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The Model of Dependence of the Temperature of the Surface Layer of Atmosphere from the Earth's Albedo and Thermal Inertia of the Hydrosphere

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ABSTRACT

The assumption of M. Milankovich about the constancy of the Earth's albedo during the interglacial period was replaced with the alternative one. The model was developed where anomalies of the average annual temperature of the surface atmosphere were related with interannual changes in the planetary albedo and the thermal inertia of the hydrosphere. The surface temperature changes due to albedo actual and model changes were calculated. Possible external causes of albedo changes were considered.

1. Introduction

Let D denote the annual radiation imbalance of the Earth. By convention,

$$D = E - E_{sw} - E_{lw} \quad (1)$$

where E is the amount of solar radiation arriving over a year at the cross section of the Earth by a diametral plane perpendicular to the axis of solar beam; E_{sw} , E_{lw} are shortwave radiation (OSR) and longwave radiation (OLR) respectively, both outgoing from the Earth during one year.

To what extent can the imbalance (1) change? This entirely depends on the time scale. Thus, Kondratjev et al.^[1] indi-

cate that "if the unbalance value was kept $\sim 1 \text{ W/m}^2$ throughout the entire Holocene period (10 thousand years), this would be enough to melt the global ice sheet 1 km thick. Therefore, it is natural to assume that on a geological time scale the unbalance could not exceed a small proportion of 1 W/m^2 ".

The current change in the Earth's surface air temperature by $0.6\text{--}0.7 \text{ }^\circ\text{C}$ ^[17] is caused by an energy imbalance of $\sim 1 \text{ W/m}^2$, that in 2003 still remained^[2] $D_{2003} = 0.85 \text{ W/m}^2$.

How can changes in the planetary albedo create an imbalance and, as a result, the changes in the temperature of the surface atmosphere? Let's build a model of this process.

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2. Model Background

The incoming solar radiation changes in 11-year cycles of solar activity by an order 0.1% [18], and these fluctuations undoubtedly affect the geophysical processes. But for the time being, we will not take them into account, assuming that the integral solar radiation flux $I(R, t)$ at a distance $R_0 = 1 AU$ from the Sun, incoming per unit time per unit area perpendicular to the flux, is unchanged in any year

$$I_0 = I(R_0, t) = const. \tag{2}$$

Consider the following model. Let each hemisphere of the Earth reflect its constant proportion of solar radiation during an year: α is Northern hemisphere albedo, β is Southern hemisphere albedo, and r is the Earth's radius. Then the total albedo of the Earth at time t (time in fractions of an year) is

$$A(t) = \frac{\alpha(2\pi r^2 + 2\delta(t)r^2) + \beta(2\pi r^2 - 2\delta(t)r^2)}{4\pi r^2} = \frac{\alpha + \beta}{2} + \frac{\alpha - \beta}{2} \frac{\delta(t)}{\pi}$$

There, the angle $\delta + \pi / 2$ is the angle between the axis of the Earth rotation and the Sun-Earth the true anomaly of the Earthvector $R_{(t)}$. The angle δ is determined by equation [19]

$$\text{Sin}(\delta) = -\text{Sin}(\varepsilon) \text{Cos}(v-v_p);$$

where ε is the inclination of the Earth rotation axis; v is the true anomaly of the Earth; v_p is the angle from the Earth's perihelion to the point of the winter (in the Northern Hemisphere) solstice.

We will assume that on the Earth's orbit

$$4\pi R^2 I(R, t) = 4\pi R_0^2 I_0,$$

where $R = |R(t)|$. Therefore, the difference between incoming and reflected shortwave solar radiation over the time interval $T = 1$ year is

$$E - E_s = \int_0^T I(R, t) \pi r^2 (1 - A(t)) dt = I_0 R_0^2 \pi r^2 \int_0^T \frac{(1 - A(t)) d}{R^2(t)} \tag{3}$$

Let us denote the eccentric and true anomalies of the Earth at the moment of time t as $\mu = \mu(t)$ and $v = v(t)$, respectively, and write out the necessary relations [19]:

$$R(v) = \frac{1 - e^2}{1 + e \text{Cos}(v)} a \quad R(\mu) = (1 - e \text{Cos}(\mu)) a,$$

where a is the semi-major axis of the Earth's orbit; and e is eccentricity.

To take the integral (3), we first proceed from time t to $\mu = \mu(t)$, differentiating the Kepler equation, and then to the true anomaly v . Now we have [19]:

$$dt = \frac{T}{2\pi a} R(\mu) d\mu \quad d\mu = \frac{R(v)}{a\sqrt{1-e^2}} dv \quad R(t) = R(v(t)) = R(\mu(t))$$

Substituting the last-mentioned relations in (3), we get

$$E - E_s = \frac{I_0 R_0^2 r^2 T}{2a^2 \sqrt{1-e^2}} \int_0^{2\pi} (1 - A(v)) dv = \frac{I_0 \pi r^2 T}{\sqrt{1-e^2}} \left[1 - \frac{\alpha + \beta}{2} - \frac{\alpha - \beta}{(2\pi)^2} \int_0^{2\pi} \delta(v) dv \right].$$

The integral of $\delta(v)$ will be equal to zero if we set $\text{Sin}(\delta) = \delta$ based on the smallness of $\text{Sin}(\varepsilon)$. So,

$$E - E_s \approx E_0 (1 - A_0), \tag{4}$$

$$\text{where } E_0 = \frac{I_0 \pi r^2 T}{\sqrt{1-e^2}} \quad A_0 = \frac{\alpha + \beta}{2}$$

Within a framework of this model, we obtain the following conclusions from equation (4):

a. The amount of annual solar radiation arriving at to the Earth's surface does not depend on the longitude of the point of the winter solstice in the orbital coordinates of the Earth. This fact corresponds to the independence of the total heat of the caloric half-year according to the model of M. Milankovich [3] from the longitude of the perihelion of the Earth's orbit.

b. In annual resolution, the amount of solar radiation reaching the Earth's surface does not depend on the difference between hemispheric mean annual values of albedo.

c. At time intervals when the solar constant of the Earth and the eccentricity of its orbit can be considered constant, it is only the Earth's planetary albedo that determines the variability of the annual influx of solar radiation on the Earth's surface.

3. Albedo-temperature Model

Further, following M. Milankovich [3], let us suppose:

M1. The surface of the Earth is uniform and horizontal at all latitudes;

M2. The atmosphere and hydrosphere of the Earth are motionless;

M3. The atmosphere is transparent to direct and diffuse solar radiation;

M4. Heat is exchanged between the Earth's surface and air only through radiation.

M5. Heat flow from the depths of the Earth is zero;

M6. Humidity and cloudiness have the same meaning everywhere;

M7. In the interglacial period, the Earth's albedo is constant.

Under these conditions, the temperature of the Earth's surface radiation, on the basis of the laws of Stefan-Boltzmann and Kirchhoff, is proportional to

$$\Theta^4 \sim (1 - A_0) A_0 (1 + p) \tag{5}$$

where A_0 is the fraction of solar radiation reflected by the geospheres during one year; p is the part of long-wave radiation returned by the atmosphere to the surface of the Earth during one year (counter-radiation of the atmosphere); E_0 is defined by the formula (4).

Expand the model (5). Suppose that:

Z7. The annual albedo of the Earth can vary from year to year.

Z8. The annual counter-radiation of the atmosphere is

constant and equal to $p = p_0 = \text{const}$.

Z9. The annual heat balance between the lithosphere and the other geospheres is zero.

Z10. The atmosphere annually transfers a fraction of the heat obtained during the year to the cryosphere, A_c .

Z11. The hydrosphere annually receives the fraction of energy H , from which it annually transfers the fraction of heat H_c to the cryosphere, and brings the rest of heat from the deeper layers back to the surface layer during the next L years in fractions h_1, h_2, \dots, h_L :

$$H = H_c + h_1 + h_2 + \dots + h_L.$$

The formula (5) and assumptions M1-M6 and Z7-Z11 imply that

$$\Theta_k^4 \sim E_0(1 - A_k)(1 + p_0 - A_c - H) + E_0 \sum_{j=1}^L h_j(1 - A_{k-j}) \quad (6)$$

Designating

$$d_0 = (1 + p_0 - A_c - H_c) \quad d_k = \sum_{j=1}^L h_j(A_k - A_{k-j}), \quad (7)$$

we get

$$\Theta_k^4 \sim E_0(1 - A_k)d_0 + E_0 d_k = E_0 d_0(1 - A_k) \left(1 + \frac{d_k}{d_0(1 - A_k)} \right) \quad (8)$$

We will consider the year N as normal, if $d_N = 0$. This means that the amount of heat transferred by solar radiation to the deep layers of the hydrosphere in the N -th year is equal to the amount of heat received by the upper layer from the deep layers in the same year:

$$A_N \sum_{j=1}^L h_j = \sum_{j=1}^L h_j A_{N-j} \quad (9)$$

Then the formula (8) implies:

$$\left(\frac{\Theta_k}{\Theta_N} \right)^4 = \frac{(1 - A_k)}{(1 - A_N)} \left(1 + \frac{d_k}{d_0(1 - A_k)} \right) = \left(1 + \frac{A_N - A_k}{1 - A_N} \right) \left(1 + \frac{d_k}{d_0(1 - A_k)} \right)$$

The summands in brackets are small in comparison to 1. Therefore, leaving the first two terms in the corresponding Taylor series, we get

$$\frac{\Theta_k}{\Theta_N} = \left(1 + \frac{A_N - A_k}{4(1 - A_N)} \right) \left(1 + \frac{d_k}{4d_0(1 - A_k)} \right) \quad (10)$$

Let us designate $\lambda_k = \frac{A_N - A_k}{4(1 - A_N)}$ and neglecting the small terms, rewrite the formula (10) in the form

$$\Theta_k = \Theta_N + \Theta_N \lambda_k + \frac{\Theta_N}{4} (1 + \lambda_k) \frac{d_k}{d_0(1 - A_k)}$$

$$\frac{\Theta_k - \Theta_N}{\Theta_N} = \frac{T_k - T_N}{\Theta_N} = \lambda_k + \frac{(1 + \lambda_k)d_k}{4d_0(1 - A_k)} \approx \lambda_k + \frac{d_k}{4d_0(1 - A_k)}.$$

In the last transition, we exploited the smallness of λk when compared to 1.

Finally, if year N satisfies the condition (9), then

$$\frac{T_k - T_N}{T_N + 273} = \frac{(A_N - A_k)}{4(1 - A_N)} + \frac{1}{4d_0(1 - A_k)} \sum_{j=1}^L h_j(A_k - A_{k-j}) \quad (11)$$

Consequently, the anomaly of the average annual temperature of the surface layer of the atmosphere, as a function of the average annual values of the Earth's albedo, has the following general form:

$$T_k - T_N = Q_0 + Q_1 A_k + \sum_{j=1}^L q_j \frac{A_k - A_{k-j}}{1 - A_k} \quad (12)$$

where $Q_0, Q_1, q_1, \dots, q_L$ are some constants independent of A_k .

Model (11) has too many degrees of freedom, given the paucity of experimental data set on the Earth albedo dynamics. We can somewhat improve the situation if we assume that the sequence $\{h_k\}$ which determines the thermal inertia of the hydrosphere, has some definite form, for example, for some constants of h_0 :

- H1: $h_k = h_0$,
- H2: $h_k = h_0(1 - k/L)$,
- H3: $h_k = h_0 \exp\{-c_k\}$,

and other options used in hydrodynamic models, but with the indispensable condition that

$$h_1 + h_2 + \dots + h_L = H - H_c. \quad (13)$$

Whatever is the dependence of the thermal inertia of the hydrosphere, the theoretical result (11) allows for affirmative answer to the question posed in [4]. We are talking about the relationship between the temperature of the surface of the atmosphere and changes in the planetary albedo.

4. Calculation of Air Temperature Anomalies: Actual and Model Variants

The application of the general formula (12) to the assessment of surface air temperature anomalies requires knowledge of the average annual values of the Earth's albedo over several decades (taking into account the thermal inertia of the hydrosphere) with high accuracy. Indeed, assuming that $E = 342 \text{ W/m}^2$, $A = 0.3$, and the error in estimating the albedo is 1%, that is, $\Delta A = 0.003$, we obtain the estimate of the accuracy of the OSR: $E_{sw} = 342 \times 0.3 \times (1 \pm 0.01) = 102.6 \pm 1.0 \text{ W/m}^2$.

What is the accuracy with which the modern albedo measurements are made? The study [5] reported that measurements of outgoing radiation carried out on two different types of equipment, are in good agreement with each other. Deviations in the OSR measurement are $1.5 \pm 0.1 \text{ W/m}^2$, and in the OLR measurement are $0.7 \pm 0.1 \text{ W/m}^2$ during daytime and $0.4 \pm 0.1 \text{ W/m}^2$ at night. With annual averaging, these deviations are reduced by almost 20 times, that is, to hundredths of 1 W/m^2 , which is quite

acceptable for the purposes of our study. But here it is necessary to distinguish the origin of the error: with or without bias. If the error is of a systematic nature (lowering of the satellite orbit, loss of instrument accuracy, calibration, etc.), then averaging the daily data, of course, does not eliminate this error in the annual resolution.

It follows from (12) that the anomaly of the average annual temperature of the Earth, on a first approximation, is a linear function of the average annual value of the Earth's albedo in the same year. The albedo values for the period 1984–2003 are taken from^[6], and the mean annual air temperature anomalies for the same period are taken from^[7] Fig. RP-1. Using the method of minimal squares, we find $Q_0 = 4.2 \text{ } (^{\circ}\text{C})$ $Q_1 = -12.7 \text{ } (^{\circ}\text{C})$

Figure 1 shows the graphs of the anomalies of average annual temperatures of the surface air and their assessment by the model (12) at $L = 0$. The correlation coefficient between these series is 0.8, and it is statistically significant at the 5% significance level.

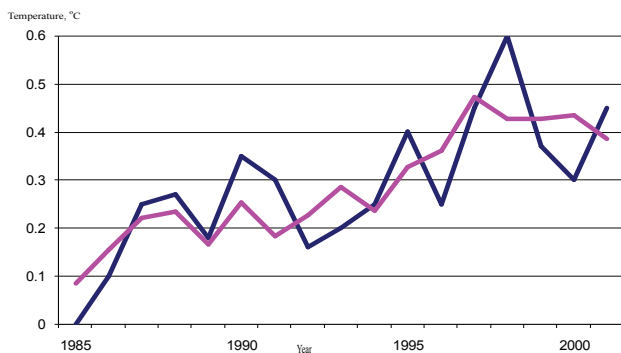


Figure 1. Influence of linear regression of the annual planetary albedo of the Earth (red) on the average annual temperature of the surface atmosphere (blue)

A year later, the authors of^[6] corrected their results by four-time reducing the range of albedo oscillations: from 8% to 2%^[8]. However, the range does not matter for the analyzed model in the linear approximation: here the relative changes in the albedo are important, the discussion of which continues to the present time.

Now let us suppose that planetary albedo has been constant and equal to A_N during at least L years. After that, in the year we took as datum, it changed abruptly to the value $(1-\Delta)A_N$, and then this value did not change $\Delta = -0.01$, $T_N = 18^{\circ}\text{C}$,

The question is how will the surface temperature change? From (11), we obtain

$$4 \frac{T_k - T_N}{273 + T_N} (1 - A_N) = A_N - (1 - \Delta)A_N + \frac{1 - A_N}{d_0(1 - (1 - \Delta)A_N)} \sum_{j=k}^L h_j (1 - \Delta)A_N - A_N = A_N \Delta - \frac{(1 - A_N)\Delta A_N}{d_0(1 - A_N + \Delta A_N)} \sum_{j=k}^L h_j = \Delta A_N (1 - \frac{1}{d_0} \sum_{j=k}^L h_j) + o(1) .$$

Let us designate $\rho_0 = \frac{\sum_{j=1}^L h_j}{d_0}$ and $g_k = \frac{\sum_{j=k}^L h_j}{\sum_{j=1}^L h_j}$, and, neglecting $o(1)$, we obtain

$$T_k - T_N = \Delta A_N (1 - \rho_0 g_k) \frac{273 + T_N}{4(1 - A_N)} . \tag{14}$$

The parameter ρ_0 shows the fraction of energy that is transferred to the deep layers of the hydrosphere during one year, and the parameter g_k , the fraction of heat that remains in the hydrosphere after k years.

Suppose that $A_N = 0.3$, $\Delta = -0.01$, $T_N = 18^{\circ}\text{C}$, $h_k = h_0(1 - k/L)$. Then the temperature anomaly in the surface layer of the atmosphere for different variants of ρ_0 will, in accordance with (14), have the form shown in Fig. 2.

If we neglect the atmospheric heat content, then ρ_0 will reflect redistribution of solar radiation between the hydrosphere and the cryosphere: at $\rho_0 = 1$, all energy goes into the hydrosphere, and at $\rho_0 = 0$, into the cryosphere.

The model shows quite realistic results: as the albedo decreases by 0.01, the temperature of the lower atmosphere asymptotically increases to 1.1°C . At that, 20 years after the jump in albedo, the atmosphere temperature anomaly is 0.75°C at $\rho_0 = 0.75$ and $L = 50$, which is very close to the current changes of the lower troposphere temperature.

5. External causes of changes in planetary albedo

There are Earthly causes for changes in albedo (volcanic emissions, deforestation, etc.) and there are external causes. Let us specify some of them.

In 1985, at the All-Union Seminar on Solar-Terrestrial Physics held in Novosibirsk^[9], A.Dmitriev reported on the mechanisms of the influence of heliogeophysical factors on weather and climate.

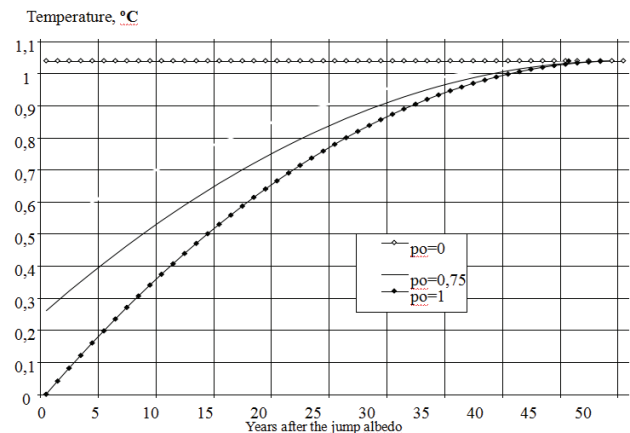


Figure 2. Dynamics of the anomalies of the average annual surface air temperature during an abrupt change in the planetary albedo. $A_N = 0.3$; $\Delta = -0.01$; $T_N = 18^{\circ}\text{C}$, $L = 50$; $g(k)$ is linear decrease

In particular, he said that the global cloud cover increases by 0.5 on average the next day after the X-ray burst, and locally by 2-3^[10]. Later, after the publication of the study of Svensmark et al^[11], this research direction began to develop intensively.

The second mechanism is a change in the chemical composition of the upper layers of the atmosphere caused by high-energy proton fluxes. For the first time, this mechanism of albedo change was highlighted by Pudovkin et al.^[12], who estimated its effect as reaching 2%, which turned out to be close to the current changes in the planetary albedo.

At large, the climate change, as was shown in^[13], is largely initiated by the displacement of the Sun from the center of mass of the Solar System. This parameter in most cases determines the maxima of solar activity^[14] and, as a result, the Forbush effect which changes the concentration of galactic protons.

The sum of the ordinates of the Sun's displacement wholly satisfactorily correlates with the sum of the winter temperature anomalies of the atmosphere surface layer in the center of Eurasia^[15]. Consequently, the displacement of the Sun from the center of mass of the Solar System determines a part of changes in the Earth's planetary albedo. Perhaps, the main one.

6. Conclusion

The main conclusion of the Fourth Assessment Report of the IPCC on inability to explain the current warming only by natural factors^[16] is, of course, correct, when the fluctuations of only incoming integral flux of solar radiation. But there is an outgoing flux also.

We expanded the Milankovitch model, replacing the condition of the constancy of the Earth's albedo with the alternative one. The developed model taking into account the variability of the planetary albedo quite satisfactory estimates both the magnitude and the rate of modern warming (Fig. 2). Notice, that the result was obtained with a fixed annual counter-radiation of the atmosphere.

References

- [1] Kondratyev K.Ya., Krapivin V.F. The "nature – society" system and climate. On the thermal balance of the Earth // *Energy*. 2006, 3, 2–6. In Russian.
- [2] Golovko V.A. Modern energy imbalance of the Earth. Proof of coexistence and possible consequences. Electronic resource. URL: <http://www.iki.rssi.ru/earty/hres2006/golovko.pdf>. In Russian.
- [3] Milankovich M. *Mathematical Climatology and Astronomical Theory of Climate Change*. Moscow-Leningrad: GONTI, 1939. p19. In Russian.
- [4] Palle E., Goode P.R., Montanes-Rodriguez P., Koonin S.E. Can Earth's Albedo and Surface Temperatures Increase Together? *Eos. Trans.* 2006,87(4),37–43.
- [5] Golovko V.A., Pakhomov L.A., Uspensky A.B. Study of the field of outgoing radiation of the Earth using a scanning radiometer for radiation balance installed in the Russian satellites «Meteor» and «Resource» // Investigated in Russia. Electronic resource. URL: <http://zhurnal.ape.relarn.ru/articles/2003/106.pdf>. In Russian.
- [6] Goode P.R., Palle E.R. Shortwave forcing of the Earth's climate: Modern and historical variations in the Sun's irradiance and the Earth' reflectance. *J Atmos Solar Terrest Phys.* 2007, 69, 1556-1568.
- [7] The Third Assessment Report of the IPCC. *Climate Change, 2001: Scientific Aspects. Technical Summary of the Working Group I Report*. 2001. p101.
- [8] Palle E., Goode H.R., Montanes-Rodriguez P. Inter-annual variations in Earth's reflectance 1999-2007. *J Geophys Res.* 2009, 114, D00D03. DOI:10.1029/2008JD010734.
- [9] Zavalishin N.N., Pon'ko V.A. On the 20th anniversary of the Fifth All-Union Seminar on the cycling of heliogeophysical processes. *Sun, Earth, Water and Energy: Materials of Scientific Readings dedicated to the 75th anniversary of the birth of Academician I.P. Druzhinin. Proceedings of the East-Siberian Branch of the Academy of Water Sciences. Issue 2.* Novosibirsk: Science, 2005,10-20. In Russian.
- [10] Dmitryev A.A. From heliogeophysical hypotheses to forecasts. Long-term Forecasting of hydrometeorological Conditions: Proceedings of the Academy of Agricultural Sciences. Novosibirsk, 1985, 3-14. In Russian.
- [11] Svensmark H., Friis-Christensen E. Variation of cosmic ray flux and coverage. *J Atmos Terr Phys.* 1997, 58, 1225-1232.
- [12] Pudovkin M.I., Raspopov O.M. The mechanism of solar activity influence on the state of the lower atmosphere and meteorological parameters: review. *Geomagnetism and Aeronomy.* 1992, 32(5), 1-22. In Russian.
- [13] Landshaitd T. Solar rotation, motion speed and climatic variation. *Climate Change.* 1987, 12, 265-295.
- [14] Zavalishin N.N. Assessment of the impact of the Sun shift from the inertia center on troposphere temperature. *Optika Atmosfery i Okeana.* 2009, 22(01), 31-33. In Russian.
- [15] Zavalishin N.N. On the geophysical effects of solar system dissymmetry. *Solar-terrestrial physics.* 2005, 8, 185-186. In Russian.
- [16] The Fourth Assessment Report of the IPCC. *Climate Change 2007: Synthesis Report*. IPCC, Geneva, 2008. p104.
- [17] Hansen, J., Mki. Sato, R. Ruedy, K. Lo, D.W. Lea, and M. Medina-Elizade, 2006: Global temperature change. *Proc. Natl. Acad. Sci.*, 103, 14288-14293, doi:10.1073/pnas.0606291103.
- [18] <https://www.pmodwrc.ch/en/research-development/solar-physics/tsi-composite/>
- [19] *Astronomical calendar. Permanent part.* / Publishing "Science". Moscow, 1973. p728. In Russian.