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Simulation of the Salt Wind Transport from the Desiccated Bottom of the Aral Sea During Dust Storms

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Abstract: Extensive salt removal from the dried seabed of the Aral Sea, which began with the desiccation of the sea, has a negative impact on the environment. Sulphates are especially dangerous, affecting public health, soil salinisation, and biota in general. The need for quantitative estimates of the mass of toxic salts falling out to clarify the mechanism and degree of these impacts determines the relevance of studies of wind-driven salt removal. Absence of ground measurements of sulphate concentration, impossibility to separate sulphate fraction from the total mass of atmospheric aerosol by remote sensing methods, determines the use of applied mathematical modelling methods to track the spatial and temporal dynamics of salt distribution from the dried Aral Sea bed. This paper presents a numerical model of a salt-dust storm for wind-driven transport of salt-dust aerosol, which is a system of three sub-models of the meteorological block, from which the input data for the fourth sub-model - the turbulent diffusion equation, by which the concentration fields of sodium and magnesium sulphates are calculated. The result of the implementation is a 4-dimensional data array on spatial and temporal dynamics of the concentration distribution of these salts, as well as the volume of salts exported during one dust storm. In addition, the dynamics of the total volume of wind-driven salt removal from the dried seabed by decades of the period (1961-2020) is calculated using this model. The modelling results also revealed some regularities of the salt-dust storm plume structure.
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1. Introduction

Wind-driven dust and salt transport from the dried Aral Sea bed, despite more than half a century of existence, remains a process with a number of uncertainties. In our opinion, this is mainly due to the dynamism of its base - Aralkum - and the absence of a special monitoring network in the Aral Sea region for continuous registration of aerosol concentrations in the atmosphere. In this connection, many studies of salt transport carried out at different times and by different methods present a mosaic picture of estimates of salt transport parameters, which have a large range of variation. Thus, according to calculations of N.M. Mozhaitseva and T.F. Nekrasova (1984), on the average from drying 1960-1980, from 60 to 100 $t{\cdot}ha^{-1}$ of salts were delivered to the atmosphere. In the work (Chub, 1994) it was noted that 53 million tonnes of salts are taken out from the sea area, 57 million tonnes from the drying zone, and 13 million tonnes from solonchaks. I.V. Rubanov and N.M. Bogdanova (1983) consider that the removal of only water-soluble salts without terrigenous component of dust storms is equal to 2286 $t{\cdot}km^{-2}$ on average, and from the whole drying area 43 million tonnes per year. According to Uyala MS data (Galaeva and Semenov, 1997; Galaeva et al., 1996). Only from two sources located on the Kazakh part of the dried seabed, the total aerosol mass removal is 7.3 million tonnes, and the volume of salt removal is 50-70 thousand $t{\cdot}year^{-1}$. According to R.M. Razakov and K.A. Kosnazarov (1998), salt removal from malodorous solonchaks of the drying bed is 12-20 $t{\cdot}ha^{-1}$ per year. The authors also recognise that observations of individual years are random and do not reflect regularities of aeolian export and deposition of dust and salt particles from the sea bottom (Razakov and Kosnazarov, 1987). In (Azydova and Semenov,1985), the capacity of the entire Aral source of aerosols is estimated at 20-30 million $t{\cdot}year^{-1}$, including salts - 200-300 thousand $t{\cdot}year^{-1}$.

As we can see, estimates of the volume of salt removal from the dried Aral Sea bed date back to the last century and are controversial. The phrase circulating in scientific literature for decades "75-100 million tonnes of sand and salts are taken out annually from the dried Aral Sea bed" does not stand up to criticism from the point of view of salt transfer dynamics, in the sense that these figures may have been real only for a certain short time interval.

A forecast of some scientists (Rubanov and Bogdanova, 1983) that in the 2000s there will be a decrease in the volume of blown salts despite the increase in the area of drying was not justified either. Moreover, the tendency to intensification of salt blowing has been observed everywhere in the past decade (Iwasaki, 2006; Goudie and Middleton, 2006; Shao and Dong, 2006).

This is evidenced by the unprecedented dust storms in Central Asia on 27-28 May 2018 with a dust concentration of 23000 $\mu g \cdot m^{-3}$ in Nukus, 3-4 November 2021 with a dust concentration of 18000 $\mu g \cdot m^{-3}$ in Tashkent (Eurasianet, 2021), as well as in Iran (Rashki et al., 2021; Dargahian et al., 2023).

Positive dynamics of dust storms recurrence is undoubtedly of concern for countries with vast desert territories, as excessive air dustiness is the cause of numerous diseases. Dust-related diseases are known to occur when dust particles are inhaled together with microbes, heavy metals, pesticides and other contaminants in the soil (Bozlaker et al., 2013; Chen et al., 2004; Erel et al., 2006; Kaiser, 2005; Poulsen et al., 1995; Sanchez de la Campa et al., 2013; Schulz et al., 2012). Due to their micro- and nano-size, particles easily enter the lungs and penetrate into the bloodstream. Dust storms contribute to an increase in diseases such as asthma, tracheitis, pneumonia, allergic rhinitis and silicosis (Wu et al., 2021). In addition to these well-known respiratory system diseases (Bartzokas et al., 2004; Nastos et al., 2011; Middleton, 2020; Al-Hemoud et al., 2018; Kang et al., 2012; Wang et al., 2014), mineral dust is considered one of the most important risk factors for allergies and meningitis in Iran (Miri et al., 2007) and West Africa (Martiny and Chiapello, 2013), cardiovascular (Aghababaeian et al., 2021; Aili and Oanh, 2015), psychological, cognitive (Ghaisas et al., 2016; Gordeev et al., 2013), neurodegenerative diseases (Aleya and Uddin, 2020; Chin-Chan et al., 2015; Galán-Madruga et al., 2020; Galán-Madruga and García-Cambero, 2022; Shafiee et al., 2021).

Diseases of the circulatory system, malignant neoplasms, and tuberculosis are of the greatest importance. The solution of these problems is especially relevant for Karakalpakstan, whose main population lives in the central oasis surrounded on all sides by the Kyzylkum, Karakum, Ustyurt and Aralkum deserts, which are a source of large-scale atmospheric pollution during dust storms (Veysov et al., 2021).

Despite the numerous studies (Indoitu et al., 2015; Abitaev et al., 2014; Issanova et al., 2015; Wang et al., 2022) on dust storms on the dried Aral Sea bed, the salt aspect (spatial distribution of salts) of these negative processes remains practically unexplored. At the same time, it is the salt fraction of dust storms on the dried Aral Sea bed (sodium and magnesium sulfates) that has the most dangerous impacts on soil salinisation in the Southern Aral Sea Basin (Tleumuratova, 2018) and public health (Veysov et al., 2021; Abitaev et al., 2014; Isaeva, 2007).

To confirm the correlation between the increase in sulphate concentration and the increase in morbidity in the Aral Sea region, a thorough correlation analysis of the synchronised spatial and temporal dynamics of morbidity and salt concentration is required. Such a study is possible only in the presence of representative data series on both morbidity and aerosol concentrations in the surface layer. Note that this is a study of long-term health effects of sulphates, and it requires information on the annual average sulphate concentration, which can only be obtained by mathematical modelling methods for the above reasons. A study using a quasi-stationary model of salt transport (Arushanov and Tleumuratova, 2012) has shown that the correlation coefficient between upper respiratory tract diseases and average annual sulphate concentration in Karakalpakstan is 0.72 (Tleumuratova et al., 2015).

Equally important are studies of acute health effects of dust storms, which are known to be much stronger than long-term effects and can be fatal (Goudie, 2014). The regional specificity of dust storms due to the presence of sulphates in the composition of wind-borne dust reinforces the relevance of quantifying the health effects of salt and dust storms. The aim of such studies should be to calculate the probability of disease depending on the received single dose of sulphates and to identify the mechanism of sulphate influence on the human body. The significance of the effect of sulphates on living organisms is evidenced by the fact that immediately after the salt and dust storm on 27-28 May 2018, diseases and deaths of livestock grazing at that time were observed. A prerequisite for detailed studies of the correlations between salt export and the condition of farm animals is the modelling of salt export from the dried Aral Sea bed.

In addition to its application in health studies, the results of modelling of wind-driven salt transport from the dried seabed can be used in studies of regional climatic problems due to the significant role of sulphate in precipitation and radiation regime (Bauman et al., 2003).

A dust storm is a complex dynamic process with non-linear systemic links with atmospheric circulation (development of storm conditions) and with the properties of the underlying surface (erodibility, texture, humidity, temperature, roughness, etc.) (Hoffmann et al., 2011; Lancaster et al., 1998). Numerical models are commonly used for the mathematical description of dust storms (Shao et al., 1996; Lu and Shao, 2001) based on the principles of gradient transfer theory (K-theory) (Monin and Yaglom, 1965).

Numerical models of sand storms have a high degree of details, since the problem of turbulent aerosol diffusion is often synthesised with a model of the surface layer of the atmosphere (meteorological module), designed to calculate the meteorological parameters of the transport equation (Avissar and Pielke, 1989; Aloyan et al., 1981; Kazakov and Lazriev, 1978). To describe the surface layer of the atmosphere, most authors (Aloyan et al., 1981; Kazakov and Lazriev, 1978; Kamst and Lyons, 1982) apply the Monin and Obukhov (Monin and Yaglom, 1965) similarity theory based on the theory of turbulent flow in a thermally stratified medium over a flat and homogeneous surface under stationary conditions.

Modelling of dust storms is predominantly carried out for individual case studies, allowing for rapid validation of the model by space-based methods and ground-based measurements (Gong, S. L., and Zhang, 2008; Benedetti et al., 2019; Randles et al., 2017). If the appropriate equipment is available, the meteorological module of the model can be corrected in real time by inputting meteorological parameters recorded by ground-based monitors synchronously with the flow of the dust storm (Lu and Shao, 2001). However, models for specific cases of dust storms often turn out to be inapplicable for other regions.

The need for atmospheric aerosol transport models is increasing due to their integration into regional and global climate models, global vegetation models, ozone layer models, nature management computing systems and other applications (Chen et al., 2022). At the same time, it is noted that atmospheric dust models are the main source of uncertainties in climate models (Tanaka and Chiba, 2006; Neff et al., 2008).

Analysis of dust storm studies and ecological conditions of the studied region leads to the following conclusions:

1. Windborne salt export from the dried seabed represents a special case of dust storm because:

a) contains significant concentration of toxic sulphates;

b) the recently formed Aralkum desert is highly variable in terms of both its extent and salt content of the soil.

2. Quantitative assessments of sulphate levels in the atmosphere are required to tackle pertinent public health and climate change concerns in the Southern Aral Sea Basin.

3. At present, mathematical modelling methods are the only means of obtaining these estimates, as there is insufficient ground-level data on sulphate concentration and remote sensing methods have difficulty in distinguishing the sulphate fraction from the total mass of atmospheric aerosol.

4. Current dust storm models are unsuitable for assessing salt removal. They lack a module for determining salt source capacity and use ground-based monitoring data.

This paper presents a numerical dynamic model of a salt-dust storm, which allows tracking the spatial and temporal dynamics of salt distribution during dust storms. The concentration of only the sodium and magnesium sulphate fractions, as the most toxic and deflation-prone substances, is calculated. This is the difference and novelty of this work from many studies of dust storms, in which the substrate carried in the atmosphere is sand and soil particles.

1.1. Study Area

The study region is the geosystem of the Aral Sea and its dried bed, limited by the coastline of 1961, as well as the adjacent territory of the Southern Priaralie. The dynamism of the sea desiccation determines the growing rates of salinisation of the dried seabed of the Aral Sea and, accordingly, the volume of wind salt removal.

Thus, salinity of the upper horizons (0.5 m) of soil on drylands with the age of 10-20 years increased from 70 $t{\cdot}ha^{-1}$ in 1980 to 700 $t{\cdot}ha^{-1}$ in the last decade. Correspondingly, the volume of annual salt removal from the whole area has increased from 4.6 to 117 million $t{\cdot}year^{-1}$ (Kublanov and Tleumuratova, 2023).

The exposed solonchak plains of the dried bed are characterised by high erodibility - from 60 to 620 $t{\cdot}km^{-2}$ for crusty solonchaks and from 440 to 2800 $t{\cdot}km^{-2}$ for puffed solonchaks (Bogdanova and Kostuchenko, 1979).

The key source of salt storms in Priaralie are crust and crust-puffed solonchaks, whose tenardite fluff is easily weathered and transported over long distances. Salt removal occurs predominantly from eastern drying, and the time of drying of the most powerful centres of salt removal is 10-30 years. In 1997 in the south-western part of the dried Aral Sea bed, 8 powerful centres of salt and dust export were identified and mapped, representing extensive barchan massifs - Prichinkoviy - beach (117 km^2), Central (Arkhangelsky shaft - 312 km^2), Adzhibaysky (93 km^2), Inzhenerozeksky (80 km^2), Urdabaysky (58 km^2), Ostrovnoy (42 km^2), Yerzharsky (124 km^2), Akkala-Uzunkairsky (135 km^2) (Kurbaniyazov, 2017).

2. Material and Methods

Since the research method is mathematical modelling, this section of the paper describes the salt-dust storm model, methods of its numerical implementation, as well as simplifications and approximations inevitable in modelling.

2.1. Model description

When solving the problem of impurity dispersion in the lower atmosphere, the information on the distribution of meteorological characteristics in the atmospheric boundary layer and, especially, in the near-ground layer of the atmosphere, where their gradients are 1-2 orders of magnitude larger than in the rest of the atmosphere, is crucial. Therefore, it is very important for solving the turbulent diffusion equation describing dispersion of an impurity in the atmosphere to determine wind profiles, vertical diffusion coefficient, air and soil temperatures. Since it is impossible to achieve the required degree of data detail by direct measurements (to determine values of meteorological parameters in each node of the three-dimensional computational domain at each time step), it seems reasonable to solve the turbulent diffusion equation and the atmospheric dynamics equations together. Thus, the mathematical model of a salt-dust storm is a set of 4 sub-models. Salt diffusion is traditionally described by semiempirical turbulent diffusion equation (in Cartesian coordinate system):

$$\frac{\partial C}{\partial t}+|U|\frac{\partial C}{\partial x}-w_g\frac{\partial C}{\partial z}=K_x\frac{\partial^2 C}{\partial x^2}+K_y\frac{\partial^2 C}{\partial y^2}+\frac{\partial}{\partial t}K_z\frac{\partial C}{\partial z}+F(x,y,t) \quad (1)$$

with the following initial and boundary conditions:

$$C(\bar{x},\bar{y},z,0)=0 \text{ at } z>z_0,$$
$$C(\bar{x},\bar{y},z,0)=C_H(x,y) \text{ at } z<z_0 \quad (2)$$
$$C(\bar{x},\bar{y},z,t)=0 \text{ at } \bar{x},|\bar{y}|,z\to\infty \quad (3)$$
$$C(\bar{x},\bar{y},z,t)=0 \text{ at } x<0 \quad (4)$$
$$K_z\frac{\partial C}{\partial z}=(\beta-w_g)C-F(x,y,z)=0 \text{ at } z=z_0 \quad (5)$$

here $C(x,y,z,t)$ is impurity concentration, $U(z,t)$ is wind speed, w_g is gravitational speed of impurity deposition, F is source power, K_z is vertical diffusion coefficient.

The meteorological parameters included in the semi-empirical turbulent diffusion equation as coefficients are determined from the meteorological block of the model consisting of the equations of dynamics for three layers:

1) The surface atmospheric layer $(0<z\le h)$;

2) The part of boundary layer above the surface layer of the atmosphere $(h<z\le H)$;

3) Active soil layer $(0<z\le h)$.

The vertical division into three layers is due to the fact that each of these three layers has its characteristic horizontal and vertical scales.

2.2. A sub-model of the surface atmospheric layer

The physical processes occurring in the near-ground layer of the atmosphere are of particular practical and scientific interest as the interaction of air masses with the underlying surface through the exchange of motion, heat and moisture, whose turbulent fluxes in the near-ground atmospheric layer can be assumed constant in height (Monin and Yaglom, 1965). Knowing the values of these fluxes is necessary for solving most of the atmosphere dynamics problems. It is known that the vertical gradients of meteorological elements in the near-ground atmosphere layer are 1-2 orders higher than in the rest of the atmosphere. Therefore, in order to determine turbulent flows in the near-ground layer of the atmosphere with satisfactory accuracy in numerical models for this part of the atmosphere, a much finer mesh should be taken, which leads eventually to essentially non-uniform vertical difference grids, complicating the computational process. In connection with this, in almost all atmosphere dynamics models the near-ground layer of the atmosphere is parametrically considered. For the physical description of this layer, Monin and Obukhov proposed a model based on the theory of turbulent flow in thermally stratified medium under the condition of horizontal homogeneity and on the theory of similarity and dimensions. Accordingly, the model of the surface atmospheric layer is the following system of equations:

$$U=\sqrt{u^2+v^2}=\frac{u_* f_u(\zeta,\zeta_0)}{\kappa} \quad (6)$$
$$\vartheta-\vartheta_0=\vartheta_* f_\vartheta(\zeta,\zeta_0),\ q-q_0=q_* f_\vartheta(\zeta,\zeta_0) \quad (7)$$
$$L=\frac{u_*^2}{\kappa^2\lambda\vartheta_*},\ \zeta=\frac{z}{L},\ \zeta_0=\frac{z_0}{L} \quad (8)$$
$$v_i=\frac{\kappa u_* z}{\varphi_i(\zeta)},\ i=u,\vartheta \quad (9)$$
$$\varphi_i(\zeta)=\zeta\frac{\partial f_i(\zeta,\zeta_0)}{\partial\zeta},\ i=u,\vartheta \quad (10)$$
$$\alpha(\zeta)=\frac{v_\vartheta}{v_u}=\frac{\varphi_u(\zeta)}{\varphi_\vartheta(\zeta)} \quad (11)$$

where U is the wind velocity modulus, u,ϑ are horizontal components of the wind velocity, q is relative humidity, L is the Monin-Obukhov length, κ - is the Carman constant, v_u, v_ϑ are the turbulent exchange coefficients for momentum and heat, respectively, ϑ - is the potential air temperature, φ_i

and f_i are universal functions whose specific form is given in (Kazakov and Lazriev, 1978) depending on atmosphere stratification conditions.

2.3. A sub-model for the part of boundary layer above the surface layer of the atmosphere

Since horizontal homogeneity is assumed, simplified (one-dimensional in z) equations are used to describe the processes in the part of boundary layer above the surface layer of the atmosphere. Let's assume that in this layer air flow movement, potential temperature and humidity changes are determined only by vertical turbulent exchange:

$$\frac{\partial u}{\partial t}=\frac{\partial}{\partial z}(\nu_u\frac{\partial u}{\partial z}) \quad (12)$$

$$\frac{\partial v}{\partial t}=\frac{\partial}{\partial z}(\nu_u\frac{\partial v}{\partial z}) \quad (13)$$

$$\frac{\partial q}{\partial t}=\frac{\partial}{\partial z}(\nu_\upsilon\frac{\partial q}{\partial z}) \quad (14)$$

$$\frac{\partial \vartheta}{\partial t}=\frac{\partial}{\partial z}(\nu_\upsilon\frac{\partial \vartheta}{\partial z}) \quad (15)$$

where

$$\nu_u(z,t)=\frac{H-z}{H-c}\nu_u(h,t) \quad (16)$$

$$\nu_\vartheta(z,t)=\frac{c-z}{H-h}\nu_\vartheta(h,t) \quad (17)$$

ν_u,ν_ϑ - are the turbulent exchange coefficients for angular momentum and heat, respectively; u_g,v_g are the geostrophic wind components; H - upper boundary of the second layer of the model; h - lower boundary of the second layer (height of the surface layer of the atmosphere).

The validity of relations (16) and (17) of the second sub-model, i.e., linearity of the vertical profiles of turbulent exchange coefficients, is confirmed by numerous observations (Estoque, 1973; Schayes, 1982).

To solve the system of equations (12) - (15) the following initial and boundary conditions are set:

$$t=0: u=u(z),\ v=v(z),\ q=q(z),\ \vartheta=\vartheta(z) \quad (18)$$

$$z=H: u=u_g,\ v=v_g,\ q=q_H,\ \vartheta=\vartheta_H \quad (19)$$

$$z=h: u=u_h,\ v=v_h,\ q=q_h,\ \vartheta=\vartheta_h \quad (20)$$

A sub-model of the active soil layer consists of the soil thermal conductivity equation:

$$\frac{\partial T_S}{\partial t}=\frac{\partial}{\partial z}(k_S\frac{\partial T_S}{\partial z}) \quad (21)$$

initial temperature distribution $T_S(z,0)$ and boundary conditions, i.e. surface temperature $T_S(0,t)$ and temperature $T_S(d,0)$ at depth d. The thermal conductivity coefficient k_S is also given as input parameters for the soil layer model.

Vertical calculations were performed for 19 levels (m): 9 levels for the surface layer of the atmosphere: 0, 0.01, 0.5, 5, 10, 20, 30, 40, 50; 10 levels for the second layer: 100, 200, 300, 400, 500, 800, 1100, 1400, 1700 and 2000 m. Horizontal spacing of the grid is 10 km.

The main input parameter of the model is the given scenario of wind speed dynamics. For example, wind velocity at the moment t=0 is moderate (5 m·s^{-1}), after half an hour it rises sharply to 10 m·s^{-1}, after another half an hour it reaches maximum (17 m·s^{-1}), by the third hour it decreases to 15 m·s^{-1}, by the end of the process - to 8 m·s^{-1}.

The calculation algorithm for the meteorological block is extremely complex due to the numerous nonlinear links between the sub-models (Tleumuratova, 2004). Joint implementation of the sub-models of the surface atmospheric layer and the active soil layer is carried out using the dynamic balance method (Kazakov and Lazriev, 1978). The coupling link is the underlying surface energy balance equation:

$$G_S-\rho_0C_p\left[\nu_\vartheta\frac{\partial\vartheta}{\partial z}\right]_0-\rho_0L_w\left[\nu_\vartheta\frac{\partial\vartheta}{\partial z}\right]=I_0-\sigma_ST_0^4 \quad (22)$$

where G_S - heat transfer through the soil surface; ρ_0 and C_p - air density and specific heat capacity, respectively; L_w - latent heat of evaporation; I_0 - influx of total short-wave radiation taking into account albedo of the underlying surface; σ_S - Stefan-Boltzmann constant multiplied by the coefficient taking into account the influence of humidity and cloudiness; T - air temperature. The index 0 means the correspondence of physical values to the roughness level $z=z_0$.

The output of the meteorological block serves as input data for solving the turbulent diffusion equation by splitting by physical processes and spatial coordinates.

The commonly used lower boundary condition which is an admixture balance at roughness level $z=z_0$ does not quite adequately describe the processes occurring at this level, as the coefficient related to roughness level is usually measured at best at 0.5 m. Moreover, during deflation the phenomenon of concentration jump at $z=0$, whose value is proportional to the concentration gradient. The physical state of impurity also experiences a discontinuity, if one may say so, from compact at underlying surface to suspended at $z>0$, which leads to difficulties with approximation of boundary condition for concentration at $z=0$. Considering that processes of dust particles detachment from ground surface and absorption of admixture by underlying surface are difficult to formalize, we accept the following simplified representation of deflation mechanism by "black box" principle. Let us introduce a thin near-surface layer of thickness z_S comparable with the thickness of the contaminant layer in the soil and assume that the admixture entering this layer is instantaneously and uniformly distributed along z, i.e. the soil-atmosphere boundary as if it acquires a third dimension, the thickness z_S. The concentration in this layer will be called the ground layer and denoted by C_H. Similar representation of dusty surface is given in (Vozzhenikov and Nesterov, 1991). This artificial approach is applied only for numerical solution of the concentration equation and does not extend to the meteorological block of the model. Eligibility of such approach is conditioned by relative autonomy of concentration sub-model and meteorological block implementation.

Salt yield from near-surface layer and entering the atmosphere (source capacity) is given by the following formula (Kamst and Lyons, 1982):

$$F=\frac{0.12C_H g\rho_S}{p}Q \qquad (23)$$

$$Q=\frac{c\rho_a u_*^3}{g}\left[1-\frac{u_{*k}}{u_*}\right]^2 \qquad (24)$$

$$(u_*-u_{*k})=0.04(u_2-u_{2k}) \qquad (25)$$

where Q is admixture flow rate, ρ_a - air density, ρ_S is particle density, p is deformation pressure exerted by soil surface on aerosol particles moving along it, g is gravitational constant, u_* is friction velocity, $c=0.25+0.33w_g(t)/u_*$ is Owen coefficient, d is particle diameter, u_{*k} is critical speed of friction.

2.4. Weather preconditions

Since satellite images of dust storms do not show any significant deviation of dust flows from the straight-line motion at least for 200 km, firstly, we can assume horizontal homogeneity of motion, and secondly, we can neglect vertical wind shear in modelling the dust storm.

Statistical analysis of three-day dynamics of 134 cases of dust storms on the dried bed of the Aral Sea in 1970-2020 using data from UzHydrometcentre archive (Shardakova and Usmanova, 2006) allowed to reveal the average statistical course of meteorological parameters (pressure, temperature, relative humidity, wind speed) for a day before the dust storm, during and a day after the dust storm (Urazimbetova and Tleumuratova, 2023). The mean statistical ensemble of near-surface meteocharacteristics aggregated in this way was used as input data for the meteo module. In other words, the model under consideration is a model of an average statistical dust storm. The main input parameter of the meteorological block of the salt-dust storm model is a given scenario of wind speed dynamics at the 2 m level. The wind speed at the moment t=0 is set moderate (5 m·s^{-1}), after half an hour it sharply increases to 10m, after another half an hour it reaches the maximum (17 m), by the third hour the wind speed decreases to 15 m·s^{-1}., by the end of the process - to 8 m·s^{-1}.

Impurity conditions. The impurity simulating sulphate salts from the dried Aral Sea bed is considered to be practically homogeneous in composition and particle size (average size 15 µm, average particle density - 1.8 g·cm^{-3}). The impurity is considered passive in terms of chemical and physical interaction with other fractions of the salt-dust flux.

3. Results

3.1. Results of the calculations

Two qualitatively and quantitatively different components can be distinguished in the structure of wind salt transport - saltation and atmospheric transport (Figure 1).

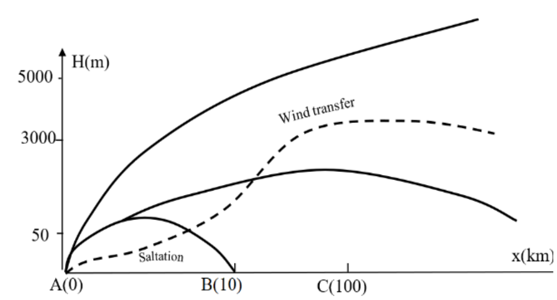

Figure 1. Separation of aerosol flow and the trajectory of the concentration maximum (dashed line)

The saltation part is a continuous, adjacent to the ground surface, clubbing mass of heavy particles travelling discontinuously under the action of individual wind gusts and turbulence. The height of the saltation part (segment AB in Figure 1) does not exceed a few tens of metres, and the range of transport is a few tens of kilometres. The main substance of the saltation part is sand particles and soil aerosol. Particles of sulphates, the most harmful fraction of salt transfer, having less specific weight and size, rise much higher at the first gusts of wind. Thus, sulphates are characterised by atmospheric transport, the modelling of which is the subject of this paper.

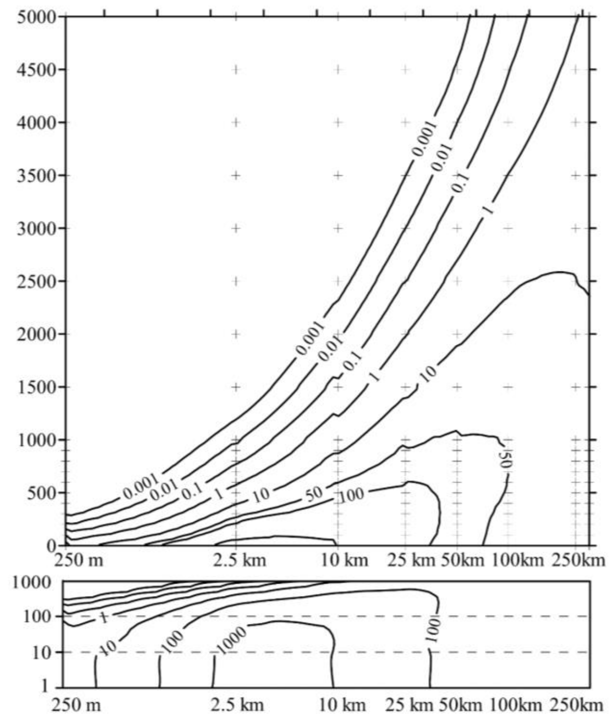

Figure 2: Salt aerosol concentration distribution during dust storm, calculated

The spatial distribution of salts during wind transport is very dynamic in time. During the first half-hour of wind transport within the saltation part (≈10 km), the maximum concentration is near the eroding surface (Figure 2). The concentration of salt particles in this part of the aerosol flow exponentially decreases with distance from the source and with increasing height. Figure 2 shows the calculated salt concentration at 1m, 50m, 500m and 1000m levels and extrapolated to a height of 5km one hour after the start of the process (12.00).

Beyond the saltation part, the salt concentration profile becomes inverted. The maximum concentration is located in the axial part of the atmospheric transport plume (Figure 3) and the maximum height changes accordingly: at a distance of 10 km from the source at the level of 400 m, at 100 km the maximum is at the height of 3 km, then it starts to decrease and at 300 km the maximum concentration is already at the level of 1 km.

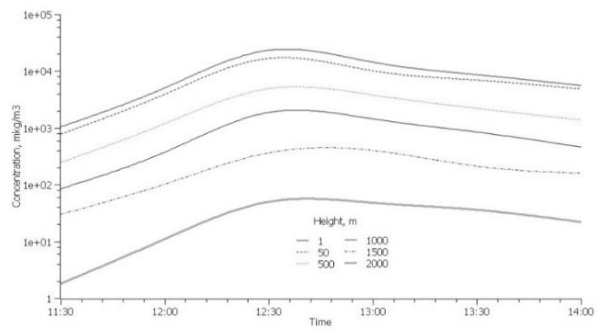

Figure 3: Calculated concentration of the salt impurities at 1 m, 50 m, 500 m, 1000 m, 1500 m and 2000 m levels

As the salt-dust flux advances, its velocity decreases and particle deposition increases. The mass ratio of deposited particles to the advective flux increases during the dust storm, but always remains in favour of advection. At the occlusion stage of the dust storm (at a wind speed of 8 $m \cdot s^{-1}$), this ratio is 1:6. Note that the model does not take into account the secondary advection of impurity into the atmosphere. The logarithmic wind profile and low deposition velocity (Darmenova and Sokolik, 2007) cause the nonlinearity of the deposition trajectory. Thus, a particle that started gravitational deposition from a height of 2 km at a distance of 80 km from the source of deposition reaches the ground surface at a distance of 500 km in 30 hours, provided that the dust storm characteristic of this phenomenon abruptly subsides. The abrupt subsidence of the dust storm causes the greatest cumulation and deposition of salt aerosol in the end part of the plume. Since this work simulates the actual salt storm with high wind speeds, the post-conditions were not modelled. The assessment of the direct effects of the dust storm in terms of atmospheric and surface pollution is a separate task.

The total mass of sulphate removal during one dust storm is calculated by time integration of the power of each source and summation of these integrals. The Table 1 reflects the progressive dynamics of dust source productivity by decades due to increasing salinity of dried Aral seabed and increasing total area of solonchaks.

Table 1: Dynamics of salt mass transported during one salt storm by decades (million tons)

Decades	Wind transfer from all the desiccated seabed
1961-1970	0.01
1971-1980	0.08
1981-1990	0.27
1991-2000	0.65
2001-2010	1.36
2011-2020	2.22

Taking into account the statistics of recurrence of sand storms and the results of salinity modelling of the dried Aral Sea bed in 1961-2020 (Arushanov and Tleumuratova, 2012; Kublanov and Tleumuratova, 2023) using this model, we can trace the dynamics of the total volume of salt removal during this period (Table 2).

Table 2: Mean annual salt emission (million tons per year)

Decades	Wind transfer from total area of desiccated seabed
1961-1970	1.8
1971-1980	4.4
1981-1990	15.5
1991-2000	37.9
2001-2010	78.7
2011-2020	128.8

3.2. Model verification

Verification of models usually involves ground-based observations as well as remote sensing data on aerosol optical thickness (Gong, S. L., and Zhang, 2008; Benedetti et al., 2019; Randles et al., 2017).

Due to the lack of similar studies, direct measurement data and remote sensing data on sulphate concentrations, the model results cannot be fully ratified. It is only possible to relatively validate the quality of the model by calculating the atmospheric transport of the entire aerosol volume using it and comparing the calculations with the results of dust storm modelling by other authors. Such a comparison of the results of the model realisation with data (Lu and Shao, 2001; Ganor and Mamane, 1982; Dulac et al., 2001; Erell and Tsoar, 1999; Semenov, 1972) was carried out in two aspects: 1) the distribution of impurity by height; 2) the dynamics of impurity concentrations as they move away from the source. As expected, the largest discrepancies (up to 1500 $\mu g \cdot m^{-3}$) were found in the quantitative assessment of aerosol concentration, which is explained, firstly, by the differences in the applied models; secondly, by the difference of sources: an extensive area source in other authors and a set of discrete downy solonchaks in our case.

The best validation of model quality can be carried out with maximum similarity with the models being compared. Such a model, for example, is given in (Lu and Shao, 2001) for calculating aerosol concentrations during a dust storm in Australia that passed over the entire continent in February 1996.

We note good agreement with the Lu and Shao modelling results for such important characteristics of impurity transport as source power and flow rate. Thus, the discharge of impurity at increasing wind speed from 10 to 20 $m \cdot s^{-1}$ increases from 197 to 2065 $mg \cdot \cdot m^{-1} \cdot s^{-1}$ according to the model, and from 200 to 1890 $mg \cdot m^{-1} \cdot s^{-1}$ according to the Lu and Shao model; in the same wind speed range, the source capacity increases from 80 to 835 $\mu g \cdot m^{-2} \cdot s^{-1}$ according to the model, and from 100 to 700 $\mu g \cdot m^{-2} \cdot s^{-1}$ according to the Lu and Shao model.

Since in the works concerning salt removal, only values (mostly approximate) are given for salt removal from a unit area and from the whole area, we present a comparison of these figures with the results of synchronised calculations (lower figures) according to the model (Table 3).

Table 3: Comparison of literature data and results of the model implementation

Authors	Wind transfer from area unit [103 $t \cdot km^{-2}$]	Wind transfer from the whole dried seabed [106 $t \cdot year^{-1}$]
N.M. Mozhaitseva, T.F. Nekrasova (1984)	6-10	
	4.9	
Azydova, Semenov (1985)		0.2-0.3
		10.8
I.V. Rubanov, N.M. Bogdanova (1983)		43
		15.5
V.E. Chub (1994)		70
		37.9
R.M. Razakov, K.A. Kosnazarov (1998)	1.2-2	
	8.4	

Denominator – result of the calculation following proposed model.

The largest differences by 2-3 orders of magnitude correspond to the works of Semenov et al. (1991). The rest of the compared data are of the same order. The excess of literature data is explained by the fact that they meant all salts, including chlorides, while we calculated only sulfates.

In general, the results of all works agree in the exponential decrease of concentration with distance from the source and in the range of aerosol transport - 150-300 km.

4. Conclusion

It is essential to obtain data on the spatial distribution of salt concentrations, the total volume and the timing of dry salt deposition in order to investigate the negative effects of salt export from desiccated seabed. The most reliable means of acquiring such information is through quantitative measures, such as mathematical modelling.

The developed salt-dust storm model's implementation results can be considered unique due to the absence of comparable works in the studied region, the scarcity of data, and the lack of ground measurements of sulphate concentrations in the surface layer of the atmosphere in this area. As up to 83% of aerosols are transported from the dried seabed during dust storms (Semenov et al. 1998), it is necessary to model individual dust storms to understand the annual concentration of sulphates and their total transport volume.

The salt-dust storm model is highly applicable in practical scenarios, such as identifying disease history. Furthermore, this technique is versatile in addressing real-world concerns related to climate change at the regional level. The calculated sulphate concentration within the atmospheric layer up to 3 km can provide input data for modeling the impact of sulphates on the radiation regime and precipitation processes.

It is important to note that the lack of a contemporary, well-equipped ground-based monitoring system in the studied region poses a challenge for the application of simulation modelling of environmental and climatic processes. This is because the system's unrepresentativeness and the lack of contact measurement data hamper the process. In general, it is challenging to establish a correlation between the scientific interest in the Aral problem and the scarcity of adequate technical equipment for studying the situation in the region where the Aral crisis is at its peak.

The microdispersity of salt aerosols guarantees their migration into high atmospheric layers for extended periods (up to one month). Salts from the desiccated Aral Sea bed are also present.

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Nomenclature

C	impurity concentration	$[kg \cdot m^{-3}]$
U	wind velocity modulus	$[m \cdot s^{-1}]$
K	turbulent diffusion coefficient	$[m^2 \cdot s^{-1}]$
F	source power	$[kg \cdot m^{-3} \cdot s^{-1}]$
Z	vertical height	[m]
w_g	gravitational speed of impurity deposition	$[m \cdot s^{-1}]$
x,y	coordinates	[m]
T	time	[s]
u,v,	horizontal components of the wind velocity	$[m \cdot s^{-1}]$
Q	relative air humidity	[%]
F	universal function	
L	length	[m]
P	pressure	[k·Pa]
Greek letters		
Ρ	density	$[kg \cdot m^{-3}]$
β	dry deposition velocity	$[kg \cdot m^{-2}]$
ϑ	potential temperature	[K]
ζ	height normalized to Monin-Obukhov length	
λ	buoyancy factor	$[m \cdot K^{-1} \cdot s^{-2}]$
α	heat and momentum exchange coefficients ratio	
φ_u, φ_ϑ	universal functions	
σ_s	Stefan-Boltzmann constant multiplied by the coefficient corrected with the influence of humidity and cloudiness	$[W \cdot m^{-2} \cdot K^{-4}]$

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