L'ÉNERGIE AU CŒUR DES ONDES
RESSOURCES ET ENVIRONNEMENT :
GESTION "INTELLIGENTE"

Lightning propagation in a 3D cloud

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Résumé/Abstract

This paper deals with leader propagation in a typical cloud structure. From a cloud photography, an elevation of the base layer of the cloud is determined by a picture analysis. A cloud structure is then formed with its typical 3 layers: positive bottom and upper layer, and a negative layer in the middle. This space charge repartition is used to calculate an electrical potential distribution above the ground. A leader propagation modelling is then proposed: the leader propagates in the direction of the maximum difference in term of electrical potential. Different inception altitudes for the leader inception are tested. The simulations tend to validate the hypothesis that positive cloud to ground lightnings come from the base layer. This positive base layer form also a shield for the negative lightning which tends to be intracloud. Negative lightning must benefit from weakness or holes in the positive base layer to propagates toward the ground.

Cet article traite de la propagation de la foudre (leader) dans une structure nuageuse typique. À partir d'une photographie de nuage, une élévation de la couche de base du nuage est déterminée par une analyse d'image. Une structure nuageuse est alors formée avec ses 3 couches typiques : une couche inférieure et supérieure positive, et une couche négative au milieu. Cette répartition de la charge d'espace est utilisée pour calculer une distribution de potentiel électrique au-dessus du sol. Un modèle de propagation du leader est ensuite proposé : le leader se propage dans la direction de la différence maximale en termes de potentiel électrique. Différentes altitudes de début de propagation du leader sont testées. Les simulations tendent à valider l'hypothèse selon laquelle les éclairs positifs nuage-sol proviennent de la couche de base. Cette couche de base positive forme également un bouclier pour les éclairs négatifs qui ont tendance à être intra-nuageux. Les éclairs négatifs doivent profiter de la faiblesse ou de trous dans la couche de base positive pour se propager vers le sol.

1 Introduction

A typical cloud charge structure is based on three different layers: on top of the cloud a positive charge, in the middle a negative charge and at the bottom a limited positive charge. Several simulations have been made based on heuristic rules for the leader propagation, but to our knowledge none consider a realistic cloud. The different cloud layers may impact the propagation of the leader as proposed by Nag and Rakov[1]: the positive base layer can in one part accelerate the development of cloud to ground lightning, but it can also shield the bottom part of the cloud from upper lightning, favoring the development of cloud-to-cloud lightning, depending of the originate point of the leader inception.

2 Cloud Modeling

Figure 1 Cloud over Paris

Figure 1 represents a picture of thunderstorm clouds above Paris. The image luminosity is analyzed and converted in altitude level of the cloud base layer (more light means less altitude). See figure 2 where the color represents the sign of the space charge (red for negative and blue/orange for positive charge). The values for the layer thickness, charge value are taken from various article and book in the literature [2-3].

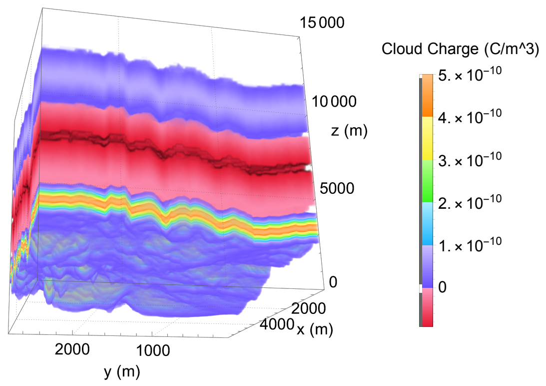

Figure 2 Cloud Charge structure

3 Leader propagation

The leader propagation model is based on an electrostatic model of the space charge along an optimization of the propagation during each step. A start point X_0 for the leader propagation is chosen in the cloud. For each iteration n of the propagation, we first find with the help of a deterministic gradient optimisation algorithm the maximal potential difference in a sphere of 50m radius around the leader's head. In the case of a positive leader, this leads to the problem:

$$\max_{\mathrm{X}} V(X_n) - V(X)$$

$$\text{Subject to : } |\mathrm{X} - \mathrm{X\_n}| < 100$$

and in the case of a negative leader to the optimisation problem:

$$\max_{\mathrm{X}} V(\mathrm{X}) - V(X_n)$$

$$\text{Subject to : } |\mathrm{X} - \mathrm{X\_n}| < 100$$

These two formulations can be reformulated respectively as:

$$\min_{\mathrm{X}} V(X)$$

$$\text{Subject to : } |\mathrm{X} - \mathrm{X\_n}| < 100$$

and:

$$\max_{\mathrm{X}} V(X)$$

$$\text{Subject to : } |\mathrm{X} - \mathrm{X\_n}| < 100$$

To represent the stochastic behaviour of the leader propagation, a random point is chosen around this maximum (in a sphere of 10m radius) which becomes the new leader head. The leader is propagated with a constant radius (5m) and a space charge density equals to $50.\,10^{-6}/(\pi r_l^2)\mathrm{C/m^3}$ if the leader originates from a positive region and $-150 \times 10^{-6}/(\pi r_l^2)\mathrm{C/m^3}$ if it originates from a negative region [2]. With $r_l = 5\mathrm{m}$ the radius of the leader (largely overestimated due to mathematical constraints for the Poisson equation resolution). The potential is then finally recalculated by the equation taking into account the new space charge and a new refined mesh.

4 Electric potential calculation

The formation and propagation of lightning are mainly due to electrostatic phenomena, that are caused by the electric field. To compute the electric field E, one needs to solve the Poisson equation. The boundary conditions are defined by a Dirichlet condition on the earth's surface: V(x,y,0)=0 and Neumann conditions on the others borders $\left.\frac{\partial V}{\partial n}\right|_{\partial\Omega} = 0$. We use a finite elements method to solve the Poisson equation in three dimensions.

The resulting electric potential induced by a full cloud structure is shown on figure 3 and the electric field on the figure 4.

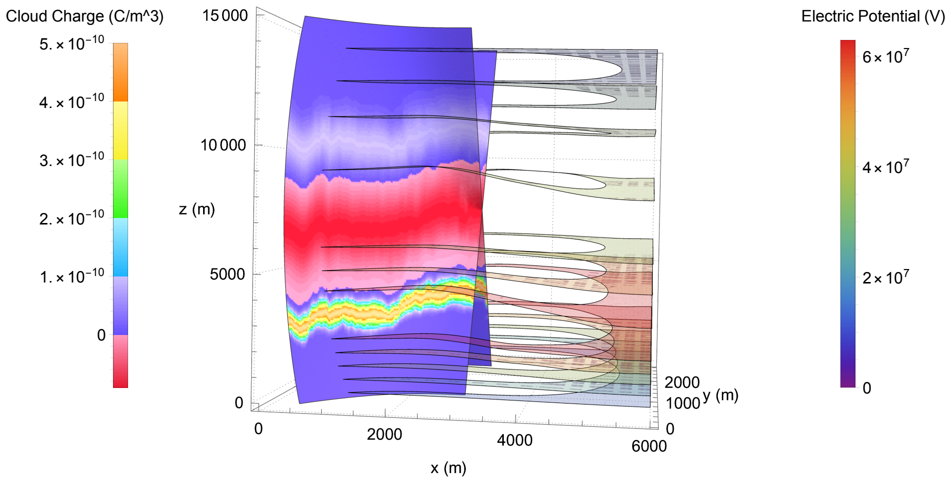

Figure 3 Electric potential (iso surface on the right) induced by a cloud structure (right surface)

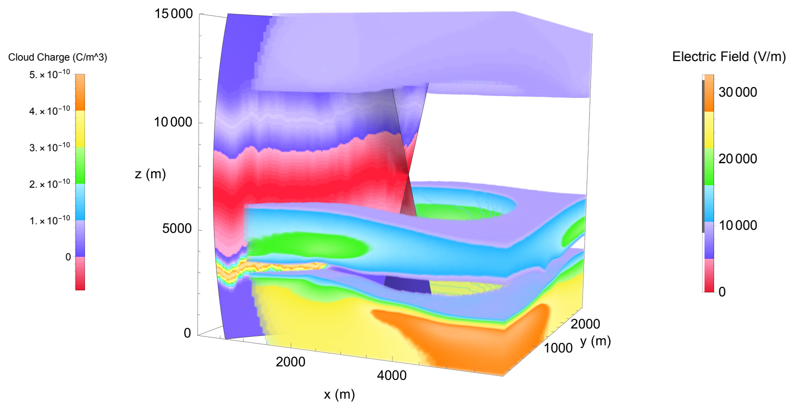

Figure 4 Electric field (volume on the right) induced by a cloud structure (right surface)

5 Results

A First result is shown on figure 5 where a positive leader at the inception point 3000 meters above the ground propagates towards the ground and a negative leader (inception point 6000m) propagates in the cloud.

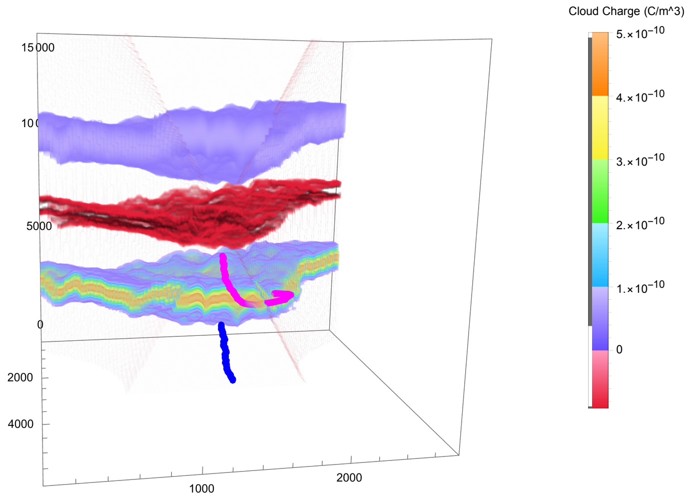

Figure 5 Leader Propagation (Blue 3000m, Pink 6000m)

The only leader who connects to the ground is the positive one coming from the bottom part of the base positive layer (inception at 3000m in blue). The negative leader from the negative middle part of the cloud (6000m) is trapped between the two (bottom and top) positive layer. It reaches the separation altitude between the layers and then cannot propagate vertically anymore. The negative leader cannot reach the ground, which is blinded and protected from the bottom positive layer as shown theoretically by Nag and Rakov [1].

6 Conclusion

A cloud typical cloud structure is proposed and used as a background electrostatic field to model the propagation of leaders. Positive leader propagates toward the ground (cloud-to-ground), and negative leader taking inception into the cloud to propagate into the cloud (cloud-to-cloud). Various inceptions point and discussion will be presented in the full paper.

Bibliography

[1] A. Nag et V. A. Rakov, « Some inferences on the role of lower positive charge region in facilitating different types of lightning », Geophysical Research Letters, vol. 36, no 5, 2009, doi: 10.1029/2008GL036783.

[2] P. Lalande et V. Mazur, « A Physical Model of Branching in Upward Leaders », AerospaceLab, no 5, p. 1-7, déc. 2012.

[3] The Lightning Flash. IET Digital Library, 2014. doi: 10.1049/PBPO069E.