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A Previously Underappreciated Impact on Global Warming caused by the Geometrical and Physical Properties of desert sand

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Abstract**—**The previous researches focused on the influence of anthropogenic greenhouse gases exerting global warming, but not consider whether desert sand may warm the planet, this could be improved by accounting for sand's physical and geometric properties. Here we show, sand particles (because of their geometry) at the desert surface form an extended surface of up to $1 + \pi/4$ times the planar area of the desert that can contact sunlight, and at shallow depths of the desert form another extended surface of at least $1 + \pi$ times the planar area that can contact air. Based on this feature, an enhanced heat exchange system between sunlight, desert sand, and air in the spaces between sand particles could be built up automatically, which can increase capture of solar energy, leading to rapid heating of the sand particles, and then the heating of sand particles will dramatically heat the air between sand particles. The thermodynamics of deserts may thus have contributed to global warming, especially significant to future global warming if the current desertification continues to expand.

Keywords**—**global warming, desert sand, extended surface, heat exchange, thermodynamics

I. Introduction

GLOBAL warming has been receiving increasing attention from researchers. The causes of the recent warming trend are generally ascribed to human activity, which is believed to have caused most of the warming observed since the start of the industrial era [1-2]. Recently, analysis of Antarctic ice cores, deep-sea sediments, and deposits in China's Loess Plateau has revealed a series of repeated alternations of cold and warm climates during the past 800 000 years[3]. Factors such as motion of plate tectonics, variations in Earth's orbit, variations in the sun's energy output, volcanism, and so on, have been proposed to account for the observed changes, but cannot fully account for the observed trends [4]. In the field of industry, the feature of extended surface is often used to enhance heat exchange between solid and fluid [5-8], but the application of this feature in natural materials is less studied by scientific community. As desert is mainly composed of countless granular materials, and a random arrangement of these materials on desert's surface can create some kind of physical structure to efficiently contact solar radiation with air, thereby a process of heat exchange between these components may be operated. It is generally agreed that deserts in summer are clearly very hot, and there is a dramatic temperature difference between day and night, but the mechanism of this discrepancy is still unclear. In the present paper, we propose that the physical and geometric properties of desert sands, combined with changes in the area of Earth's surface covered by desert, may be partially responsible for the recent warming and past alternations of cold and warm climates.

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II. Analysis of the Physical Properties of Sand Surfaces

Sand particles in the desert are typically rounded [9] (nearly spherical) as a result of long-term abrasion by windblown. To clarify their properties, we analyzed a sample of sand particles from China's Taklamakan Desert to determine their geometrical properties. As expected, some of the particles showed clear rounding in Fig. 1. Based on particle diameter, we classified the sample into four grades: larger than 0.5 mm, 0.5 to 0.25 mm, 0.25 to 0.075 mm, and less than 0.075 mm. The proportions of the sample in each size class are shown in Figure 1. In contrast, the particles larger than 0.5 mm in diameter accounted for 57.7% of the total sand sample (by weight) and are clearly rounded, and to a first approximation, they can be modeled as spheres.

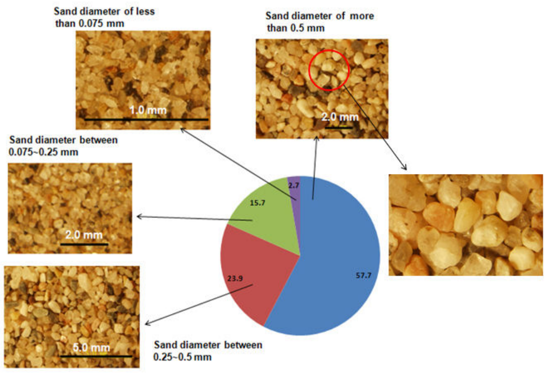

Fig.1 Shapes of sand particles from a sample obtained in China's Taklamakan desert, and the percentages of the particles (by weight) in different diameter classes

This geometry has important consequences for the properties of the sand. When sunlight irradiates a solitary sphere, the irradiated area approximately represents a hemisphere, as shown in Fig. 2, which has a considerably larger area than the sphere's circular cross-section.

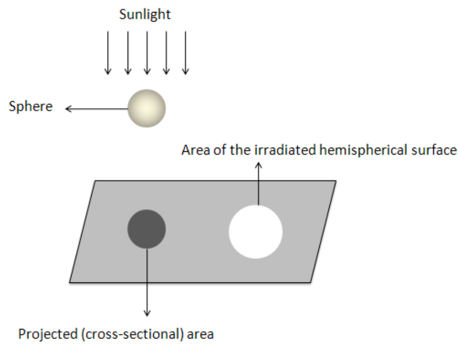

Fig.2 Illustration of the relationship between a sphere's cross-sectional area and the surface area irradiated by the sun

This means that spherical sand particles will capture more sunlight than would be predicted from their diameter (i.e., their cross-sectional area) alone.

In the desert, the loss of fine particles to wind erosion means that the surface sand is enriched in the largest sand particles, whereas smaller sand particles are concentrated in deeper layers, where they are protected from wind erosion. If we consider these rounded sand particles to be spheres, we can model their ability to capture solar radiation based on the extended surface area; here, that phrase represents the increase in total surface area compared with the cross-sectional area represented by the particle diameter. Because solar photons and air molecules are very small relative to the size of the sand particles, and have high densities per unit of area, they can be considered to be analogous to a fluid that completely covers the sand particles. In thermodynamics, the conduction of the thermal energy between solid and fluid is closely determined by their contact area. The spherical sand particles in the desert surface thus form two kinds of extended surface that can fully contact both sunlight and air. To better understand the effects of this two kinds of extended surface, we have modeled this surface for two components of the energy exchange between the sunlight, the sand and the surrounding air: the extended desert surface, which represents the total area that captures sunlight, and the surface area of the sand that is in contact with the air, which represents the even larger surface area that is available for heating of the air.

A. The extended desert surface

First, let us consider a rectangular planar area that is filled with uniformly distributed spherical sand particles of similar size. Because there are spaces between the spherical sand particles, the actual quantity of sand particles that can fill the plane is determined by equation $S/4r^2$, where S denotes the area of the rectangular plane and r denotes the mean radius of the sand particles, therefore the effect of regular laid spheres on the plane is equal to the effect of irregular laid spheres, this insures the accuracy of experimental analysis. By calculating the quantity of sand particles that fit within the plane, we can estimate the planar surface area available to capture sunlight in Fig. 3.

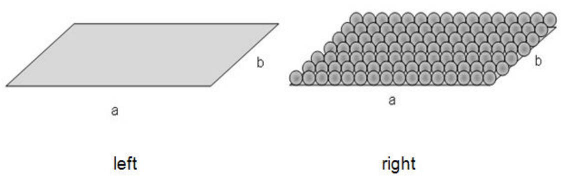

Fig. 3 A rectangular plane (left) can be covered by spherical sand particles (right) that fill the plane. Here, *a* and *b* denote the lengths of the sides of the rectangular plane

When sunlight irradiates the rectangular plane of spheres at an incidence angle α, the pattern of irradiation can be modeled as illustrated in Fig. 4. Because each angle α corresponds to a different irradiated area, because of geometrical symmetry, the magnitude of the irradiated area of 0° < α < 90° is equal to the magnitude of 90° < α < 180°, therefore we only divided the range of potential solar angles between 0° and 90° into three parts based on the different calculations required to describe the illuminated area:

(1) As α approaches 0°, the irradiated area of the sphere approaches πrb because the first row of spheres at the right shades the other spheres. Because the contact between a sphere and the underlying plane is a point, the projection of those points on the plane forms a line, and the area of the line can be ignored; as a result, the irradiated area is approximately ab, therefore the total irradiated area is $\pi rb + ab$. Because r is very small, the total irradiated area approaches ab.

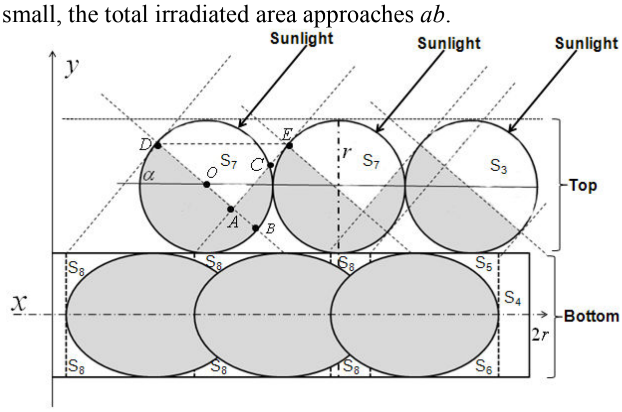

Fig. 4 Illustration of solar irradiation of spherical sand particles in a rectangular plane. The white regions represent the area irradiated by sunlight, grey regions are shaded areas that cannot receive sunlight; r denotes the radius of the spheres; Top: the surface layer of particles. Bottom: the projection of the surface layer of particles immediately on the plane. The values S_3 to S_8 represent illuminated areas (see the text for details)

(2) When 0° < α < 90°, the irradiated area of the sphere increases with increasing α, but the total irradiated surface area changes in a complicated way because of the spherical projection of the particles. To calculate this pattern of illumination, it is necessary to divide the irradiated area that includes the sphere and the underlying plane into two parts: the irradiated area (S_1) of the first row of spheres in the surface layer at the right side of Figure 3 and the plane that sunlight passes through this row to irradiate, and the irradiated area (S_2) of other adjacent spheres and the underlying plane that sunlight passes through these spheres to irradiate.

Calculation of S_1:

As shown in Fig. 4, S_1 is composed of S_3, S_4, S_5, and S_6, therefore $S_1 = (b/2r)(S_3 + S_4 + S_5 + S_6)$, where $b/2r$ denotes the number of spheres in the first row of the array at the right side of the plane. Because the illuminated portion of S_3 is a hemisphere, $S_3 = 2\pi r^2$. Calculations for S_4, S_5, and S_6 are shown in Fig. 5.

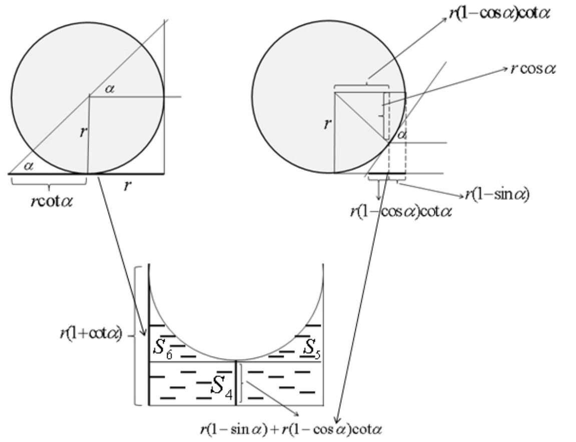

Fig. 5 Illustration of calculations of the area irradiated on the plane by sunlight that passes the first row of spheres (the spheres at the right of Figure 3, which have an illuminated area S_3 in Fig. 4). The region covered by short black lines denotes the irradiated area on the plane.

Fig. 5 provides the following equations:

$S_4 = 2r[r(1-\sin\alpha) + r(1-\cos\alpha)\cot\alpha]$

$S_5 = S_6$

$S_5 + S_6 = [2r \times (2r/\sin\alpha) - \pi r \times (r/\sin\alpha)]/2$

$= [r^2(4-\pi)]/2\sin\alpha$

Therefore:

$S_1 = (b/2r)(S_3 + S_4 + S_5 + S_6)$

$= (b/2r)\{2\pi r^2 + 2r[r(1-\sin\alpha) + r(1-\cos\alpha)\cot\alpha] + [r^2(4-\pi)]/2\sin\alpha\}$

$= \pi rb + \{rb[4(\sin\alpha + \cos\alpha) - \pi]\}/4\sin\alpha$

Because the value of a, which represents the length of the long side of the rectangular plane in Fig. 3, is fixed, calculating S_5 and S_6 requires a limiting condition. According to Figure 4, $r(1 + \cot\alpha_1)$ should less than a, so the limiting condition is satisfied while $\alpha > \alpha_1 = \tan^{-1}(a-r)/r$. While $\alpha < \alpha_1 = \tan^{-1}(a-r)/r$, the magnitude of S_1 approaches the magnitude of the rectangular plane area (ab) because r is very small.

Calculation of S_2:

As shown in Fig. 4, S_2 is composed of S_7 and S_8, where S_7 denotes the irradiated area of other spheres (except those in the first row at the right of the plane). The irradiated area of one sphere is $(2\pi rDA)/2$, thus S_8 denotes the area in which sunlight that passes through the spaces between spheres irradiates the underlying plane. Because $DA = DE \times \sin\alpha = 2r\sin\alpha$, therefore,

$(2\pi rDA)/2 = 2\pi r^2 \sin\alpha$

Therefore:

$S_7 = (b/2r) \times [(a/2r) - 1] \times 2\pi r^2 \sin\alpha$

$= [\pi b(a-2r)\sin\alpha]/2$

where $(b/2r) \times [(a/2r) - 1]$ denotes the number of other spheres, excluding spheres in the first row at the right.

Calculation of S_8:

Fig. 4 shows that the projection of a sphere forms an ellipse, thus the magnitude of S_8 is the area of the rectangular plane minus the area of the projected ellipse. To more precisely perform this calculation, we must first establish a two-dimensional coordinate system for the projected ellipse, then calculate the lengths of the semimajor and semiminor axes of the ellipse, as well as the coordinates of these axes and the points of intersection between ellipses, through an integral calculation. With increasing α, the magnitude of S_8 also increases. When α = 90°, the magnitude of S_8 reaches its maximum. Because the calculation of S_8 as a function of α is very complicated, we have therefore used the function $S_p(\alpha)$ to indicate the magnitude of S_8, therefore:

$S_2 = S_7 + S_8 = [\pi b(a-2r)\sin\alpha]/2 + S_p(\alpha)$

According to this analysis:

$$S = S_1 + S_2 = \begin{cases} ab & 0^\circ < \alpha < \tan^{-1}(a-r)/r \\ \pi rb + \dfrac{rb[2+2(\sin\alpha+\cos\alpha)-\pi]}{2\sin\alpha} + \dfrac{1}{2}\pi b(a-2r)\sin\alpha + S_p(\alpha) & \tan^{-1}(a-r)/r \le \alpha < 90^\circ \end{cases}$$

(3) When α = 90°, all spheres on the plane receive vertical irradiation, so the total irradiated area of all spheres reaches its maximum, namely $\pi ab/2$, and the irradiated area of the plane is $ab[1-(\pi/4)]$, therefore the total irradiated area is $ab[1+(\pi/4)]$, which is the maximum irradiated area.

Because there is a geometrical symmetry, the magnitude of the irradiated area of 0° < α < 90° is equal to the magnitude of 90° < α < 180°.

To summarize the results of the preceding calculations, we can present an integrated equation for the total irradiated area of the rectangular plane and all spheres as follows:

$$S = \begin{cases} ab & 0^\circ < \alpha < \tan^{-1}(a-r)/r \text{ or } 180^\circ - \tan^{-1}(a-r)/r < \alpha < 180^\circ \\ ab(1+\dfrac{\pi}{4}) & \alpha = 90^\circ \\ \pi rb + \dfrac{rb[2+2(\sin\alpha+\cos\alpha)-\pi]}{2\sin\alpha} + \dfrac{1}{2}\pi b(a-2r)\sin\alpha + S_p(\alpha) & \tan^{-1}(a-r)/r \le \alpha < 90^\circ \text{ or } 90^\circ < \alpha \le 180^\circ - \tan^{-1}(a-r)/r \end{cases}$$

Let us define k_1 as the area-amplification coefficient for the capture of solar radiation, which represents the amount by which the cross-sectional area of each particle is multiplied to account for the total area irradiated by the sun. Because the magnitude of the cross-sectional area of the plane is ab, the equation for k_1 is:

$$k_1 = \begin{cases} 1 & 0^\circ < \alpha < \tan^{-1}(a-r)/r \text{ or } 180^\circ - \tan^{-1}(a-r)/r < \alpha < 180^\circ \\ 1+\dfrac{\pi}{4} & \alpha = 90^\circ \\ \dfrac{\pi r}{a} + \dfrac{r[2+2(\sin\alpha+\cos\alpha)-\pi]}{2a\sin\alpha} + \dfrac{1}{2a}\pi(a-2r)\sin\alpha + \dfrac{S_p(\alpha)}{ab} & \tan^{-1}(a-r)/r \le \alpha < 90^\circ \text{ or } 90^\circ < \alpha \le 180^\circ - \tan^{-1}(a-r)/r \end{cases}$$

In the equation, because when α approaches 0°, the total irradiated area approaches ab, when α = 90°, the total irradiated area reaches a maximum of $ab[1+(\pi/4)]$, therefore,

$$ab < \pi rb + \frac{rb\left[2+2(\sin\alpha+\cos\alpha)-\pi\right]}{2\sin\alpha} + \frac{1}{2}\pi b(a-2r)\sin\alpha + S_p(\alpha) < ab(1+\frac{\pi}{4})$$

therefore,

$$1 < \frac{\pi r}{a} + \frac{r\left[2+2(\sin\alpha+\cos\alpha)-\pi\right]}{2a\sin\alpha} + \frac{1}{2a}\pi(a-2r)\sin\alpha + \frac{S_p(\alpha)}{ab} < 1+\frac{\pi}{4}$$

Therefore $1 \leq k_1 \leq 1 + \pi/4$, depending on α that represents the elevation of the sun.

If x, y, and k_1 define the area of a desert, the extended surface area of the sand particles at the desert surface, and the area-amplification coefficient, respectively, there will be an equation such that:

$$y = k_1 x \text{ and } 1 \leq k_1 \leq 1 + \pi/4 \quad (1)$$

Because the area of a typical desert is huge and the size of the sand particles is very small, the desert's surface can be considered to be structured as a large series of rectangular planes formed by sand particles that lie flat and touch each other within the same plane. Because the actual irradiated area is between 1 and 1 + π/4 times the area of each plane, and because this irradiation is strengthened by diffuse reflection of light rays from the sand particles, the spherical nature of the sand particles can increase their total capture of sunlight, thereby greatly increasing absorption of solar energy by the desert.

B. The extended surface area of the sand in contact with the air

We use a test tube and water to roughly measure the void space in a sample of desert sand particles. Using our sand sample from the Taklamakan Desert, 144 g of dry sand particles has a volume of 86 mL, and we add just enough water to the tube to saturate these sand particles, the total mass of the sand particles, the test tube, and the water increases by 23.9 g. This increase amounts to the volume of the spaces between the sand particles, which are filled by a 23.9 g volume of water. Because the density of water is approximately 1 g/mL, the volume of added water is therefore 23.9 mL. This suggests that an 86 mL volume of our sample of dry desert sand contains 23.9 mL of air space, and that the corresponding voidage (the percentage of the gross volume accounted for by the spaces between sand particles) of the sand equals 23.9 mL/86 mL = 27.8%.

In the desert, the larger sand particles are generally located at the desert surface while the smaller particles are located at deeper positions below the surface particles. As shown in Figure 1, the shape of these particles is more irregular, making it very difficult to calculate their surface area without making certain simplifying assumptions. Because spheres have the smallest surface area to volume ratio for a given volume, we can assume that irregular particles would have a surface area at least as large as a sphere of comparable volume. Therefore, we can simplify the calculation by assuming that the irregular small sand particles are also spherical to allow us to approximate their surface area. Because adjacent spherical sand particles contact each other at a single point, the spaces between subsurface sand particles can be assumed to be completely filled with air, and then we can assume that the extended surface of the subsurface sand particles can directly contact the surrounding air.

Several parameters should be defined before discussing the effect of these subsurface particles available to contact air:

A_1 = the area of a desert

A_2 = the area of the extended surface of sand particles that can contact air

H = the depth to which solar energy intercepted by the desert surface can be conducted deeper into the sand

V_1 = the gross volume of the sand particles that can receive thermal energy

V_2 = the net volume of sand particles, excluding spaces between particles

γ = the voidage of desert sand (the percentage of the gross volume accounted for by the spaces between sand particles)

$\bar{r}$ = the average radius of the particles of desert sand that can receive thermal energy

n = the total number of sand particles that can receive thermal energy

k_2 = the area-amplification coefficient (i.e., the amount by which the area of desert is multiplied to account for the total surface area of the sand particles that can exchange thermal energy with the surrounding air).

Based on these definitions:

$V_1 = A_1 \times H$

$V_2 = V_1 \times (1-\gamma$

$n = V_2 / [4\pi(\bar{r})^3/3]$

$A_2 = n \times 4\pi(\bar{r})^2$

$k_2 = A_2 / A_1$

Therefore: $k_2 = A_2 / A_1 = 3\,H\,(1-\gamma)/\bar{r}$

The latter equation indicates that this kind of area-amplification coefficient for the sand particles is correlated with three factors: the depth to which the solar energy received by the desert surface can be conducted deeper into the sand, the voidage of desert sand, and the average radius of the desert sand that can receive thermal energy.

If x, y, and k_2 denote the area of a desert, the area of the extended surface of sand particles that can contact the air, and the area-amplification coefficient, respectively, there will be an equation such that:

$$y = k_2 x \text{ and } k_2 = 3\,H\,(1-\gamma)/\bar{r} \quad (2)$$

In a real desert, even if the desert is filled with only a layer of spherical sand particles, the magnitude of k_2 will be 1 + π, therefore the limiting condition is $k_2 \geq 1 + \pi$. Thus, we can conclude that the surface area of a desert available to exchange solar radiation with the surrounding air equals at least 1 + π times its planar surface area.

The analysis described above shows how a desert that comprises a large quantity of approximated spherical particles can create one huge extended surface at the desert surface that is capable of absorbing sunlight and another even larger extended surface at both the desert surface and in the subsurface desert sand that is capable of transferring that absorbed energy into the surrounding air. Newton's law of cooling states that the rate of heat loss or gain by a body is proportional to the contact area between that body and its surroundings. Thus, these two kinds of extended area mean that a desert can capture an unexpectedly high proportion of the incident solar energy and can dramatically heat the surrounding air with the intercepted energy.

Let us consider an example in which the sun irradiates the world's biggest Sahara Desert with an ideal planar area of 4 300 000 km^2 (this magnitude accounts for only a half of the whole area 8 600 000 km^2), that the depth to which the received solar energy can be conducted is 0.2 m, that the average radius of the spherical sand particles is 0.1 mm, and that the voidage of sand particles is 20%. On the basis of the equation (1) and (2), the area of the extended surface that contacts sunlight is (1 to 1 + π/4) × 4 300 000 km^2 (i.e., a maximum of 7 654 000 km^2), and the area of the extended surface that contacts the surrounding air is about 20 640 000 000 km^2. It is apparent that an area of (1 to 1 + π/4) times the presumed desert's planar area can capture solar energy, and that an area equivalent to 4800 times the presumed desert's planar area can heat the air that surrounds the sand particles.

Two significant physical properties of desert sand ensure that the desert surface will reach a higher temperature than non-sandy surfaces in surrounding regions that receive comparable amounts of solar irradiation. For example, the thermal conductivity of sand is relatively low: dry sand, water, and wet soil at a temperature of 25°C have thermal conductivities of 0.35, 0.58, and 1.5 W/m-K, respectively [10], and the volumetric heat capacity of dry sand is also smaller than those of water and soil. These differences mean that desert sand will heat up faster than the surface materials of surrounding regions. Furthermore, the poor thermal conductivity means that the energy received by desert sand cannot be conducted quickly into deeper sand layers. This, combined with the sand's small volumetric heat capacity, leads to rapid increases in both the surface and the subsurface sand's temperature. On the contrary, after the sun's radiation the sand's powerful extended surface enables a heated desert to rapidly release the captured energy and become cool, which results in desert a dramatic temperature difference between day and night.

III. Conclusion

In this paper we treat countless solar photons that compose of countless sunlight rays as a fluid, according to Newton's law of cooling and our analysis of desert sand's physical properties that can create two kinds of extended surface, an enhanced heat exchange system between sunlight, desert sand, and air can be constituted. In this system, desert sand plays a role of heat engine that directly utilizes the captured solar energy to warm air within their spaces, this point may be seen in Fig. 6. As there is a large area of desert sands around our planet, under the condition that solar irradiation is powerfully effective, the effect of warming caused by this system area of the desert that are available to capture solar radiation and transfer heat should not be neglected.

It should note two constraints in this work. First, the extended surface energy to air will vary continuously through the day as the elevation of the sun changes. As a result, the total energy captured over the course of a day must be calculated by means of a complex integration of the total irradiated surface area at a given time of day multiplied by the energy capture per unit area. We hope to examine this calculation in future research. Despite these limitations, our analysis provides a good starting point for future modeling of the thermodynamics of desert sands. Currently, the effect of greenhouse gases warming the planet is well understood: these gases trap heat within the surface–troposphere system [11]. However, deserts, in virtue of their inherent physical property, also absorb and reradiate enormous quantities of solar energy, leading to heating of near-surface air. A report by the United Nations stated that the total area of all deserts around the world was approximately 33.7 million km^2 [12]. Our research suggests that such a huge area of desert would create a vastly large heat exchange system that can effectively capture enormous amount of solar energy and can dramatically release the captured energy to heat the air. The effect will greatly increase if desertification continues to devour more than 52 000 km^2 of land worldwide every year [13].

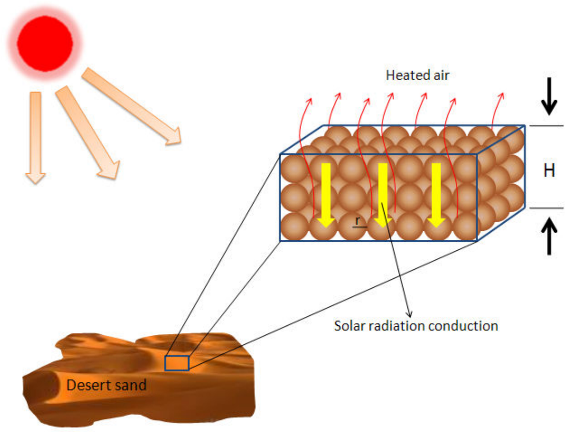

Fig. 6 A model of heat exchange system in desert sands under the sun's radiation. H represents the depth that the sun's radiation is conducted into desert sands. r represents the radius of sand particle

In general, people believe that among general materials such as desert sand, vegetation, bare soil, and so on, desert sand has a high albedo, the expansion of desertification can reflect much more incident solar energy to outer space, and then our planet can undergo a cooling rather than a warming. However, this estimation is not all-around because it does not consider the effect of desert sand heating air. Let us make an example to demonstrate. Other research shows that the albedos for vegetation (green grass), desert sand, and bare soil are 0.25, 0.4, and 0.17, respectively [14]. Now we assumed the incident solar energy is 100 J, which is equal to the same area of three samples. According to their albedos, the solar energy reflected is 25 J, 40 J, and 17 J, respectively, and then the remainder solar energy is 75 J, 60 J, and 83 J, respectively, this amount is theoretically captured by three samples. As we mentioned previously that desert sand has a low thermal capacity and a weak thermal conductivity, therefore the captured solar energy cannot be conducted into deeper sand. But because of the presence of a powerful heat exchange system between sunlight, desert sand, and air, an effect of desert sand warming air is inevitable. As for vegetation and bare soil, both of them have a large thermal capacity that can effectively preserve the captured energy, but the effect of them warming air is not evident. Now we further consider that the expansion of a desertification covers some regions of sample vegetation and bare soil. In this case, although desert sand has reflected more solar radiation from the previous regions of vegetation and bare soil out to space, a larger heat exchange system is formed, which is in favor of desert sand warming air. Moreover, so far there is no direct evidence to approve that the expansion of desertification had cooled the Earth. But on the contrary, this expansion is always accompanying with global warming. Furthermore, if we ideally divide the Earth's surface into two parts: one is covered by desert sand and another is covered by other materials like water, bare soil, vegetation, ice, and so on, and then it may be inferred that, with the spread of desertification, the heat exchange system between sunlight, desert sand, and air is ever-increasing, a forcing effect of desert sand warming atmosphere is thereby necessary.

A research revealed that during the last glacial period, the Sahara was even bigger than it is today, extending south beyond its current boundaries [15]. In 1987, the North Greenland Ice Core Project revealed a previously unrecognized warm period initiated by an abrupt climate warming approximately 115 000 years ago, before glacial conditions had fully developed [16]. It is interesting to speculate that a large-scale swing of desert area in favor of the pattern variation of absorbing and reradiating thermal energy on the Earth's surface might have contributed to the past alternations of cold and warm climate. In particular, a climate feedback effect [17] may arise, in which warming of the air in turn leads to expansion of desertification as a result of increased evaporative demand. If such a feedback effect occurred, it may explain the abrupt climate warming revealed by the ice core data. However, to support this hypothesis, it will be necessary to compare geological and other data on the timing of desert expansion with the timing of climate warming and cooling.

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