CONDITIONS OF ANTHROPOGENIC AND ARTIFICIAL CLOUDS AND FOGS FORMATION

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No less than seven different kinds of clouds and fogs of anthropogenic origin are known. They change the radiative regime and thermohygrometric characteristics of the near surface air and optical properties of the atmosphere. This paper deals with the analysis of conditions of their formation and the results of numerical, laboratory, and field experiments. Field experiments were carried out using helicopters and ships. It is shown that the conditions of development of anthropogenic and artificial clouds and fogs are similar. They are changeable.

Ecological load on the environment including the atmosphere increases from year to year. As a result, one can isolate now no less than seven different kinds of cloud formations of the anthropogenic origin. These are aerodynamic trails behind aircrafts,[14] helicopters,[10] and sea ships,[11,18] the airport (stove) fogs,[14] photochemical smogs,[16] plumes of the stacks of industrial enterprises[16] and big fires, especially forest fires.[5]

Some of their spatiotemporal characteristics (STC) and conditions of origin are given in Table I. Analysis of the latter shows that their air temperatures are quite different (from −28°C in airplane cloud tracks to +32°C in sea ship tracks and smogs), but humidity in these formations is more uniform, because they appear mainly at its high values, except smog.

By studying the conditions and regularities of anthropogenic cloud formations (ACF), one can try to affect their appearance. Stimulation of their development can be useful for smoothing the extremal temperature, and, in particular, for frost-fighting in agriculture.

According to data obtained by E.P. Borisenkov,[2] the artificial cirrostratus and alto-stratus can change the near-ground air temperature by up to 3–5° a day.

TABLE I. Some characteristics of anthropogenic clouds and fogs.

No.	Kind of formation		Temperature, °C	Relative humidity, %	Wind speed, m/s	Time	Geometrical size
1	Cloud tracks	behind airplanes	< −28 < −38 < −39	at f = 100 at f = 60 at f = 0	any	round-a-clock	thousand km long and 1 km wide
2		behind helicopters	< −15	> 85	< 3	–	area of 10–100 km^2
3		behind sea ships	from 32°C and lower, including below zero	> 70	from calm to 5	–	up to 1000 km long and up to 50 km wide
4	Airport (stove fogs)		< −30	> 60	from calm to 3	–	area of 10–100 km^2
5	Smogs (photochemical fogs) Los-Angeles		+24 − +32	60–70	calm	noon	area from 100 to 1000 km^2
	London		−1 − +4	80–100	up to 3	night, morning	area from 100 to 1000 km^2
6	Stack plumes of the industrial enterprise		at any temperatures, more intensive at negative ones	< 100	any	round-a-clock	100–200 km long
7	Cloud plumes of big fires, especially of forest fires		at any temperature	< 100	any	–	up to 5600 km long and up to 400 km wide

Note: In all cases the anthropogenic formation develops under the entrapping layer as temperature inversion or isotherm.

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According to Ref. 10 (Table 10.1) one can conclude that at cloud lanes spontaneously appearing behind flying helicopters, temperature near the underlying surface (US) increases from 0.5 to 2.5° during an hour, while the relative humidity decreases. The latter fact can be explained by both the temperature increase and the transport of water vapor upwards to the layer of the appearing cloud lanes.

In addition, all the aforementioned ACF worsen the ecological situation (for example, by smoking the area)[16] and hamper the observations from space in the optical range.[7]

In general, one can refer the following physical-meteorological conditions as causing the appearance of non-convective cloud formations: 1) the presence of the entrapping layer (see the note of Table I); 2) temporal decrease of air temperature; 3) low wind speed, down to the calm; 4) high air humidity, often close to 100% (see Table I); 5) presence of condensation nuclei; 6) effect of air mass (AM) mixture; 7) vertical motions that are characteristic of the given kind of formation.

Analyzing these conditions, one should state that the first three of them cannot be created artificially, and only the entrapping layer can be broken, for example, by means of a meteotron,[8] thus preventing the appearance of anthropogenic formations by emitting admixtures into higher layers. Creation of the last four conditions is technically feasible.

The role of the first six ones is well known. There can occur the inversion layers without cloudiness with poor visibility, but no non-convective cloudiness or fogs without the entrapping layer can occur. Moisture and various atmospheric admixtures serving as condensation nuclei are accumulated under these layers. Calm or weak wind favor such an accumulation. As a result, condensation or sublimation of water vapor begins. Its intensity increases at mixing of air masses.

Radiative cooling of the near ground air, especially at night, often leads to appearance of fogs and stratus. However, it is only theoretically possible to artificially decrease the air temperature to the dew point in any region. In fact it is very expensive and will lead to the condensation of moisture on the cooling tools and drying of air.

The role of hygroscopic nuclei of condensation is well known.[14] The nuclei can be injected artificially as well as the additional moistening, for example, as it is applied to creation of the upper and middle layer clouds.[6] The effect of AM mixing also plays its role here.

One should consider in detail the 7-th condition. It is the presence of upwelling fluxes or some circulation in the cloud. Indeed, it is known[13] that each kind of clouds has its own vertical motion. They provide the existence of cloud as a whole. The circulation in a closed contour is maintained in a cloud. It is confirmed by photos from space[18] where the artificial cloudiness formed in the aircraft and ship aerodynamic trails is presented. Under certain conditions, this cloudiness is quite stable and horizontally extended (see Table I).

The artificial circulation can be created, for example, in the aerodynamic trails of such a vehicle as airplane, helicopter, and ship. It will make it possible to stimulate creation of artificial nonconvective cloud formations and increase the values of their STC.

Since ACF develop under the inversions, the repetition of inversions in the atmospheric boundary layer (ABL) was considered in order to determine the probability of their appearance. Climatically it occurred to be quite high. The frequency of inversion occurrence is 80–90% in winter over Russian Federation (more than 90% over Arctic) and 60–80% in summer morning. For operative estimates it is expedient to use the acoustic probe[4] for determining the entrapping layer height, in addition to the radiosonde data. Since we had not it, we had to use the signal pistol or smoke gun when conducting field experiments. At the vertical shot, the smoke track is bent due to the wind at the upper boundary of inversions. Below it the optimum altitude for injecting the reagent is situated. In addition, when planning the work, we created a special map of the 300-m layer, that characterized the distribution of the vertical temperature gradient γ in this layer over the area covered by the ring map of Moscow region. The technique for creating such a map from the radiosonde data is described in Ref. 12.

To determine the geometrical size of the aerodynamic trail behind a helicopter, its numerical simulation was carried out using the discrete vortex method[1] at the first turns of the carrying propeller.

When considering the remote aerodynamic fields of the helicopter, we used the A.V. Larin and V.I. Mavritskii discovery[9] on the secondary vortex formation, where the circulation occurs in a closed contour. Then the injection of water vapor or reagent into it results in their concentration in a half-closed space. That makes the results of field experiments similar to the laboratory ones.

We carried out more than 10 series of field experiments on creating the artificial cloud formations using the MI-6 and MI-8 helicopters. They were carried out in the Middle Belt of Russia in winter and summer at air temperatures from −27 to +32°C in the atmospheric boundary layer. Atmospheric pressure varied from 990 to 1027 hPa. Air humidity varied in the wide range from 27 to 100%, and the wind speed varied from 0 to 10 m/s near the ground and reached 60 km/h at the working altitudes.

According to the radiosonde data, as a rule, near ground inversion was observed in the morning and in the evening, and weak instability near the point of convection was observed on warm days. Such weather phenomena as haze, rain, and snow in winter were observed.

The results of experiment varied depending on the weather conditions. The analysis shows that the STCs of the created clouds most strongly depend on the thermodynamic stability of the air layer. The maximum cloud size was observed on June 9 in the evening, when the near ground inversion had formed. When it had intensified by 8 p.m., the size of a cloud created at the injection of the same quantity of reagent at the same altitude and flight speed of 120 km/h increased. Maximum size of the cloud created was 500×260 m in 3 min. One cloud existed more than 10 min, while another one disappeared on the cloudiness background.

In order to increase the efficiency of creating the artificial cloud formations over sea, the numerical hydro- and aerodynamic simulation of the ship model was carried out for determining the characteristics of the aerodynamic trail. As in helicopter case, we paid the main attention to the role of the 7-th condition of cloud development, namely, for creation of artificial circulation in a closed contour.

L.G. Kachurin[8] primarily studied the variations of thermohygrometric characteristics of horizontal streams, in general, and aerodynamic trails, in particular, but we paid attention to the study of STCs of the aerodynamic trails and its intensity.

The plane model was considered for numerical simulation, and calculations were carried out based on the discrete vortex method.[1] The main results are shown in Fig. 1, where it is seen that the cross section of the aerodynamic trail has the ellipse shape and expands when moving away from the stern. The elevation angle α is equal to 7°, and the expansion angle of the track in horizontal direction is γ = 11°.

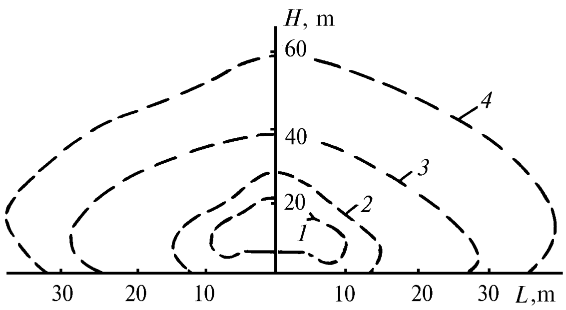

FIG. 1. Shape and size of zones of active turbulent mixing (aerodynamic trail) perpendicular to the ship axis, as obtained from the numerical simulation of the plane ship model at the distance from its bow of 65 *(1),* 140 *(2),* 260 *(3), and* 455 m *(4).*

A three-dimensional model of a ship was blown around in the aerodynamic tube at the angles of β = 0, 30, 90, and 180°. The three-dimensional model was also studied in the hydrotray. The vortex structure of aerodynamic trail was better observed in the first case by means of the vapor screen method,[1] and the vortex axis shown by the pigmented stream was better observed in the second case. It made it possible to determine the optimum points of mounting the sprayers for injecting the reagent and the regime of their operation.

Elevation angle α of the vortex track at the aerodynamic blowing was 11°, and the track expansion angle γ was 58°. It is greater than in the numerical simulation of the plane model, that can be explained by the effect of the symmetrical deck superstructure. Some characteristics of the vortex areas from the data of tube and field experiments are given in Table II.

TABLE II. Some characteristics of the vortex areas from the data of tube (t) and field (f) experiments for the flowing around at the angle β = 0° *and* 30°.

Cross section	β = 0°				β = 30°			
	Altitude of the vortex area, m		Vortex radius, m		Altitude of the vortex area, m		Vortex radius, m	
	t	f	t	f	t	f	t	f
I	5.6	–	1.3	–	6.0	–	1.4	–
II	8.4	10	2.25	2.4	10.0	13	3.0	4.5
III	15.5	17	–	2.8	14.5	18	–	–
IV	17	–	–	–	14.0	20	–	–
V	16	–	–	–	14.0	28	–	–

Analysis of the data from Table II shows a satisfactory agreement between actual and calculated characteristics, because the order of their magnitude is the same, and the values in the field experiments are, as a rule, only 15–30% greater than in the tube experiments. The exception is the altitude of the vortex area in the section V (at the stern) for blowing of the model under the angle of β = 30°, where the difference is 100%.

The patterns of flowing around the model in experiment and the ship in field tests coincided very accurately. In both cases air vortex on the lee side falls on the surface (water) and does not develop. This shows that one should switch off the sprayers on this side to use the reagent sparingly. In general, the pattern of vortex fluxes in the experiment is more idealized than in the field tests. However, the cost of the latter is 2–3 orders of magnitude higher.

The conditions of the development of cloud lanes following the sea ships were compared with the conditions of development of analogous lanes formed behind small (less than 50 km diameter) islands.[17] They occurred to be very similar. The exception is the contribution of fuel burnt in ship power-plants that are absent on islands. However, the calculations carried out for six kinds of ships showed that such a contribution into the formation of the cloud lanes can be essential only at the relative humidity of 98% at positive temperature and 95% at negative one.[11]

In addition to such a direct calculation of additional moistening of an aerodynamic trails of sea ship due to burning fuel, the role was assessed of isobaric mixing of exhaust gases and ambient air in formation of the cloud tracks behind a sea ship. It is known that there are two competing processes in mixing: moistening, which approaches the mixture to saturation, and heating, that moves it away from this state. Boundary conditions for these processes have also been determined. According to Ref. 15, humidity of the gas mixture can be determined by the formulas:

$$s(T) = \frac{(ls_1 - s_2)(T - T_2) + s_2(T_1 - T_2)}{(l-1)(T - T_2) + (T_1 - T_2)}; \quad (1)$$

$$e(T) = \frac{(l\,e_1 - e_2)(T - T_2) + e_2(T_1 - T_2)}{(l-1)(T - T_2) + (T_1 - T_2)}; \quad (2)$$

where $l = C_{p2}/C_{p1}$ is the ratio of heat capacities; e is the partial pressure of water vapor; s is its mass fraction. Temperature and humidity characteristics with subscripts 1 and 2 refer to the masses mixed, while without indices it refers to the mixture.

The formulas (1) and (2) can be reduced, for $l = 1$, to the form:

$$s(T) = \frac{\Delta s}{\Delta T}(T - T_2) + s_2\,,\ e(T) = \frac{\Delta e}{\Delta T}(T - T_2) + e_2\,. \quad (3)$$

These relationships make it possible to determine humidity, at any temperature of the gas mixture T varying within the range from T_1 to T_2, from the known initial values of characteristics of the gases to be mixed. Then relative humidity f is described by the expression $f = e(T)/E(T)$ where $E(T)$ is the pressure of saturated water vapor.

If $\Delta e/\Delta T \ge \Delta E/\Delta T$, the tracks are formed. The value in the left-hand side depends on the hydrogen content in the fuel. The boundary of cloud track formation is the tangent to the curve of temperature dependence of saturation pressure.[14] These tangents and all secants characterize the processes yielding the track formation, and no tracks are formed below the tangent. More high temperatures of the cloud track formation behind sea ships in comparison with the airplane and helicopter tracks[10,14] are explained by the fact that temperature at the turboprop engine (TPE) nozzle is more than 1000°C, and it is one order of magnitude less at the sea ship exhaust pipe nozzle. So $\Delta s/\Delta T = 0.0336\cdot 10^{-3}(°C)^{-1}$ for TPE, and this ratio is one order of magnitude greater for sea ships (see curve *2* in Fig. 2). Curve *2* is drawn for the pressure $p = 1000$ hPa and the analogous curves for the lower pressure values are above it, up to the curve *1* that characterizes the dependence of $\Delta E/\Delta T$ on air temperature and humidity.

As follows from Fig. 2, the cloud track formation behind sea ships can be observed at temperatures higher than 28°C, especially in the context of the planned changing for fuel with higher hydrogen content.[3] By injecting water into the exhaust gases, or increasing the content of hydrogen, which can oxidize, it is possible to create the artificial cloud lanes behind sea ships. On the contrary, by cooling and drying the exhaust gases, one can decrease the probability of formation of such lanes of anthropogenic origin.

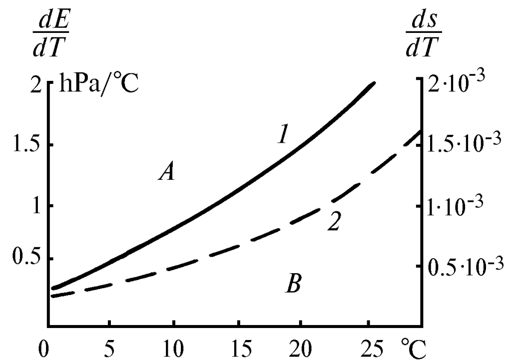

FIG. 2. Cloud track formation behind ship at isobaric mixing of exhaust gases and air as a function of temperature and humidity of the latter as well as the fuel properties. Area A: lanes appear, B: they do not appear; dE/dT (curve 1) and ds/dT (curve 2) as functions of temperature.

Taking into account all the aforementioned theoretical outcomes, the field experiments on creation of artificial cloud formations over Baltic and Black Seas were carried out in summer. A group of 15 persons headed by the author provided collection of hydrometeorological data. The standard meteorological and aerological data were used, including the protocols and weather maps (near ground and high-altitude ones), as well as the results of radio sounding of the atmosphere, nephanalysis maps and cloud pictures taken from space. Photo- and video recording of the experimental results and description of the experimental process have also been done.

All experiments were carried out in the morning and at daytime, when it was possible to observe the artificial cloud formations and make pictures from coast, ships, and airplanes. The reagent was injected from the ship, bow stern or the sprayers along all the ship side. The ship moved at different angles to the wind, the speed varied from 0 to 50 km/h. Taking into account the sprayer location on the ship and relations between its movement and wind vectors, all techniques for injecting the reagent were reduced to six typical. The techniques when the ship moved exactly against the wind and ejected the reagent from the bow or from the stern occurred to be the most promising from the point of view of stability of the artificial cloud formations.

In addition to the standard meteorological data, the results of gradient observations up to the height of 8–12 m on the ship were used as well as the data of tied radiosonde at 90 m height. Similar data were obtained over the ground up to 300 m with a 10 m step. The data were related to the data of the nearest radiosonde launched every 6 hours. Water temperature was measured to the depth of 40 m. The AT-925 and AT-850 altitude maps were used for the analysis.

Generation of artificial clouds was strongly affected by the state of the near-water layer, and the main attention was paid to its analysis. The influence of wind velocity on the stability of the created cloud formation was examined at the ship movement along a circle of 1000 m radius at the speed of 50 km/h. The results of this experiment were photographed from an An-26 airplane at the altitude of 300 m. They confirmed the conclusion that the side wind decreases the stability of the created formation, while the head wind increases it due to high speed of air flowing around the ship and appearance of a more dense track. The circulation created along a closed contour resists the natural one. As a result, the formation moves along the leading flux as a whole.

The results of one of the experiments were recorded on the radar screen (see Table III), and the other was photographed from the Meteor-3 satellite. From the evolution of the cloud patch on the radar screen, it is estimated that it moved to the east along the leading flux at a speed of 5 m/s, and its area was 60 000 m^2 in 1 min, and it increased up to 800 000 m^2 in 15 min.

TABLE III. Variations of the horizontal size of the cloud created in one of the experiments observed on the radar screen in 1, 10, *and* 15 min *at different distances.*

Time, min	1	10	15
Distance, m	300	3000	5400
Horizontal size, m	200×300	400×1800	800×1000
Area, m^2	60000	720000	800000

The created cloud has been recorded from a satellite only once, when the satellite flew in 1 hour and 55 min after the reagent injection. During this time the cloud was blown by the north-east wind to the south-west of the city of Sevastopol' at a distance of 30 km, that is quite real for the wind speed of 4 m/s. It was observed at this distance on the satellite picture, and its size was 50×10 km. According to the An-26 airplane data, it was at the altitude of 200 m under the inversion layer that was observed on the aerological diagram of radiosonde obtained at 09 a.m.

Air temperature during the experiments varied from 12°C over the Baltic Sea to 25°C over the Black Sea, and water temperature varied from 13 to 24°C, respectively. Humidity varied from 100 to 54%, i.e. high values were observed over Baltic Sea, and low values over Black Sea. Similarly, in the first case the swell was 2 to 3 points while in the second case it was only 1 or 2 points. Sometimes the sea was calm. It was determined by the wind speed. It varied from 2 to 17 m/s (mostly, 8–12 m/s) over Baltic Sea, and 1–6 m/s over Black Sea, and there was only one day when the wind speed reached 10–12 m/s. Wind was observed in practically all directions.

According to the radiosonde data, the stable stratification in the form of inversion or isothermy was mostly observed in the morning, especially in the near-water layer. It was kept during whole day independently of the wind speed. Atmospheric pressure varied from 1025 hPa over Baltic Sea to 997 hPa near Sevastopol'. The haze with the visibility range of 4 km was observed, as well as the rain over Baltic Sea.

Poorer weather conditions and turbulent state of the atmosphere over Baltic Sea determined the experimental results. Mean values of STC of the formations created near Baltiisk and Sevastopol' are presented in Table IV. The analysis of its data shows that in the second case their length and lifetime are 1.5 times greater than in the first case, thickness is 1.2 times greater, and the width is 10 times greater. It should be noted that the anomalously great size of the created cloud once recorded from satellite was not taken into account.

TABLE IV. Mean STC of the formations created in the field experiments over Baltic and Black Seas.

STC types	Length, m	Thickness, m	Width, m	Lifetime, min
Baltic Sea	800	150	50	8
Black Sea	1300	180	530	13
Taking into account the anomalous case photographed from satellite	5350	180	1320	22

The field experiments carried out over the sea made it possible to draw some conclusions. The main effect on the variations of STC of the formations created using the ships is due to:

1. Stratification of the lower part of the ABL (the stable one favors the increase of STC of the artificial cloud formations, and the unstable one favors the decrease).

2. Direction of the ship motion relative to the wind (β) and the speed of its motion. The highest efficiency of creation of artificial cloud formations is reached at the ship motion against the wind ($\beta = 0$). This effect can exceed the effect of ABL instability for some time. STC decrease at the side wind ($\beta > 0$) and especially at the fair wind.

3. Wind speed that has dual effect. The wind less than 2 m/s and the weak turbulence connected with it favor keeping the artificial cloud formation, and it spreads slowly. The wind more than 5–6 m/s at the ship motion against the wind favors the creation of the intense track and the increase of the artificial cloud formation stability, and the strong turbulence connected with such a wind spreads the cloud quickly, especially at the side wind.

Unexpectedly no effect of relative humidity on STC of artificial clouds was observed. It can be explained either by the fact that the cloud consists of aerosol, and the reagent injected is not hygroscopic, or by the effect of water from the water surface that could be strong due to the strong induced turbulence.

Absolute values of such weather characteristics as atmospheric pressure, air and water temperatures did not influence (if only due to small variations).

Elevation angle of the cloud α varied in field experiments by order of magnitude from 3 to 31° depending on the air flux speed and stratification of near-water air layer. It was 11° in the wind tunnel at the flow speed of 26 m/s. It is greater than the speed of the head wind.

In general, the results of field and laboratory experiments coincided in both the circulation type and its intensity. The highest efficiency of creating artificial cloud formations is reached at the ship motion at the maximum speed windward. At the side wind, the cloud on the lee side "fallsB on the water and does not develop. When creating the cloud at the ship drift, it develops along the vertical direction and is unstable.

The results of the field experiments are in a good agreement with the results of numerical simulation for the elevation angle $\alpha = 7°$ ($\tan\alpha = 0.1$). However, the horizontal vortex extension angle is $\gamma = 11°$. It can be explained by consideration of the plane ship model (without deck superstructure).

In general, the analysis of aerometeorological conditions of development of the cloud formations of anthropogenic origin and artificial ones shows their identity. In addition to purely aerometeorological conditions noted in the beginning of this paper, the 7-th condition is an important impetus for cloud development. It is the powerful turbulent zone of disturbed air, that appears at the airplane or helicopter flight and sea ship motion. When there is an entrapping layer in the atmosphere, air masses with different properties are mixed above it, and the products of fuel burning are accumulated in the form of additional moistening and condensation nuclei. Thermohygrometric conditions for appearance of ACF can be changed both increasing and decreasing the probability of their appearance.

The first is reached mainly due to the first four conditions noted in the beginning of this paper. The effective and quite new is the effect on the 7-th condition, i.e. the induction of the artificial circulation by means of creation of the aerodynamic trail. As a result, the reagent injected hits to the area with circulation along a closed contour and moves as a whole with slow destruction under the effect of atmospheric circulation.

However, practically all cases of extension of the boundary conditions, geometric size of the created formations and their stability occur to be 1–2 orders of magnitude less than the formations of the anthropogenic origin have (see Tables I and IV). This can be explained by the fact that many thousands of aircrafts and ships are ploughing air and ocean, and only a few of them enter the atmospheric layer with metastable state. We did not manage to conduct the experiments in such conditions.

One can decrease the probability of appearance of anthropogenic formations for aircrafts by changing the altitude, i.e. to fly above the entrapping layer[10] or in the layer with low humidity, and for ships by changing the motion direction relative to the wind, i.e. so that the wind is side. In addition, one can dry the exhaust gases of the ship, or to decrease the hydrogen content in the fuel used.

One can decrease the probability of the smog appearance by ventilating the ABL by means of a meteotron.

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