Annual Dynamics of Shortwave Radiation as Consequence of Smoothing of Previously Plowed and Harrowed Soils in Poland

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ABSTRACT

Smoothing a rough, deeply plowed soil increases its albedo, which determines a lower amount of shortwave radiation absorbed by its surface layer. That surface emits less longwave radiation, leading to a reduction in its temperature, which in turn can affect the climate, influencing the energy transfer between soil, vegetation, and the atmosphere. This paper presents a multistage procedure for estimating the annual dynamics of shortwave radiation reflected from bare soils as a consequence of smoothing the previously plowed and disk-harrowed fields in Poland. This procedure takes into account the spatial diversity of soil units and their properties within bare soil surfaces (extracted from Landsat 8 images), analyzed using digital maps of land use and soils as well as soil datasets stored in soil databases. One minimum and two peaks were found in the annual distribution of the radiation amount reflected from the soils only when smoothing the data. Expressing this reflected radiation as a fraction of the daily energy reaching the studied areas with clear-skies, it was predicted that those spring and summer peaks can reach about 2.2%–2.3% and 1%, respectively, of the incident shortwave radiation for soils that had been plowed and disk harrowed.

1. Introduction

The albedo of Earth’s land surfaces in midlatitudes varies between seasons. It is the highest in the winter because of snow cover with extremely high values, ranging between 0.8 and 0.95, and lowest in the spring during snow melting, before vegetation appears, reaching 0.05–0.1. The albedo of crops and natural vegetation increases during the growing season to about 0.25 with their maturation and an increase in their height and leaf area (Dexter 2004; Song 1999). Cultivated plants reduce the albedo of fields with light-colored soils and increase the albedo of fields with dark-colored soils (Rechid et al. 2005). In the autumn, when vegetation becomes senescent and deciduous and trees lose their leaves, the albedo of surfaces covered with vegetation decreases.

The broadband blue-sky albedo of Earth’s land surfaces is highly diverse except for moments when the low position of the sun near the horizon causes the albedo of all surfaces to approach 1. The albedo of cultivated soils, like that of other land surfaces, depends mainly on their brightness. The brightness of bare soils, mainly resulting from their relatively unchanging properties (the content of organic matter, iron oxides, and carbonates) decides the overall soil albedo level. Variable soil properties, such as soil surface moisture and roughness, dynamically change its albedo. The albedo of dark-colored, wet, rough soils reaches about 0.05–0.15, like that of coniferous forests, while light-colored, dry, and smooth surfaces have values around 0.35–0.4 (Oke 1987; Dobos 2006). A decrease in soil moisture causes an increase in soil spectral reflectance, reaching the reflectance minimum with water content at about the field capacity (Baumgardner et al. 1986; Bowers and Smith 1972; Weidong et al. 2002; Wang et al. 2005). The spectral reflectance of a bare soil increases with a decrease in the soil particle size (Bowers and Hanks 1965; Orlov 1966; Bowers and Smith 1972; Piech and Walker 1974). A more spherical shape of smaller aggregates causes higher reflectance than a more irregular shape of larger aggregates (Mikhajlova and Orlov 1986). Plowing smooth, sandy, and loamy soils can cause a decrease in their reflectance by about 25% (Matthias et al. 2000). Conversely, after a rain event causing the leveling of soil surface irregularities, the reflectance of a bare soil can
increase by 20%–30% (Potter et al. 1987; Cierniewski 1999, 2001). A crust around soil aggregates, formed as a result of the sequential wetting and drying of soil surfaces, reduces soil roughness (Kondratyev and Fedchenko 1980; Baumgardner et al. 1986; Cipra et al. 1971). Moreover, the albedo of soil surfaces varies during the day with the change in the solar zenith angle (θ), reaching a minimum at the local noon (Monteith and Szeicz 1961; Kondratyev 1969; Pinty et al. 1989; Lewis and Barnsley 1994; Wang et al. 2005; Oguntunde et al. 2006; Roxy et al. 2010). The greater the cloud cover with a higher diffuse light ratio, the smaller is the impact of θ on the albedo.

Studies on seasonal and diurnal changes in albedo of Earth’s land surfaces are important for the improvement of descriptions of biophysical processes associated with the energy transfer between soil, vegetation, and the atmosphere (Norman et al. 1995; Wang et al. 2002; Desjardins 2010). The albedos are used as input data in global climate models (Schneider and Dickinson 1974) and weather forecasting (Betts and Ball 1997). Smoothing a soil surface, previously deeply plowed, using, for example, a smoothing harrow, increases its albedo. Its higher albedo results in a lower amount of shortwave radiation absorbed by its surface layer, leading to a reduction in its temperature and longwave radiation emission (Lobell et al. 2006; Desjardins 2010; Farmer and Cook 2013).

The average diurnal value of Earth’s surface rather than its instantaneous value appears to be more useful for modeling processes associated with the flow of energy between Earth’s surface and the atmosphere in the diurnal cycle as well as in longer periods: monthly, seasonal, and annual (Grant et al. 2000; Cierniewski et al. 2013b). Studies of reasons for albedo variations on Earth’s surfaces, including cultivated bare soils, seem especially important in the context of statements by Henderson-Sellers and Wilson (1983) and Sellers et al. (1995), who determined the required accuracy of the albedo for the global climate models at ±5% and ±2%, respectively.

This paper presents a multistage procedure for estimating the annual dynamics of shortwave radiation reflected from bare soils as a consequence of smoothing the previously plowed and disk-harrowed fields in Poland. This procedure takes into account the spatial diversity of soil units and their properties within these extracted bare soil surfaces, obtained from digital maps of land use and soils as well as soil datasets stored in soil databases. Using the properties of soils located within the extracted bare soil surfaces, the diurnal albedo variations of the soils were predicted using the developed procedure and assuming that their roughness corresponded to soil surfaces shaped by a plow (Pd), a disk harrow (Hd), and a smoothing harrow (Hs). For simplicity, it was assumed that all the soil surfaces were air dried and illuminated in clear-sky conditions.

2. Methods

This procedure began with the selection of two Landsat scenes, 187024 [eastern scene (ES)] and 190024 [western scene (WS)], in the eastern and western parts of Poland. The selected locations are representative of all Polish arable soils. Moreover, we downloaded all Landsat 8 images that would be useful in determining the variation in the bare soil area over a year (Fig. 1). These images were obtained from the U.S. Geological Survey (USGS), Earth Resources Observation and Science (EROS), and EROS Center Science Processing Architecture (ESPA) (http://espa.cr.usgs.gov). They were recorded between April 2013 and October 2014. Because of clouds frequently occurring over the study area and the relatively long repeating cycle of the Landsat 8 platform (16 days), images from the neighboring scenes were additionally used to analyze possibly the largest number of Landsat 8 satellite data. These additional scenes, 188024 and 186024 for the ES as well as 191024 and 189024 for WS, covered more than 45% of both the ES and WS. To limit image data processing, the Landsat high-level data science products were used. These data have calibrated surface reflectance, received after applying radiometric calibration, an atmospheric correction, and sun angle incidence normalization (USGS 2015). The surface reflectance of the ES scene, registered on 26 December 2013 as illuminated at θ, higher than 75°, was corrected by the PCI Geomatica software package with a built-in atmospheric and topographic correction (ATCOR)-3 model.

Spectral data of the operational land imager (OLI) bands (one of the two Landsat 8 instruments) were used in the second stage to extract soil areas not covered by plants. These soils were identified as bare if their reflectance (R_b) in the bands (B) 2–7 fulfilled the following conditions: R_2 < R_3 < R_4 < R_5 < R_6; R_6 > R_7; R_5/R_3 > 1.8; and R_6 - R_5 > 0. This set of conditions was created on the basis of the shape of the spectra of the main soils types occurring in Poland (Cierniewski et al. 2010; Piekarczyk et al. 2016). Classification of bare soils has been limited to the extent of the arable land category based on the Coordination of Information on the Environment (CORINE) land-cover data of 2012 (European Environment Agency 2012) acquired from the Copernicus land monitoring service (http://land.copernicus.eu/pan-european/corine-land-cover/clc-2012). The results of bare soil identification, performed for
each image without snow and with up to 10% of cloud cover, were presented in the form of binary maps. Validation of the effectiveness of bare soil classification according to the adopted criteria was carried out by comparing the results with a visual interpretation for 5% of the arable lands of WS and ES scenes for each selected date, including winter, spring, summer, and autumn. The visual interpretation was conducted using the color composition in the RGB model as a combination of spectral bands $R_5$, $R_4$, and $R_3$ (color infrared), $R_7$, $R_4$, and $R_3$ (shortwave infrared), and $R_4$, $R_3$, and $R_2$ (natural colors). A digital soil map (http://esdac.jrc.ec.europa.eu/content/google-earth-files), classified according to the world reference base for soil resources (WRB) (International Union of Soil Sciences Working Group World Reference Base 2014), was superimposed on the bare soil maps. Then the total area of soils not covered by plants for WS and ES scenes was calculated.

In the situation when adjacent, partially overlapping images were used, the bare soil area was scaled proportionally to the area of the entire scene. Scaling was performed using the relationship between the bare soil area of a fragment of a scene and its full area. This allowed measuring bare soil area for each WRB soil unit.

In the third stage, the properties of the soil samples located within these WRB soil unit contours describing the content of soil organic carbon (SOC) and CaCO$_3$ in their surface horizon were obtained from the collection of the following soil georeferenced datasets: Land Use/Cover Area Frame Survey (LUCAS) (Toth et al. 2013), monitoring of arable land of Poland (Terelak et al. 2008), and the soil database of the Department of Soil Science and Remote Sensing of Soils (http://150.254.126.236/soil/test25/Spectral%20Properties%20of%20Polish%20Soils.htm). Each identified soil unit was characterized by averaged SOC and CaCO$_3$ values, taking into account the data of all soil samples described within the contours of the unit. Figure 2 shows the locations of the samples in WS and ES on the background of the contours of the bare arable soils extracted from the Landsat 8 images recorded on 6 September 2013 and 16 March 2014, respectively. Then, in view of the proportions of areas of the soil units, the weighted average values of soil properties representative of the ES and WS scenes were calculated.

In the fourth stage of the procedure, using these weighted average values of soil properties, complemented with roughness indices of the analyzed soils, half-diurnal albedo variations of the soils within the ES and WS with given roughness states as the $\theta_r$ function
were determined. The equations proposed in a previous paper by Cierniewski et al. (2015a),

\[ \alpha_0 = 0.301 - 0.042\text{SOC} + 0.007\text{CaCO}_3 \]

\[ - 0.088T_{3D} \quad \text{and} \]

\[ S_\alpha = 0.0054\text{HSD}^{-1.535}, \]

were used here, where \( \alpha_0 \) expresses their \( \alpha \) at \( \theta_s = 0^\circ \), while \( S_\alpha \) describes the intensity of the \( \alpha \) increase of the soils from \( \theta_s \) of 0° to 75°. The variables HSD and \( T_{3D} \) are the roughness indices mentioned above. The quantity HSD, as in a previous paper by Cierniewski et al. (2015a), is defined, after Marzahn et al. (2012), as the standard deviation of a soil surface area within its basic unit and \( T_{3D} \), after Taconet and Ciarletti (2007), as the ratio of the real surface area of the unit to its flat horizontal area. It was assumed that the analyzed soil surfaces within ES and WS were treated by a Pd, an Hd, and an Hs, creating a specific roughness state of the soils described by the HSD values 25, 10, and 5 mm, respectively, and the \( T_{3D} \) values 1.5, 1.15, and 1.05, respectively. These HSD and \( T_{3D} \) values for soil surfaces formed by these farming tools were adopted from previous papers of Cierniewski et al. (2015a,b,c). Because usually the \( \alpha \) values for \( \theta_s > 75^\circ \) increase sharply, reaching 1 for \( \theta_s = 90^\circ \), the \( \alpha \) distribution in the full \( \theta_s \) range up to 90° was determined using the formula

\[ \alpha_{\theta_s} = \frac{a + cb^{0.5}}{1 + b^{0.5}}, \]

where \( a \), \( b \), and \( c \) are parameters. This equation was individually fitted to the soils with roughness created by a Pd, an Hd, and an Hs within WS and ES using TableCurve 2Dv5.01 (Systat Software Inc.).

In the fifth stage, the half-diurnal \( \alpha_{\theta_s} \) distributions of the soils treated by these farming tools within ES and WS were first matched with the variation of \( \theta_s \) for each day of the year from the local noon to sunset. Then these distributions were expressed as a function of time, replacing \( \theta_s \) by solar local time, which made it possible to predict the average values of the diurnal albedo of the soils (\( \alpha_{\text{d}} \)) formed by a Pd, an Hd, and an Hs within ES and WS for all days of the year.

In the sixth stage, the diurnal amount of shortwave radiation reflected from the soils treated by a Pd, an Hd, and an Hs within ES and WS each day (Rr\(_{\text{d}}\)) was estimated by multiplying the total amount of shortwave energy reaching the scenes in clear-sky conditions (Ri\(_{\text{d}}\)) by the \( \alpha_{\text{d}} \) of the soils and the share of arable soils (Fb\(_{\text{d}}\)) changing dynamically throughout the year. The Rr\(_{\text{d}}\) values were calculated using the formulas contained in Allen et al. (1998).

In the last stage, the diurnal amount of shortwave energy reflected from the soils within ES and WS only as a result of smoothing their surfaces by an Hs, previously shaped by a Pd and an Hd (\( \Delta\text{Rr}_d \)), was calculated as the difference between the Rr\(_{\text{d}}\) reflected from the surfaces treated by a Pd and an Hd and the Rr\(_{\text{d}}\) reflected for an Hs within ES and WS. These \( \Delta\text{Rr}_d \) values were also expressed as a percentage of the amount of energy Ri\(_{\text{d}}\) reaching the studied scenes (FRb\(_{\text{d}}\)).
The total area of the two scenes ES and WS in the universal transverse Mercator projection covers about 75,000 km², which corresponds to 24% of the area of Poland. Arable soils in these scenes contain more than 90% of all soil units occurring on arable land in Poland, where the main crops are wheat, rye, maize, rapeseed, barley, potato, and sugar beet (Joint Agricultural Weather Facility 1994; Central Statistical Office 2015). We selected 10 and 11 of those units, which individually occupy more than 1% of the area of arable soils in WS and ES, respectively, for a spectral reflectance analysis of the scenes.

The areas of bare soils within the contours of arable lands were extracted from spectral reflectance data of 18 and 14 images of Landsat 8 for the ES and WS scenes, respectively. The data describing properties of all soil units were obtained from 170 and 123 soil samples for WS and ES, respectively. Soils within both scenes developed mainly from loamy and sandy materials (Table 1). Taking into account the share of the area of the WRB soil units, most of them, 73% and 68% within the ES and WS, respectively, developed from sandy loam (SL) and silt loam (SIL) materials. Within the ES and WS, 17% and 23%, respectively, have developed from loamy sand (LS). The average SOC values of the units within the ES and WS ranged from 0.76% to 1.08% and from 0.86% to 1.33%, respectively. The average content of CaCO₃ of the units within both scenes is low and does not exceed 0.5% and 0.3%. Figure 3 shows contours of the WRB soil units in the fragment of WS (shown in Fig. 1), which correspond to the contours of the bare soils extracted from the Landsat 8 image as an example. Figure 4 shows the distributions of half-diurnal δ variations for the soils within the ES and WS with roughness corresponding to the use of a Pd, an Hd, and an Hs. The influence of the soil roughness disclosed in distributions associated with the Pd and Hd effects is quite similar to distributions related to soils studied in Israel shaped by similar agricultural tools (Cierniewski et al. 2013a). The distributions were generated in the full range from 0° to 90° using similar SOC values, 1.03% and 1.09%, established for the soils within ES and WS, respectively. Figure 5 presents examples of these δ distributions generated as a function of the solar local time for chosen dates, which allows an accurate calculation of the average diurnal albedo values (δₐ) for a specific day of the year. These examples show how significantly δₐ values of soils vary with their roughness and the date. The δₐ values for the soils shaped by a Pd, an Hd, and an Hs, generated for the shortest, 358th, day of the year (DOY) (22 December) are 7%, 20%, and 33% higher, respectively, than for the longest, 173rd, DOY (22 June). The δₐ values of the same soils formed by these tools in the same order at the beginning of the astronomical winter by about 100% and 50%, at the astronomical

### Table 1. Share (%) of the WRB soil units within the CORINE arable land contours in ES and WS vs the soil-selected properties. Texture is presented with respect to types in Soil Survey Staff (1975): sandy loam (SL), loamy sand (LS), loam (L) and silt loam (SIL). WRB soil units: gleyic albeluvisol (ABgl), haplic arenosol (ARha), eutric cambisol (CMeu), eutric fluvisol (FLeu), gleyic fluvisol (FLgl), mollic gleysol (GLmo), eutric histosol (HSeu), rendzic leptosol (LPrz), gleyic luvisol (LVgl), haplic luvisol (LVha), haplic podzol (PZha), and leptic podzol (PZle).

<table>
<thead>
<tr>
<th>WRB soil units in Poland</th>
<th>Share</th>
<th>Texture</th>
<th>SOC (%)</th>
<th>Carbonates</th>
<th>Share</th>
<th>Texture</th>
<th>SOC (%)</th>
<th>Carbonates</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABgl</td>
<td>9.6</td>
<td>SL</td>
<td>0.89</td>
<td>0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>ARha</td>
<td>4.1</td>
<td>LS</td>
<td>0.92</td>
<td>0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>CMeu</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>10.3</td>
<td>LS</td>
<td>1.08</td>
<td>0.1</td>
</tr>
<tr>
<td>FLeu</td>
<td>6.7</td>
<td>L</td>
<td>1.09</td>
<td>0.5</td>
<td>8.1</td>
<td>L</td>
<td>1.26</td>
<td>0.3</td>
</tr>
<tr>
<td>FLgl</td>
<td>2.8</td>
<td>SL</td>
<td>1.12</td>
<td>0</td>
<td>9.6</td>
<td>SL</td>
<td>1.33</td>
<td>0.1</td>
</tr>
<tr>
<td>GLmo</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>4.0</td>
<td>LS</td>
<td>1.26</td>
<td>0.1</td>
</tr>
<tr>
<td>HSeu</td>
<td>6.0</td>
<td>SL</td>
<td>1.69</td>
<td>0</td>
<td>4.8</td>
<td>LS</td>
<td>1.00</td>
<td>0.1</td>
</tr>
<tr>
<td>LPrz</td>
<td>1.2</td>
<td>LS</td>
<td>0.76</td>
<td>0.1</td>
<td>2.5</td>
<td>SL</td>
<td>1.29</td>
<td>0</td>
</tr>
<tr>
<td>LVgl</td>
<td>17.6</td>
<td>SL</td>
<td>1.08</td>
<td>0.1</td>
<td>12.4</td>
<td>SL</td>
<td>1.03</td>
<td>0</td>
</tr>
<tr>
<td>LVha</td>
<td>27.8</td>
<td>SIL</td>
<td>1.05</td>
<td>0.1</td>
<td>30.2</td>
<td>SL</td>
<td>1.09</td>
<td>0.2</td>
</tr>
<tr>
<td>PZha</td>
<td>9.0</td>
<td>SL</td>
<td>0.89</td>
<td>0</td>
<td>4.9</td>
<td>LS</td>
<td>0.86</td>
<td>0</td>
</tr>
<tr>
<td>PZle</td>
<td>12.2</td>
<td>LS</td>
<td>0.81</td>
<td>0</td>
<td>13.0</td>
<td>LS</td>
<td>0.93</td>
<td>0</td>
</tr>
<tr>
<td>Sum 94.7</td>
<td>97.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>99.8</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Weighted average</td>
<td>—</td>
<td>—</td>
<td>1.03</td>
<td>0.08</td>
<td>—</td>
<td>—</td>
<td>1.09</td>
<td>0.11</td>
</tr>
</tbody>
</table>
spring and autumn equinoxes by about 75% and 40%, and at the beginning of the astronomical summer by about 65% and 35%, respectively.

The annual variations in the share of bare arable soils ($F_{b_d}$) show one minimum and two peaks of $F_{b_d}$ in the year (Fig. 6b). The minimum, of about 1%, was observed near the 173rd DOY, while the peaks, of 25%–28%, were found near the 80th DOY and between the 245th and 255th DOY (2–12 September). At the beginning and end of the year, the $F_{b_d}$ value was about 15%. The diurnal amount of shortwave radiation ($R_{i_d}$), calculated in the sixth stage of the procedure, reaching the scenes in clear-sky conditions varied from about 5 TJ km$^{-2}$ day$^{-1}$ (at the beginning of the astronomical winter, on the 358th DOY) to 31 TJ km$^{-2}$ day$^{-1}$ (at the beginning of the astronomical summer, on the 173rd DOY) (Fig. 6c).

Taking into account the $\alpha_d$ values of bare arable soils as well as their $F_{b_d}$ so strongly fluctuating throughout the year, it was predicted that the amount of shortwave radiation reflected from them ($\Delta R_{r_d}$) only as a result of smoothing their surfaces shaped earlier by a Pd and an Hd (Fig. 6d) also had one minimum and two peaks, like their $F_{b_d}$ data (Fig. 6b). This minimum, also occurring on the 173rd DOY, was assessed at 20 and 9 GJ km$^{-2}$ day$^{-1}$ for soils previously treated by a Pd and an Hd, respectively. It was found that the spring peaks, of about 430 GJ km$^{-2}$ day$^{-1}$ for a Pd and 195 GJ km$^{-2}$ day$^{-1}$ for an Hd, and the summer peaks, of 485 GJ km$^{-2}$ day$^{-1}$ for a Pd and 215 GJ km$^{-2}$ day$^{-1}$ for soils earlier formed by an Hd, could occur between the 85th and 95th DOY (26 March–5 April) and the 230th and 240th DOY (18–28 August), respectively. Expressing this reflected radiation as a fraction of the $R_{i_d}$ in a day, those spring and summer peaks occurred 30 days earlier and 30 days later, respectively, than the $\Delta R_{r_d}$ peaks.

![Fig. 3. WRB soil units: leptic podzol, haplic luvisol, and eutric fluvisol within the upper-left corner of the WS fragment (shown in Fig. 1), which correspond to the contours of the bare soils extracted from the Landsat 8 image recorded on 15 Apr 2013.](image1)

![Fig. 4. Distribution of $\alpha$ over the whole $\theta_s$ from 0° to 90° for average bare soils within ES and WS treated by a Pd, an Hd, and an Hs, and generated by Eq. (3) with the parameters $a$, $b$, and $c$.](image2)
The spring peak can reach 2.3% and 1.1% of the values for soils previously shaped by a Pd and an Hd, respectively. The summer peaks can be about 0.1% lower than the spring ones, whereas this minimum on the 173rd DOY predicted for the soils previously treated by a Pd and an Hd reached only 0.05% and 0.03%, respectively.

Climatologists can probably assess more credibly whether this increased amount of the radiation reflected from arable soils changing their areas during the year as a consequence of their smoothing may noticeably affect the climate. If they assessed that the impact could be real, preferring such treatment of arable land could be a relatively easy way, among others, to slow the progressive warming of Earth’s climate in the recent decades. Morice et al. (2012) report that the linear trend of near-surface air temperature over land and sea for the Northern Hemisphere was 0.24°C per decade between 1979 and 2010.

(Fig. 6e). The spring peak can reach 2.3% and 1.1% of the values for soils previously shaped by a Pd and an Hd, respectively. The summer peaks can be about 0.1% lower than the spring ones, whereas this minimum on the 173rd DOY predicted for the soils previously treated by a Pd and an Hd reached only 0.05% and 0.03%, respectively.

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4. Concluding remarks

The procedure presented in this paper allowed quantifying the annual variation of shortwave radiation reflected from bare soils within arable land in Poland only as the consequence of smoothing their surfaces previously treated by a plow and a disk harrow. The obtained numbers describe the situation in an average-sized country located in eastern Europe. They show the radiation to be the greatest in the spring before the start of the growing season and in the summer after the cereal harvest. For soils previously treated by a plow and a disk harrow, these amounts during those periods can reach about 2.2%–2.3% and 1% of the radiation that reaches them, respectively.

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