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Correlation between Increases of the Annual Global Solar Radiation and the Ground Albedo Solar Radiation due to Desertification—A Possible Factor Contributing to Climatic Change

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Abstract: Background: This study investigates the connection between annual global solar radiation and ground albedo solar radiation due to desertification in line with previous research on the correlation between climatic changes and desertification. Methods: A simulation study was performed using an algorithm formulated by the authors and the typical albedo coefficient values of forested ground, green grass and desert sand. Results: It is shown that changing the albedo coefficients from values corresponding to forested ground or green grass to values corresponding to the desert sand causes a significant increase in the annual global solar radiation acquired at different latitudes, leading one to hypothesize a mechanism of reduction of convective overturning and precipitation decreases due to desertification. Conclusion: In this scenario, modifications of local and global climate can be connected to changes of ground solar albedo induced by desertification.

Keywords: ground solar albedo; annual global solar radiation; desertification; climatic changes

1. Introduction

It has been shown that changes in radiative forcing due to several manmade sources such as anthropogenic emissions of gases like carbon dioxide and methane, manmade sulphur emissions, overgrazing and deforestation can influence Earth's climate [1–5].

Desertification is defined as land degradation in arid, semi-arid and dry sub-humid areas induced by various factors such as climatic variations and several manmade agents. Desertification was also defined as the reduction or loss of biological or economic productivity resulting from land use and human activities (International Agreement on Combating Desertification (IACD), Paris, 1994).

A conference on desertification was organized in Nairobi in 1977 by the United Nations General Assembly in order to plan actions to contrast desertification through 28 recommendations. Successively, in 1992, in occasion of the United Nations Conference on Environment and Development (Unced) in Rio, the problem of desertification was put again at the top of the agenda following requests by the countries affected by this problem.

Hence, the international community recognized that desertification was a global environmental problem and a Convention to combat desertification was adopted in Paris on 17 June 1994 and it was ratified in 1996 by more than 50 countries (the United Nations Convention).

Deforestation can induce land degradation because it modifies the biophysical functioning processes of ecology, inducing a progressive loss of vegetation and soil productivity. In this framework it was hypothesized that desertification can have significant effects on the global climate [6–9].

As a matter of fact, it should be also taken into account that climate change itself can be a main driver of desertification.

Indeed, since the end of the 19th century, Earth has been affected by a large scale increase of air temperature of about 0.5 °C, a value which varies with latitude [10–12].

Previous studies have been reported in the literature concerning mechanisms to explain the connection between local evaporation and variations in the temperature of ground surface [13]. In particular, one of these interactions should be an increase in albedo which in turn induces a reduction of the energy available to the soil. Global atmospheric energy balance should be influenced by changes in ground albedo due to degradation of arid land, soil humidity and water presence changes, dust emission and variations in carbon emission or absorption, which, when in the atmosphere, produce a change in radiative balance [7].

The ground albedo modification should be the dominant factor in arid zones related to the evolution of environment. Ground albedo may serve as an indicator of soil degradation which can be induced by various agents such as removal of vegetation that gives rise to a larger exposition of the higher reflective soil background.

In this study we focus our attention on the mechanisms underlying the correlation between desertification and ground albedo solar radiation and on their change in radiative balance in the atmospheric environment.

In particular, the use of the algorithm of [14] allowed us to calculate the annual global solar radiation in a given location as a function of the physical parameters provided by meteorological stations at various latitudes and to test empirical models that are related to the ground albedo coefficient.

2. The Definition of Ground Albedo Solar Radiation

Solar radiation incident on a surface consists of three components: the direct solar radiation I_b, the diffuse solar radiation I_d and the ground albedo solar radiation I_r (see Figure 1), so that daily solar radiation on a tilted surface for a given month can be estimated as follows [15]:

$$I_T = I_b + I_d + I_r \tag{1}$$

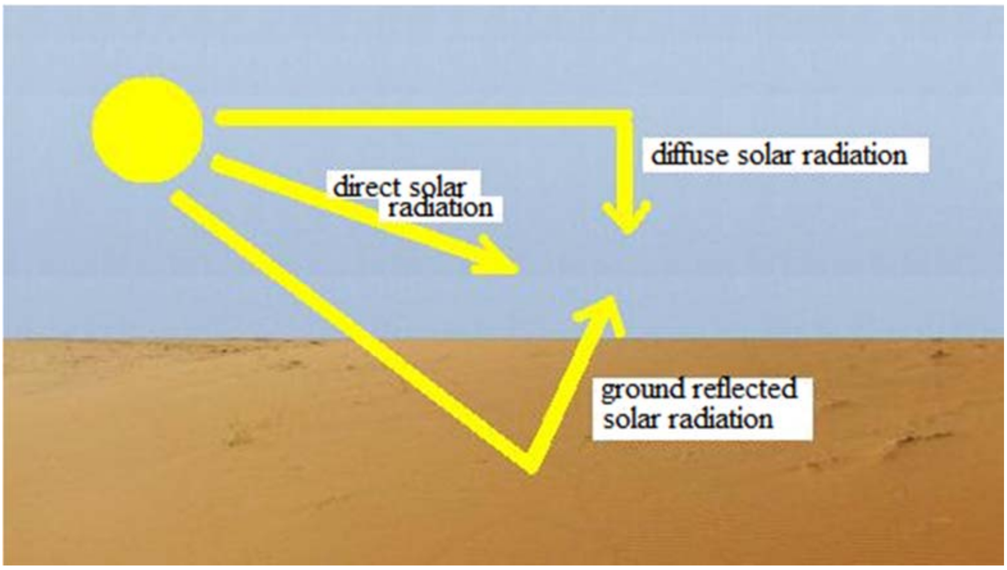

Figure 1. Scheme of direct solar, diffuse solar and ground albedo solar radiations.

Direct radiation comes from the Sun without change of direction, whereas diffuse radiation is the result of scattering of the sunbeam due to atmospheric constituents and is incident from all directions in the sky. Indeed, solar radiation is scattered by clouds, gases and particulate matter. Reflection by clouds of incident solar radiation back into space can vary with their thickness and albedo so that regions with cloudy climates can receive less solar radiation than cloud-free desert climates.

In less arid regions, where soil humidity is high, zones affected by desertification more often show an increase in temperatures linked to the reduction of evapotranspiration.

Daily extraterrestrial radiation on a horizontal surface, named H_o, can be computed for the day n from the following equation [15,16]:

$$H_o = 86400 \times G_{sc}/\pi(1 + 0.033\cos(2\pi \times n/365))\cos\varphi\cos\delta \times (\pm(1 - \tan^2\varphi\tan^2\delta)^{1/2}) + \cos^{-1}(-\tan\varphi\tan\delta) \times \sin\varphi\sin\delta \quad (2)$$

where G_{sc} is the solar constant (1367 W/m^2), n the number of the day, δ the solar declination, φ the geographical latitude. The hour angle of sunrise ω_s has been expressed as a function of φ and δ by Cooper's equation.

The ratio of solar radiation at the surface of the Earth to extraterrestrial radiation is called the clearness index, with the monthly average clearness index, K_T, defined as:

$$K_T = \underline{H}g/H_o \quad (3)$$

where $\underline{H}g$ is the monthly average of daily solar radiation on a horizontal surface.

The global horizontal solar irradiation $\underline{H}g$, provided by meteorological stations, includes the horizontal direct beam irradiation $\underline{H}b$ and the horizontal diffuse sky irradiation $\underline{H}d$.

Direct solar radiation can be measured by solar tracking systems such as planned by [17,18].

In contrast, ground albedo radiation should be measured only using empirical models. It refers to reflected light from the ground and surroundings, and corresponds to the ratio of reflected-to incident light at a surface considered.

The evaluation of the ground reflected solar radiation depends mainly on the monthly average of daily global solar radiation impinging on a horizontal surface at a location, $\underline{H}g$, and on the diffuse reflectance of the ground, ρ , called ground albedo.

Most studies showed that ground albedo may be considered isotropic. In this case, ground reflected solar radiation $\underline{I}r$ can be calculated as follows [15]:

$$\underline{I}r = \underline{H}g \times \rho \times (1 - \cos\beta)/2 \quad (4)$$

where β is the slope of the surface.

Other models for the evaluation of the ground-reflected solar can be considered depending on parameters such as latitude, height of the sun, the season, the nature of the incident radiation and other geometrical or meteorological parameters [19].

Moreover, measurements of ground albedo's coefficient ρ have been performed for different ground vegetation and other conditions [20–22].

3. Experimental Design and Results

Energy is continuously exchanged between Earth and air through solar radiation so that these fluxes influence the state of atmosphere both locally and globally. In particular, ground albedo variations can affect this energy balance. Indeed, it was shown that as ground albedo is increased, surface latent and sensible heat flux decreases at the surface because of the reduction of solar radiation energy absorbed at the surface, resulting in a reduction in convection and precipitation [23,24].

Nevertheless, another effect due to ground albedo increase has to be taken into account, that is, the increasing latent and sensible heat flux in air layers in the proximity of the ground, according to Equations (1) and (4).

In order to evaluate whether ground albedo variations can produce a significant variation of heat flux in neighboring air layers, a simulation model was applied to different ground albedo coefficients using the algorithm of [14].

The simulation study was carried out using the radiative transfer models of [25–28] in order to determine the atmospheric parameters to be used. Latitude values φ ranging from 36° to 46° were used in the simulation and the longitude was fixed at ψ = 12°. Finally, the simulation was performed with azimuth at 0°, because the preferred orientation is facing south in the northern hemisphere, and facing north in the southern hemisphere, as suggested in the previous literature [29].

The simulation model was performed calculating the global solar radiation collected in a year by a hypothetical air layer inclined by β = 35° with respect to the horizontal plane.

In order to evaluate the surface latent and sensible heat flux as a function of ground albedo coefficient, different ground albedo coefficients were taken into account in the simulation at the fixed parameters reported above, focusing our attention on the difference between ground albedo of forested ground and that of desert soil. To this aim, the amount of global solar radiation collected in a year was calculated using the values of ground albedo ρ = 0.10, ρ = 0.25 and ρ = 0.45, corresponding to the conifer forest [30], the green grass [31] and the desert sand [32], respectively. The result of the computation of the annual global solar radiation as a function of ground albedo coefficients above reported and latitudes ranging from 36° to 46° was plotted and represented in Figure 2.

As a result, the annual global solar radiation acquired by a generic air layer in the proximity of a desert soil, increased significantly ($p < 0.01$) by 210 ± 20 MJ/m^2 for latitudes ranging from 36° to 40° and by 175 ± 15 MJ/m^2 for latitudes ranging from 41° to 46° with respect to the annual global solar radiation collected by a generic air layer in the proximity of a forested ground.

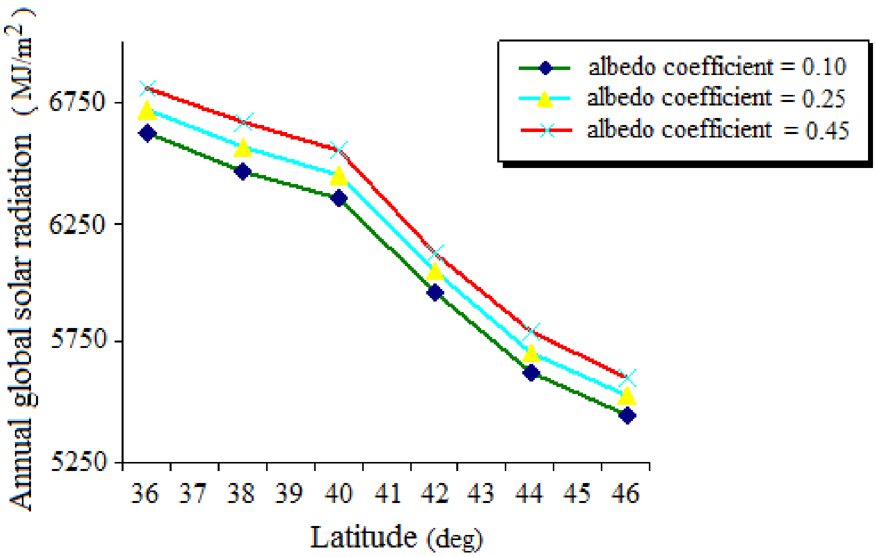

Figure 2. Annual global solar radiation as a function of latitude and three albedo values, collected by a typical surface with a tilt angle of β = 35°. The green, turquoise and red lines refer to the annual solar radiation collected on the surface as a function of the albedo values ρ = 0.10 (conifer forest), ρ = 0.25 (green grass) and ρ = 0.45 (desert sand), respectively.

4. Discussion

The results of the simulation can be explained as follows.

Energy absorbed by neighboring air layers close to the ground should depend on the ground albedo according to Equations (1) and (4) or other empirical models, so that daily solar radiation I_T (to which annual global solar radiation is related) should increase with increasing ground albedo.

Hence, an increase of the ground albedo coefficient should induce an increase of the solar radiation energy acquired by surrounding air layers due to the effect of solar radiation reflected by ground, even though the loss of solar radiation energy at the desert soil induces a local cooling.

As a result, an increase of annual global solar radiation collected by surrounding air should induce increasing latent and sensible heat fluxes in neighboring air layers.

These air layers close to the ground become less dense and begin to rise producing air motions in vertical direction following convection rules in meteorology.

This result is in agreement with [33] who demonstrated that whenever there is a process of a desertification it should be followed by a corresponding temperature rise. The air temperature increases at areas where a decline of available water occurs and latent heat of evapotranspiration shifts to sensible heat.

In previous literature some models have been developed explaining how desertification can influence global climate.

For instance, Otterman J. showed that soils denuded by overgrazing are cooler than soils covered by natural vegetation. This "thermal depression" should produce a decreased lifting of air necessary for cloud formation and precipitation, leading to regional climatic desertification [34].

Elthair E.B. developed a theory for explaining a model which showed that convective precipitation decreases with decreasing of radiation at the surface due to deforestation and increasing surface albedo [35].

Hansen J. et al. also calculated the radiative forcing for a change in a land surface albedo obtaining an expression that implicitly accounts for the fact that the land surface occupies about 30% of the total surface area of the globe [36].

Furthermore, Dirmeyer P.A. found that the prescribed albedo change may be critical in determining the response of the climate to tropical deforestation, showing that precipitation anomalies were negative when deforestation was accompanied by an increase in albedo and positive when albedo did not increase as a result of deforestation [23].

Dirmeyer P.A. et al. developed the Simple Biosphere Model in order to investigate the effects on local climate due to tropical deforestation in Amazonia. The authors showed that changes in climate should be dependent on the change in ground albedo due to deforestation [24].

Finally, a calculation of the Life Cycle for the aridity variable performed by Núñez, M. et al. [37] showed that 38% of the world area is at risk of desertification. This large percentage leads us to extrapolate the result found in this study, assuming that the increase in ground albedo due to desertification can be a co-factor that can contribute to a global climate change.

5. Conclusions

Desertification can have significant effects on local and global climate and manmade removal of vegetation is one of the causes of land desertification.

Desertification induces a significant increase in soil's ground albedo, producing an increase of reflected annual global solar radiation and a consequent loss of radiation absorbed at the surface. The algorithm used in this study has been applied to latitude values ranging from 36° to 46° using data from meteorological stations and typical ground albedo coefficients corresponding to forested ground, green grass and desert sand. The results show that changing the albedo coefficient from a value corresponding to forested ground to a value corresponding to desert sand produces a significant increase in the annual global solar radiation in neighboring air layers, so inducing increasing latent and sensible heat fluxes and temperature and a consequent decrease in density of air; as a consequence, this produces air motions in vertical direction following convection rules in meteorology and inducing local climatic change.

In view of these results, ground albedo could be used as an indicator of soil degradation and of change of climate parameters. Further research is needed to specify how the degree of change in albedo associated with desertification can affect global climate. Such information is relevant in order to plan, for example, the processes of reforestation above all in those desert areas where the effects of deforestation on global climate may be more significant.

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Conflicts of Interest: The authors declare no conflict of interest.

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