

Figure 3. Difference between PAR from Version 2.2 and PAR from Version 2.0 for input radiance of 10 and 20 mW/cm^2/μm/sr. Units are Einstein/m^2/day.

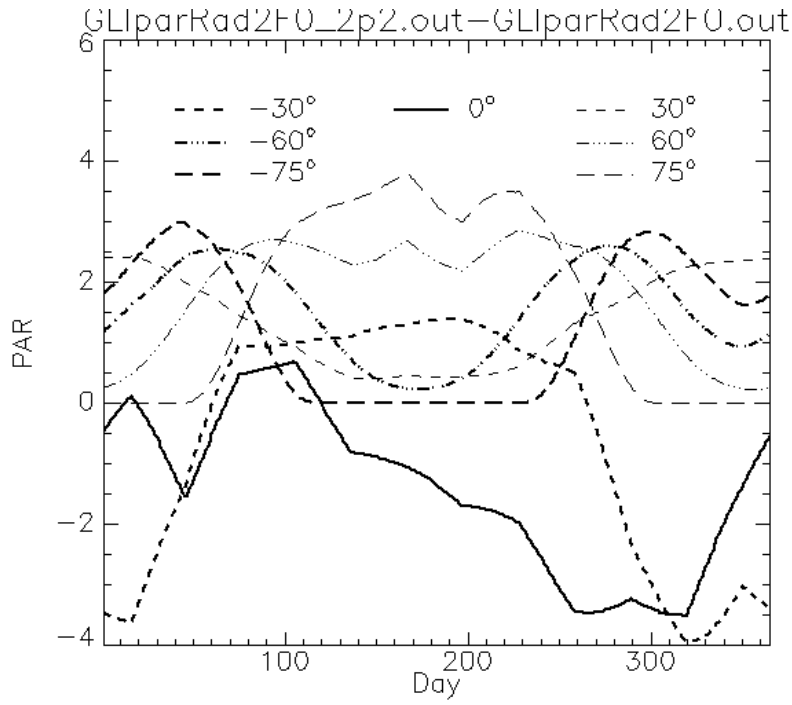

Figure 4. Same as Figure 3, but for input radiance of 20 mW/cm^2/μm/sr. Units are Einstein/m^2/day.

C. References

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