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RePLaT-Chaos-edu: an interactive educational tool for secondary school students for the illustration of the spreading of volcanic ash clouds

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Abstract. The continental- and global-scale spreading of pollutants emitted from volcano eruptions or industrial accidents is an everyday issue in our life. Nevertheless, students are generally not aware of the fact that pollutant clouds do not spread in the atmosphere like dye blobs on clothes, rather an initially small and compact pollutant cloud becomes soon strongly stretched, while becoming filamentary and folded. This paper introduces an application called RePLaT-Chaos-edu by means of which students can investigate the characteristics of the atmospheric dispersion of volcanic ash clouds and other pollutants in an interactive way. The simulations utilize meteorological data and follow the time evolution of pollutant clouds consisting of a large number of individual particles. RePLaT-Chaos-edu is also a suitable tool for studying the so-called chaotic features of the advection. The software was tested at the Berzsenyi Dániel Grammar School and the Szent István Grammar School (Budapest, Hungary) in the framework of Physics classes and during a project week, respectively.

1. Introduction

In everyday life we often read about hazards due to volcanic ash clouds and other atmospheric pollutants. Due to their huge global impacts, the most known pollution events of the last decade include, e.g., the 2010 eruptions of the Icelandic Eyjafjallajökull volcano which caused airspace closures across Europe [1–2] as its volcanic ash clouds reached not only Northern Europe, but even the Iberian Peninsula and Italy, thousands of kilometers away from Iceland [3–6]. One year later, in the spring of 2011, the Fukushima Daiichi nuclear disaster in Japan drew people’s attention to the global environmental consequences of local emissions. As a result of the accident, radioactive materials were transported in the atmosphere over the Pacific Ocean traveling around the Northern Hemisphere within a few weeks producing measurable concentration even in Europe [7–8].

Nevertheless, through a questionnaire among students, we concluded that it is not well known that pollutant clouds do not disperse in the atmosphere like dye blobs on clothes, rather an initially compact pollutant cloud becomes soon strongly stretched, while becoming filamentary and folded. This is the result of the fact that in three-dimensional flows, such as the atmosphere, the advection of pollutants is chaotic, i.e., the advection dynamics of pollutants shows the typical characteristics of chaos, such as sensitivity to initial conditions, irregular motion, and complex but regular (fractal) structures [9].



Chaos (deterministic chaos, in a more strict terminology) is a relatively new branch of science (for a popular book, see [10], for an introductory text, see [9]), which originates from the discovery that simple, deterministic processes might lead to temporally irregular behavior. This implies unpredictability, a rapid growth of initial uncertainties, referred to as “butterfly effect” [10] in everyday language by now. An older form of chaos, molecular chaos, originates from statistical physics and refers to a kind of microscopic disorder of high degree-of-freedom systems, leading to e.g. Brownian motion and diffusion. The latter represents complete randomness, while the former is less irregular reflected by its relation to structured, fractal patterns. The students have a chance to contrast these two kinds of chaos by realizing that their naïve expectation of blob-like spreading in the atmosphere originates in their familiarity with diffusion, but atmospheric spreading is completely different being governed by the laws of (deterministic) chaos.

In this project, creating an application as an educational reconstruction [11] of the topic of large-scale atmospheric spreading, we studied how to arise students’ interest by bringing these phenomena closer to them. For this purpose, we created the RePLaT-Chaos-edu (Real Particle Lagrangian Trajectory model – Chaos version for educational purposes) application [12] which has a user-friendly interface designed by taking into account the opinions and suggestions of students and teachers as well.

The RePLaT-Chaos-edu software was created specifically for educational purposes, so that the features of atmospheric spreading could be studied in an easy and interactive way through simulations designed by the users on their own. RePLaT-Chaos-edu can also determine two quantities that describe the chaoticity of the advection processes: the stretching rate that quantifies the strength of the exponential stretching of pollutant clouds; and the lifetime that characterizes the rapidity by which the settling particles of the pollutant clouds leave the atmosphere. It also includes easy-to-understand explanations on the properties of atmospheric spreading and chaos. The application is based on the previously developed RePLaT (Real Particle Lagrangian Trajectory) model [13] and has the same computational background as the “full” version called RePLaT-Chaos [14]. The latter version of the application differs from RePLaT-Chaos-edu being designed for advanced experts (e.g. for university students) and allows every simulation parameters of the spreading, generally not necessarily known by secondary school students, to be set up by the user. RePLaT-Chaos-edu is a desktop application freely downloadable from the webpage of the Department of Theoretical Physics, Eötvös Loránd University [12] with detailed instructions on how to install it to the user’s computer.

The paper is organized as follows. Section 2 demonstrates the applicability and possibilities of RePLaT-Chaos-edu describing the function of its pages. Examples on stretching rate and escape rate calculations are also presented to get an impression about their meaning. Section 3 gives a brief overview on our experiences on using the application by students and the change in their knowledge about the atmospheric spreading. Section 4 summarizes the main features and advantages of the application. The Appendix presents the calculation of the spreading of pollutant clouds and the computation of the two chaotic measures, the stretching rate and escape rate.

2. The RePLaT-Chaos-edu application

RePLaT-Chaos-edu simulates the atmospheric spreading of pollutant clouds in the time interval of the Eyjafjaljökull’s eruption: 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 welcome page students can choose language: for now it is English or Hungarian, but it is easy to add other languages to the software due to the dictionary files applied in the code.

The model which this educational application is based on, RePLaT, has carefully been validated in a number of particular cases [15–16]. RePLaT also describes the effect of turbulent diffusion, which is, however, only relevant in a narrow layer close to the surface, and is thus not taken into account in RePLaT-Chaos-edu.

2.1. *Becoming acquainted with the main features of atmospheric spreading*

The RePLaT-Chaos-edu application is divided into different pages, as besides providing the possibility for the students to design their own volcanic eruptions it also serves as an introduction and tutorial to learn about the basic features of atmospheric spreading. Therefore, the aim of the first pages is to arise the students' interest in large-scale atmospheric spreading events and related environmental issues containing examples on volcano eruptions with eye-catching animations.

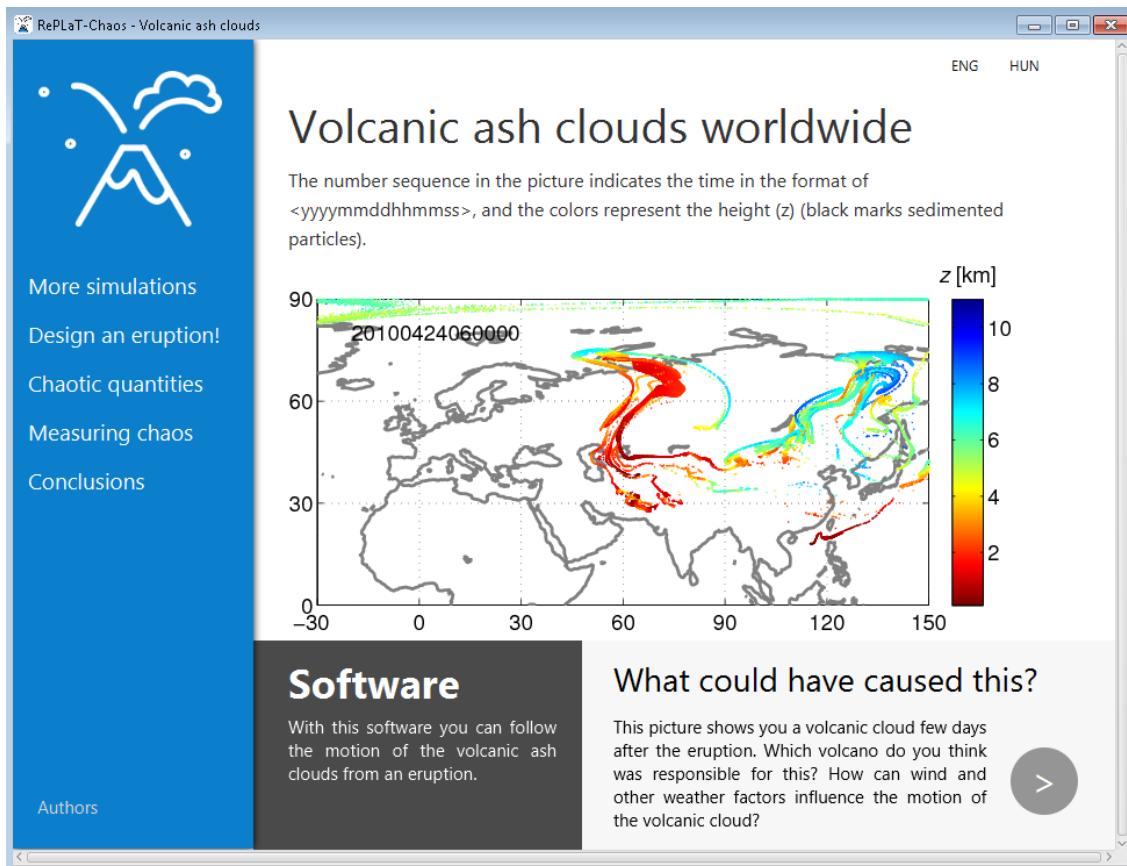


Figure 1. The first page of the application: the shape of a pollutant cloud from the Eyjafjallajökull eruption on April 24, 2010 at 6 UTC. The pollutant cloud is initialized on April 14, 2010 at 6 UTC at the altitude of 7 km and in an extension of $100 \text{ km} \times 100 \text{ km}$ with 10^5 particles.

As a first example, the distribution of a volcanic ash cloud can be seen 10 days after the eruption of the Icelandic Eyjafjallajökull volcano, on April 24, 2010 (figure 1). It shows a pollutant cloud with a very complicated shape with several foldings and meanders, covering a large part of Siberia. The altitude of the particles is marked by colors. They are distributed in a remarkable range, up to 11 km. In general, students do not imagine by themselves that this distribution could be caused by a single, instantaneous eruption. They can also experience that it is almost impossible to guess which volcano is responsible for the distribution based on the image. Nevertheless, the solution – in the guise of an animation – reveals that the observed image is indeed a result of the spreading of an initially compact and small volcanic ash cloud injected into the atmosphere at the southern part of Iceland. Not only the extension and shape of the cloud change considerably within a short time, but also the particles of the pollutant cloud reach different altitudes soon due to the locally rising and sinking air at certain locations.

On the next page “More simulations” the spreading originating from three other, hypothetical eruptions can be seen for the same time interval as further interesting examples. Students can see how the ash cloud from Vesuvius (Italy) could cover Asia, and compared to this how different paths the

particles from Badacsony (a Hungarian inactive basalt volcano) can perform due to the different atmospheric conditions, despite that the two volcanoes lie not so far from each other. It can be seen that the volcano cloud from Badacsony stretches at the beginning mainly in the east-west direction into a filamentary shape, and most of its particles are transported above the Atlantic Ocean, Scandinavia and Turkey, while only few particles reach Asia within 10 days. Based on this example the students' attention can also be drawn to the fact that the particles trace out fingerprints of atmospheric features, such as a cyclone south to Greenland revealed by a spiral structure in the pattern of April 23–24. The particles altitude becomes higher at these locations due to the ascending flow within cyclones. The third animation shows the movement of volcanic ash from a hypothetical eruption of Chimborazo (Ecuador) which is intended to demonstrate how the spreading differs for clouds initiated in the tropical region, subjected mainly to the trade winds, from the previous two ones emitted at mid-latitudes dominated by cyclonic activity. For Chimborazo, it can be seen that particles ascend quickly into the higher layers of the troposphere due to the upward flows of the Intertropical Convergence Zone, then parts of the pollutant cloud which are close to the equatorial region spread slowly westward along the Equator, while other parts forming lobes propagate in the opposite direction.

2.2. *Designing an eruption and measuring chaos*

After students have become acquainted with the basic features of atmospheric spreading based on these examples, on the “Design an eruption” page (figure 2) they are free to design their own eruptions. The initial position, altitude, size (in the form of a rectangular cuboid) and the number of particles of the pollutant cloud, and the particles' properties (diameter and density) can be set on the user interface. The information marks “*i*”s help them if they are not exactly sure about the meaning of a certain parameter. The site of the eruption can be chosen by clicking different locations on the map. For example students can observe that the deposition of even initially compact ash clouds does not happen in patches, rather in inhomogeneous, generally filamentary structure. Large particles spend much less time in the atmosphere than smaller ones, and volcanic ash clouds from the tropical region do not stretch so much in general as the ones started at middle or high latitudes. Once the simulation has started, for the sake of easier observation, the users can zoom in or out on the map by changing its boundaries or enlarge the mark of the particles.

By means of these simulations the students can discover that the 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. They can also experience that even if they initialize a volcanic ash cloud of very small size its extension increases rapidly, and initially nearby particles get far away from each other within a short time. This is the result of the fact that in three-dimensional flows, such as the atmosphere, the advection of pollutants is chaotic, i.e., the advection dynamics of pollutants shows the typical characteristics of chaos, such as sensitivity to the initial conditions, irregular motion, and complicated but regular (fractal) structures.

The “Chaotic quantities” page provides a brief overview of these chaotic properties and also introduces the two quantities: stretching rate and lifetime of particles which RePLaT-Chaos-edu can calculate.

On the page “Measuring chaos” these quantities can be measured in user-friendly simulations designed by the students. These pages are similar to the previous “Design an eruption” page but, additionally, after the simulation is over, students can also see the time-dependence of the quantity needed for the computation of one of the chaos measures (see figure 3 and figure 4).

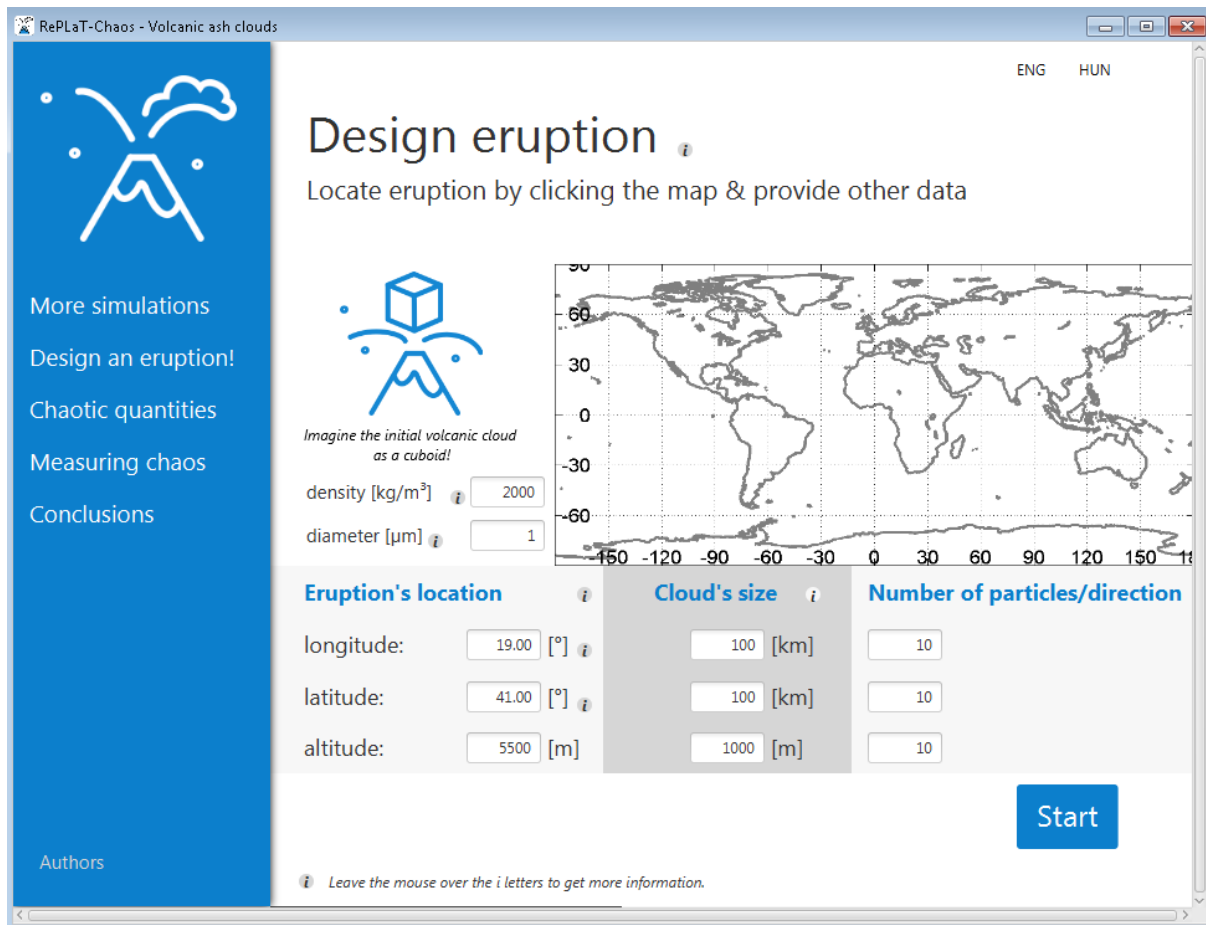


Figure 2. The “Design an eruption!” page.

Figure 3 shows the shape of a cloud evolved from a set of particles distributed along a line segment of a filament (a 1-D pollutant cloud) of initial horizontal length 400 km. In the lower part of the panel it can be seen that the length of the cloud has grown rapidly during the 10 days of simulation, while the top panel shows that it has become more and more folded and tortuous, covering an extended part of the mid- and high latitudes of the Northern Hemisphere. The time-dependence of the length L of the filament proves that the filament grows in a highly non-linear way, in an exponential manner in time, and by clicking the “Calculate stretching rate” button, students can determine their eruption’s own stretching rate h . Based on its definition (see Appendix A.2) this value implies that the length of this cloud grows by a factor of 10 in every $1/h = 2.865$ days. One can see that it results in the fact that despite the short initial length of 400 km, by the 10th day its length reaches 1.25×10^6 km, that is, it has stretched by a factor of about 3000 within merely 10 days. This also implies that originally nearby points deviate rapidly in time, the user thus becomes faced via this experience with the “butterfly effect”, a basic feature of (deterministic) chaos. The number of points of the initial clouds can freely be chosen in the simulations. If one takes here only two particles, at a distance of a few km, a traditional illustration of the sensitive dependence on initial conditions of chaos is obtained (although in a much less appealing optical appearance because of the movement of just two dots).

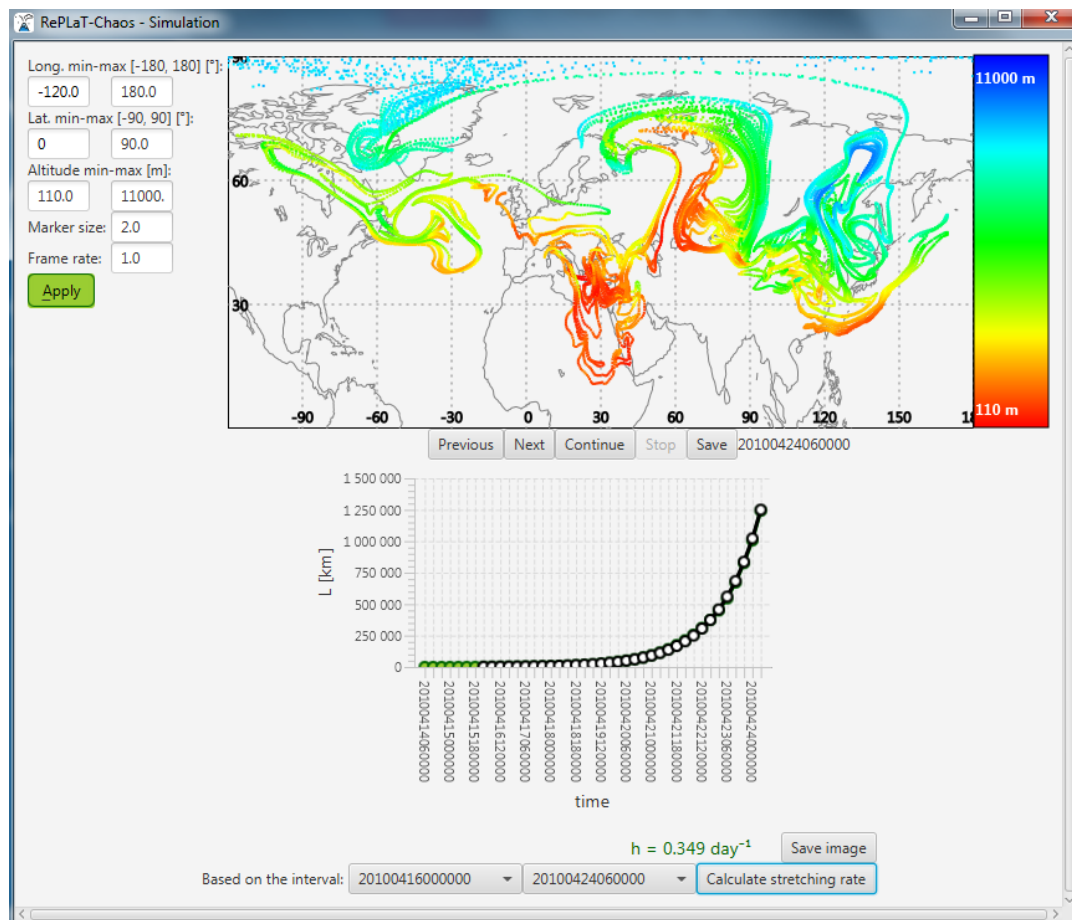


Figure 3. Example on an advection image of a 1-D pollutant cloud after 10 days and the corresponding time-dependence of its length L . The filament consisting of 10^5 particles is initialized as a meridional line segment of initial length of 400 km at 19° E, 47° N at the altitude of 5.5 km on April 14, 2010 at 6 UTC. Particle radius is $0 \mu\text{m}$ corresponding to gas particles.

The other quantity which RePLaT-Chaos-edu can measure is the lifetime of particles that characterizes the rapidity by which the settling particles of the pollutant 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 4 illustrates that the number of particles not yet settled from the atmosphere starts to decay approximately exponentially after some days. Choosing an appropriate interval for the exponential decay and clicking the “Calculate lifetime” button the value of the lifetime T (See Appendix A.3) appears on the screen. In this case it means that $T = 10.684$ days after the starting time t_0 of settling only one tenth of the particles can be found still in the air.

It is also interesting to discover on the map of Figure 4 that even though the initial extension of the pollutant cloud is much smaller than the area of a hemisphere, within the investigated time interval, particles of the pollutant cloud cover almost the whole hemisphere. Another important feature characteristic to chaotic processes is that the deposition pattern (black color) of the cloud is not homogeneous: the particles do not settle on the ground as a compact patch, but in an inhomogeneous structure with denser and sparser regions.

The graph of the non-settled particles also draws attention to the fact that the individual lifetime of even identical particles may differ considerably, from a few days to tens of days. Furthermore, it is interesting to discover that if the particles initial position is colored according to the particles’ individual

lifetime, which can be seen on the last page of “Chaotic quantities”, also a filamentary, fractal geometry can be observed in this pattern, typical for chaos.

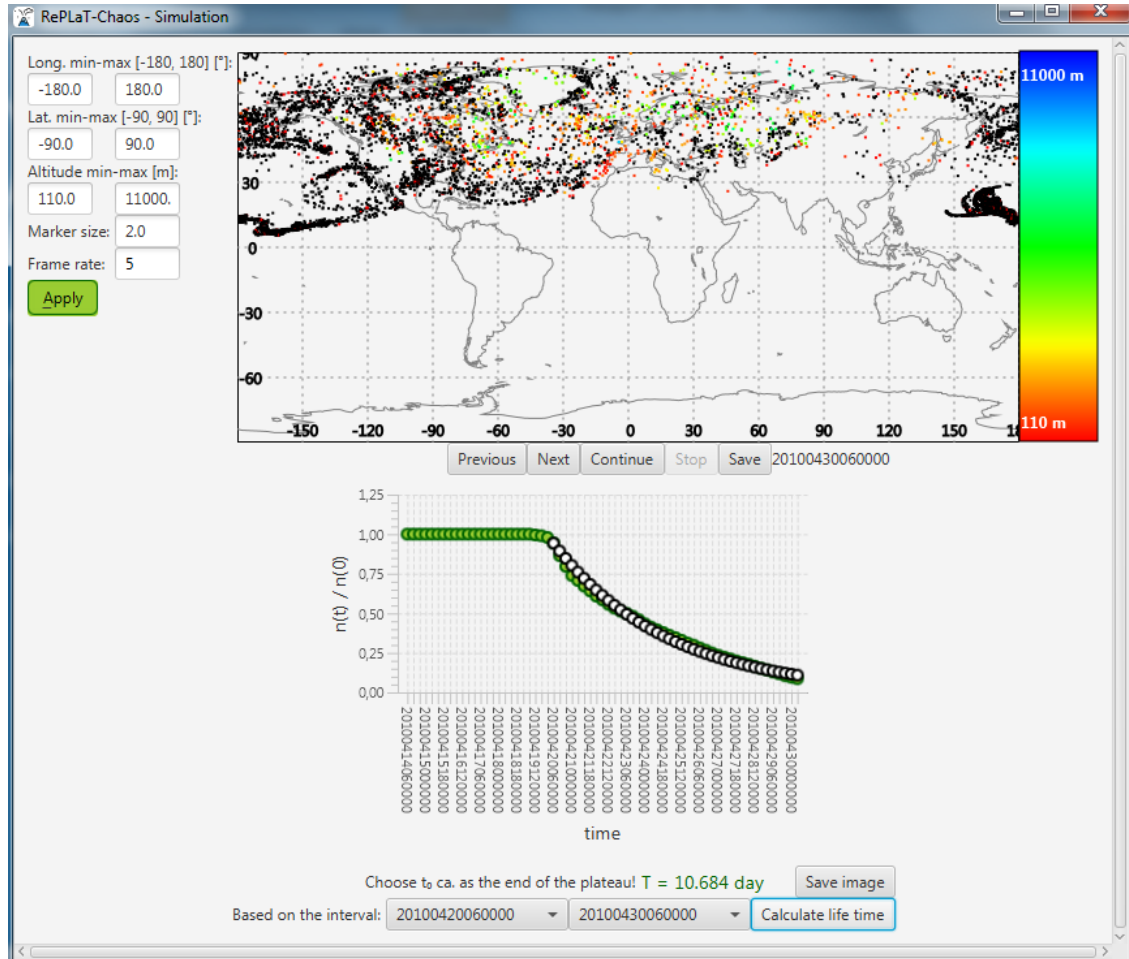


Figure 4. Example on an advection image of a pollutant cloud after 10 days and the corresponding time-dependence of the ratio $n(t)/n(0)$ of non-settled particles. Black color indicates deposited particles. The pollutant cloud is initialized as a rectangle in a size of $10^3 \text{ km} \times 10^3 \text{ km}$ at 138.73° E , 35.35° N (Japan) at the altitude of 5.5 km on April 14, 2010 at 6 UTC. Particle diameter is $5 \mu\text{m}$, particle density is 2000 kg m^{-3} (typical for volcano eruptions).

The “Conclusion” page summarizes the main features of atmospheric spreading with which the students have become acquainted in the application.

3. First experiences in schools and the efficiency of the application

As a pilot project, to test the applicability of the material for secondary school teaching, the RePLaT-Chaos-edu application has been tested within small groups of students in the Berzsenyi Dániel Grammar School (Budapest, Hungary) during Physics classes among student in their 7th and 12th grade (i.e. 13- and 18-year-old students).

One question of a pre- and post-test (figure 5) before and after using the RePLaT-Chaos-edu application revealed that considerably more students have become aware how pollutants in the atmosphere spread after their own experiences with the application. As the left panel indicates, they had a number of different misconceptions (no one appeared to be aware of the typical filamentary structure

before the project started, although such patterns are clearly visible in pollution-related satellite pictures often published in the media.). This implies that current physics (or science) teaching is not handling this problem properly, and perhaps, more generally, the issue of environmental physics as a whole; explicit education is thus needed.

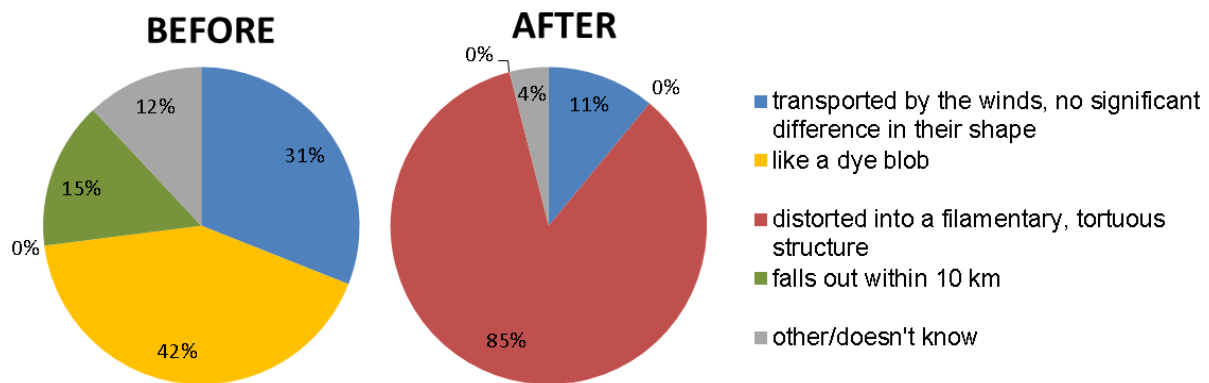


Figure 5. The results of a question in the pre- and post-test: “How do you think volcanic clouds spread in the atmosphere?” carried out before and after using the RePLaT-Chaos-edu application in Berzsenyi Dániel Grammar School (Budapest, Hungary). Questionnaire is compiled by M. Kiss.

The answers received on other questions indicated that students became acquainted with basic concepts of chaos as well. They were also able to understand and measure the characteristic numbers of chaos and studied their dependence on geographical location.

Teachers can also find opportunity for discussing the difference between the spread of oil and volcanic ash. The former is the consequence of a *microscopic* process. Particles exhibit a kind of Brownian motion due to their interaction with the surrounding ones leading to a fully random dynamics. The chaotic nature of the spreading of volcanic ash is due to the spatial inhomogeneity of winds: on short distances wind is homogeneous, but on the scale of 10 to 100 m the speed and direction of wind can be rather different, and it is this so-called wind shear that forces nearby particles to quickly deviate. Chaos is thus less random, and more inhomogeneous, than microscopic diffusion.

To summarize the results of this pilot project we found that the students were interested in using this tool. Students enjoyed designing their volcano eruptions and understood the basic differences between the spreading of dye on clothes and volcanic ash in the atmosphere.

It is important to emphasize that the spread of volcanic ash is just one example for the spreading of pollutants. The advection of any material is typically chaotic on large scales because the spatial inhomogeneity of fluid flows leads to strong stretching of material filaments, and this is valid in liquids, too. What has been learned here on the example of volcanic ash, is valid for any kind of large scale environmental pollution, should it occur in the atmosphere or in the oceans.

After the completion of this pilot project we have launched a PhD project for the exploration of the use of RePLaT-Chaos-edu in public education. The first experiences gained at the Szent István Grammar School (Budapest, Hungary) during a project week on Chaos Physics–Environmental Physics among students specialized in Science and Mathematics in grades 9–11th are promising. The PhD study is currently ongoing and a comprehensive result from it can be expected within a year or so. The sudden change in teaching circumstances due to the Corona virus crisis lead our MTA-ELTE Physics Education Research Group to make all its on-line teaching material freely and widely accessible in March 2020 [18]. A short promoting material appeared about this in the monthly journal of Hungarian physics teachers and physicists, *Fizikai Szemle*, with all the links explicitly given. RePLaT-Chaos-edu is of course part of this, and is also accessible from the English language home page of the Research Group. With this widened publicity, we hope to gather experiences from a large number of colleagues from different types of schools which might enable us to have access to reliable statistics.

4. Summary

The application presents that the spreading of pollutants differs from the dispersal of dye droplets on our clothes, as a cloud of ash or gas disperses in a filamentary, fractal-shaped form, not in a slowly growing circular shape. It is because the spreading itself is a process of chaotic nature, independent of the properties of the spreading substance. One can see that the forecast of the dispersion patterns is rather difficult because there are contamination free areas between the filaments, while the entire territory covered by the filaments may be extremely large. It is also worth knowing that under usual atmospheric wind conditions, any pollution would spread over one hemisphere within approximately a month.

Students can see that the intensity of chaos might be characterized by the so-called stretching rate of the filaments, showing the rapidity of their length growth in time. With several experiments they can also discover on their own that its value is the lowest around the Equator because cyclonic activity, a characteristic feature of medium and high latitudes, does not play much role there. Due to the ascending air movements, even ash particles are frequently stirred up into the higher layers of the atmosphere, therefore, they may easily spend months in the atmosphere, during which they may get quite far away from their source. The average duration spent by ash particles in the air can be measured by their lifetime. Students can also learn that the deposition pattern of particles onto the ground is also a filamentary fractal. It is worth noting that a similar pattern applies to the distribution of precipitation as well, which might be consistent with every-day experiences of students.

To summarize, we have found that the RePLaT-Chaos-edu application is a suitable tool for secondary school students to get a basic knowledge about the main features of atmospheric large-scale spreading and chaos characteristics. It also provides an opportunity to talk about potential global challenges, e.g., the environmental consequences of pollution events, and why it is hard to predict the spreading of contaminants. One can also learn certain meteorological structures in the atmosphere based on the shape of pollutant clouds. Furthermore, the utilization of the application can be linked, e.g., to the topic of Geography classes on wind systems of different regions on the globe or the topics of Physics classes on how particles move in the fluids. Based on these features, this application can be considered as an example of an educational reconstruction of results of contemporary research on the chaotic features of advection processes.

Acknowledgements

Fruitful discussions with T. Tél on chaotic advection and how to introduce it to secondary school students are gratefully acknowledged. The authors thank I. Bajkó (Szent István Grammar School) and the students of Berzsenyi Dániel Grammar School and Szent István Grammar School for testing the application. The project is funded by the Content Pedagogy Research Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences and by the National Research, Development and Innovation Office (NKFIH) under Grants PD-121305, PD-132709, FK-124256.

Appendix: Methods

A.1. Calculation of the spreading of a pollutant cloud

RePLaT-Chaos-edu computes the atmospheric spreading of pollutant clouds consisting of a large number of individual spherical aerosol particles with realistic size and density. The trajectory of the particles is determined by taking into account the effect of advection (transport by the local instantaneous wind), the ascending or descending vertical air velocity component of the air and the impact of gravity on the particles through their terminal velocity. (The terminal velocity is the velocity by which a particle would fall in still air.) That is, in the simplest form, the equation of motion of a particle in vector form is the following:

$$\frac{d\mathbf{r}(t)}{dt} = \mathbf{v}(\mathbf{r}(t), t) + w_{\text{term}}(\mathbf{r}(t), t)\mathbf{n}, \quad (\text{A.1})$$

where $\mathbf{r}(t)$ is the position of the particle at time instant t , $\mathbf{v}(\mathbf{r}(t), t)$ is the air velocity, $w_{\text{term}}(\mathbf{r}(t), t)$ is the terminal velocity of the particle at the particle's position at time t , and \mathbf{n} is a unit vector pointing upwards.

For small and heavy particles investigated in spreading simulations, the terminal velocity, following from Stokes law, depends on the density ρ_p and radius r of the particle, the gravitational acceleration g , the density ρ and kinematic viscosity ν of air as follows:

$$w_{\text{term}} = -\frac{2\rho_p r^2 g}{9\rho\nu} \quad (\text{A.2})$$

The movement of the ash particles stops as soon as they hit the ground, but gas particles which corresponds to particles with radius $r=0$ may be stirred up again into the higher layers of the atmosphere.

RePLaT-Chaos-edu utilizes observation-based meteorological data given on a regular latitude–longitude grid on different pressure levels with a given (6 hours) time resolution. In order to solve the equations of motion of the particles the meteorological data (such as wind components) are interpolated to the location of the particles in each time step. RePLaT-Chaos-edu uses linear interpolation in each of the three directions and in time.

The ordinary differential equation system of equation (A.1) is then solved by an explicit second-order Runge–Kutta scheme, by the Petterssen scheme, using variable time step, i.e., the maximum time step for each particle is determined based on the grid size and the current atmospheric velocity components. In this way even the smallest features resolved by the meteorological fields are taken into account [17]. A more detailed discussion of the equations of the motion can be found in [13–14].

A.2. Stretching rate

The spreading of volcanic ash and other atmospheric pollutants is peculiar, because it is an example of what is called a chaotic process. Such behavior is characterized by the appearance of filamentary, complicated, yet organized patterns, as well as by the sensitivity to the initial conditions. The latter means that ash particles starting off in nearby positions are soon drifted quite far away from each other. One of the instrumental quantities characterizing such motions is called the *stretching rate*. It quantifies the complexity and irregularity of the motion. It can be shown that the pollutant cloud gets not only longer and longer over time, but more folded and interwoven. The shape of the ash clouds becomes soon distorted into a thin line the length L of which grows in an exponential manner over time t :

$$L(t) \sim 10^{ht}. \quad (\text{A.3})$$

The positive exponent h is called the stretching rate. The greater value it takes, the more quickly the length of the ash cloud grows. Any chaotic motion is characterized by the amplification of the minute initial differences; therefore, the stretching rate is one of the possible measures of the strength of chaos. It is similar in spirit to Lyapunov exponents, perhaps the most widely used chaos indicator [9], but for the stretching rate the infinitesimal closeness of the initial distance is not required (which is anyhow impossible to ensure due to the finite resolution of the atmospheric data). Anyhow, the stretching rate can be considered as a measure of the strength of “butterfly effect”.

In order that RePLaT-Chaos-edu could appropriately determine the length of a pollutant cloud and its time-dependence, the user should initiate 1-D “pollutant clouds”, i.e., line segments or filaments. In this case the length of a filament is calculated as the sum of the distances between neighboring particle pairs. The stretching rate is then calculated based on equation (A.3) as the slope h of the linear least squares fit applied to the base 10 logarithm of the length $L(t)$ of the filament for the time interval chosen by the user.

A.3. Lifetime

For settling particles, the lifetime characterizes the rapidity by which they leave the atmosphere. The number $n(t)$ of particles not yet settled after time t hardly changes for a while, but after a time t_0 it starts to decay rapidly, exponentially:

$$n(t) \sim 10^{-\frac{t-t_0}{T}} \quad \text{for } t > t_0. \quad (\text{A.4})$$

This implies that in this quickly decaying stage merely a tenth of the particles remain in the atmosphere after time T . The value of lifetime T is longer for light and small particles, but depends on the atmospheric conditions, too.

Analogously to the determination of the stretching rate, based on equation (A.4) the value of the lifetime T is calculated as the reciprocal of the $(-1) \times$ the slope of a linear least squares fit applied to the base 10 logarithm of the ratio $n(t)$ of non-settled particles for the time interval chosen by the user.

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