საქართველოს მეცნიერებათა ეროვნული აკადემიის მოამბე, ტ. 6, №2, 2012
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 6, no. 2, 2012

Geophysics

Preventing Severe Convective Storm: Anticipatory Restratification of Lower Atmosphere

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ABSTRACT. **The distributed anticipatory restratification concept (DARC) points the way to prevent severe convective storm. DARC provides artificial discharge instability energy of moist unstable lower atmosphere by convective clouds proactively forced in the area to be protected. The paper discusses some problems associated with the implementation of distributed proactive forcing (DPF) (the previous scheme of DARC). It is shown that the so-called meteotron, previously developed as a technical means to increase rainfall in arid areas, can be much more effective through the realization of DARC in a moist unstable lower atmosphere close to the development of severe convective storm. As follows from the simplified analysis, the required trust of the meteotron and its single run time strongly depend on the distance up to the bottom of capping inversion, the other conditions being equal. This puts to the fore the implementation of the schemes with location of meteotrons on mountain tops and in the marine environment. On this basis the new scheme of imported proactive forcing (IPF) is proposed. The potential applications of IPF for preventing hailstorms in the Alazani Valley (with location of the meteotrons on the mountain tops) and excessive rains in Ajara (with location of the meteotrons in the marine environment) are considered. The potential of DARC to prevent the development of severe tornadoes is outlined. The evaluation is made showing that the main conclusion of simplified analysis of the strong dependence of the main operating parameters on the distance up to the capping inversion will remain in force after a thorough analysis of the problem as well.** *© 2012 Bull. Georg. Natl. Acad. Sci.*

Key words: *hailstorm, capping inversion,instability energy,convective available potential energy,distributed anticipatory restratification,imported proactive forcing.*

Introduction. R&D activities in the field of modification of convective clouds are mainly focused on the technology of cloud seeding to mitigate the hail impact [1-5]. There is also another approach aimed at restriction of the development of a severe convective storm by modification of its energy basis [6].

According to generally accepted ideas, in the warm season, a severe storm depends largely on the interaction between lower atmosphere warmed by the sun and the capping inversion [7-9]. Solar heating is a supplier of the instability energy (convective available potential energy (CAPE)) for the upcoming convective development. Capping inversion represents a remainder of a stable boundary layer formed through cooling the air by the earth surface in the night time.

After sunrise, the cool boundary layer is not completely destroyed by solar heating and gradually climbs into a capping inversion, limiting the convection height. In the daily cycle, capping inversion not only retards a lot of instability energy in the lower atmosphere, but contributes to the collection of a large amount of CAPE in a single convective cloud, supporting strongly the development of severe convective storm [6-9].

On this basis, DPF (the previous scheme of DARC [6]) points the way to prevent development of severe convective storm through discharging a great amount of CAPE, held under capping inversion, by several convective clouds, proactively forced in locations distributed across the territory to be protected.

The paper discusses the conditions for implementation of DARC. Strong dependence of the efficiency of the so-called meteotron on the distance up to the capping inversion is identified. The new scheme of imported proactive forcing (IPF) is proposed applied to the hailstorm problem in the Alazani Valley and excessive rains in the Autonomous Republic of Ajara. The potential of applying DARC to prevent strong tornadoes is outlined.

2. Conceptual basics of the study. The strength of a convective cloud depends on the instability energy involved in its development. The more CAPE is collected by the cloud, the stronger it becomes and the higher. According to [6], in pre-hailstorm situation, CAPE and absolute humidity in the lower atmosphere are more than 225 J/kg and 7×10^{-3}, respectively. Besides, “medium” hail-producing convective cloud collects CAPE at least from 1000-1500 km^2.

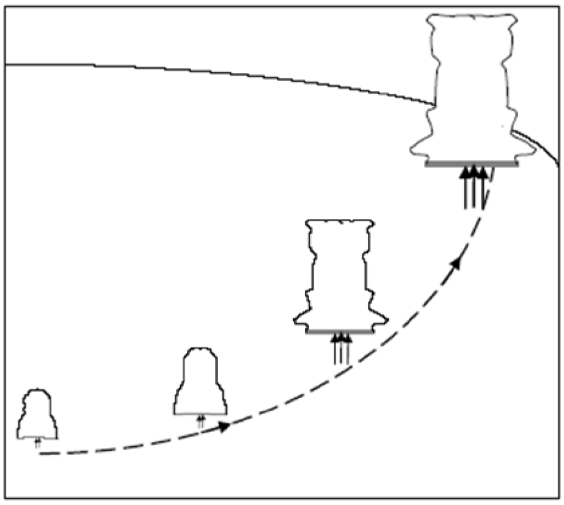

Fig. 1. A scheme of development of strong convective cloud.

A scheme of development severe storm is shown in Fig. 1. Since the first air stream breaks capping inversion, ascending air flow turns into the structure-forming dynamic core of the future convective cloud. At this point, capping inversion serves as a kind of “umbrella” collecting warm moist air in a single convective cloud from a large area.

As shown in Fig. 1, the cloud moves along the earth’s surface, permanently gaining strength. In addition, the cloud gradually discharges CAPE from adjusted area and prevents other pass-through channels on a large territory. Finally, such a cloud can lead to severe storm with possible dangerous consequences, such as a tornado, hail or thunderstorm.

According to modern concepts [7-9], pass-through channel rarely results in the break of capping inversion by internal convection and is mainly caused by external forcing. Interaction of regional winds or weather fronts with local orography, development of upslope flows by solar heating of mountains or combination of these mechanisms are typical forms of forcing.

Based on these provisions, DPF offers prevention of a severe convective storm by proactive discharge of previously accumulated CAPE by several convective clouds artificially formed in capping inversion [6].

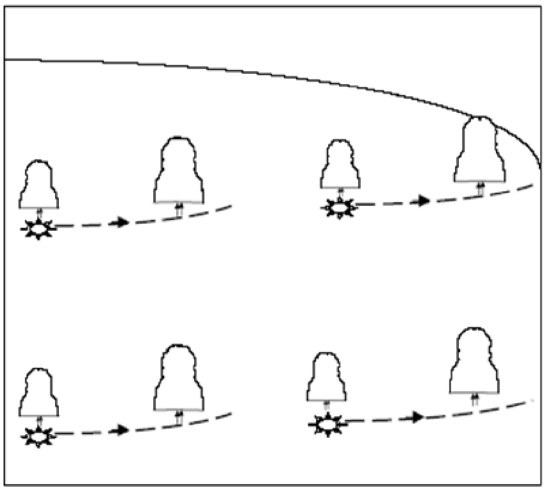

Fig. 2. A scheme of DPF moist unstable lower atmosphere using the meteotrons (eight-pointed stars).

A protection system based on DPF [6] is shown in Fig. 2. The meteotrons are uniformly distributed over the territory to be protected. When the monitoring system detects a pre-hail situation, the meteotrons are launched and a system of convective clouds is formed. After collecting the CAPE from the vicinity, a cloud can only move to an area where CAPE is already mastered by another cloud. Thus, each convective cloud remains underdeveloped with little chance to result in a severe storm. Integral effect should be sufficient to proactively “soft” discharge CAPE above all territory.

3. Conditions of realization of DARC and associated problems. Development of severe storm requires collecting instability energy from the area greatly exceeding the cross-section of the cloud. At low values CAPE required collection route proves very long, which extremely reduces the likelihood of a severe storm. The higher is CAPE the shorter the required collection route and the higher the chance of a severe storm.

The parameters of numerous severe storms observed in the USA in 1997-1999 are presented in Fig. 3 [10]. The estimate [6] also is shown. Gaining by CAPE and wind shear the role of main influential environmental parameters fully fit in the above logic (collection route depends on regional wind). An overwhelming majority of severe storms is observed at high values CAPE (200-3,000 J/kg) in the range of wind shear 5-15 m/s. Rare severe storms, corresponding to low CAPE (0.2-100 J/kg), are observed at high wind shears (20-50 m/s), that is, they are linked to

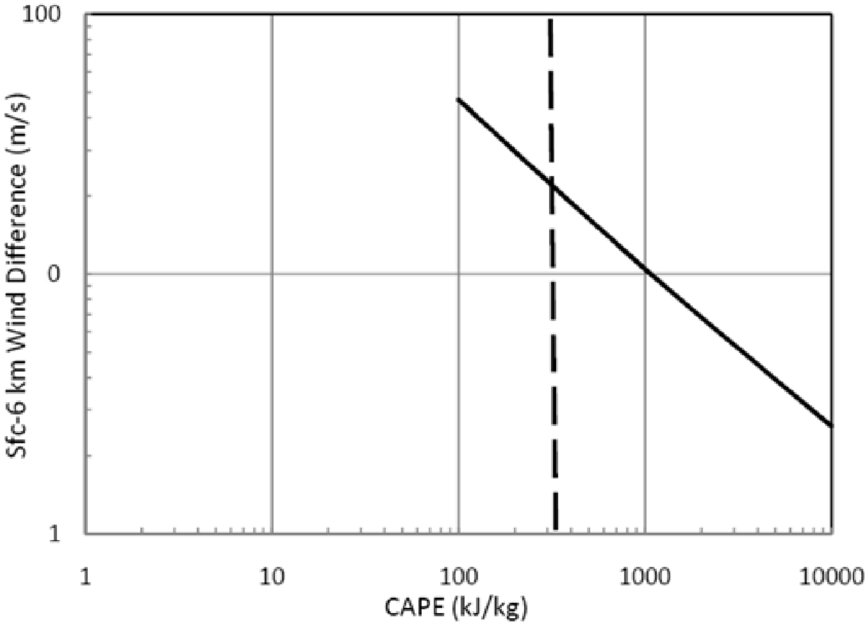

Fig. 3. The best discriminator of environmental parameters of the severe convective storms observed in the USA in 1997-1999 (sloping solid line) [10] and the estimate [6] (vertical dashed line).

long collection routes. The estimate [6] is in rough agreement with the results [10].

The estimate [6] also is roughly consistent with the analysis of convective storms observed in Europe during the warm seasons in 2006 and 2007 [11]: CAPE around 250 J/kg discriminates between thunderstorm and no thunderstorm group and predicts the probability of severe events when 500 J/kg is exceeded. Thus, proactive reduction of CAPE in the lower atmosphere may be an effective way to prevent a severe storm.

DPF should be supported by effective meteorological monitoring. Accurate identification of a pre-hailstorm situation may limit the number of startups of the protection system. The number of the meteotrons involved in a single run of the system also depends on the accuracy of the identification of a pre-hailstorm situation over the protected territory.

Another problem is prevention of a merger forced by the system clouds. According to [6] the merger can be avoided by keeping the distance between neighboring meteotrons more than 6-8 km. However, the estimate needs further validation.

4. Artificial forcing: Technical means and operational parameters. Previously, the so-called meteotron, burning petroleum products, was used to increase rainfall in arid areas [12]. Later the meteotron was improved by the use of a turbojet engine [13]. However, realized experimental systems proved insufficient for systematically obtaining precipitation in arid areas. The proposed new options with very powerful meteotrons [13] raise concerns in terms of economic feasibility.

The task is considerably simplified when implementing DARC. If in the arid zone the CAPE is about 50 J/kg [13], in the atmosphere with the potential to generate a severe storm CAPE exceeds 500 J/kg [11]. In the arid zone meteotron is to force cloud in a rather stable atmosphere, in the case of DARC the same should be done in unstable moist atmosphere close to natural initiation of cloud.

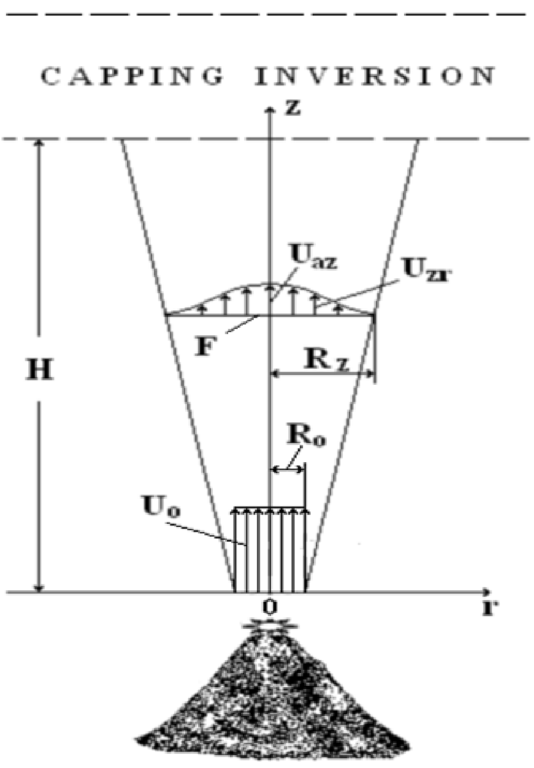

Fig. 4. A scheme of the ascending air jet between the meteotron and the bottom of the capping inversion.

In the case of mountain convection, almost every summer day, solar heating results in air updrafts that penetrate the capping inversion and contribute to forcing a convective cloud [14-15]. Acceleration of this natural cloud-forcing process by the meteotron also is obviously an easier task. A similar situation also occurs with the marine atmospheric boundary layer, where low location(800-1000 m) and relatively small thickness (200-400 m) of the capping inversions [16-17] especially eases the cloud-forcing.

Now let us look, at a first approximation, into the dependence of the development of an artificial air jet on the main parameters of the meteotron.

A scheme of the ascending air jet is presented in Fig. 4. We suppose that to overcome the capping inversion requires upward air jet with a certain specified maximum (axial) velocity (U_{aH}) at the bottom of the capping inversion. The total momentum (Q) and total kinetic energy (E) of the air mass in the jet can be equated to:

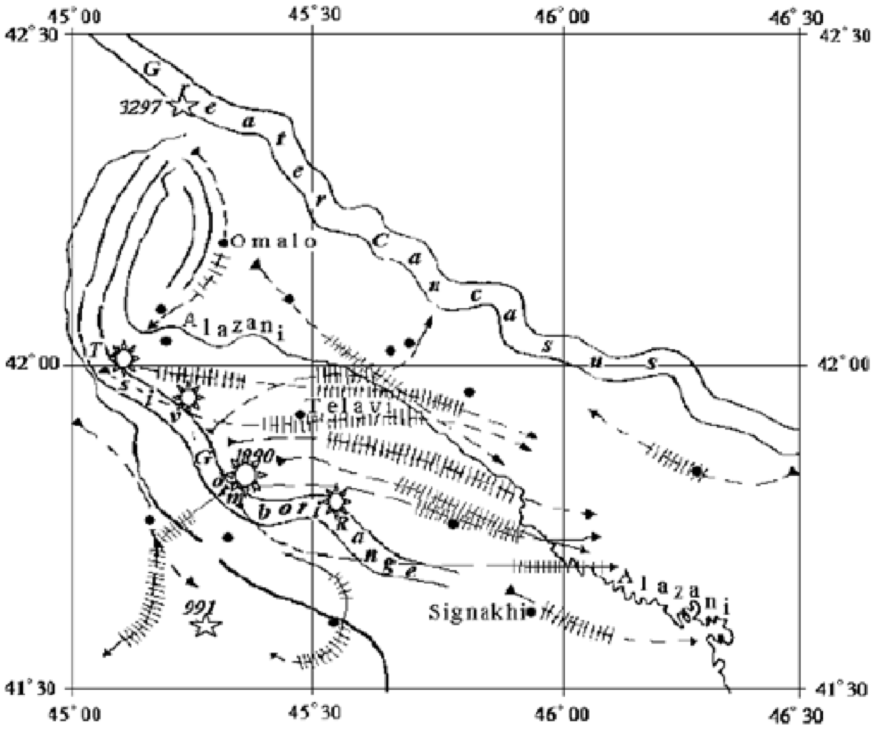

Fig. 5. The map of the Alazani Valley with natural centers forcing convective clouds (solid triangles), the most frequent hailstorm trajectories (dotted curves) and potential locations of the meteotrons (eight-pointed stars).

$$Q = \int_0^H \int_0^{R_z} \rho U_{zr} 2\pi r dr dz \tag{1}$$

$$E = \int_0^H \int_0^{R_z} \left(\rho U_{rz}^2 / 2\right) 2\pi r dr dz \tag{2}$$

Here, ρ is the density of the air; H is the distance up to the capping inversion; U_{zr} is vertical velocity of the air at the height z and the radius r; R_z and F_z are outer radius and transverse section area of the jet at the height z, respectively.

Since the jet velocity drops below 100 m/s at the height of 20 m above the meteotron [18], we neglect the momentum accumulated in this small initial section (the point z=0 is placed on the top of this section) and reduce the problem to propagation of the free isothermal isobaric circular jet of an incompressible fluid. Extra lift effect of heated air and the natural updrafts also are neglected. Compliance with the condition of $z/R_0 >> 1$ along nearly the entire height allows to use the following versions of the relations [19]:

$$U_{rx} = U_{az}\left(1 - \frac{3r^2}{R_z^2} + \frac{2r^3}{R_z^3}\right), \tag{3}$$

$$U_{az} = \frac{10.7 U_0 R_0}{z}, \tag{4}$$

$$R_z = 0.22z. \tag{5}$$

Here, U_{az} is vertical velocity at the axis of the jet at the height z; U_0 and R_0 are vertical velocity and outer radius at z=0, respectively.

Solutions of the inner integrals from (1) and (2), respectively, are:

$$\int_0^{R_z} \rho U_{az}\left(1 - \frac{3r^2}{R_z^2} + \frac{2r^3}{R_z^3}\right) 2\pi r dr = \\ = 0.3\pi R_z^2 \rho U_{az} = \pi R_z^2 \rho U_{am} \tag{6}$$

$$\int_0^{R_z} \left(\rho U_{az}^2 / 2\right)\left(1 - \frac{3r^2}{R_z^2} + \frac{2r^3}{R_z^3}\right)^2 2\pi r dr = \\ = 0.171\pi R_z^2 \left(\rho U_{az}^2 / 2\right) = \pi R_z^2 \left(\rho U_{ak}^2 / 2\right) \tag{7}$$

Here averaged by momentum (U_{am}) and by kinetic energy (U_{ak}) cross-sectional mean velocities are equal to:

$$U_{am} = 0.3U_{az} \quad (8)$$

$$U_{ak} = 0.414U_{az}\,. \quad (9)$$

It may be noted that the specific mean values (8) and (9) complement the other two mean values; they are listed in the fundamental reference book [20].

Next, we take the outer integrals and represent the final results relative to U_{aH} and H:

$$Q = \int_0^H 0.3\pi R_z^2 \rho U_{az} dz = 0.244\rho U_0 R_0 H^2 = \\ = 0.0228\rho U_{aH} H^3 \quad (10)$$

$$E = \int_0^H 0.171\pi R_z^2 \left(\rho U_{az}^2 / 2\right) dz = 1.49\rho U_0^2 R_0^2 H = \\ = 0.013\rho U_{aH}^2 H^3. \quad (11)$$

Since the total momentum is roughly equal to the product of the thrust of the meteotron and its single run time, we can state a very strong dependence of the operating parameters of the meteotron on the distance H at the constant U_{aH}. Below we shall return to the issue of the validity of this conclusion when considering the implementation of a particular case of DARC.

5. Alazani Valley: potential area for application of DARC. The Alazani Valley is the heart of Georgian province Kakheti. The valley stretches about 200 km and a width of about 50 km. From the south-west it is adjacent to Tsiv-Gombori Range, from the north and north-east it is bordered by the Greater Caucasus Range. The region rather frequently is affected by hail (Fig. 5) [21].

According to [21] several mountains of Tsiv-Gombori Range are the main cloud-forcing centers providing the valley by imported convective clouds. Reproduced trajectories represent the most repetitive events. Some hailstorms have more diverse trajectories.

Pre-hailstorm situations in Alazani Valley are linked to high CAPE in lower atmosphere [21]. The role of capping inversion is particularly strongly reflected by vertical distribution of absolute humidity. It remains in the range (7-11)×10^{-3} up to 2.5-3.0 km and decreases sharply at higher layers [21]. As for cloud-forcing, in full accordance with the above modern views, a significant role is played by the mountain upslope air flows linked to solar heating. Regional winds, cold and occluded fronts amplify the primary effects and import the arisen clouds into the valley.

In this context, the realization of DARC through the imported proactive forcing (IPF) can be proposed, reproducing in a modified form, the same natural import forced clouds.

IPF can be illustrated by the same Fig. 5. Compared to the natural base, the novelty is equipping of the same “active” mountains by the meteotrons. Compared to the natural process the novelty is artificial proactive forcing of convective clouds that should repeat the natural phenomenon with one fundamental difference: it is always to be ahead and provide proactive cloud-forcing at CAPE still insufficient for severe storm.

Now let us compare the parameters of two cases of operation of the meteotron: in the Alazani Valley with a height of nearly 500 m above sea level and on the top of the mountainTsivi with a height of nearly 2,000 m above sea level. The height of the bottom of the capping inversion can be equated to 3,500 m above sea level [21]. The required value of U_{aH} could be considered in both cases as identical.

As shown by simple calculations based on relationship (10), the required value of the product of the thrust of the meteotron and its single run time is about 15 times less during operation on the top of the mountain Tsivi (H=1,000 m) than in the Alazani Valley (H=2,500 m). It is also clear that, relative to the arid zone, such a factor of increasing the meteotron effect (FIME) will be much higher.

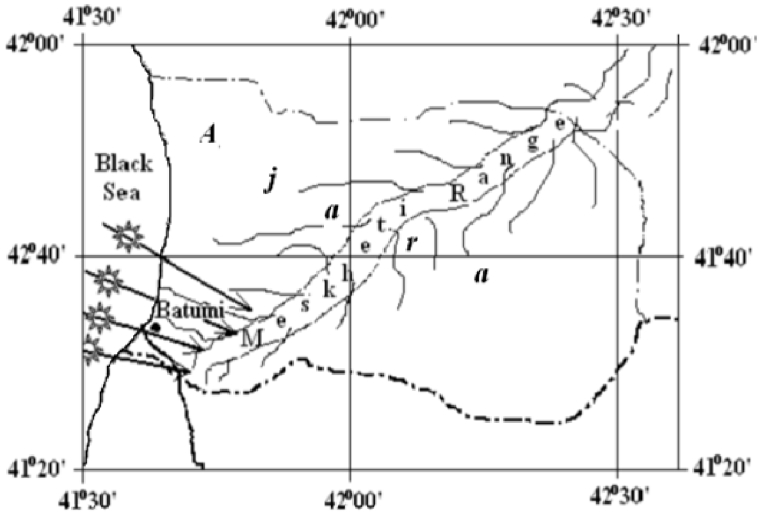

Fig. 6. Scheme of IPF aimed at reducing rainfall in Ajara with potential locations of the meteotrons (eight-pointed stars).

Now let us assess what changes this conclusion may undergo with further thorough analysis of the problem.

The first assumption made on the constancy of the required values of U_{aH} in both cases is equivalent to the assumption of the identity of the capping inversion over the mountain and the valley. Further, this assumption can be clarified only a bit toward the comparatively faster thinning the inversion over the mountain during day hours because of the natural upslope convection by solar heating. Obviously, such a clarification would increase the FIME.

The second assumption suggests the possibility of characterization of the meteotron effect only by dynamic component of the momentum, implying that the thermal component of the momentum (extra lift effect of heated air generated by the meteotron) is equally proportional to the dynamic component, both over the mountain and the valley. This assumption is quite logical and its refinement is unlikely to lead to a significant change in the FIME.

The most significant refinement of the analysis may be due to taking into account the momentum of the same natural updrafts because of the mountain natural upslope convection by solar heating (absent in the plain). Fortunately, such a clarification can only lead to a significant increase in the FIME.

Thus,we have every reason to believe that the main conclusion about the strong dependence of the main operating parameters of the meteotron on the distance up to capping inversion will remain in force after a thorough analysis of the problem as well.

6. The Problem of Eexcessive Rains in Ajara. In principle, potential applications of DPF and IPF can be considered to prevent excessive rains in coastal and other areas or mitigate tornadoes.

The map of the Autonomous Republic of Ajara is presented in Fig. 6. The system Black Sea – Meskheti Range contributes to the concentration of moist air masses and intensive formation of convective clouds, turning Ajara into a region with the highest rainfall in Georgia and in the Caucasus. In this regard, reducing the intensity of rainfall would improve the benefits of the region as an important seaside resort and mitigate the negative environmental impact of excessive rains in mountainous Ajara.

IPF should provide proactive forcing of convective clouds over the sea at the distance ensuring the completion of the cloud life cycle (including precipitation) before reaching the shore. According to preliminary estimates, the meteotrons should operate from the positions located at a distance of 30-60 km offshore. As an alternative to the natural process,