EVOLUTION OF CONVECTIVE CLOUDS IN TERMS OF THE GENERAL SYSTEMS THEORY

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Abstract

Some features (laws) of the evolution of convective clouds fit into and are summarized in terms of a simple "resource–consumer" Lotka – Volterra model. Based on this model, taking into account the revealed system-wide patterns, we analyze the possibility of an impact on convective clouds to control their intensity (redistribution of precipitation, hail suppression).

1. Introduction

Previous studies of the development of convective clouds [2, 3] have shown that the use of the nonconventional approach (model) in which an individual convective cloud is regarded as an open evolving system is promising.

A system is a set of interacting elements (Bertalanffy L. von [4]). According to this definition, we consider a convective cloud (*Cb, Cu cong*.) as a set of interacting convection elements (CEs), and a cloud convective cell (CC) is none other than a dominant CE.

The evolution of *Cb* (*Cu cong*) is the evolution of a "complex whole," of a system. Systems and laws of their evolution are the subject matter of the general systems theory (GST).

The main idea of the GST is the principle of isomorphism of the laws governing the functioning of system objects regardless of their nature. In line with this principle, the basis of our approach is the use of the Lotka – Volterra model versions to study the evolution of *Cb* (*Cu cong*) [2, 3, 13, 14].

2. Lotka – Volterra Model

The Lotka – Volterra model describes, in particular, the evolution of the "consumer-resource" system; in our case, the "*Cb* (*Cu cong*.) – resource" system. By the resource we mean wet subcloud air (water vapor) which is used by the cloud ("consumer") during its evolution. It is the water vapor that provides the dynamics of growth (development) of the cloud in the exothermic processes of phase transitions.

The Lotka – Volterra model in one of its versions can be written through the following system of equations:

$$dR/dt = Q - aMR, \quad (1)$$

$$dM/dt = bMR - cM, \quad (2)$$

where dR/dt and dM/dt are the time variation of the amount of resource R in the system (interpreted as the change in the water vapor mass in the atmospheric boundary layer in a neighborhood of the cloud) and the respective change in the mass M (integrated water content) of the cloud; *a* and *b* are the coefficients that determine the efficiency of "assimilation" of the resource by the cloud; *c* is the specific rate of the natural dissipation of the cloud (*a*, *b*, and *c* are positive constants); *Q* is the rate of resource inflow from the outside (in [13, 14], M and R are used with the dimension of density rather than mass).

3. Evolution of a Cloud–Resource System on a Nonrenewable Resource

Figure 1 shows the features of evolution of model clouds on a nonrenewable resource (the resource isolation of the system, Q = 0) versus the initial amount of the resource: in the first case (black) R1 = 1500 arb. units; in the second case (green) R2 = 2000 arb. units.

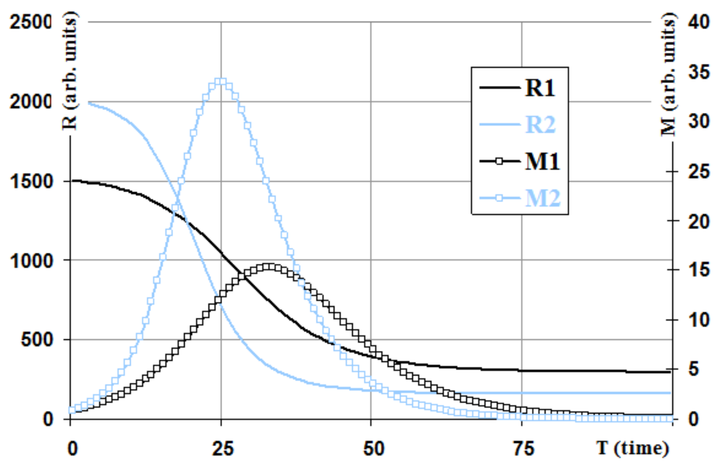

Fig. 1. Evolution of model clouds in the version of a nonrenewable resource (the resource isolation of the system) versus the initial amount of resource in the system. Initial conditions: R1 = 1500 arb. units, R2 = 2000 arb. units; M1 = M2 = 0.9 arb. units of mass (integrated water content) of the cloud.

"Time" in iteration steps is plotted along the horizontal axis; the resource mass in the system and the cloud mass in arbitrary units are plotted along the vertical axes on the left and on the right, respectively. At the initial stage of evolution, the growth of cloud masses occurs exponentially. The cessation of growth and the subsequent dissipation of the cloud are the result of a decrease in the amount of the resource in the cloud–resource system.

The pattern of evolution of *Cb* (*Cu cong*.) changes depending on the initial amount of the resource in the system. With a larger amount of the resource, the cloud develops faster and achieves a larger mass at its maximum, while the time of the growth phase decreases. The growth rate of the cloud → maximum value of its parameters relationship [6, 10] is known to be used for assessing the possibility of transition of the cloud into a hail-hazardous state [11].

This evolution of the model cloud is interpreted as the evolution of a single-cell cloud (the presence of a single mass maximum in the evolution of the cloud). The finiteness of the resource is the cause of the termination of the evolution of the model cloud. We assume that the suppression of the influent upward flow by precipitation is not a necessary condition for the dissipation of the cloud. The evolution of a deep convective single-cell cloud is a rapid process; this causes a reduction in the time limit for making decisions on the impact on the cloud at its higher power at the growth peak.

4. Evolution of the Cloud–Resource System with a Constant Resource Inflow

According to the model experiment, the resource is constantly flowing into the system (Q > 0). Ten arbitrary units of the resource mass are added per iteration step in the R1 version and 30 arbitrary units for R2 (Fig. 2).

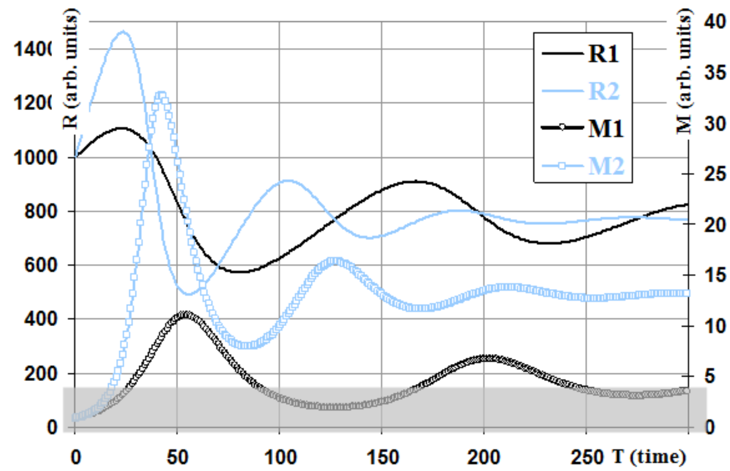

Fig. 2. Evolution of model clouds with a constant resource inflow into the system: in the R1 version, 10 arb. units of resource mass per iteration step are added; in the R2 version, 30 arb. units. Initial conditions: R1 = R2 = 1000 arb. units of resource mass; M1 = M2 = 0.9 arb. units of mass (integrated water content) of the cloud.

The main feature of evolution in this case is the occurrence of an oscillation mode in the system: out-of-phase oscillations of the masses of the cloud and the resource occur (at a constant inflow of the resource). An increase in the amount of the resource in the system is observed in the phase of minimum cloud mass.

The studies of the evolution of *Cb* fields [1, 15] showed that the periods of minimum parameters of the dominant *Cb* (in terms of the model, they are the resource growth stages in the evolving system) are accompanied by the formation of new convective entities (*Cb*, *Cu cong*.). In storm-hail processes in this period, a more frequent formation of new radio echoes was observed; in mesoscale *Cb* complexes, the frequent formation of new radio echoes and structural rearrangements of radio echo fields were observed; for the *Cb* scales (with a decrease in its parameters), an increase in the cloud canopy area was revealed, i.e., the formation of new cloud CEs (Khomenko, 2008). Thus, we can apparently state the similarity of processes in the evolution of convective systems of different scales (scale invariance).

As the resource inflow increases (Fig. 2, R2 version), the cloud grows at a higher rate and achieves a greater mass at its maximum. At the same time, the oscillation frequency of the cloud mass and the resource amount in the system increases. Radar observations (MRL-5) revealed different periods of formation of new CCs in multicell clouds of 15 to 25 min [8].

The evolution with an oscillatory variation in the model cloud mass is interpreted as the evolution of a multicell cloud with the sequential formation of new CCs in the cloud.

According to simulation results, the growth of another CC in the cloud is possible with a sufficient amount of available resource. We assume that the occurrence of the outflow of the cold air in the surface layer, which results from the precipitation from the previous CC ("trigger mechanism"), is not a necessary condition for the generation of new CCs in the cloud.

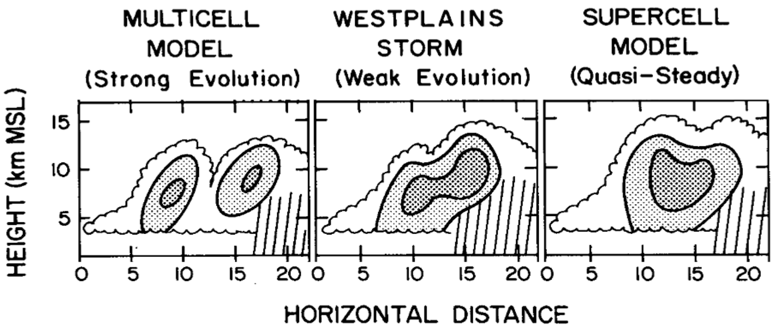

Fig. 3. Fragment of a schematic diagram of evolution of three types of storms taken from [18].

Taking into account the sensitivity threshold of the MRL, we find that a multicell cloud can be identified as a time-sequential formation of single-cell clouds: in Fig. 2 (M1 version), we shaded the conventionally unrecordable integrated water content (<4 arb. units).

Based on the solution to equations (1) and (2) in the form of spatial waves of M and R in [13], we assume that an increase in the resource inflow leads, in addition to an increase in the frequency of formation of new cells (Fig. 2), to a decrease in the distance between the formed cells. Thus, increasing the resource inflow to the cloud resource system, we can simulate the known sequence of conventional typing of *Cb*: single-cell, multicell, supercell clouds. The transition of a multicell cloud into a supercell cloud will occur through an intermediate structure of "weak evolution" [18] (see Fig. 3).

Note that the resource inflow into the cloud can be implemented through its displacement over the field of the uniformly (as an idealization) distributed resource. The rate of movement of the cloud relative to the resource field (wet air of the sub cloud layer of the atmosphere) and, therefore, the magnitude of the resource inflow will be higher for greater vertical wind shear within the troposphere. It is known that the intensity of *Cb* increases (with a change in its structure) with increasing vertical wind shear [12, 16].

The decrease in the amplitude of oscillations of mass and resource over time in the versions under discussion (Fig. 2) occurs at a constant magnitude of the resource inflow. An increase in the inflow over time can lead to an increase in the amplitude, and the fluctuations in the resource inflow into the cloud–resource system can cause resonance effects.

The difficulty of describing the evolution of a cloud lies in the fact that the space distribution of the resource is nonuniform. This is evidenced, in particular, by the nonuniform distribution of temperatures of dry and wet bulb thermometers in the surface layer. It is shown that the spatial localization of hail processes is attributed to this nonuniformity [5].

We assume that the oscillations of the cloud parameters are a combination of (a) natural oscillations of the cloud–resource system (self-oscillations at a constant resource inflow) and (b) the nonuniformity of the spatial distribution of the resource and, as a consequence, the nonuniformity of the resource influx into the cloud that is moving relative to the field of the resource.

The foregoing suggests that some of the observed features of the evolution of *Cb* fit (are summarized) into the terms of the used model and can be explained by it.

5. Impact on a Convective Cloud (CC, CE): Nonrenewable Resource

One of the effects of impact on *Cb* (*Cu cong*.) via the seeding of its super-cooled part with an ice-forming agent (AgI, etc.) is the stimulation of convection and, as a consequence, an increase in the mass of the cloud. This effect is theoretically substantiated and confirmed by full-scale experiments. It is used as a basis for the implementation of relevant programs of the artificial increase in precipitation from *Cb* (*Cu cong*.) [7]. It is this effect that is used by us in the modeling of the evolution of a cloud during impact (the model gives the possibility to simulate this effect).

Figure 4 depicts the results of these model experiments on impacts:

(a) No impact was conducted. Clouds that develop on a common resource enter into a competitive interaction (limit one another in growth). Cloud 2 is formed 10 iteration steps later than cloud 1 (given by the model for all the cases under discussion); as a consequence, it develops not so rapidly and achieves a lower mass. In this case, the ratio of the masses of the clouds at the stage of their maximum development is **2.8**. The clouds achieve their mass maxima simultaneously in the 76th iteration step.

(b) An impact on cloud 1 in order to stimulate its growth was carried out in the 30th iteration step (indicated by a red arrow); in this step, a mass of 0.4 arb. units (stimulus value is constant in all the versions) was added to the cloud. As a result, the ratio of the masses of the clouds is **3.2**. The growth of the mass of cloud 1 is accompanied by a loss in the mass of cloud 2. The maximum mass is achieved in step 75.

(c) An impact on cloud 2 was carried out in the 30th iteration step. The mass ratio of the clouds is **2.1**. An increase in mass of cloud 2 and a loss in the mass of cloud 1 take place. The maximum mass is achieved in step 75.

(d) An impact on cloud 2 was carried out in the 15th iteration step. The mass ratio of the clouds is **1.2**. The maximum mass is achieved in step 73.

According to the results of the simulation experiment:

- The effect of the impact on a cloud in a complex of competing clouds is shown as a stimulation of the cloud exposed to the impact, and the magnitude of the cloud reaction is not proportional to the value of the stimulus. The impact is accompanied by a redistribution of the influent resource between the clouds of the complex with respective changes in the masses of the clouds (it is assumed that the spatial redistribution of precipitation also occurs in this case).
- The period of growth (time to the maximum mass of the clouds) decreases.
- The earlier (at the growth stage) the impact is carried out and the higher the stimulus value, the greater these effects (as obtained in experiments with varying stimulus value).

The authors of [17] analyze the possible hail suppression techniques and give preference to an active impact for redistributing the resource (using our terminology) between competing clouds. The simulation results confirm that this approach to impacts on *Cb* (*Cu cong*.) is promising.

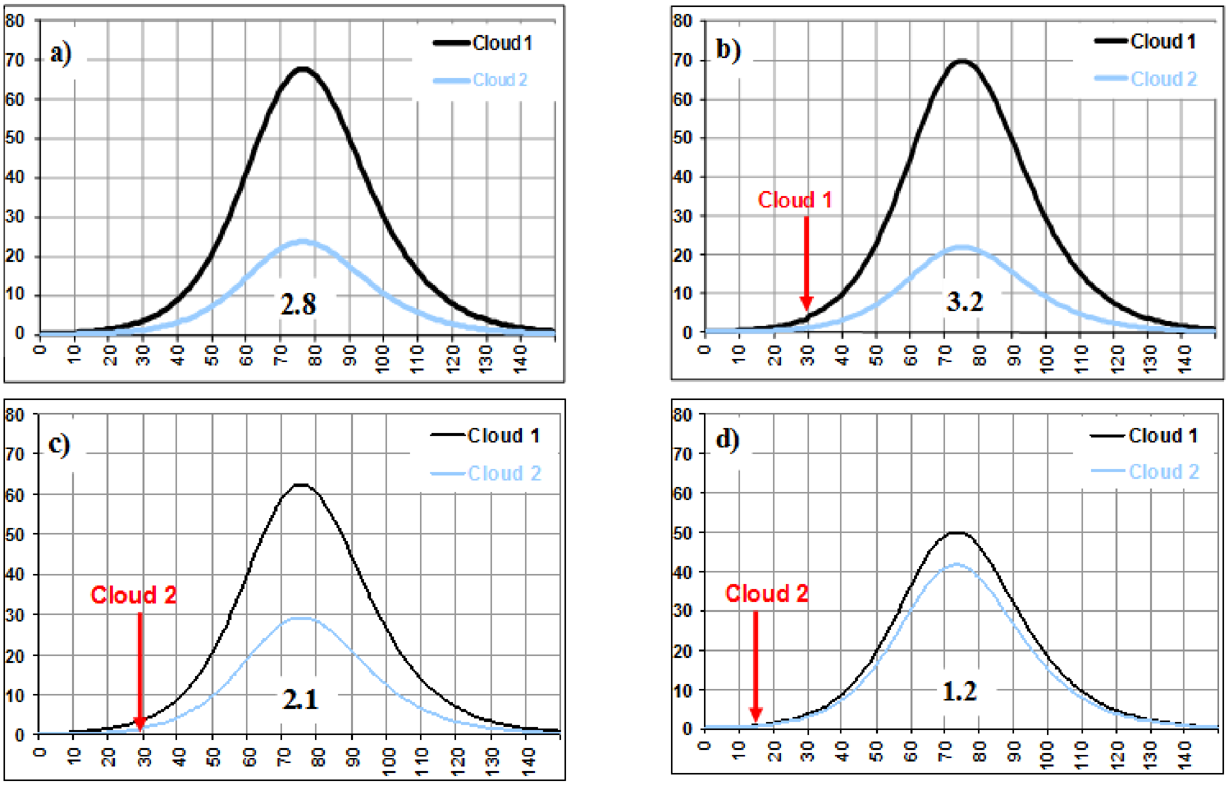

Fig. 4. Simulation of a stimulating impact on a convective cloud. The mass (integrated water content) of the clouds in arb. units is plotted along the vertical axis; "time" in iteration steps is plotted along the horizontal axis. See the text.

6. Evolution Link (Time Unit Cell of System Evolution)

Zhirmunskii and Kuz'min [9], based on the generalization of the features of development of different systems, introduce the notion of a time unit cell of system evolution, i.e., an evolution link (Fig. 5a). The total period of an evolving system is the sequence of these links. The minimum possible lifetime of the system is the duration of a link. It has two components: a growth phase and a rearrangement phase (critical period). The rearrangement phase is of particular interest. By the assumption of the authors, in this period, the system is most sensitive to an external impact. Small fluctuations in the rearrangement phase can significantly change the trajectory of the evolution of the system.

Figure 5b shows the behavior of the parameters of a hail cloud as of August 5, 2008, where H45 is the height of the upper boundary of the isosurface of 45 dBZ, which is the parameter used to estimate the hail hazard (intensity) of the cloud, and S45 canopy is the area of the cloud canopy in the contour of 45 dBZ.

If we consider the period of decrease in H45 (from 15:45 to 15:52) as a rearrangement phase in an evolution link of the cloud system, then this rearrangement consists in an increase in the canopy area, i.e., an intensification of formation of new CEs and the formation of another CC. According to the model, these periods are characterized by an increase in the amount of the resource in the cloud–resource system (in Fig. 2, ~60 to the 100th iteration step for R2). The increased sensitivity of the cloud system in this phase of development becomes clear: this is the "sensitivity" of new convective entities (CEs) which are in a competitive interaction between each other (see the conclusions of previous section 4).

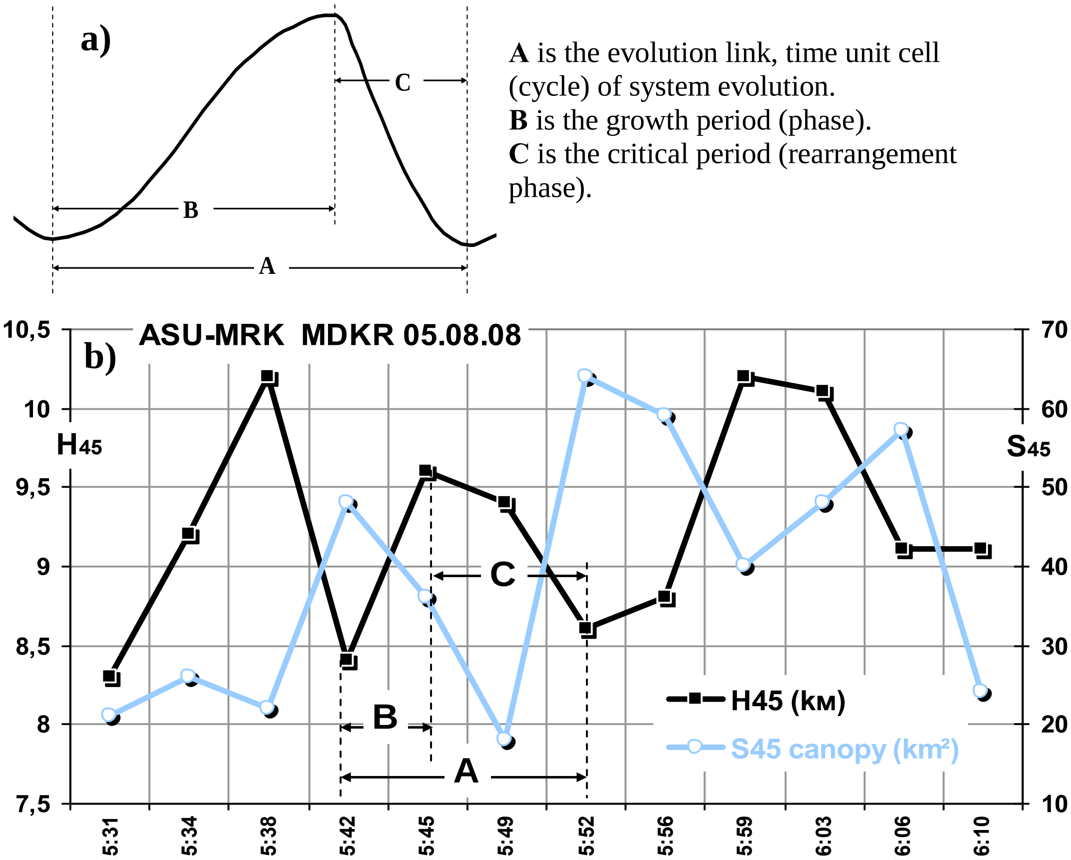

Fig. 5. (a) Evolution link, time unit cell (cycle) of system evolution; diagram according to [9]. (b) Behavior of parameters (H45 and S45 canopy) of a real hail cloud according to the
ASU-MRL archives as of August 5, 2008. Time period: **A** is interpreted as a cloud evolution link: **C** is the cloud structure rearrangement.

7. An Alternative Concept of Active Impacts on *Cb* (*Cu cong*) to Suppress Hail

Based on the used approach (method) for describing the evolution of a convective cloud, we formulate some proposals on a possible alternative concept of active impacts (AIs) on *Cb* (*Cu cong*) to suppress hail. The AI problem reduces to the prevention of the formation of a dominant CE (hail CC) through the redistribution of the resource inflowing into the cloud between competing CEs (CC, *Cb*, *Cu cong*.).

This can be achieved in the following ways:

- Seeding the supercooled cloud volumes with an ice-forming reagent in order to locally stimulate the convection.
- Seeding the periphery of the cloud (the region of newly formed CEs in their initial development stage).

- Seeding the formed satellite clouds.
- Abandoning the seeding (stimulation) of the cloud volume responsible for the formation of a dominant CC which, in its natural evolution, can achieve a hail stage.
- Impacting the cloud in the phases of its structural rearrangements (a decrease in parameters, an increase in the canopy area, the possible formation of satellite clouds); in this case, the periodicity of seeding is determined by the frequency of generation of new cells in the cloud and the increase in the canopy areas (periodicity of rearrangement phases).

The intended effects of impact:

- A failure/destruction of the space-time structure of the cloud;
- An increase in the precipitation field area;
- A decrease in the kinetic energy of falling solid precipitation.

Some of the represented proposals are being implemented in the AI practice, for example, seeding the periphery of *Cb* (new CEs).

Conclusions

We summarize the foregoing in the form of a brief sequence.

- Based on the fact that a cloud is a complex entity (system), we use the capabilities of the GST.
- Based on the principle of isomorphism, we employ one of the versions of the Lotka – Volterra model to describe/study the evolution of *Cb* (*Cu cong*.).
- It is shown that, in terms of the selected model, it is possible to summarize and explain a number of dissimilar facts derived at different times by different researchers in the observations of the evolution of convective clouds (the descriptive component of the model is satisfactory).
- The possibility of an AI on *Cb* (*Cu cong*.) to suppress hail has been explored (simulation experiments). The results show that an AI can be advantageous through the redistribution of the resource between competing CEs (CC, *Cu cong*., *Cb*) via local convection stimulation. According to the results of simulation experiments, a possible alternative concept of AIs has been formulated.
- Based on the concepts of a link as a time unit cell of system evolution and the rearrangement phase in this link (system-wide pattern), we have specified the methodological issues of the alternative concept of AIs.

In this study, we do not discuss the complex processes occurring in a convective cloud; we put an emphasis on describing the "behavior" of a cloud as an active entity (complex object, system) which, in its evolution, interacts with the external environment, i.e., a medium that exhibits specific properties and contains resources of "vital importance" for the cloud, and with similar convective entities which are competitors for the resource.

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