Methodological approach to the problem of increasing precipitation in specific physical and geographical regions of Russia by affecting cloud cover

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Annotation. The article presents a methodological approach to the problem of increasing precipitation in a specific physical and geographical area of the country by modifying clouds of various shapes in order to cause artificial and intensify natural precipitation. The implementation of this approach is carried out in the work on the example of the central region of the European territory of Russia (Moscow).

1. Introduction
Among the main areas of work in Russia on the impact on clouds and fogs (the dispersion of fogs and low clouds over airports, the fight against hailstorms in the southern regions of the country, weather protection of large cities, etc.), a significant place is occupied by measures to increase precipitation. The need for this kind of work is due to the fact that the increase in precipitation by affecting clouds of various forms can contribute to solving a wide range of applied tasks: increasing crop yields, accumulating snow reserves in the cold half of the year in river basins and reservoirs, redistributing precipitation in time and space, extinguishing forest fires and preventing their occurrence, cleaning the air basins of large cities, etc. [1-3].

Based on this, it is relevant to evaluate cloud resources over different physical and geographical regions (FGR) of Russia in relation to the problem of exposure in order to increase precipitation in different seasons of the year. In this paper, the central region of the European territory of Russia (CR ETR) is taken as the study area, which is determined by its socio-economic significance. The capital of the Russian Federation is located in this area, where cultural and sports events are repeatedly held every year, requiring work on weather protection, including in terms of precipitation redistribution [4, 5].

The aim of the work is to develop a methodological approach to the problem of increasing precipitation by affecting clouds of various shapes.

2. The main stages of the methodological approach
The first stage of the proposed approach is to substantiate the relevance and feasibility of work to increase the amount of precipitation in a particular FGR of Russia. This stage is reflected in the introduction in relation to the ETR CR selected in the work.

The second stage of the work is to justify the selection of the initial data necessary for conducting research. As the main source material, the authors used the protocols of aircraft atmospheric sounding (AAS) TAE-7.7m over Vnukovo airport (Moscow) for 1953-1964. Their choice is due to the following circumstances [6-8]:
first, the most complete and accurate values of the characteristics of meteorological variables and phenomena (water content, water reserve, phase structure, heights of the lower and upper cloud boundaries, temperature characteristics, precipitation, icing, etc.) can be obtained only with the help of the AAS. No other means (in particular, aerological, radar, space) can achieve such accuracy in measuring the characteristics of clouds today [6]; secondly, the statistical sample of the AAS materials over Vnukovo airport is representative and includes about 6,000 ascents of sounding aircraft. It allowed us to obtain statistically supported estimates of the suitability of clouds of various shapes for exposure to a specific purpose for the seasons and half-years for the selected area; third, the data obtained for Moscow can be considered representative of the area under consideration. The basis for this is the results of studies of the spatio-temporal variability of the characteristics of clouds, primarily undulatus and stratiform [7, 8]; fourth, the materials of the TAE-7.7 m AAS allow us to obtain the most objective assessment of the suitability of clouds for exposure, taking into account the relevant criteria available to date. For example, clouds with a vertical length of the cloud layer of at least 250-300 m, a drop or mixed structure, with a cloud temperature of no more than minus 4 °C and located above the earth's surface of no more than 1000 m are considered suitable for causing precipitation from undulatus and stratiform clouds [9]. When the clouds are affected in order to intensify precipitation, the value of the height of the lower cloud boundary is removed from the criterion [9].

Convective clouds (mainly powerful cumulus clouds) with a vertical length of at least 2000 m, a drop or mixed structure with a cloud temperature of no more than minus 4 minus 5 °C are considered suitable for the purpose of causing artificial precipitation [10]. The specific values of the cloud characteristics included in the relevant criteria for suitability for exposure leave no doubt about the correctness of the choice of the TAE-7.7m AAS protocols as the main working material for the study.

The third stage of the proposed methodological approach is to determine the main forms of clouds that are a source of additional precipitation during exposure in order to cause artificial and intensify natural precipitation in the cold and warm half-years. It is known from cloud physics [11] that in natural conditions precipitation can fall from wave-like (layered (St), layered-cumulus (Sc), high-cumulus (Ac)), layered (layered-rain (Ns), high-layered (As), cloud system Ns-As) and cumulonimbus (Cb) clouds. Therefore, the clouds of the above-mentioned forms can be an object of influence for the purpose of intensifying precipitation.

The practice of working on the effects on clouds has shown that a certain amount of precipitation can also be obtained by affecting all the forms of undulating clouds listed above that do not give precipitation, as well as by affecting the cloud systems Ns-Sc (without precipitation), As clouds (without precipitation) and convective clouds (mainly power-cumulus (Cu cong). Taking this into account, it can be seen that the main forms of clouds as objects of impact for obtaining additional precipitation can be: St-Sc, Ac, Ns-Sc, Ns, As, Ns-As and Cu cong clouds 2-5, 10, 12].

The definition of clouds of specific shapes as objects of influence in order to increase precipitation, in turn, makes it necessary to obtain data on their repeatability in specific FGRS of Russia (in our case, the CR ETR). The results of research in this direction based on the materials of the SZA over the Vnukovo airport are presented in table. 1. The possibility of conducting such a study on the protocols of the AAS is justified in the work of Zavarina M.V. and Gaul M.L. [13]. The authors showed that the AAS materials sufficiently well reflect the distribution of clouds of various shapes, and the cloud cover characteristics obtained from them are reliable.

When processing the AAS protocols, continuous single - and multi-layered layered and layered-cumulus clouds, observed both separately and in combination with high-cumulus clouds, were considered to be undulating.
Table 1. Relative repeatability (%) of continuous cloud cover of various shapes.

| Season, half-year | Only St-Sc (single-and multi-layer) | St-Sc in combination with Ac | Ns, Ns-As | As | Ac | Cu, Cb only | Cu, Cb in combination with clouds of other forms | number of ascents of sounding aircraft |
|-------------------|-------------------------------------|-----------------------------|-----------|----|----|-------------|-----------------------------------------------|---------------------------------------|
| Winter            | 46,3                                | 11,7                        | 19,8      | 17,6 | 4,3 | 0,1         | 0,2                                           | 1645                                  |
| Spring            | 24,4                                | 9,7                         | 14,9      | 19,4 | 13,7 | 7,9         | 1,0                                           | 1333                                  |
| Summer            | 11,8                                | 8,0                         | 7,9       | 11,4 | 18,8 | 20,5        | 21,6                                          | 1350                                  |
| Autumn            | 44,1                                | 11,0                        | 15,1      | 13,9 | 8,9  | 2,5         | 4,5                                           | 1545                                  |
| Cold              | 45,7                                | 12,0                        | 19,1      | 17,8 | 4,5  | 0,2         | 0,7                                           | 2585                                  |
| Warm              | 22,7                                | 8,58                        | 11,2      | 13,69| 15,1 | 12,7        | 14,6                                          | 3288                                  |

When considering layered clouds, two classes of them were considered. The first class included layered rain clouds, which are observed both separately and in combination with other cloud forms, including As clouds. The second class includes As clouds that are observed both independently and in combination with other cloud forms (excluding Ns).

The analysis of the data in table 1 allows us to conclude that St-Sc clouds (with and without precipitation) in the CR ETR can be one of the main objects of influence on them both for the purpose of causing artificial and for the purpose of intensifying natural precipitation.

Another object to influence in order to intensify precipitation during the year (except in summer (7.9%)) these are Ns clouds and Ns-As cloud systems.

The above trends in the distribution of Ns, Ns-As clouds by season and half-year are fully valid (except for summer) for the distribution of As clouds, but the values of the repeatability of these clouds are slightly lower. So, the frequency of As clouds in the cold half of the year accounts for 17.8%, in the warm -13.9%.

In general, the frequency of frontal clouds in the cold half of the year accounts for 36.9% (with the maximum occurring in the winter (37.4%)), in the warm half – 25.2%. It follows that frontal layered clouds can also be one of the main objects to influence in order to increase precipitation.

High-cumulus clouds have a noticeable repeatability, mainly in the warm half of the year (15.1%), with the maximum repeatability occurring in the summer – 18.8%. However, it is unlikely that such clouds will be an object of influence for the purpose of causing artificial precipitation.

As for convective clouds, which are observed both independently and in combination with other forms of clouds, it can be noted that they are observed mainly in the summer – 18.8 and 20.5%. In general, the frequency of convective clouds in summer accounts for 42.1%, in the warm half of the year – 27.3%. It is quite obvious that in the warm period (and, first of all, in the summer), along with frontal layered clouds, the main object of influence for the purpose of increasing precipitation can be over the considered area convective clouds (first of all, powerful cumulus).

The impact on cumulonimbus clouds (Cb) is unlikely to be carried out, since the use of aviation means in this case is not possible.

The data obtained above regarding clouds of predominant forms necessitate the next stage of the study, which is to obtain quantitative estimates of the suitability of clouds for the purpose of causing and intensifying precipitation. The results of the research carried out in this direction constitute the content of the fourth stage of the methodological approach.
Below are quantitative estimates of the various forms of supercooled clouds that are suitable for exposure. So, in the table, 2 such estimates refer to supercooled undulatus clouds over the CR ETR.

**Table 2. Repeatability (%) of supercooled undulating clouds suitable for exposure.**

| Impact goal            | Season | Half-year |      |      |      |
|------------------------|--------|-----------|------|------|------|
|                        | Winter | Spring    | Summer | Autumn | Cold | Warm |
| Causing precipitation  | 40.9   | 19.1      | –     | 14.2  | 37.2 | 5.6  |
| Precipitation intensification | 45.8 | 32.5      | –     | 25.9  | 43.8 | 10.7 |

From the analysis of the data in table 2, it follows that the repeatability of supercooled wave-like clouds suitable for causing precipitation in the cold half of the year accounts for 37.2% (in winter – 40.9%), in the warm half – 5.6%; for intensification – 43.8% (in winter – 45.8%) and 10.7%, respectively. In spring and autumn, St-Sc clouds that produce precipitation in natural conditions have a noticeable repeatability, that is, the repeatability of such clouds to influence in order to intensify precipitation is 32.5% and 25.9%, respectively, in these seasons.

Table 3 shows the data on the repeatability of supercooled frontal layered clouds (FLC) (with and without precipitation).

**Table 3. Repeatability (%) of suitable frontal layered clouds.**

| Impact goal            | Season | Half-year |      |      |      |
|------------------------|--------|-----------|------|------|------|
|                        | Winter | Spring    | Summer | Autumn | Cold | Warm |
| Causing precipitation  | 26.9   | 10.5      | 0.6   | 5.2   | 23.9 | 2.8  |
| Precipitation intensification | 44.0 | 36.7      | 1.1   | 25.0  | 44.1 | 14.0 |

Analyzing the data given in table 3, we can draw the following conclusions:

- it is advisable to influence the FLC in order to cause artificial precipitation only in winter (26.9%);
- the impact on the FLC for the purpose of intensifying precipitation can be carried out in winter (44.0%), in spring (36.7%) and, much less often, in autumn (25.0%). As a result, the frequency of such clouds, suitable for intensifying precipitation in the cold half of the year, accounts for 44.1%.

It is important to note that in the vast majority of cases, a single layer is suitable for both intensifying and causing artificial precipitation. Thus, the repeatability of the suitability of one layer for causing precipitation is 87.7% in the cold half – year, 92.9% in the warm half-year, and 90.4% and 90.9% for precipitation intensification, respectively.

The above results of studies on the repeatability of suitable wave-like and layered clouds allow us to conclude that in the cold half of the year, the main amount of additional precipitation can be obtained when the Ns and Ns-As cloud systems are exposed. This is due to the fact that the vertical extent of such clouds is much greater than that of undulating and frontal layered clouds without precipitation. However, it is also necessary to take into account the fact that the Ns and Ns-As suitability ratings are higher than the estimates of the suitability for the effects for causing precipitation of undulatus clouds and FLC without precipitation.

A study based on the materials of the AAS of the forms of convective clouds for the months of the warm period of the year over the CR ETR showed that in the afternoon hours, powerful cumulus clouds are most often observed. The average values of the recurrence of convective cloud forms for the three summer months were: for cumulonimbus flat (Cu hum), cumulonimbus medium (Cu med) and powerful cumulonimbus clouds (Cu cong)-7.0, 8.0 and 75.0%, respectively. In general, during the
warm half of the year, Cu hum clouds are observed in 12% of cases, Cu med – in 13% of cases, Cu cong-in 75% of cases [14]. Therefore, it can be concluded that in the warm half of the year over the CR ETR, the main object of influence for causing artificial clouds will be the Cu cong clouds.

Below, in figure 1, we present data that characterize quantitative assessments of the suitability for exposure to cause precipitation from convective clouds (Cu cong) in the months of the warm half of the year [14].

![Figure 1. Repeatability (%) of convective clouds suitable for causing precipitation over the CR ETR.](image)

As follows from the data shown in figure 1, on average for the warm half of the year, convective clouds are suitable for impact in 48% of cases. The maximum repeatability is observed in May (55%), the minimum – in September (32%), which can be explained by a greater degree of warming of the troposphere in August compared to May.

The quantitative estimates obtained in this paper of the suitability for the impact of clouds of various forms for the purpose of causing (intensifying) precipitation on the CR ETR are necessary both to justify the possibility and feasibility of planning and conducting such work, and to obtain calculated quantitative estimates of additional precipitation in the area under consideration. At the same time, in the future, it is necessary to obtain data on the water content and water reserve of convective clouds (in particular, Cu cong), the phase structure, the vertical extent, stratification, the width of the cloud cover, etc.

To date, in relation to the CR ETR, there is information in the literature about the phase state [15], water content and water reserves of undulatus and stratiform clouds [16], temperature and geometric characteristics of convective clouds [14] in relation to the impact problem.

In addition, a method of influencing supercooled undulatus clouds to cause precipitation has been developed [17], which includes the choice of a seeding scheme taking into account the time for turning, the seeding area, the reagent consumption, etc. The paper [18] presents a method for calculating the cost of measures to modify undulatus clouds.

In the future, it is planned to conduct research on the development of methods for calculating the amount of additional precipitation when exposed to all forms of clouds that are suitable for causing artificial and intensifying natural precipitation.

One of the stages of the proposed approach is to determine the list of applied problems that can be solved with increasing precipitation. In the first approximation, it can include the tasks listed in the introduction of this paper.

Of great importance is also the stage associated with the assessment of the technical capabilities for carrying out work related to the impact on clouds of various forms in order to obtain additional
precipitation. The analysis of works in this area shows that in our country there are quite specific technical means of both delivery and dispersion of chemical reagents for cloud seeding [2-4]. Currently, aviation vehicles (AN-12, AN-26, AN-30, YAK-42D, etc.) equipped with special devices and generators for dispersing chemical reagents (solid carbon dioxide, liquid nitrogen, silver iodide) are used as means of delivering reagents. Technical means of influence and their characteristics are described in detail in [1, 3, 19].

Ground-based generators and unmanned aerial vehicles can also be used as means of delivering chemical reagents [1, 3]. The technical implementation of means of influencing supercooled clouds and fogs (including on large areas – thousands of km2) is confirmed by a whole series of practical works on weather protection of large cities over the past 30 years [5]. In a number of the above works, the possibilities of reallocation of precipitation by time and place were successfully demonstrated. For example, as a result of the impact on the clouds over Moscow on May 9, 1995 [4] the precipitation layer within the city limits ranged from 0 to 1.3 mm, while at many weather stations around Moscow, the amount of precipitation significantly exceeded these values.

The proposed methodological approach to the problem of increasing precipitation can be applied to any FGR of our country. According to the authors of this work, it can also be useful in justifying the feasibility of planning, preparing and conducting work on the impact on clouds of various forms in specific physical and geographical regions of Russia without directly conducting field experiments.

3. Conclusion

– Using the example of the CR ETR, a methodological approach to the problem of increasing precipitation by influencing clouds in order to cause artificial and intensify natural precipitation has been developed. A brief description of the stages of this approach is given.
– Using the example of this area, it is shown that the main objects for the impact in order to increase the amount of precipitation in the cold half of the year can be mainly layered rain clouds and Ns-As cloud systems, in the warm half of the year – powerful cumulus clouds. A certain additional amount of precipitation in the cold half-year can also be obtained by affecting layered, layered-cumulus clouds (with and without precipitation) and frontal layered clouds without precipitation.
– It is shown that in our country, for the delivery of chemical reagents to the clouds (solid carbon dioxide, liquid nitrogen, silver iodide), there are appropriate technical means (for example, aircraft such as AN-12, AN-26, AN-30, YAK-42D, etc., equipped with special devices and generators for their dispersion).

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