PHYSICAL SCIENCES

INCREASE IN SURFACE AIR TEMPERATURE AS A RESULT OF CONVECTIVE AEROSOL REMOVEMENT TO DESERT TERRITORIES

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Abstract

We modified the mathematical model of the influence of convective aerosol removal (CR) from desert surfaces on near-surface air temperature, which we previously developed for "ideal" conditions (the absence of vegetation cover and the presence of wind loads - calm weather conditions) [1, 30].

During field experiments to validate the model, a significant influence of wind and vegetation cover on the thermal effect of convective aerosol removal (CR) was revealed, causing significant discrepancies between model and experimental data. Based on the obtained empirical dependences of the thermal impact of CR F on wind speed and the general projective cover of vegetation, as well as changes in some parameters of the model of convective aerosol removal (MCR), the MCR-2 version was developed taking into account real operating conditions.

According to the results of the implementation of MCR -2 for the territory of the Southern Aral Sea region in the warm period of the year (May-October) in desert zones, an increase in temperature in the near-surface layer is noted, on average, by 3.5 ° C, as a result of convective removal of aerosol. This value is very significant, which indicates the need to take into account the convective removal of aerosol in prognostic and climate models of surface air temperature in desert areas.

Keywords: convective removal, aerosol, near-surface air temperature, Southern Aral Sea region.

Introduction. The most important process characterizing the state of the atmosphere is heat and mass transfer in the soil-atmosphere system. This process is of a special nature in desert areas, where due to the convective removal of aerosol from the heated soil during the warm period of the year, additional heating of the air in the near-surface layer of the atmosphere occurs. In turn, one of the main factors of global environmental change are processes that stimulate desertification. In these processes in the arid regions of the planet, in particular, the Southern Aral Sea region, an important component is the removal of aerosol particles from the underlying surface and its subsequent atmospheric transport. The removal of aerosol with heated short-wave radiation from the underlying desert surface, along with dust storms, is a natural component of the climate system. It is necessary to note here that the far from simple mechanism of this phenomenon has not been sufficiently studied to date.

Convective removal of aerosol from desert surfaces as a forcing of an increase in surface air temperature in the Southern Aral Sea region was considered by us for the first time in [30] for «ideal» conditions (lack of vegetation cover, calm conditions) . Subsequently, during field experiments carried out to validate the model, significant discrepancies were revealed for individual implementations associated with the real conditions of the atmosphere and underlying surface, namely wind loads and, as expected, the presence of vegetation cover. However, it was revealed from measurements of near-surface air temperature in the summer that the presence of desert vegetation practically does not correlate with air temperature. This can be seen in Fig. 1, where the surface air temperature (Tv) is presented as a function of soil temperature (Tp) and percentage vegetation cover (PV) at the points of the Ustyurt, Muynak and Karauzyak plateaus, where an obvious linear relationship between air temperature and soil temperature and the absence of such for the vegetation cover of desert areas (Table 1). At the same time, it is necessary to keep in mind that the indirect influence of vegetation cover on near-surface air temperature is manifested in a decrease in aerosol concentration during its convective removal from the soil of desert areas relative to areas devoid of vegetation, and the dependence itself is different from linear. This nonlinearity is determined by the mutual influence of wind speed and the vegetation cover of desert areas on the convective removal of aerosol, which can be seen in fig. 2, which shows the air temperature surface as a function of wind speed and vegetation cover.

The drying up of the Aral Sea caused significant regional climate changes [2, 11, 12, 16], leading to increased aerosol pollution of the atmosphere, affecting the radiation regime [8, 20, 26].

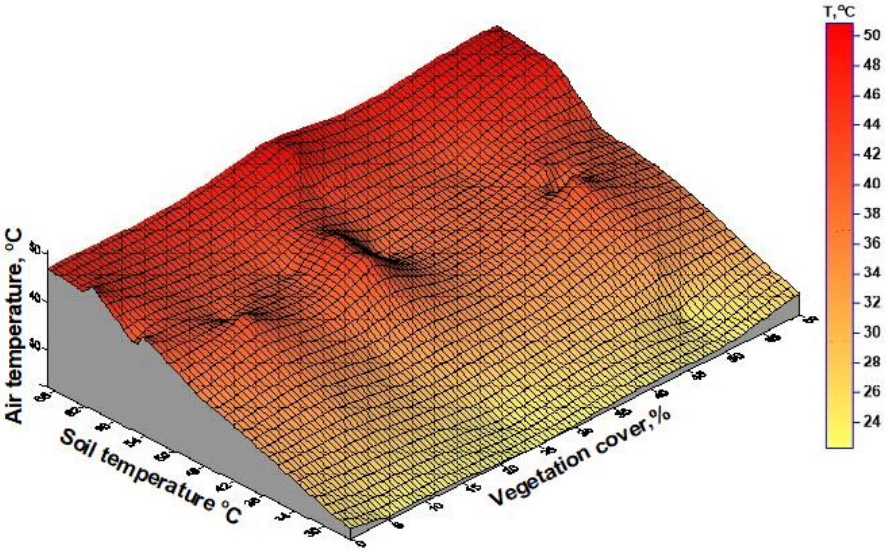

Fig 1. Surface air temperature as a function of soil temperature and amount (%) of vegetation cover.

Table 1

Correlation matrix of surface air temperature (Ta), soil (Ts) and vegetation temperatures (VC)

Quantities	Ta	Ts	VC
Ta	1,00	0,93	0,11
Ts		1,00	0,04
VC			1,00

Many works on aerosol pollution of the atmosphere consider dust storms as the main source [19, 21, 22, 29]. However, a significant factor in increasing the concentration of atmospheric aerosol in a desert area, such as, for example, the Southern Aral Sea region, is the convective removal of aerosol from the resulting desert surface (Aralkum desert) [6, 10]. The mechanism of the influence of aerosol on climate changes in the boundary layer of the atmosphere has been studied quite well by various methods [8, 12]. In this work, based on an analysis of modeling conditions and conducting field experiments, the need to introduce some amendments to the previously developed model (MCM) is shown, taking into account the influence of wind speed and vegetation cover, as well as a revision of some model parameters.

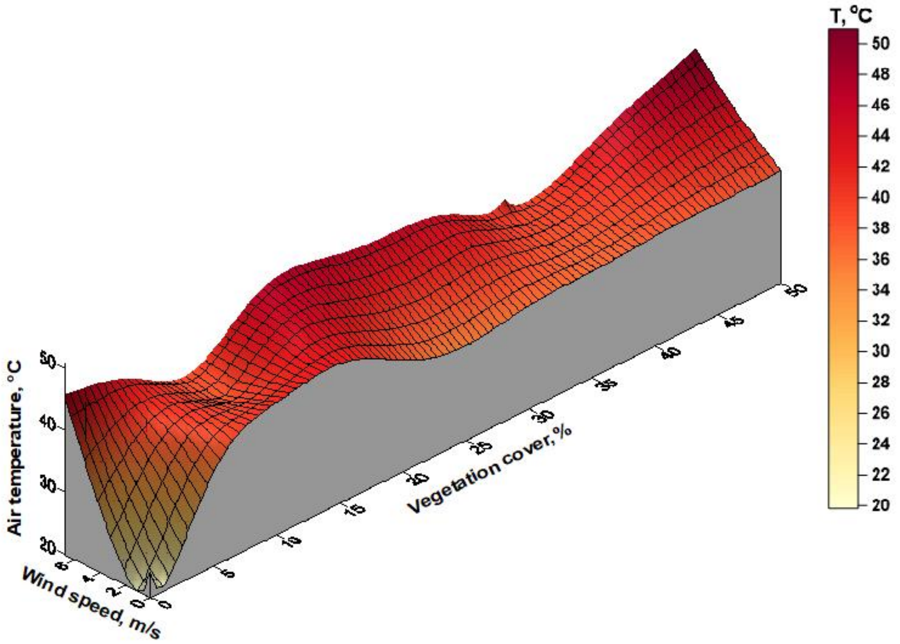

Fig. 2. Surface air temperature as a function wind speed and amount (%) of vegetation cover.

Thus, field measurements of near-surface temperature taking into account wind loads and vegetation cover showed the need to modify the MCI of the influence of convective removal (CR) of aerosol from desert surfaces on surface air temperature.

Research methods. A mathematical model for assessing the contribution of convective aerosol emission to the increase in surface temperature (SST) is described in detail in [30]. Here is a brief summary of the model indicating and justifying the corrections made.

The MKV consists of two blocks. In the first block, the aerosol mass concentration generated by convective currents is calculated. For this purpose, an empirical relationship was used, the theoretical justification of which is given in [4].

$$\Delta\rho = 0,12\ \delta T^{0,58} \qquad (1)$$

where Δρ is the deviation of the mass concentration of aerosol particles from the background concentration (mg/m^3), δT is the jump (drop) in temperature in the thermal boundary layer, the thickness of which varies from 10 to 30 cm.

A comparison of experimental measurements and model calculations showed that formula (1), obtained for the conditions of the Kalmyk deserts (southern Russia), must necessarily be adapted to the territory of the Southern Aral Sea region, which was obtained in the form:

$$\Delta\rho = 0,1866 \cdot \delta T^{0,535} \qquad (1a)$$

In the second block, the “Particle-In-Cell” particle method [15] calculates the increase in ambient air temperature (in the 0-3 m layer) by heated suspended soil particles [30]. Based on the deviation of the aerosol mass concentration calculated in the first block of the model, the counting concentration N and the volume of air dV occupied by one particle are determined. In the ICM it is assumed that the volume dV is invariant with respect to the particle size. However, provided that the polidispers aerosol is uniformly distributed over space, it can be assumed that the volume dV occupied by a particle is proportional to the cube of its radius.

Field experiments. To validate the modeling results in the warm season of 2021-2023. A series of field experiments were conducted in the desert regions of the Southern Aral Sea region (Ustyurt, Muynak, Karauzyak, Nukus region).

The experiments were carried out in the afternoon (14-15 hours). The following were measured: air temperature at levels of 0.2, 0.5, 1.5 and 2 m, soil surface temperature, countable concentration and dispersion of aerosol (SorhisSX-L301T device), wind speed with fixation of geographic coordinates using GPS points where measurements were taken.

Background air temperature and aerosol concentration for the same dates were measured in takyr-like, slightly wetted, nearby areas. To identify and evaluate the influence of vegetation cover on the forcing under study, experiments were carried out for surfaces with different projective vegetation cover.

Discussion of residuals from modeling results and field experiments. Numerical experiments with the MCF model with various variants of the distribution functions of particle and substance sizes, as well as the thickness of the thermal boundary layer, revealed that the desired temperature change ΔT is most sensitive to variations in dispersion. In fig. 3, displaying the results of calculations for a monodisperse aerosol, it can be seen that the maximum values of ΔT correspond to submicron particle sizes.

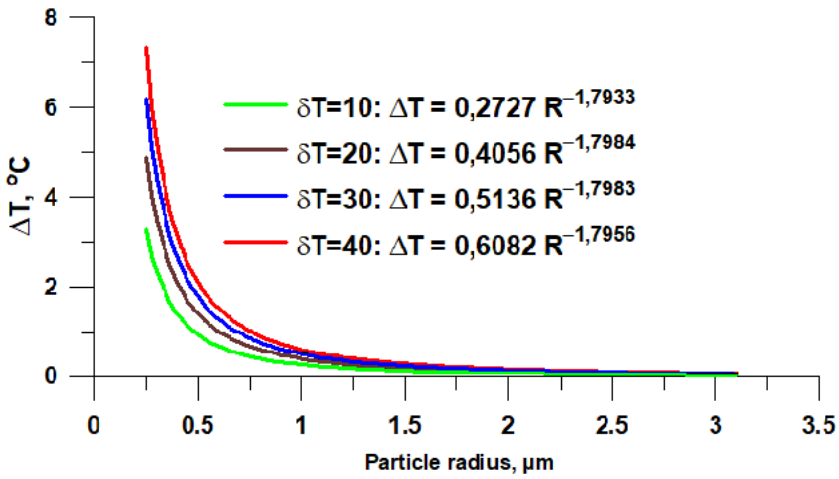

Fig. 3. Dependence of ΔT on the radius R of monodisperse aerosol particles and the thickness of the thermal boundary layer δT (June).

It should be noted that this dependence is significantly nonlinear: ΔT increases sharply for particles whose radius is less than 0.5 μm. In the same range, the significance of the thickness of the thermal boundary layer δT is manifested: the values of ΔT drop from 10°C to 0.8°C. The differences due to δT and size are leveled out for particles whose radius is greater than 1 μm.

It is obvious that changes in the temperature ΔT of the air layer adjacent to the underlying surface should significantly depend on the particle size distribution function. Calculations based on the MAC, presented in [30], were carried out using the distribution function determined for the desert conditions of Tajikistan [5]. Using an aerosol counter (resolution 0.3 μm), instrument readings and extrapolated values for the range 0.1-0.3 μm are taken as input.

Note that measurements of the countable concentration and dispersion of the aerosol showed the predominance of particles with sizes of 0.3-0.5 microns, which give the maximum thermal effect. The predominance of the range of 0.3-0.5 μm (78%) is typical for all observation points. The variation in the distribution function depending on the coordinates and time of year turned out to be insignificant within the Southern Aral Sea region.

The introduction of amendments 1-3 reduced the average discrepancy between the experimental and model data from 1.8K to 1.1°C, but the differences remained significant for individual implementations (Table 2). They are partly explained by measurement errors associated with the pulsating nature of the wind (gustiness) and convection (separation of individual thermals).

As can be seen from the table reflecting part of the full-scale experiments, at different wind speeds and RP, the smallest discrepancy corresponds to the absence of wind and RP. Negative ΔTd (increased thermal effect) was observed only for cases of weak wind (1-3 m/s), which additionally supplies a portion of heated fine aerosol (wind aerosol removal). Increased wind (with speeds greater than 3 m/s), when the fraction of coarse aerosol increases sharply, leads to the opposite effect.

To quantify the influence of wind on the thermal effect of the CV, the model is supplemented with module «A»: to calculate the additional concentration of aerosol entering the atmosphere during wind gusts, the source power formula is used [23]:

$$F = \frac{0{,}12 C_g g \rho_s}{\rho} Q,$$

$$\begin{cases} \frac{c\rho u_*^3}{g}\left[1-\left[u_*^{\kappa p}(d)/u_*\right]^2\right] & u_* \geq u_*^{\kappa p} \\ Q = 0 & u_* < u_*^{\kappa p} \end{cases} \quad (2)$$

where F is the power of the source, Q is the flow rate of the impurity, □ is the air density, $□_s$ is the density of particles, p is the deformation pressure exerted by the soil surface on aerosol particles moving along it, g is the gravitational constant, u_* – friction speed, c = 0, 25+0.33w_g(d) is the Owen coefficient [25], w_g(d) is the particle velocity as a function of its diameter d, $u_*^{\kappa p}(d)$ – critical friction speed, C_g is the ground aerosol concentration [13].

Table 2

Residuals of model (ΔT_{mod}) and experimental (ΔT_{exp}) data

Region measurements	VC	V, m/s	T_s, °C	T_a, °C	T_b, °C	$\Delta T_{мод}$	ΔT_{exp}	ΔT_d
Ustyurt Plateau 10.11.22	0%	0,0	31,5	24,0	22,0	2,15	2,0	0,15
Ustyurt Plateau 07.10.23	30%	4,6	55,1	42,5	41,1	4,55	1,4	3,15
Ustyurt plateau 3.31.05.23	5%	2,2	51,9	38,8	34,9	2,94	3,9	-0,96
Nukus 05.31.23	15%	3,0	59,0	44,4	37,5	3,90	6,9	-3,00
Nukus .31.05.23	45%	2,6	59,8	41,3	36,3	3,88	5,0	-1,12
Nukus 07.03.23	10%	4,3	48,5	38,2	37,1	2,72	1,1	1,62
Nukus 07.03.23	35%	6,8	51,6	41,9	37,1	7,90	4,8	3,10
Nukus 07.03.23	50%	2,9	53	42,7	37,1	3,85	5,6	-1,75

Note: VC – total projective vegetation cover, V – wind speed, Ts – soil surface temperature; T_a – air temperature; T_b – background temperature; ΔT_d = ΔTmod – ΔTexp – residuals.

As a result, the dependences of the additional aerosol mass concentration ΔC and changes in the thermal effect of CR on wind speed were obtained (Fig. 3, 4). The ΔC trend equations expressing these dependencies, together with formula (2), constitute, in addition to the *MCR* model, the developed module «A».

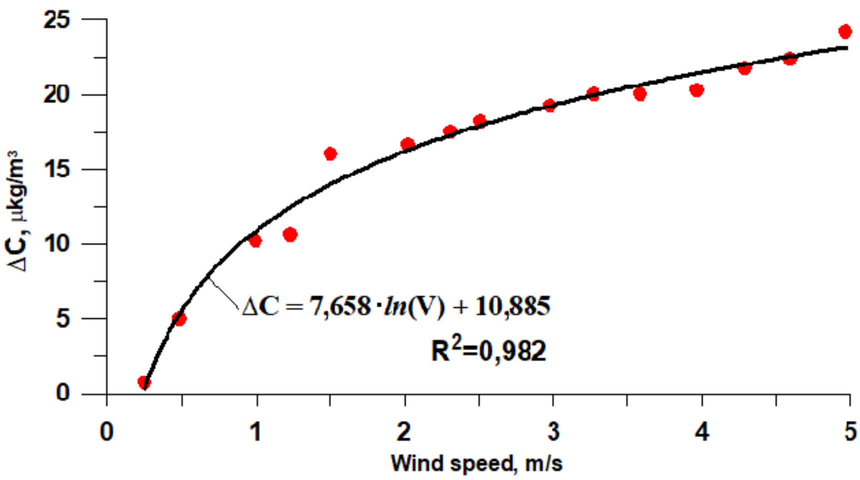

Fig. 3. Dependence of additional mass concentration aerosol ΔC on wind speed.

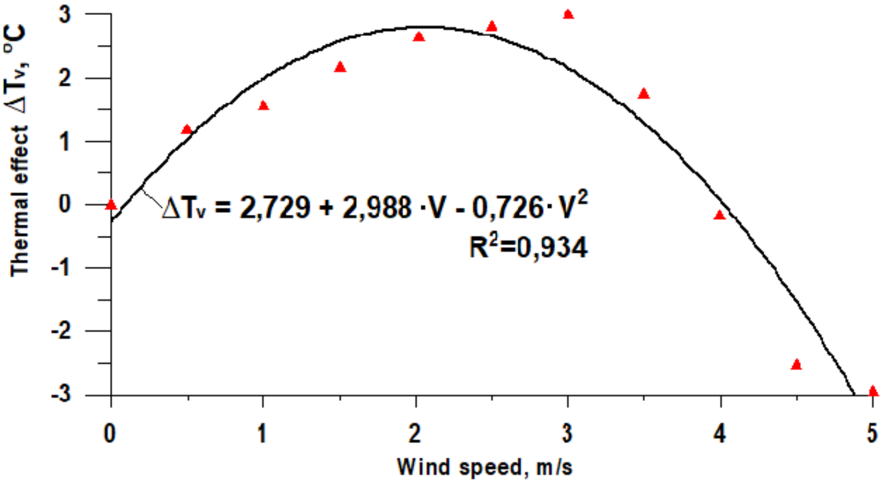

Fig. 4. Dependence of the change in the thermal effect of CV on the wind speed.

Taking into account the influence of wind speed, the thermal effect at CR changes according to the equation in fig. 4.

The warming effect of convective aerosol removal, as it turned out during field experiments, significantly depends on the vegetation cover. It is known that vegetation cover significantly influences heat and moisture exchange, and during convective removal of aerosol, mass exchange at the boundary between the underlying surface and the ground layer, reducing, as noted above, the amount of aerosol removed from the soil. The decrease depends on the overall projective cover and vegetation transpiration. The influence of vegetation cover is expressed mainly in the fact that the leaf surface retards the convective flow of aerosol, as a result, some of the heated microparticles remain in the plant layer (PL). Therefore, the air temperature at the upper boundary of the PL is lower than above the bare surface. At the same time, the accumulation of detained heated microparticles in the PL causes an increase in air temperature (AT) in the PL compared to the surrounding bare surface. This conclusion is confirmed by the results of AT measurements in the PL. The mechanism of influence of plant transpiration is as follows. An increase in air humidity slows down convection by condensing moisture on microparticles, increasing the mass of microparticles; in addition, as is known, evapotranspiration itself reduces the air temperature. Since the influence of plant transpiration on the convective aerosol flux requires a separate study, we limited ourselves to the empirical equation for the reduction of the convective aerosol flux as a function of RP, obtained as an approximation of the logarithmic curve of experimental data (fig. 5).

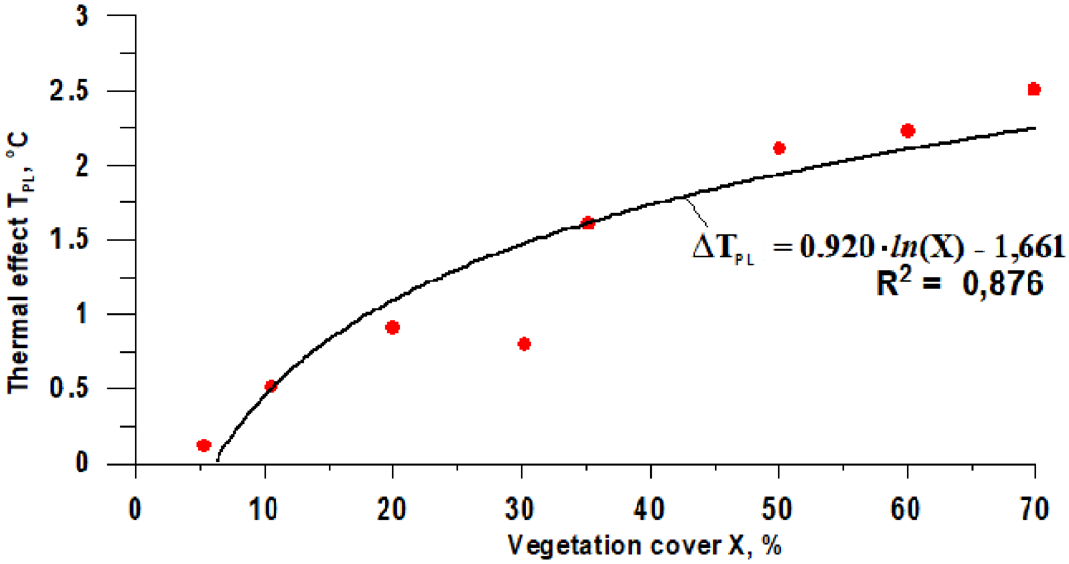

Fig. 5. The dependence of the thermal effect $\Delta T_{РП}$ caused by convective aerosol removal, on the value (%) of vegetation cover.

Vegetation cover reduces the thermal effect of CR, according to the equation shown in fig. 5.

Thus, the modification of the *MCR* model makes it possible to calculate the thermal effect of CR not only for ideal conditions of complete calm and absence of vegetation cover (ΔT), but also for real conditions (ΔT_r) of the presence of vegetation and wind gusts of up to 5 m/s:

$$\Delta T_p = \Delta T + \Delta T_v - \Delta T_{PL} \qquad (3)$$

Conclusion. The study showed the importance of convective removal of aerosol from desert surfaces in real conditions, as a forcing of near-surface air temperature in the summer months. On average, in the southern Aral Sea region in the warm season of the year (May-October) in desert zones, convective removal of aerosol causes an increase in air temperature by 3.5 ° C.

The inverse positive relationship that exists between warming and the forcing under consideration only strengthens it. It should be noted that the aerosol concentration, increased during daytime emission, inhibits nighttime radiation due to the absorbing properties of soil aerosol, which also enhances the warming effect.

Vegetation cover significantly reduces the warming effect of convective aerosol removal in a nonlinear dependence on projective cover. This reinforces the importance of phytomelioration as a measure against desertification and mitigation of climate warming.

Numerical and field experiments revealed the high sensitivity of the convective outflow model to aerosol dispersion, conditions of the underlying surface and wind speed. Thus, it turned out that the thermal effect of the convective rise of desert aerosol is a particularly subtle mechanism of interaction between the underlying surface and the atmosphere.

To assess regional and global climate changes taking into account the influence of desert zones as “heat islands”, further research is needed taking into account the speed of convection, turbulent diffusion, nonlinear effects, vertical gradients and heat exchange of desert areas with neighboring qualitatively different landscapes, the influence vegetation cover, statistics of the wind regime of the study area. There is an obvious need to use mathematical modeling methods, system analysis and remote sensing data in such studies.

Conducted field experiments made it possible to reduce the discrepancies between model and experimental data from 1.8 to 0.3 °C. The accuracy of the experimental data and their information content, taking into account the pulsating nature of the wind (gustiness) and convection (separation of individual thermals), may have increased significantly through the use of instruments with continuous recording of meteorological quantities.

A modified model of the contribution to climate change in global temperature due to convective removal of aerosol, taking into account the planetary trend of desertification, can be applied to other desert territories of the planet with its preliminary adaptation.

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