AIP Conference Proceedings

RESEARCH ARTICLE | JULY 24 2023

Inquiry-based science teaching – The use of RePLaT-Chaos application

Ildikó Bajkó

Check for updates

AIP Conference Proceedings 2843, 050007 (2023)
https://doi.org/10.1063/5.0150682

CrossMark
View Online
Export Citation

25 July 2023 08:16:25

AIP Publishing

AIP Advances
Why Publish With Us?
25 DAYS average time to 1st decision
740+ DOWNLOADS average per article
INCLUSIVE scope
Learn More
AIP Publishing

Inquiry-based Science Teaching – The Use of RePLaT-Chaos Application

Ildikó Bajkó[1, 2, a)]

[1]Szent István High School, 1146 Budapest Ajtósi Dürer sor15., Hungary
[2]Eötvös Loránd University, Physics Education PhD Programme, Budapest, Hungary

[a)] Corresponding author:bajkoildi@gmail.com

Abstract. In the last couple of years, we offered a few different chaos teaching modules to high-school students. A great new opportunity to teach chaos has emerged with the appearance of an application named RePLaT-Chaos developed for high schools via simulating the atmospheric spread of material emanated from volcanic eruptions. Students can use RePLaT-Chaos as an experimental tool to study the typical characteristics of the dispersion of pollutants in the atmosphere. Via this example they learn about chaos, such as sensitivity to the initial conditions (butterfly effect), irregular motion, and complicated but regular (fractal) structures. It helps students to raise awareness on the importance of chaos in environmental phenomena, and it is easy to use. We report on our experience according to which RePLaT-Chaos proves to be a complete success: it is a useful experimental tool and students use it with great enthusiasm.

25 July 2023 08:16:25

CHAOS TEACHING IN HIGH SCHOOL

As a high school teacher, besides teaching Physics, one of my main interest is introducing chaos physics in high school. Chaotic processes can be experienced in almost every branch of science. They are present in several areas ranging from populations dynamics, via chemical reactions to cardiac fluctuations. Many books available in the chaos literature give an overview of several chaotic applications [1], [2], some others concentrate mainly on specific fields like meteorology [3], astronomy [4] or oceanic plankton patterns [5]. Chaotic systems are not only subject for researchers, but we all encounter them in our everyday life. A particularly interesting phenomenon is chaotic mixing, such as stirring cream in coffee or hot chocolate.

In the last decade, I developed possible chaos teaching modules for high school students within both extracurricular framework and by incorporating them into high school physics curriculum. My teaching material is based on experiments with simple chaotic systems and simulations. The teaching modules have been tested with different student groups, and they proved to be useful [6]. Other approaches for teaching chaos in general [7] or based on simulation [8] are also available and highly recommended.

I put special emphasis on the use of handicraft, more exactly on the use of the marbling technique, which involves mixing of paints on the surface of water [9]. Stretching and folding are characteristic for chaos (the appearance of fractal filamentary structures). We can witness it in all its beauty during chaotic mixing procedures, such as mixing different paints, as we do it during marbling. The fractal filamentary pattern (Fig. 1.) obtained with this technique is typical for chaos: students experience how patterns develop. The long filaments reflect sensitivity to initial conditions, i.e. butterfly effect [10], since the mere appearance of such filaments is the result of strong stretching of initially compact small dye droplets. Handicraft is a very effective tool for becoming acquainted with chaos, and with the problem of dispersion of material in fluids.

I am reporting here about a new educational tool which, on the one hand, fits into the field of dispersion of materials, but, on the other hand, opens a new perspective of teaching physics in high school, with special emphasis

Proceedings of the TIM20-21 Physics Conference
AIP Conf. Proc. 2843, 050007-1–050007-11; https://doi.org/10.1063/5.0150682
Published by AIP Publishing. 978-0-7354-4594-9/$30.00

on environmental issues. In my experience, a whole new opportunity has emerged by the appearance of the application named RePLaT-Chaos [11].

FIGURE 1. Artwork resulted with marbling technique (photo by author). The pattern is typical for chaos: The long filaments always reflect chaos: sensitivity to initial conditions, i.e. butterfly effect

BASIC FEATURES OF REPLAT-CHAOS

RePLat-Chaos has been developed for students [12], [13], and can be used to monitor the spreading of volcanic ash in the atmosphere. It simulates the atmospheric spreading of pollutant clouds in the time interval of the Eyjafjaljökull's eruption on Iceland: April 14–24, 2010 using observation-based, realistic meteorological data, such as wind and temperature fields of several different altitudes in the atmosphere covering the whole globe (the necessary meteorological data are also included in the downloadable application).

On the "Design an eruption" page the user is free to design their own eruptions. The initial position, altitude, size and the number of particles of the ash cloud, and the particles' properties (diameter and density) can be set on the user interface. The site of the eruption can be chosen by clicking different locations on the map. An example is shown in Fig. 2.

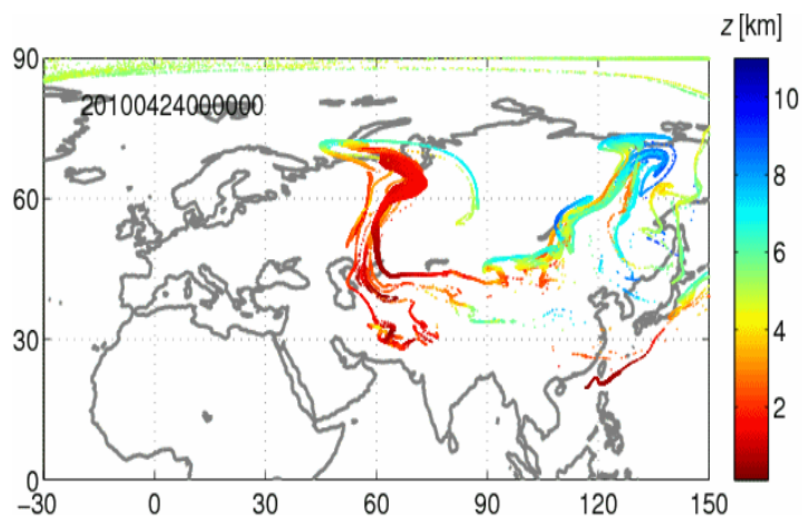
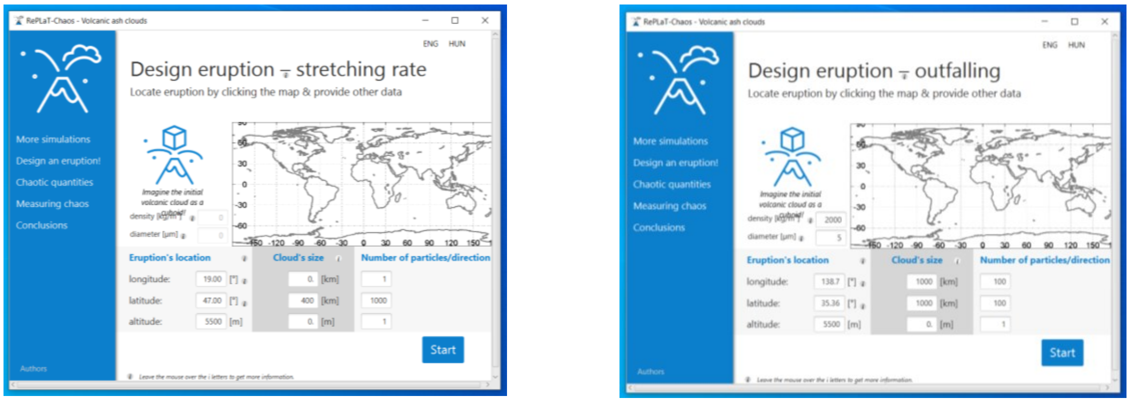


FIGURE 2. Result of a built-in simulation of the Eyjafjaljökull's eruption (initialized on April 14, 2010 at 6 UTC at the altitude of 7 km with 10^5 particles distributed on a square of 100 km x 100 km.). This picture shows the shape of the volcanic ash cloud

25 July 2023 08:16:25

ten days after the eruption, on April 24, 2010. The digits on the pictures indicate the time in the format <yyyymmddhhmmss>, and colors represent the height (z).

Furthermore, using the “Measuring chaos” page, RePLaT-Chaos can determine two quantities that describe the chaoticity of the processes: the stretching rate (Fig. 3.a) that quantifies the strength of the exponential stretching of pollutant clouds; and the lifetime (Fig. 3.b) that characterizes the rapidity by which the settling ash particles leave the atmosphere. A detailed definition of the two quantities will be given below and later in the section Students’ chaos-related discoveries.



(a) (b)

FIGURE 3. (a) In the “Measuring Chaos” page one finds two options: (a) Volcanic gas – to measure the stretching rate of a volcanic gas cloud (b) Volcanic ash – to measure the lifetime of the ash particles in the atmosphere

On the “Chaotic quantities” page (Fig. 4.) it also includes easy-to-understand explanations for the properties of atmospheric spreading and chaos. Any chaotic motion is characterized by the amplification of small initial differences, and the speed of the amplification is measured by the so called stretching rate [14]. So the stretching rate is also one of the possible measures of the strength of chaos, in other words, of the butterfly effect.

Here one learns that the greater value the stretching rate takes, the more quickly the length of the pollutant cloud grows.

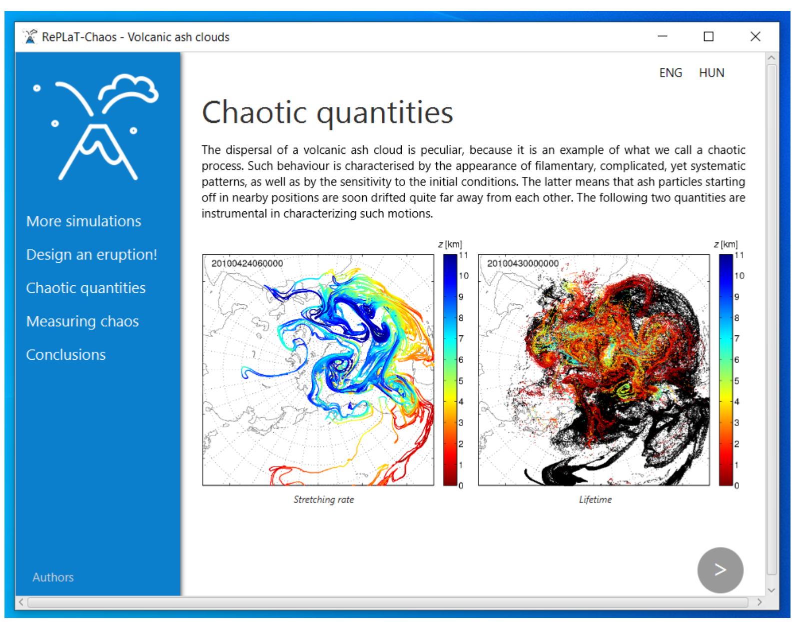


FIGURE 4. The “Chaotic quantities” page, which provides a brief overview of these chaotic quantities: stretching rate and lifetime

25 July 2023 08:16:25

USING REPLAT-CHAOS APPLICATION IN THE HIGH SCHOOL

We examined how students can use the application without any instructions, on their own. In this research at Szent István High School Budapest 123 students of grades 9, 10, 11 and 12 were involved. Students had to discover how to use the application in the framework of a 45 minutes Physics class. They had the opportunity to cooperate, and discuss in groups of two or three.

Students had the following tasks: 1. Explore the application, 2. Designs their own eruption, 3. Characterize the evolution of the pattern of the volcanic ash cloud, 4. Find similar patterns in nature. They were asked to present their experiences and their discoveries in written form.

Students' Activities

Students followed the tasks mentioned above, which were often illustrated with images of patterns in their submitted reports. The results are as follows:

1. Students were able to get acquainted with the application, as it turned out from their presentations.
2. Most of them designed their own eruption, 118 students (out of 123). They presented an image of the spreading pattern or a video about the development of the pattern. An example is given in Fig. 5.

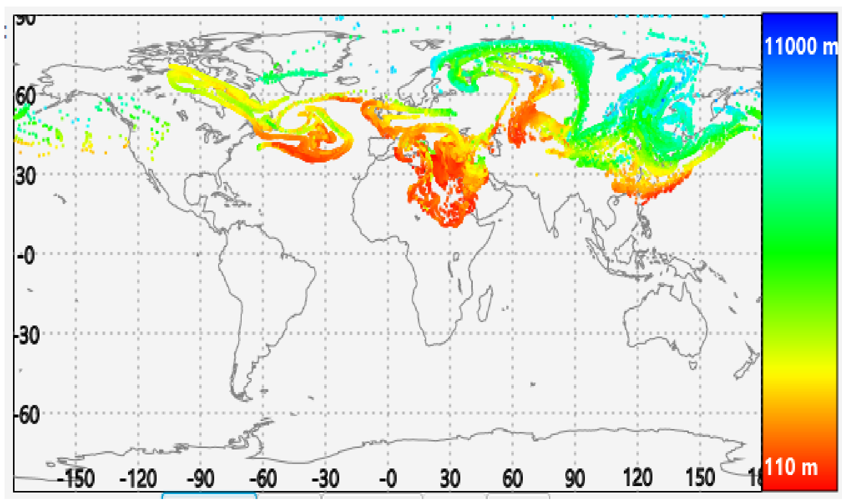


FIGURE 5. Example of a student's own designed volcanic eruption (B. Bottka 9th grader) initialized on April 14, at the altitude of 5,5 km and in an extension of 100 km x 100 km with $8 \cdot 10^4$ particles). The shape of the pollutant gas cloud is shown on April 24, 2010. The colors represent the height (dark blue the highest)

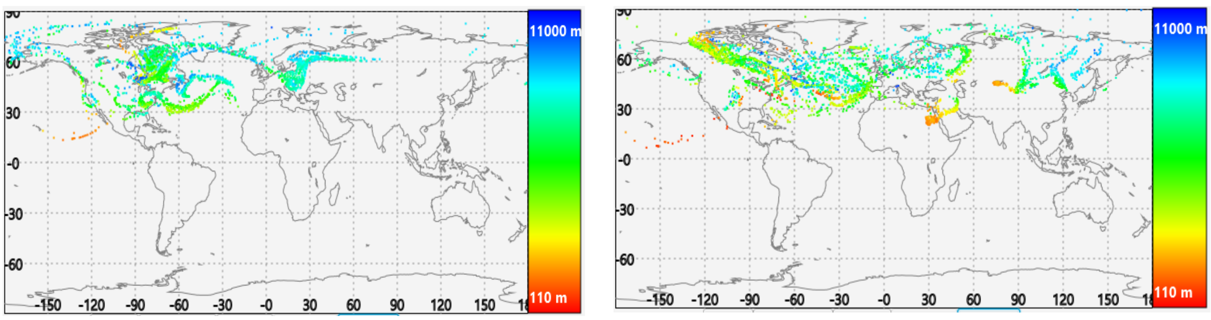
3. Students were surprised seeing how far and along what pattern the pollution spread. They realized the fact that pollutant clouds do not spread in the atmosphere like ink stain or dye blobs on clothes, instead an initially small and compact pollutant cloud becomes soon strongly stretched, while becoming filamentary and folded. This is because the ink blob is controlled by microscopic diffusion, while pollutant dispersion is controlled by high atmospheric winds which blow in a nonuniform way. By means of these simulations they discovered that volcanic ash clouds spread in the atmosphere in complicated but well-organized filamentary structures covering a large part of a hemisphere within a few days. Thus it becomes understandable that this feature leads to the necessity of blocking the air traffic for a certain time period after volcanic eruptions over extended geographical regions (as it was the case of the Eyjafjaljökull's eruption). Students were able to realize that even if initializing a volcanic pollutant gas cloud of very small size, its extension increases rapidly, and initially nearby particles get far away from each other within a short time. Many of them (more than 30 %) noticed and mentioned the effect of the winds. Students also reported that the application helped understanding the structure of large-scale atmospheric circulation.
4. Students found the topic of similar patterns really exciting. Their findings of similar patterns to those of atmospheric dispersion of volcanic pollution were the following: spread of oil contamination on water

25 July 2023 08:16:25

surface, mixing of different dyes, spread of colored liquid in a transparent one, the smoke of a blown-out candle, leaves blown by the wind – have been mentioned as examples of chaotic mixing phenomena. Images seen in weather forecast, image of tornado from above, spread of pollution in the seas or oceans, spread of radioactive contaminants – have been named as processes related to environmental flows. In many cases they illustrated their findings by photos taken from the internet.

Students' Chaos-Related Discoveries

Many students, as mentioned before, played around with the parameters, using the application as an experimental tool. There were a few of them (7 in number) who have found relevant examples for the butterfly effect, i.e. sensibility to initial conditions [10]. A quote from a student's submission on this "This is a relatively small change, so I think it's surprising that it affected the result quite intensively." This was a very important step, I did not ask them to look for it. My only request was to experiment with the parameters. It was a great pleasure for me as a teacher to see these discoveries in their submitted works. For an example, see Fig. 6.



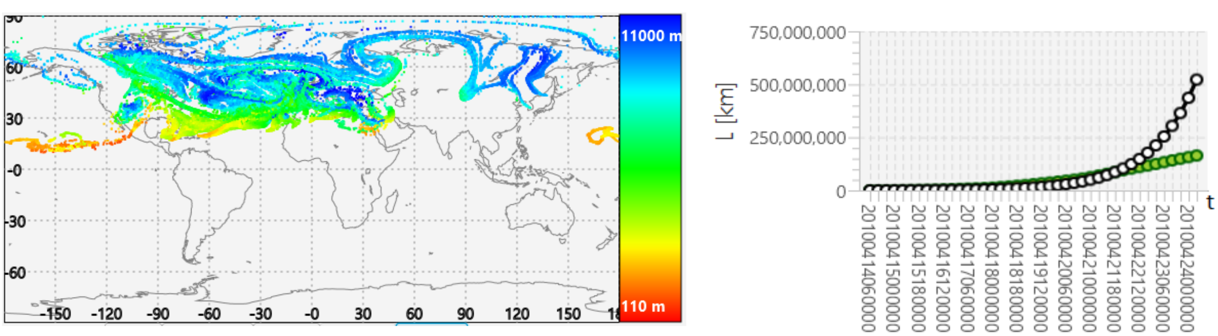
(a) (b)

FIGURE 6. Detail from a student's presentation (Zs. Keresztélyi 9th grader). A small difference in the initial height results in a very big difference in the length of the gas cloud and in the affected polluted areas as illustrated by panels (a) and (b)

Many students determined the stretching rate. This quantity reflects the fact that the length L of the pollutant cloud increases exponentially with time t, i.e. as

$$L(t) \sim 10^{ht}$$

where exponent h is called the stretching rate [14], [12]. This is a number characterizing the rate of deviation of originally nearby points, i.e., the strength of the butterfly effect in the dispersion process. An example for stretching rate determination is presented in Fig. 7, submitted by a student.



(a) (b)

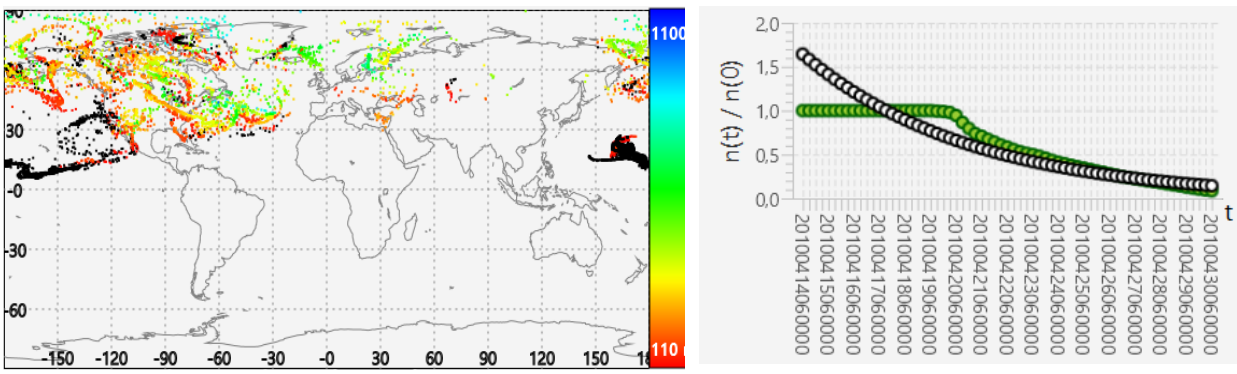
FIGURE 7. An attempt for determining the stretching rate. (a) An eruption generated by a student (Zs. Keresztély 9th grader). (b) The graph represents the length L of the gas pollutant cloud vs time (horizontal axis). Green dots indicate the measured length and the white ones correspond to a fit from which the stretching rate can be read off, which is 0.313 1/day (quoted from the student's work).

25 July 2023 08:16:25

It is worth mentioning that some students had difficulties with the proper interpretation of the result without assistance**.** It is certainly a success that the exponential form of stretching was understood, and students gave an estimate for the rate. As panel (b) shows, however, the fit applied is not appropriate over the whole interval. An accurate fit results in 0.347 1/day. Anyhow, both fitted numbers imply that the length becomes more than ten thousand times longer after 10 days.

By means of the RePLaT-Chaos one can measure the lifetime T [15], [12] of particles that characterizes the rapidity by which the settling particles of the pollutant ash clouds leave the atmosphere. For this purpose, the time-dependence of the ratio of the ash particles still in the air should be studied. Figure 8. illustrates, that the number of particles not yet settled from the atmosphere starts to decay exponentially after some time t_0. The number $n(t)$ of particles not yet settled after time t hardly changes up to t_0 but it decays rapidly, exponentially afterwards:

$$n(t) \sim 10^{-(t-t_0)/T} \text{ for } t > t_0$$



(a) (b)

FIGURE 8. An attempt for determining the lifetime diagram (a) An eruption generated by a student (Zs. Horváth, 9th grader) (black marks sedimented particles). (b) The graph represents the ratio of the number of ash particles that have not yet settled from the atmosphere to the initial number of particle vs time (horizontal axis). Green dots indicate the measured proportion and the white ones correspond to a fit.

25 July 2023 08:16:25

As the right panel of Fig. 8. illustrates, students had difficulty with fitting again. Here an exponential fit was applied to the whole interval, the student forgot about the existence of t_0 which is 6 days in this case. He got T=15 days. A correct fit would result in T=10 days. Anyhow, both fitted values imply that a tenth of the ash particles (of density 1000 and size 5μm) is still in the atmosphere about 10 days after the onset of decay, which is more than two weeks after the eruption. Students did also learn that the deposition pattern of particles onto the ground is also a filamentary fractal.

We note that around 30 % of the students used RePLaT-Chaos as a tool to determine both characteristic diagrams of chaos: the lifetime- and the stretching rate-diagrams.

As a consequence of the difficulties seen with fitting, in my next application of the teaching module I am planning to apply teacher assistance at least when students are dealing with the determination of chaos-related characteristic numbers.

Students' Feedback

We have intended to learn about how interesting and useful the application was in the opinion of the students. A questionnaire was completed after exploring the application. Before exploring the application, they were interviewed about what kind of pattern they expected for a volcanic cloud dispersion.

From 123 students 92 expected to have a patchy pattern, and 31 responses indicated that they were familiar with the filamentarity of the pattern (they had read about it or saw films about the phenomenon).

The results for some of the post-exploration questions "How interesting was it for you to explore RePLaT-Chaos application?" was as follows: 28% indicated that it was very interesting (5 on a scale of 5), and 51% that it was interesting (4 on a scale of 5) as shown on Fig. 9. None of the students replied that it was not interesting to work with the application.

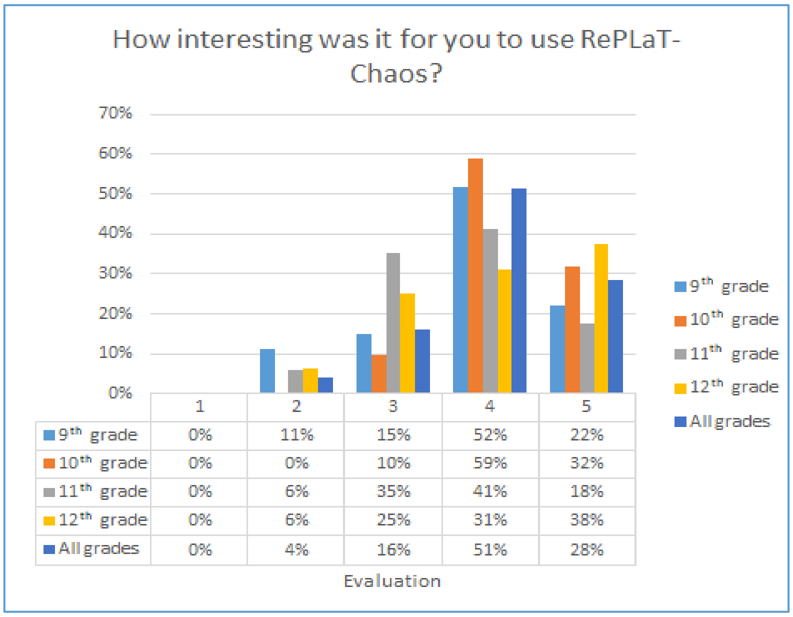


FIGURE 9. Answers for the question "How interesting was it for you to explore RePLaT-Chaos application?" by grades (very interesting – 5)

Additional questions and their evaluation are shown in Fig. 10-12.

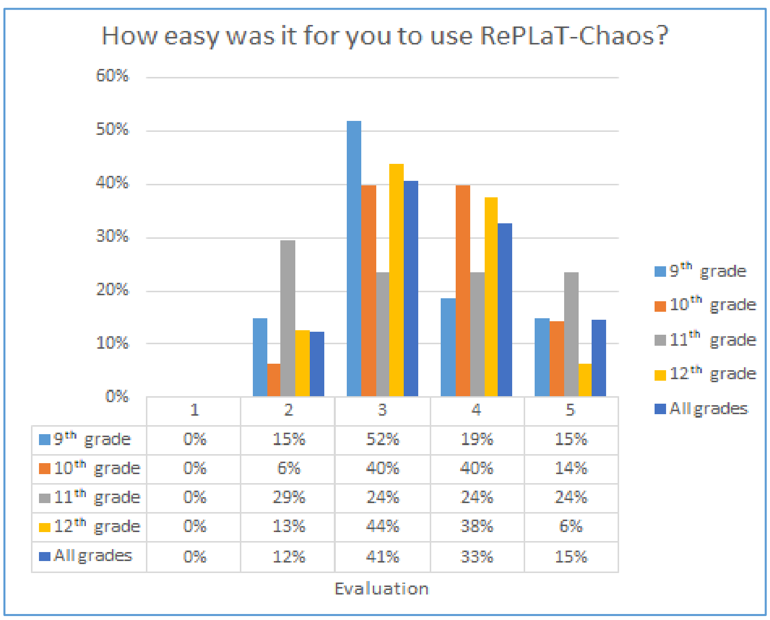
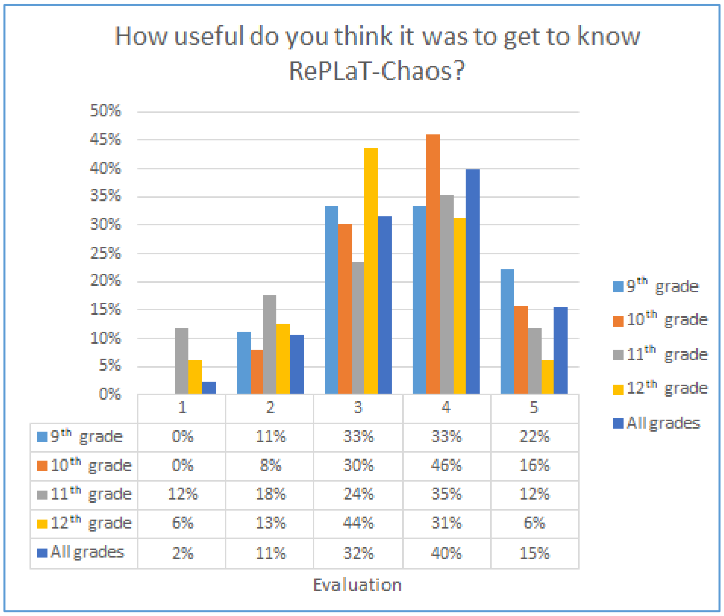


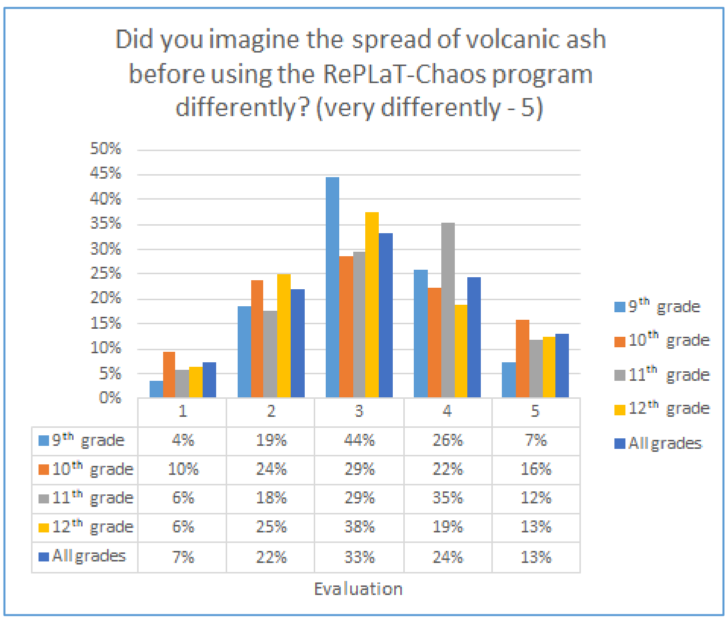
FIGURE 10. Answers for the question "How easy was it for you the use of RePLaT-Chaos?" by grades (very easy - 5)

25 July 2023 08:16:25



	1	2	3	4	5
9th grade	0%	11%	33%	33%	22%
10th grade	0%	8%	30%	46%	16%
11th grade	12%	18%	24%	35%	12%
12th grade	6%	13%	44%	31%	6%
All grades	2%	11%	32%	40%	15%

FIGURE 11. Answers for question "How useful do you think it was to get to know RePLaT-Chaos?" by grades



	1	2	3	4	5
9th grade	4%	19%	44%	26%	7%
10th grade	10%	24%	29%	22%	16%
11th grade	6%	18%	29%	35%	12%
12th grade	6%	25%	38%	19%	13%
All grades	7%	22%	33%	24%	13%

FIGURE 12. Answers for question "Did you imagine the spread of volcanic ash before using the RePLaT-Chaos application differently? (very differently - 5)" by grades

The answers to the open question "What was the most surprising finding while using the program" were very different. The most interesting types of answers were (each shared by a number of the students):

"The forms of ash spread were both the most interesting and most surprising."

"A bigger eruption could affect the whole world."

"How quickly the ash spreads."

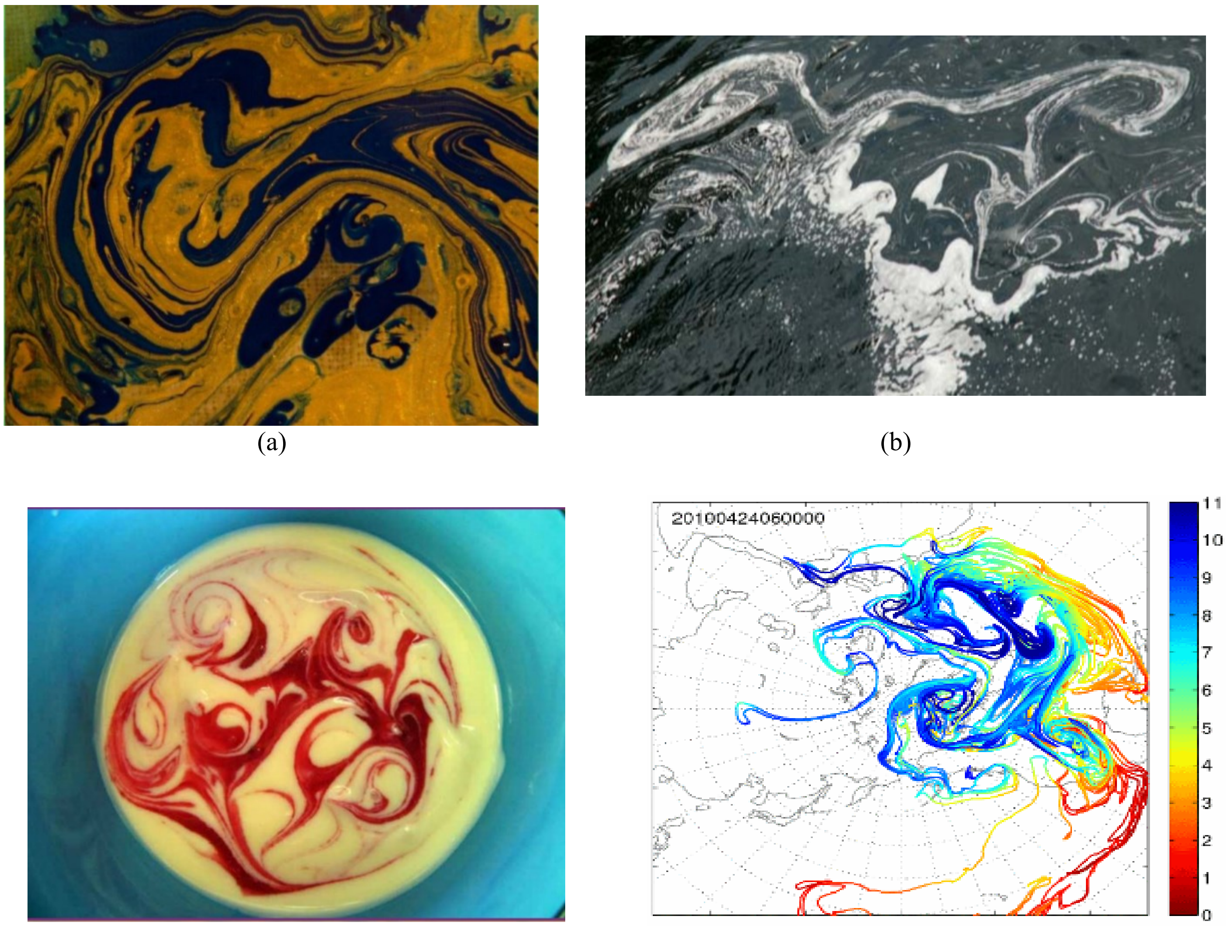
"Volcanic pollution can stay in the atmosphere for a very long time."

A particularly remarkable answer: "The most interesting was the marble-like spread."

25 July 2023 08:16:25

USING REPLAT-CHAOS WITHIN THE FRAMEWORK OF THE CHAOS TEACHING MODULES

During our traditional chaos teaching modules the marbling technique is used which involves mixing paints on the surface of water, and so the students experience how patterns develop. After these hands-on activities we typically turn to the topic of environmental flows. Students recognize similar patterns when encountering environmental contamination – in photos or in simulations. While using RePLaT-Chaos they discover that the case of the volcanic eruptions is associated with similar patterns. Structures similar to those seen in the marbling activity (Fig. 13.a) appear in environmental phenomena, such as the pattern of polluting foam on water surface (Fig. 13.b). Students have the possibility to compare their handicraft and the pattern of mixing jam with pudding (Fig. 13.c) or the pattern of the spreading volcanic ash in the atmosphere (Fig. 13.d). They conclude that filamentary patterns, typical for chaotic phenomena, occur on very different spatial scales, as also illustrated by the tableau below.



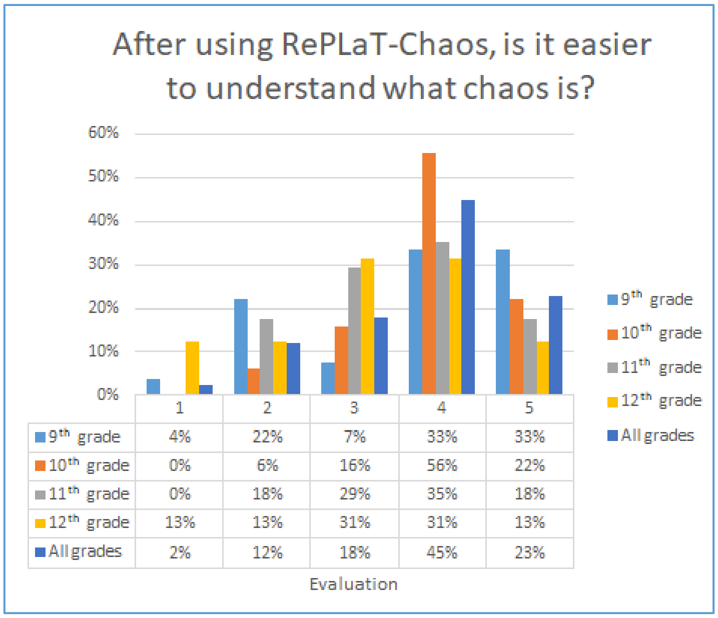
(a) (b) (c) (d)

FIGURE 13. (a.) Pattern of filamentary fractals in marbling – 10 cm scale (photo: author) (b) Pattern of polluting foam on water surface – 10 m scale (photo: Gy. Károlyi) (c) Pattern of mixing jam in pudding – 1 cm scale (photo: author) (d) Pattern of a gas cloud emanated from a volcano – 1 000-10 000 km scale (The simulation shows a gas cloud emanated from Fuji (Japan; 3776 m, Latitude: 35° 10' N Longitude: 138° 40' E) on 14 April 2010 after 10 days. Colors indicate heights – picture generated by the RePLaT-Chaos program

RePLaT-Chaos application is well suited to my chaos teaching modules in other aspects, too. Three main features can be generalized to other systems: 1. Experiencing the butterfly effect as a result of changing the initial conditions. 2. Measuring chaotic quantities. 3. Filamentary, fractal-like patterns are typical for chaotic phenomena.

25 July 2023 08:16:25

The answers to the question of the test "After using RePLaT-Chaos, is it easier to understand what chaos is" confirm that RePLaT-Chaos is efficient to use for perceiving chaos (Fig. 14).



	1	2	3	4	5
9th grade	4%	22%	7%	33%	33%
10th grade	0%	6%	16%	56%	22%
11th grade	0%	18%	29%	35%	18%
12th grade	13%	13%	31%	31%	13%
All grades	2%	12%	18%	45%	23%

FIGURE 14. Answers for the question" After using RePLaT-Chaos, is it easier to understand what chaos is?" by grades

As already mentioned, a considerable number of students noticed the effect of the winds in the spreading of pollutants. They also stated that the application helps understanding large scale atmospheric circulation [16], [17], [18]. The students recognized the fact that volcanic ash is dispersed only on one hemisphere of the globe. It is a well-known fact in meteorology that there is no material transport across the equator [3]. Students also gave an explanation of this in their works in terms of the strong upwelling existing along the equator.

So we recommend RePLaT-Chaos also for the geography class, or for any project related to environmental flows or spread of environmental pollution, for example spread of radioactive contaminants.

A quote from a student's submission on this: "When I got the job, I was curious about how the program would adjust to the winds, and I was surprised. It is very nice to see how the geographical phenomena affect the deposition of the volcanic eruption and I was able to follow the whole process."

The implementation of inquiry-based learning in science education is known to be able to increase students' motivation towards science learning and promote scientific thinking [19].

We did experience this in practice and saw how students played around, and how their motivation increased. All in all, students very much enjoyed using the application, not only did they play around, but explored the possibilities. It was superb to see them in flow. I had the opportunity to experience a very good example of how inquiry-based teaching makes the whole process enjoyable, exploratory and thus successful. It was superb to see them in flow. I had the opportunity to experience a very good example of how inquiry-based learning makes the whole process enjoyable, exploratory and thus successful. Students get into a state of flow [20]. It is worth noting, however, that this application can also be considered as a good basic idea for gamifying [21], an interesting material can be built around a volcanic eruption story.

CONCLUSIONS

The RePLaT-Chaos application is an easily manageable and accessible software. It helps students to raise awareness on the importance of chaos in environmental phenomena. Important properties of chaos, such as the butterfly effect, can easily be demonstrated.

Students very much enjoyed using the application, they not only just played around, but explored the different possibilities. I have asked them what it was like the use of the application. Here a few of their answers: "I have never

25 July 2023 08:16:25

had such a learning experience before.”, “It was good to play with it.”, “It was exciting.” As the answers show, using RePLaT-Chaos is a very good example of inquiry-based learning.

Students experienced a very good example of how inquiry-based learning makes the whole process enjoyable, exploratory and thus successful. RePLaT-Chaos proves thus to be a complete success: it is a useful experimental tool and students use it with great enthusiasm.

ACKNOWLEDGMENTS

I am thankful for fruitful discussions and useful pieces of advice to my supervisors, Tímea Haszpra and Tamás Tél. Thanks for the enthusiastic work of students from the Szent István High School, in particular to Zsófia Keresztélyi, Csenge Székely, András Zoller, Barnabás Bottka, Barnabás Rácz, Zsombor Horváth, Benedek Szatmáry and Ádám Hajas.

REFERENCES

1. T. Tél and M. Gruiz, *Chaotic dynamics* (Cambridge Univ. Press, New York, 2006)
2. J. Argyris, G. Faust, M. Haase and R. Friedrich, *An Exploration of Dynamical Systems and Chaos* (Springer, New York, 2015)
3. E. N. Lorenz, *The Essence of Chaos* (University of Washington Press, London, 1995)
4. F. Diacu and Ph. Holmes, *Celestial encounters: The Origins of Chaos and Stability* (Princeton Science Library, 1996)
5. Z. Neufeld and E. Hernandez-Garcia, *Chemical and biological processes in fluid flows: A dynamical systems approach,* (Imperial College Press, London, 2003)
6. I. Bajkó, Horizons of mathematics, physics and computer sciences **50**, 22-34 (2021).
7. T. Tél, Phys. Educ. **56,** 045002 (2021)
8. Z. Csernovszky, P. Nagy, P. Tasnádi, Canadian Journal of Physics, **98**, 593-605 (2020)
9. I. Szatmáry-Bajkó, “Handicraft and aesthetic experience in teaching chaos physics” in Teaching Physics Innovatively edited by A. Király and T. Tél, 15–20. (Budapest: ELTE) (2016)
10. Gleick J, *Chaos: Making a New Science* (Penguin Books, New York, 1987)
11. http://theorphys.elte.hu/fiztan/volcano/#edu
12. T. Haszpra, Atmosphere **11**, 29 (2019)
13. T. Haszpra, M. Kiss, É. Izsa, J. Phys.: Conf. Ser. **1929**, 012079 (2021)
14. T. Haszpra, T. Tél, J. Atmosph. Sci, **70**, 4030-4040 (2013)
15. T. Haszpra, T. Tél, Nonlin. Proc. Geophys. **20**, 867-881 (2013)
16. A. Gróf, Phys. Teacher **59**, 103-107 (2021)
17. A. I. V. Vörös, AIP Conference Proceedings **2218**, 060008 (2020)
18. M. Pető, AIP Conference Proceedings **2218**, 060003 (2020)
19. C. P. Constantinou, O. E. Tsivitanidou, E. Rybska “What Is Inquiry-Based Science Teaching and Learning?” in Professional Development for Inquiry-Based Science Teaching and Learning, 1-23. (Springer, 2018)
20. J. Nakamura, M. Csíkszentmihályi. "Flow theory and research” in Handbook of positive psychology 195-206. (Oxford University Press, 2009)
21. M. Kalogiannakis, S. Papadakis and A. Zourmpakis, Education Sciences **11**, 22 (2021)

25 July 2023 08:16:25