CLIMATE CHANGE AND ATMOSPHERIC DISPERSION PROCESSES
(PD-121305)

Final report

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Period: October 1, 2016 – September 30, 2019

In the first part of the research, the question of how a changing climate influences the spreading of atmospheric pollutant clouds on continental and global scale was investigated by the Real Particle Lagrangian Trajectory (RePLaT) dispersion model. In these simulations pollutant clouds consist of a large number of ideal tracers, corresponding to inert gases. For such particles, the velocity of a particle coincides with the velocity of the air at the location of the particle at any time instant. Due to the chaotic nature of advection, pollutant clouds spread in a filamentary, fractal structure, and the length of these filaments grows in an exponential manner in time. Thus, the intensity of large-scale spreading can be quantified by a measure of chaotic systems, by the so-called topological entropy (also called stretching rate in the atmospheric context) which describes the rate of the exponential increase. The larger the stretching rate the faster the length of the pollutant cloud grows and the more complicated and tortuous the shape of the filament is. As a measure of folding, it is also closely related to the predictability of the spreading of pollutant clouds.

Firstly, I investigated the changes in the stretching rate utilizing the reanalysis fields of the ERA-Interim database for 1979–2015 (Haszpra, 2017). In order to study the geographical dependence of the stretching rate, 1-D pollutant clouds (line segments) were initialized uniformly distributed over the globe. The zonal-seasonal mean stretching rate displays a typical zonal distribution in each year with smaller values in the tropics and larger values in the extratropics. The largest stretching rates appear in the respective winter season of the hemispheres due to the more enhanced cyclonic activity. Filaments initiated in the tropics stretch by a factor of 20-150 within 10 days, while in the mid- and high latitudes the characteristic values of length increase are between 300 and 3000. A slight increase of 3-10% in the values of the mean stretching rates from 1979 to 2015 is found. This increase is equivalent to an increase of the length of the filaments by a factor of 20-65% (200-400%) over a period of 10 days (30 days). Larger stretching rate values indicate more intense spreading, more foldings and larger geographical areas covered by the pollutants. The increased mean stretching rate of the analyzed decades, therefore, implies the risk of larger polluted regions from particular pollution events.

Finding a relationship between the stretching rate and the meteorological variables could help estimate the changes of large-scale transport properties of the atmosphere for different climate projections without the necessity to carry out computationally costly extra spreading simulations. The largest correlation for the stretching rate (0.6-0.9) was found with the area-mean of the absolute value of the relative vorticity. This correlation proved to be much stronger than those for the Equator-to-pole temperature difference, temperature at different altitudes, geopotential height, wind speed, kinetic energy, and potential vorticity.

In order to separate the effect of climate change and the fluctuations due to the internal variability of climate, and to study the impact of climate change stronger than the one observed in reanalysis data, the alterations in the spreading intensity were investigated using an ensemble of climate realizations produced by the intermediate-complexity climate model Planet Simulator (PlaSim, Fraedrich et al., Meteorol. Zeitschrift 14, 299–304, 2005) (Haszpra and Herein, 2019; Tél et al., 2019). In these simulations due to the doubling of the CO_2 concentration from 360 ppm to 720 ppm over 100 years the global mean surface temperature increases by 6 °C. The zonal distribution of the zonal-seasonal mean stretching rate is found to be similar to those using the ERA-Interim data. By utilizing single ensemble members there are regions where the existence of a trend cannot be determined for the time interval of temperature increase, however, the ensemble mean of the stretching rate shows a clear decrease of 5-10%. The typical decrease of –0.05 day^{-1} implies that in year 100 the length of 10-day-old filaments is 61% of the length of the filaments initialized at the beginning of the increase of CO_2 concentration, thus, the length changes considerably.

Since PlaSim is sometimes criticized for being only an intermediate-complexity climate model, beyond the plans described in the research proposal, simulations were carried out using the 35-member ensemble of a state-of-the-art climate model, i.e., using the Community Earth System Model – Large Ensemble Project (CESM-LE, Kay et al., Bull. Am. Meteorol. Soc. 96, 1333–1349, 2015) (Haszpra and Herein, 2019; Tél et al., 2019). The ensemble mean of the global mean surface temperature increases by about 3.5 °C from 1990 to 2080. The zonal distribution of the stretching rate, the magnitude and decreasing nature of the trends are in harmony with the results obtained using PlaSim meteorological data. The area-seasonal mean of the stretching rate and that of the absolute value of the relative vorticity are found to change in parallel, and there is a clear linear dependence between them with an average slope of $[6–7]\times10^{-5}$ s^{-1} day and correlation coefficients above 0.93 for the PlaSim and 0.83 for the CESM ensembles, respectively. This result confirms the conclusion obtained previously utilizing single time series of reanalysis data, that is, that the changes in the intensity of spreading in arbitrary climate simulations can be estimated utilizing meteorological variables (i.e. relative vorticity or velocity data) operationally computed and stored by the climate models, without carrying out numerous computationally demanding dispersion simulations.

In the next part of the research the RePLaT dispersion model has been improved (Haszpra, 2019a). Instead of the previously applied first-order integration method, it computes the particle trajectories by a more precise second-order Runge–Kutta method, by the Petterssen scheme. Furthermore, now – besides the option of choosing constant time step (given by the user) for the trajectory calculation – the users can also choose the option of a variable time step. In this case each time step for each particle is determined based on the grid size and the current atmospheric velocity components.

Another version of the improved RePLaT model was also created, called RePLaT-Chaos, applicable for educational purposes (http://theorphys.elte.hu/fiztan/volcano/index.html) (Haszpra, 2018a; Haszpra, 2019b). Its main aim is to make the demonstration of the chaotic behavior of atmospheric pollutant spreading easy. The user-friendly graphical user interface helps the user carry out spreading simulations with several different parameters. In the spreading simulations, one can observe the typical characteristics of chaos, such as sensitivity to initial conditions, irregular motion, and complicated but well-organized (fractal) structures. It can be easily observed in the RePLaT-Chaos simulations that an initially compact pollutant cloud soon becomes strongly stretched; its length grows rapidly, while it becomes filamentary, tortuous and folded. RePLaT-Chaos can also compute two quantities that describe the chaoticity of the advection and the investigations of which are the main topics of this project. One of them is the stretching rate which quantifies the exponential stretching of the length of pollutant clouds, and the other is the escape rate which quantifies the deposition rate of particles falling out from the atmosphere to the surface. The initial position, size and other properties of the pollutant cloud can be set on the user interface, and pre-generated pollutant clouds can also be read for the simulations. RePLaT-Chaos provides an opportunity to replay simulations saved in files, and due to their simple structure output files can be read or analyzed with other tools, too.

The RePLaT-Chaos-edu application (http://theorphys.elte.hu/fiztan/volcano/index.html#edu) is a version of RePLaT-Chaos with simplified user interface designed especially for secondary school students (Haszpra, 2018b). By means of RePLaT-Chaos-edu they can design their own "volcano eruptions". Here only those parameters can be set that are known by students, and the application includes eye-catching animations, more explanation and description for the observable phenomena. Currently, Hungarian and English user interfaces are available, but due to the dictionary files applied in the code, it is easy to add other languages to the software.

The chaotic features in the lifetime distribution and deposition of atmospheric aerosol particles of realistic density (2000 kg/m^3) and radius (1–10 μm) were also investigated (Haszpra, 2019a). The advection of such particles emanated, e.g., from volcano eruptions or other pollution events exhibits chaotic behavior in the atmosphere. Due to gravity the particles move downwards on average and remain in the atmosphere for a finite time. The number of particles not yet deposited from the atmosphere decays exponentially after a while, which is characteristic to transient chaos. The so-called escape rate describes the rapidity of the decrease, the reciprocal of which can be used to estimate the average lifetime of the particles. Using ERA-Interim reanalysis data, aerosol particles uniformly distributed over the globe at different altitudes were tracked. We demonstrated that the geographical distribution of the individual lifetimes shows a filamentary, fractal distribution, typical for chaos: the lifetime of particles may be quite different at very nearby geographic locations (e.g., a few days vs. 150 days within 10 km for particles of radius of 5 μm). These maps can be considered as atlases for the potential fate of volcanic ash clouds or of particles distributed for geoengineering purposes. We showed that the trajectories of nearby particles with similar lifetimes remain close to each other for a long time and they deposit at nearby locations. Thus, the boundaries among these types of coherent particle groups can be considered to form repelling Lagrangian Coherent Structures. Particles with similar lifetime deposit in filamentary structures as well, but the deposition pattern of extremely long-living particles covers the Earth more or less homogeneously. In general, particles emanated around the Equator remain in the atmosphere for the longest time, even for years, e.g., for particles of 1 μm. The rate of the exponential decrease of long-living particles does not change with the initial altitude but shows a quadratic dependence on the particle size. The independence of initial altitude indicates that there exists a unique chaotic saddle in the atmosphere. We reconstructed this saddle and its stable and unstable manifolds, and followed their time-dependence.

Results reveal that while the stretching rate considerably changes during a changing climate this does not hold for the escape rate and average lifetime. However, the average lifetime has a clear annual cycle with a larger maximum in July and a smaller one in January. This cycle proved to be related to the motion of the Intertropical Convergence Zone.

The study of the escape rate and lifetime (Haszpra, 2019a) was chosen to be promoted as an "Editor's Pick/Featured" article and one of its figures was selected to be the cover image for the July 2019 issue of Chaos. An interview about the research was also published on the web page of the American Institute of Physics Publishing. Besides the topic of the research it mentions the RePLaT-Chaos computer "game" as well. Parts of the interview were published also in other international media.

As an outlook for the investigation of the ensemble of climate realizations I took part in a research in which teleconnections were investigated in the ensemble approach using the ensembles of the PlaSim, the CESM-LE with RCP8.5, and the Max Planck Institute Grand Ensemble with RCP2.6, 4.5 and 8.5 scenarios (Bódai et al., 2017; Herein et al., 2017; Haszpra et al., 2019a; Haszpra et al., 2019b; Tél et al., 2019). The North Atlantic Oscillation (NAO) (Herein et al., 2017) using its station-based index definition, and the Arctic Oscillation (AO) (Haszpra et al., 2019b) and El Niño–Southern Oscillation (ENSO) (Haszpra et al., 2019a) using empirical orthogonal function (EOF) analysis to determine the pattern of the phenomenon and the corresponding indices were investigated. Furthermore, the temperature and/or precipitation related teleconnections of the NAO, AO and ENSO (characterized by correlation coefficients), and their time evolutions were determined during climate change. We argue on the example of the NAO teleconnections that an appropriate description of these correlations is correlation coefficients between the index of the phenomenon and the studied quantity taken over the ensemble at any time instant. Similarly, if an ensemble is available the pattern of the AO and ENSO, and their time-dependence should be studied using a reconsidered EOF (snapshot EOF) analysis which is carried out across the ensemble at any time instant. We showed that the traditional calculation method of the NAO and AO indices, which uses single realization, results in values that depend on the choice of the reference period. Results emphasize that both the AO and ENSO and the related surface temperature/precipitation patterns are non-stationary and their time evolution depends on the forcing. For example, both the AO and ENSO amplitude increases, and there exist such regions where the correlation coefficient between the AO/ENSO phase and the temperature/precipitation conditions shows a considerable change (0.2-0.4) from 1950 to 2100.

As another utilization of the ensemble framework, the effect of solar constant scenarios, consisting of an abrupt decrease, a plateau and thereafter a rapid increase, on the climate was investigated using PlaSim also in ensembles of climate simulations (Kaszás et al., 2019). In individual simulations, depending on the scenario parameters (the reduction rate of the solar constant, the length of the plateau), either the system is found to stay stuck in the so-called snowball state (Earth covered entirely by ice and snow) or to return to the current climate. However, using an ensemble, results show that within certain intervals of the parameters, at the end of the scenario both states (the two stable states permitted by the current value of the solar constant) are present simultaneously with certain probabilities. In addition, the third, unstable state (referred to as the edge state) is also recovered in the simulations.

Publication activity: The results were published in 6 articles in peer-reviewed journals (IF = 17.092) and 2 software descriptions and presented in 1 solicited talk, 4 talks and 4 posters at international conferences, and in 6 Hungarian talks. Another 4 manuscripts are currently under review.

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Haszpra, T., Herein, M.: Investigation of the relationship between the intensity of pollutant spread and the vorticity during a climate change in an ensemble approach. EGU General Assembly 2018, April 8–13, 2018, Wien, Austria. In Geophysical Research Abstracts, Vol. 20, EGU2018-13498 (poster)

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