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AN EXPLICIT MICROPHYSICS THUNDERSTORM MODEL

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Abstract

The authors present a brief description of a 1.5-dimensional thunderstorm model with a lightning parameterization that utilizes an explicit microphysical scheme to model lightning-producing clouds. The main intent of this work is to describe the basic microphysical and electrical properties of the model, with a small illustrative section to show how the model may be used to determine the electrical properties of clouds.

Key Words

Thunderstorm, lightning, atmospheric modelling

1. Introduction

Modelling of cumulus clouds, and especially thunderstorms, is challenging due to the wide range of important spatial and temporal scales. The usual approach to this task has been to explicitly model the processes of interest and to parameterize the others. Because charge transfer mechanisms are sensitive functions of particle size [1], this goal can be met only by an explicit representation of the size-dependent microphysical processes. We employ a one-and-a-half dimensional dynamic model for dynamic simplicity and short execution time for simulations (see Section 2.1 for more information about the model geometry). The geometric simplicity also allows for the inclusion of a lightning parameterization [2], whereas this task becomes increasingly difficult in higher dimensions and severely decreases the number of simulations for sensitivity tests due to computational times. The following chapter describes the cloud model (based on that on Taylor [3] and Norville et al. [4]), hereafter referred to as *EMTM* (Explicit Microphysics Thunderstorm Model).

Fig. 1 presents a box diagram of the various communicating sections within the model. The main inputs include the environmental sounding (temperature, pressure, and dew-point temperature as a function of altitude), various parameter values, and the imposed cloud-base forcing. These are used to initialize all the various routines and start the dynamics.

The dynamic routines are responsible for advection of energy, water vapour, and all water and ice particles that are returned from the microphysical routines. The explicit microphysical routines are responsible for calculating the growth, collection, glaciation, and melting of water and ice particles. EMTM has 80 mass categories of both ice and water as a function of particle mass. The microphysical routines are also responsible for determining the number of ice-graupel collisions, which is used to determining charge separation (see Section 2.3). This charge, carried by hydrometeors and treated as a passive tracer by the advection routines, is used to calculated the vertical electric field for use by the lightning parameterization. The model output includes various microphysical quantities (e.g., ice and water particle concentrations), air velocity, cloud temperature, precipitation rate, charge separated per collision, charge density, and electric field (all functions of height and time) as well as the charge produced by each lightning channel.

Intracloud lightning introduces no net charge gain, whereas cloud-to-ground lightning does. Charge is lost through the removal of charged precipitation and advection of charged cloud particles into the environment. With the addition of the lightning parameterization to the cloud model, we are able to simulate the electrical aspects of thunderstorms throughout the entire life time of a cloud.

2. The Thunderstorm Model

2.1 Dynamics and Cloud Base Forcing

The dynamics in EMTM are based on those of Asai and Kasahara [5, 7] and Yau [6, 8] for calculating the advection of energy, momentum, and so on, and for calculating mixing between the clear air/cloud boundry and between the two cloudy cylinders. The model domain is axi-symmetric, consisting of three communicating coaxial cylinders: inner and outer cloudy regions and the clear air (Fig. 2). EMTM retains all the original dynamic equations of Taylor [3]. Generally, models of this type have only one cloud region (strictly one-dimensional).

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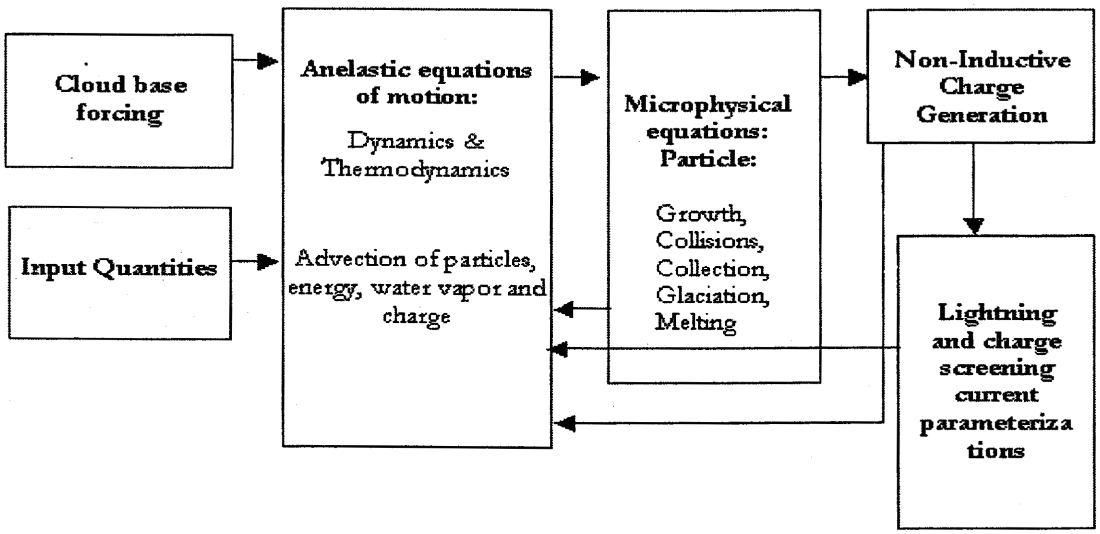

Figure 1. Schematic illustrating the thunderstorm model flow.

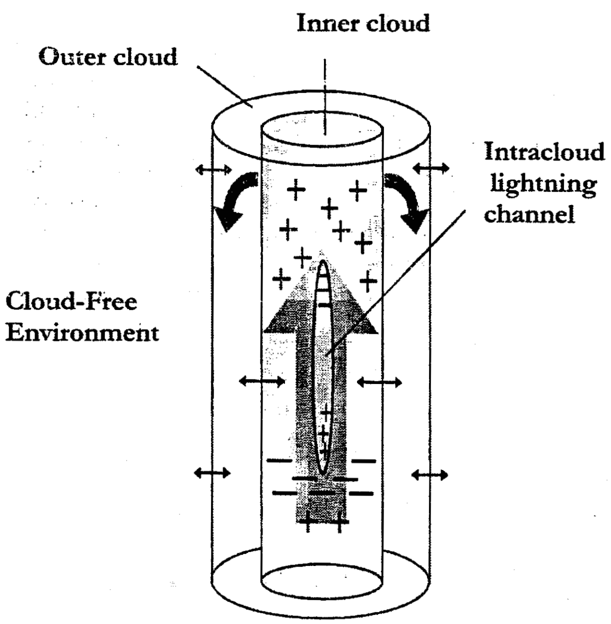

Figure 2 Schematic diagram of the model geometry with two connecting cloudy cylinders with radii A and B.

The inclusion of a second cloudy region allows for better resolution of horizontal processes such as mixing between the cloud and environment. Then EMTM is called 1.5-dimensional, as it is not, strictly speaking, one- or two-dimensional. The air entering the base of a convective cloud does not necessarily have the same thermodynamic and dynamic properties as the surrounding air. The differences between the temperature and/or velocity of the cloud-base air and those of the environment at the level of cloud-base are referred to as "cloud-base forcing" parameters. EMTM employs two types of forcing: "kinetic," or momentum, forcing where the updraft velocity of air entering the cloud-base is prescribed and assumed to have the thermodynamic properties of the environmental air at that level, and "thermal" forcing, where a temperature perturbation in excess of the environmental temperature at cloud-base altitude is prescribed. In the real world, of course, cloud forcing is some combination of these effects and can arise from many different mechanisms. For example, convergence of air near the surface of the Earth will result in upward, "kinetic forcing," or solar heating of the land can create a source of "thermal forcing." The strength of forcing is not usually known from atmospheric soundings.

2.2 Microphysics

The evolution of the water and ice microphysical distributions are explicitly calculated. The microphysical processes included are growth by deposition (i.e., water vapour condenses on the surface of particles), riming (large ice particles collect smaller drops by collisions), collection (large ice and water particles collect smaller ice and water particle respectively by collisions), melting, drop breakup, and primary glaciation and secondary ice production (see Sections 2.2.7 and 2.2.8).

2.2.1 Mass Grid

Water and ice particle masses are defined on a common grid. The mass of particles in the i-th mass bin is:

$$M_i = M_0 2^{((i-1)/2)} \tag{1}$$

where M_0 is the mass of the lowest category, $M_0 \sim 5\text{x}10^{-10}$ g. There are 80 mass categories for water and ice. Cloud condensation nuclei (CCN) and ice condensation nuclei are assumed to be spherical particles with a radius of 0.25 μm.

2.2.2 Ice Density

Each ice category has an associated density, and all particles are assumed to be spherical. This assumption may be reasonable for larger particles, but small ice crystals have distinctly nonspherical shapes. To compensate for the error introduced by assuming spherical particles, the ice density for non-riming ice crystals (i.e., if the radius of an ice particle is below a critical radius, it does not collide with other particles, often referred to as pristine ice particles) is set to 0.1 g cm^{-3}. This value is the ice crystal density needed to give a sphere the same radius as a flat ice crystal with the same mass [4]. For riming ice particles, the value of the density of riming particles with mass M_f is given by:

$$\rho(Mf) = \rho(Md) + \int_{Md}^{Mf} \left(1 - \frac{\rho(M)}{\rho a(M)}\right) \frac{dM}{Vol(M)} \quad (2)$$

where M_f is the mass of the riming particles, M_d is the mass of a particle with diameter D, Vol is the volume of the particle, and ρ_a is the density of the rime given by Mauklin [9][7]and Heymsfield and Pflaum [8, 10].

2.2.3 Fall Velocities

Fall velocities for drops and small ice particles are taken from Berry and Pranger [9, 11], and larger ice crystal and graupel fall velocities are taken from Heymsfield [10, 12]. The Berry and Pranger fall velocity is a function of the Reynolds number and the drag coefficient, which is only dependent on environmental temperature and pressure. Heymsfield uses empirical expressions derived from an observational analysis of summertime graupel.

2.2.4 Vapour Deposition

Both water and ice particles grow via the deposition of vapour. The depositional growth equation for $n(M)$, the number concentration of particles with mass M, has the form of an advection equation that is analogous to the vertical velocity in a spatial domain. Therefore an advection scheme, similar to that of Smolarkiewicz [11, 13], is used to solve the growth equation. This scheme is stable for nondivergent flow when the Courant number is less than 1.0. Because very small particles may grow through several mass categories for a given time step, a hybrid calculation is used with a Lagrangian advection scheme in regions where growth is unstable [4].

2.2.5 Collision and Coalescence

Collection of droplets by larger drops is calculated using the "continuous collection" approach [12, 14]. Particles with diameters greater than a threshold size, D_r, collect smaller drops. The number of particles *collected* per time step is $N_{collisions}$ times the sticking efficiency, E_{si}. Collision efficiencies are assumed to be 1.0 for drop-ice interactions; drop-drop sticking efficiencies are taken from Hall, [13, 15], and ice-ice sticking efficiencies are set to a specified constant.

2.2.6 Drop Breakup

Breakup of large drops can be a significant factor governing the shape of the drop size distribution. Komabayasi et al. [14, 16] suggested a function for the probability of drop breakup that gives a 100% probability of breakup for drops with a diameter of 8.8 mm. The breakup of a drop gives rise to a distribution of droplets that are then redistributed through out the mass grid.

2.2.7 Ice Nucleation

The prediction of the initial ice-crystal concentrations in numerical cloud models is difficult because ice-nucleation is poorly understood. One popular method used to predict ice-crystal concentrations has been to use a temperature-dependent function based on the compilation of ice-nuclei concentrations (e.g., Fletcher [5, 15]). This method typically underestimates ice-crystal concentrations at warm temperatures and greatly overestimates concentrations when extrapolated to temperatures below those for which it is valid ($\sim$ -25 °C) [6, 16]. Based on a number of observations of ice concentration versus ice supersaturation, Meyers et al. [6, 16] parameterize the number of pristine ice crystals predicted due to deposition-condensation based on the ice supersaturation. In a similar fashion, these authors quantify contact-freezing nuclei concentrations by fitting a function to a number of measurements. At −40 °C all drops are assumed to freeze. Both the Fletcher and Meyers et al. ice nucleation parameterizations have been included in EMTM in order to evaluate their impact on cloud properties.

2.2.8 Secondary Ice Production

Secondary ice production in cumulus clouds can have a dramatic effect on the number of ice particles, their spectrum within the cloud, evolution of clouds, and possibly their electrification. Based on experiments by Hallet and Mossop [17], Mossop and Wishart [18] suggest that the mechanism responsible is the fracture of symmetrically freezing droplets. When droplets greater than 24 μm in diameter strike a portion of a rimed surface where small ($d < 13$ μm) droplets have accreted, these large droplets are in poor thermal contact with the graupel and tend to freeze from the outside inward. Subsequent freezing then causes shattering of the ice shell, ejecting ice fragments. The production of additional ice particles by the Hallet-Mossop process is simulated within EMTM by using the production rate parameterization given by Harris-Hobbs and Cooper [19].

2.2.9 Melting

When ice particles fall into environments with temperatures greater than the freezing temperature, T_0, some fraction of each ice particle melts. Following Cotton et al. [20], we assume that a melting ice particle is in thermodynamic equilibrium with a surface temperature T_0. The melt mass that accumulates during a time step is assumed to be "sloughed" off the ice particle, and a droplet having this mass is created. If the resulting drop is smaller than the smallest size allowed, no material melts during the time step.

2.3 Model Electrification: Non-inductive Ice-Ice Interactions

We assume, based on field and model results (e.g., [21, 22]) that the dominant charge transfer mechanism is that involving collisions between ice crystals and graupel (i.e., large riming ice particles) or soft hail pellets [1, 23]. The instantaneous charge separation rate depends on the liquid water content and the numbers and sizes of ice crystals and of hail particles. The net amount of charge added to a graupel particle with diameter D, via collisions with $n_{small}(d)$ [m^{-3}] ice crystals with diameter d, is:

$$\Delta Q(d,D) = n_{small}(d)K_{cc}(d,D)(1.0 - E_{si})\delta Q_g(d,D) + Q_{small}(d)nK_{cc}(d,D)E_{si} \quad (3)$$

where $Q_{small}(d)$ is the charge on n, number of small ice crystals that are collected by the graupel particle. $\Delta Qg(d,D)$ is the amount of charge transferred per collision; $Kcc(d,D)$ is the collection kernel, which is based on the cross-sectional area of the colliding particles; and E_{si} is the ice-ice sticking efficiency. Keith and Saunders [24] show that the charge transferred per collision to the graupel target, ΔQ_g, depends on the ice crystal size, d, and the speed of the target, V. We adopt the functional form for the magnitude and sign of charge transferred per collision given by a parameterization of laboratory experiments supplied by Saunders et al. [1, personal communications].

2.4 The One-Dimensional Lightning Parameterization

In general, numerical models of thunderstorms have dealt only with early stages of electrification, before the first lightning flash. The ability to model the later stages of thundercloud development has been hampered by the lack of reasonable representations of lightning itself and of its modification of clouds. With this sort of model it is clearly very difficult to utilize the wealth of information now available from ground-based, *in situ* and remote sensing of lightning to improve our understanding of highly electrified clouds.

Lightning initiation and propagation are intensely dynamic phenomena. For this purpose we can solve a simple electrostatic problem based on the ideas of Kasemir [25] and Mazur and Ruhnke [26]. According to this conceptual model, the lightning channel can be thought of as a conductor placed in the cloud electric field. If the lightning channel does not touch the ground, there is no net charge on it, but the surface of the "conductor" carries a spatially non-uniform charge density representing the density of induced ionic and electronic charges. This induced charge moves some distance into the cloud after a discharge, thus modifying the in-cloud charge and field distributions. Building on the ideas of Kasemir, Mazur and Ruhnke, and Helsdon et al. [27], we derived a lightning parameterization that can be used to study both intracloud and cloud-to-ground flashes. We have derived this model for use in EMTM, so that in the present form we assume all discharges propagate along the z-axis.

2.4.1 Lightning Initiation

The typical way models treat lightning initiation is to initiate lightning wherever the vertical electric field exceeds a predetermined value, E_{init}. However, EMTM includes several variants for lightning initiation based on more physically observed conditions. Traditionally, E_{init} is assumed to be constant with height, and the value roughly approximates the maximum measured electric field within clouds. However, little is known about lightning initiation, which appears to occur when the magnitude of the electric field is 10% of $E_{breakdown}$, where $E_{breakdown}$ is the electric field needed for electrical breakdown of dry air, $E_{breakdown}$ = 2600kV/m at sea level. After a period of "preliminary breakdown" within the cloud, a branched discharged propagates bidirectionally away from the initiation point. Sharp increases in X-ray fluxes have been detected above thunderstorms, adjacent to thunderstorms, and at the ground just preceding and during large electric field changes. This indicates that energetic electrons (i.e., those with energies of 1 MeV or greater) are accelerated in the electric fields. According to the runaway breakdown hypothesis, these energetic electrons are descendants of high-energy electrons produced aloft by *in situ* radioactivity and (in far greater numbers) by galactic cosmic rays. An electron of around 1 MeV can accelerate despite continued collisions and collisional energy losses if the electric field exceeds some threshold. This threshold field, $E_{be}(p)$, is called the breakeven field, and the accelerating electrons are termed runaways. $E_{be}(p)$[kV/m] $\sim \pm$ 200p where p *(pressure)* is in atmospheres. Thus this break-even field is approximately an order of magnitude less than the dielectric breakdown field. The near equality of this break-even field with the maximum field in thunderstorms supports the runaway breakdown mechanism. EMTM supports two additional lightning initiation schemes: one based on the break-even electric field where lightning is initiated when the electric field exceeds E_{be} (versus a constant E_{init}), and another that is a lightning initiation scheme that calculates the enhancement of the in-cloud electric field due to runaway electrons. (See Solomon et al. [28] for more details.)

2.4.2 The Lightning Channel

Following Helsdon et al. [27], it is convenient to analyze this problem in terms of prolate spheroidal coordinates where L is the length of the channel and R_o is its maximum radius. Upon initiation, the channel has a prescribed radius at the midpoint, which remains constant throughout the

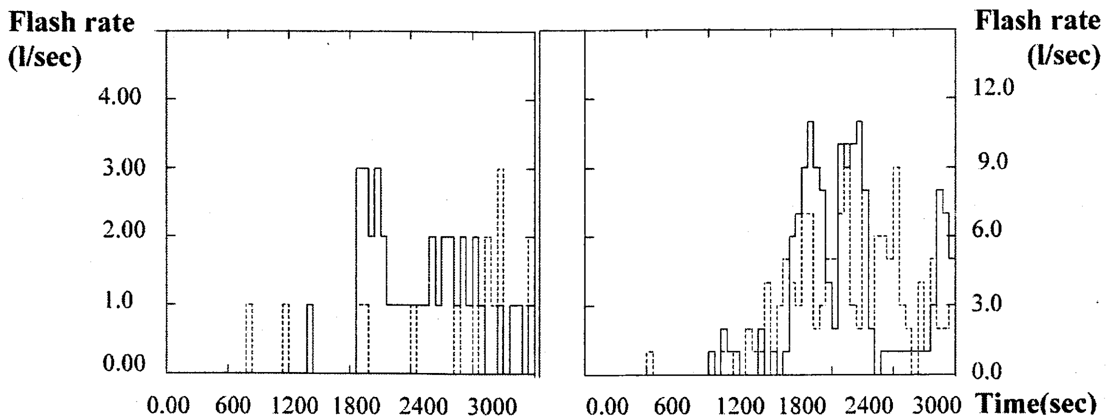

Figure 3. Lightning flash rate from observation (dashed) and EMTM (solid) for two different studies. The convective cells that we reproduce are on August 4, 2002, from 20 to 21 UTC (left) and from 22:30 to 23:30 UTC (right) in northeastern Italy. The modelled lightning compares very well with the observations.

development of the channel, and an initial length, L_0. The electrostatic potential on the surface of the conductor is due to the electric field generated by the charge on the hydrometeors.

2.4.3 Channel Length

In order to determine the vertical extent of the lightning channel, we have adopted a propagation criterion based on the results of experiments of streamer and spark propagation in gaps [29]. In these experiments, it is found that a streamer continues to propagate as long as the quantity of charge at the head of the streamer exceeds a critical value. Physically, this reflects the fact that if the electron avalanche process necessary for leader propagation is to continue, the electric field due to the streamer charge must be high enough to continually accelerate electrons near the tip, despite dissipative processes such as ionization and attachment. Parameterization of these microscopic processes gave rise to the energy criteria used in earlier studies of lightning propagation. In this lightning parameterization, we assume the lightning channel extends as long as the charge at the head of the channel does not change sign or go to zero, and that the electric field at the tip is sufficient to continue the electron avalanche process. If the channel propagates into a region where these criteria are not met, propagation in that direction is halted.

2.4.4 Intracloud and Cloud-to-Ground Flashes

If the lower tip of the channel does not reach the ground, the channel always bears zero net charge. If, however, it does contact the ground, when the surface of the channel is at potential V_{cond}, a net charge flows from the ground to the channel and is evenly distributed along the channel. This brings the channel potential from V_{cond} to zero (the potential at the ground). Downward "propagation" is no longer possible, although the top of the channel may continue upward.

3. The Thunderstorm Model in Conjunction with MM5

In this section we briefly discuss the use of EMTM in conjunction with the MM5 mesoscale model [30], wherein the EMTM is initialized with values obtained from MM5 at various locals to obtain a large collection of lightning, precipitation, and microphysical profiles. As MM5 does not explicitly treat microphysical quantities, EMTM can better determine the relationships between microphysical parameters (e.g., ice and liquid water content, hydrometeor size, and distributions obtained from the EMTM output) and represent the vertical microphysical structure of lightning-producing clouds within mesoscale models or nowcasting when lightning observations are available. We have performed a sensitivity study using EMTM over the Po Valley in northern Italy (August 4–5, 2002). In particular, we focus our study over the Friuli area to validate our results with radar and ground-based lightning networks.

We initialized EMTM with the modelled soundings taken from the output of MM5. The rationale behind this is the necessity to initialize the EMTM model with an environmental sounding that is representative of the environment where the storms occur. For this region, the only actual soundings that are available are located at Udine and San Pietro Capofiume, which have a limited temporal resolution (12 hours) and may be located many kilometres from the location of interest. Using the ensemble of MM5 soundings, we initialize EMTM to model convective cells recognized by MM5.

In this scenario, we had the chance to analyze the temporal and spatial changing of the convective cells and look at the microphysical development of the thunderstorm. All the simulations for the convective cells give us an ensemble of microphysical profiles with the lightning occurrences for different kinds of simulated storms: deep and shallow convection and those clouds that did and did not produce lightning. Output from EMTM has been validated with radar and lighting data to ensure the modelled storms are consistent with observation (Fig. 3). Note that the model gives intracloud and cloud-to-ground lightning, whereas ground base networks only give cloud-to-ground. Although this does represent a relatively specific case regarding the set of input parameters (e.g., cloud-base forcing was set to 1.0 m s^{-1}, using the Fletcher ice parameterization, and a constant value for lightning initiation = 150 kV m^{-1}), we are currently performing a range of tests to evaluate the range of input values for which the model produces physically consistent results as well as using other synoptic scale data to constrain the limits on the the input data.

4. Summary

Given the limitations in the geometry of this model, it does a very good job of modelling simple convective storms and can be quite useful in the modelling of lightning-producing storms. Solomon and Baker [2, 31] used the model to determine relationships between environmental characteristics (differences in soundings, oceanic versus continental regimes, etc.) and the resulting electrification, lightning, and microphysical profiles that lead to marked differences between these storms. As our understanding of cloud electrification and lightning processes increases, this model can easily be modified to incorporate new research and, as the model is fairly small with regard to mesoscale models such as MM5, many sensitivity tests may be performed to evaluate the findings of new research concerning the development of electrified storms. A one-dimensional cloud-and-lightning model cannot capture the effects of horizontal development of charge centres, which may be of particular importance in the development of cloud-to-ground channels. Although the thunderstorm model could accommodate nonvertically propagating channels, the lightning parameterization could not in its present, analytic, form be used for complicated trajectories. Extension of the shape of the conductor is in principle possible but would entail numerical computation of the charges induced on it.

It is clear that the results presented here are suggestive only in part because we look at a small handful of observations and because the cloud model geometry limits the ability to investigate any but the simplest unsheared air mass thunderstorms. The cloud-base forcing is imposed, and the cloud environment does not change as the storm evolves. We have included only the simplest electrostatic parameterization of an unbranched lightning channel. However, in view of the uncertainties surrounding the electrical processes in clouds, it is perhaps not worthwhile to attempt more detailed quantitative modelling studies; it might be more useful to examine the implications of simpler studies in the light of better and more extensive field and laboratory data.

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