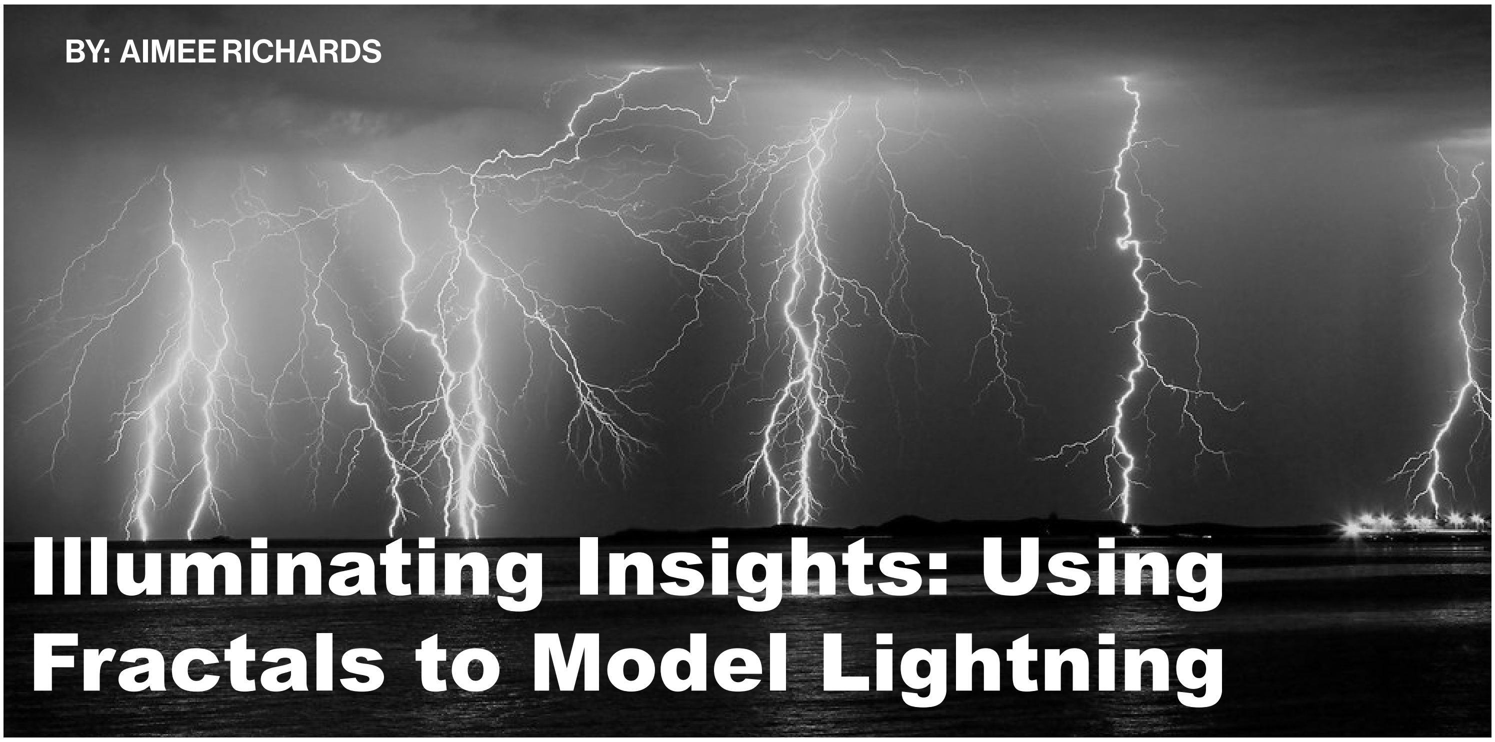


BY: AIMEE RICHARDS

Illuminating Insights: Using Fractals to Model Lightning

INTRODUCTION

Mathematics is a universal language, which uses logical ideas to model solutions to complex phenomena beyond the observable and material world. The developments and discoveries within the study of mathematics have enabled the intricate characterization of natural phenomena with examples including the Fibonacci sequence (modeling spiral patterns), the butterfly effect (an idea founded from chaos theory), and fractals (infinite repeating patterns).[1]

The concept of a fractal was discovered in 1918 by Felix Haussdorf, where he first presented the idea of a unique geometric object that contained an infinite repeating pattern, often displaying self-similarity. Self-similarity is the concept that, upon zooming in on a portion of a fractal, the smaller segment will look geometrically identical to its larger counterpart.[2] Fractals were popularized and named in 1975 by Benoit B.Mandelbrot (see figure 1).[3] Despite their abstract appearance, Mandelbrot combined this mathematical idea with his surroundings, determining that many natural objects such as clouds, mountains, coastlines, and lightning display self-similarity and satisfy the required conditions to be classed as fractals.[2]

The relatively new classification of lightning as a fractal has the potential to vastly improve existing lightning models and forecasting, due to the ability of fractals to describe the seemingly random phenomena of lighting. Previously, lightning's random nature made producing a model suitable for characterizing the destructive interactions between lighting and the earth's surface incredibly difficult.[4] As climate events become more frequent and destructive in nature, the ability to improve the precision of current models using fractals may improve preparations and predictions that aid in mitigating the damage to life and communities.[5]

FORMATION OF LIGHTNING

There are two types of lightning: intra-cloud lightning and cloud-to-ground lightning. Both of these weather events occur when a storm builds within a cloud, leading to an unbalanced charge distribution, also known as a dipole, between two locations. Specifically the upper and lower portions of the cloud become positively and negatively charged respectively. Although the exact mechanism through which a dipole forms is still unconfirmed, some researchers hypothesise that the cold temperatures within the cloud and large updrafts results in a vertical separation of ice and hail matter within the cloud due to their differing densities. During this separation collisions occur between matter, resulting in ice and hail particles gaining positive and negative charges respectively and hence forming a dipole.[6] Although the majority of lightning occurs within a cloud itself (intra cloud lightning), cloud-to-ground lightning has direct effects on human lives and communities and therefore there is a current focus on the modeling applications for this weather event.[7]

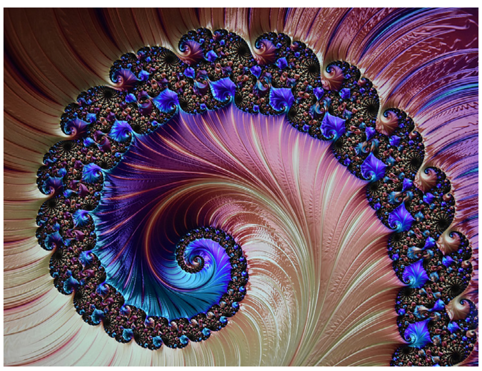
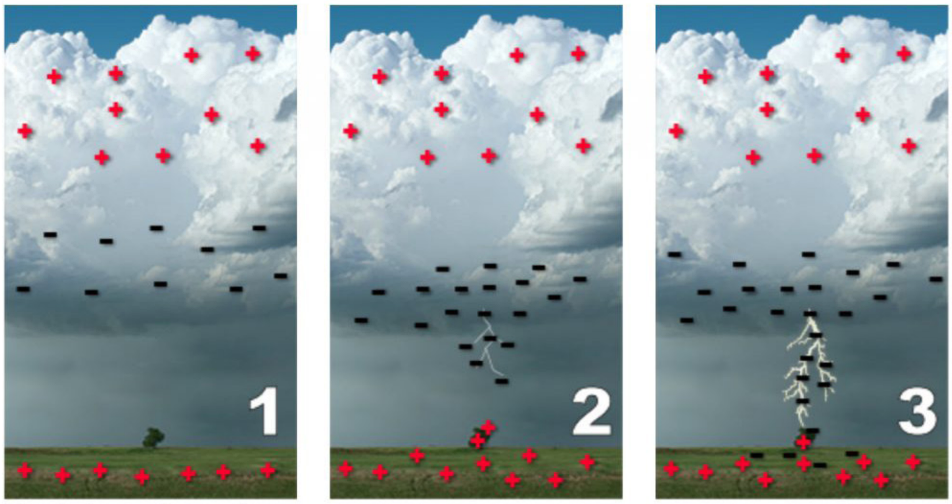


Figure 1: The image above shows an example of a fractal set named the Julia set. You can visually see the idea of self similarity such that the spiral continues to display the same pattern constantly, independent of how closely you view the image.

As the storm brews, the dipole continuously grows within the cloud until it is large enough for the air molecules in the cloud become charged.[8] This procedure kickstarts the process of a stepped leader, a collection of negative charges, which progresses towards the earth.[9] This stepped leader follows the path of the charged air, and its propagation is random in nature, with numerous branches splitting off from the main leader.[5] As the negatively charged stepped leader propagates down, an induced positive charge forms on the Earth's surface and grows in magnitude as the leader nears the ground. When the force of attraction between these opposing charges becomes sufficiently large, an upwards discharge from the ground, known as a streamer, forms and meets the stepped leader.[4,10] The visible lightning we see is due to a return stroke which occurs as a result of the streamer and stepped leader meeting. The return stroke follows the same pattern as the stepped leader did seconds before and propagates from the ground up towards the cloud.[8]

Due to the random nature of both the stepped leader and the return stroke's propagation, modeling lightning formation is challenging. Additionally there is a complex array of distinct subject matter such as electromagnetics, fluid dynamics, and atomic physics that are all necessary to describe the physics of lighting. One must use these fields in conjunction to completely understand the formation and trajectory of a lightning strike in order to accurately model it.[11] Finally, the lack of concrete understanding regarding the formation of the dipole and how the electric field becomes large enough to produce the initial stepped leader further complicates modeling attempts.



Thunderstorm gathers another pool of positively charged particles. | *Negatively charged area in the storm will send out a charge.* | *Lightning channel develops*

Figure 2: The diagram displays the process explained above regarding the formation of the lightning bolt. It shows the propagation of the negative stepped leader and the branching characteristics associated with its motion.

CURRENT MODELS

Before the discovery of fractals, modeling lightning strikes was very tedious and complex. Each bolt illuminates the sky in a unique way; hence, in order to accurately model lightning, one would have to individually account for the vast amount of separate branches which stem from the main bolt, as well as the random progression of the stepped leader through the sky.[5] One way of predicting the random motion of the stepped leader and return stroke was to use an LP model (a mathematical optimization technique). However, the usefulness and applications of this model are limited by its inability to produce the branching characteristics that real lightning possesses.[12] A variety of approaches have been made in an attempt to accomplish this, with scientists having to choose a collection of simplifying assumptions in their models due to current limitations in computational power. The large array of fields the subject matter spans can be used to individually describe specific portions of the trajectory in detail. However, these fields are all equally complex, with each requiring large amounts of computational power to model individually. Hence currently computers are unable to process a model which encompasses all of these individual fields and accounts for the precision and complexity of their associated data.[5] Furthermore, there is a high cost associated with highly analytical computer programs.[6]

APPLICATIONS OF FRACTALS IN MODELS

However, as a result of the connection made between this natural phenomena and its corresponding fractal properties, scientists can now utilize the fractal definition to advance the development of accurate lightning strike models. Now, many parts of a lightning bolt's trajectory that would previously have been modeled individually—a very complex and time-staking process—can be simplified by incorporating fractal properties such as self-similarity in models to treat the many separate branches as a single unit. For example, the LP model has been successfully improved using fractal analysis, as there is no longer a need to account for the average length of a stepped leader. Removing these highly analytical assumptions required for the previous LP model allows for the new model to only focus on the electric field generated by the leaders at any given point—a significant simplification.[12]

Currently, commercial weather stations use greatly simplified models for forecasting due to the high cost and complexity of a highly scientific model.[6] However, if fractals can encompass many of the different elements of the current scientific theory into a simplified format, it may be possibly to expand the use of more accurate models outside of purely academic research, due to the cost reduction associated with the reduced computational power associated with fractal models. This means these accurate scientific models could be more widely used forecasting and reporting, specifically regarding weather and storm predictions.[6]

CONCLUSION

The connection that was made between lightning and fractals by Benoit B.Mandelbrot has been pivotal in the development and understanding of this natural phenomenon. In the future, when computing power develops sufficiently, this ability to model lightning as a fractal may result in a more complete picture of a lightning bolt's trajectory through air. Considering that 50 years ago the ability to succinctly analyze the random motion of lighting using a singular mathematical idea was incomprehensible, it is exciting to realize how the potential groundbreaking discoveries that are sure to come will continue refining our understanding of this phenomenon. In both computing and science, such breakthroughs may simplify and unify many currently separate and disjoint areas of physics that influence this weather event.

ACKNOWLEDGEMENT

I would like to thank Dr. Jonathan Fraser, a professor of mathematics and statistics at the University of St. Andrews, for reviewing my article and providing me with useful and interesting insights regarding this area of research.

REFERENCES

1. 5 mathematical patterns in nature: Fibonacci, fractals and ... (n.d.). https://owlcation.com/stem/Astounding-Ways-How-Mathematics-is-a-Part-of-Nature
2. Jing, W., Xiaoying, Z., Lipeng, D., & Youfeng, C. (2010). Modeling of lightning based on Fractals. *2010 International Symposium on Signals, Systems and Electronics*, 2, 1–3. https://doi.org/10.1109/issse.2010.5607031
3. Britannica, T. Editors of Encyclopaedia (2024, August 15). fractal. Encyclopedia Britannica. https://www.britannica.com/science/fractal
4. Guo, J., Yang, T.-Y., Guo, S.-Y., Zhang, X.-D., Wang, B.-Y., Xie, Y.-Z., Wu, J., & Jing, Y. (2022). Validation of the lightning fractal model based on the attachment probability experiments using rod-rod air gaps. *IEEE Transactions on Power Delivery*, 37(6), 5133–5144. http://doi.org/10.1109/tpwrd.2022.3171598
5. Graham-Jones, B. C. (2006). The fractal nature of lightning - FSU digital repository. https://repository.lib.fsu.edu/islandora/object/fsu:182256/datastream/PDF/view
6. *Lightning forecasting.* NOAA National Severe Storms Laboratory. (n.d.). https://www.nssl.noaa.gov/education/svrwx101/lightning/forecasting/
7. Types of lightning. (2017,December 18). RMetsS. Https://www.rmets.org/metmatters/typeslightning#:~:text=Cloud%2Dto%2DGround%20(CG.
8. Britannica, T. Editors of Encyclopaedia (2024, September 11). Lightning. Encyclopædia Britannica. https://www.britannica.com/science/lightning-meteorology#ref121907
9. Tsonis, A.A., Elsner, J.B. (1987, May). Fractal Characterisation and Simulation of Lightning. https://myweb.fsu.edu/jelsner/PDF/Research/TsonisElsner1987.pdf
10. Engelking, C. (2019, November 20). *Lightning's strange physics still stump scientists. Discover Magazine*. https://www.discovermagazine.com/environment/lightnings-strange-physics-still-stump-scientists
11. Kostinskiy, A. Yu., Marshall, T. C., & Stolzenburg, M. (2020). The mechanism of the origin and development of lightning from initiating event to initial breakdown pulses (V.2). *Journal of Geophysical Research: Atmospheres*, 125(22). https://doi.org/10.1029/2020jd033191
12. Kawasaki, Z., Matsuura,K. (2000). Does a lightning channel show a fractal?. *Applied Energy*, 67(1-2),147-158. https://doi.org/10.1016/S0306-2619(00)00011-8

IMAGE REFERENCES

1. Header image: Newson,D. (2013). *lightning -Black and White*[image]. Flickr. https://www.flickr.com/photos/dan-newson/8801184428/in/photostream/
2. Figure 1: Zimny,J. (2021).*Julia Set Fractal*[image]. Flickr. https://www.flickr.com/photos/joeyz51/51270455274/in/photostream/
3. Figure 2: National Oceanic and Atmospheric Administration (NOAA). (2023). *Lightning states* [image]. https://commons.wikimedia.org/wiki/File:Lightning_stages.jpg