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AVIATION AND VOLCANIC ASH HAZARDS: A FLIPPED CLASSROOM APPROACH TO STUDY COMPLEX SYSTEMS

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ABSTRACT. Educational practice and, in particular, the flipped classroom models have had a significant impact on higher education recently. Challenging students with questions and problem – solving activities to learn course material is the educational approach used in the course of "Physics of Environmental Processes" that has been taught during the 2019-2020 academic year within the teaching activities of the Master of Science in "Geophysical Sciences for Seismic Risk" at the University of Messina. The study of complex systems, such as the relationship between aviation and the volcanic ash hazard, is highlighted in this paper. The particular subject being discussed in this paper presents the properties of complex systems due to the range of interdisciplinary scientific disciplines, ranging from various branches of physics to aeronautical engineering, chemistry, mathematics, volcanology, mineralogy, and management engineering, that students need to analyze and understand by using the flipped classroom model.

1. Introduction

Although the term "Complex Systems" has many interpretations, implications, and problems associated with it, in recent years, this term has been having a significant impact in many scientific disciplines and domains, contributing to understanding how systems adapt, self-organize, fluctuate, and reach and maintain equilibrium (Karcanias and Livada 2020). The study of complex systems, thus, can overall be summarized as understanding how the behavior of phenomena at different scales is related and how larger-scale patterns emerge from the interdependent components at lower scales (Magazù *et al.* 2012; Bar-Yam 2016; Yoon *et al.* 2017).

Following the logic expressed in Bar-Yam (1997), a straightforward approach to organizing the properties of complex systems that will serve as the foundation of our paper is the relationship between elements, parts, and the whole. Since there is only one property of the complex system that we know for sure — that it is complex—the primary question we can ask about this relationship is how the complexity of the whole is related to the complexity of the parts (Bar-Yam 1997). It seems reasonable to think that parts of a complex system are often complex systems themselves because when the parts of a system are complex, it seems intuitive that a collection of them would also be complex. However, there are also other possibilities. The term “emergent complexity” indicates a complex system where the behaviors of many simple parts interact in such a way that the behavior of the whole is complex. On the other hand, the term “emergent simplicity” indicates a system composed of complex parts where the collective behavior is simple (Bar-Yam 1997).

The flipped classroom evolved out of a history of experimentation with the concept of blended learning and problem – based learning, using active learning techniques and new technologies to engage students (Arnold-Garza 2014). This approach has two essential components: moving the lesson outside of class, usually delivered through some educational materials, and moving the practical application assignments into the classroom (Arnold-Garza 2014). The choice of this approach has been made because of the large number of its strengths, including, among the most important, efficient use of class time (Cole and Kritzer 2009), more active learning opportunities for students (Gannod *et al.* 2008), increased one-on-one interaction between student and teacher (Lage *et al.* 2000), and student responsibility for learning (Arnold-Garza 2014).

In the present paper, the authors present an original and comprehensive approach in designing and teaching the course of “Physics of Environmental Processes” that has been taught during the 2019-2020 academic year within the teaching activities of the Master of Science in “Geophysical Sciences for Seismic Risk” at the University of Messina. The approach proposed here is designed like a journey to discovering the features of complex systems. As with any valuable and unforgettable journey, it must be guided by curiosity and questions. Despite the great complexity and variety of systems, universal laws and phenomena are essential to our inquiry and our understanding. Therefore, whenever new concepts and ideas are presented, they are introduced by formulating preliminary queries and, in some cases, advancing doubts on what science already knows. Students should be conscious that the predictive power of science has intrinsic limitations and unavoidable uncertainties. Students must understand the principal strategies to untangle complex systems to face the challenges of the 21st century effectively (Gentili 2019).

2. The core of the complex problem

As part of the teaching process, it is important to define the particular causes and effects, which interests the system under consideration. The first direct observation of the system is to understand the core of the problem.

An unexpected event happened in April 2010 where a little-known volcano located in the southeastern part of Iceland had a small but prolonged ash-rich eruption. Between 15 April and 23 May 2010, Eyjafjallajökull volcano erupted trillions of grams of fine ash into the mid-troposphere and, because of the prevailing westerly and north-westerly winds during the period, the ash reached continental Europe, where it caused the largest shutdown of commercial aviation since World War II (Prata and Rose 2015).

As suggested by Prata and Rose (2015), the global economic impact of this disruption to commercial aviation has been estimated at billions of U.S. dollars. While the problem of jet aircraft encounters with airborne volcanic ash remains a serious safety issue, the economic impact, particularly in the crowded European, US, and fast-growing Asian air corridors, has refocused efforts to develop robust and timely means for detecting, forecasting, and mitigating the hazard.

Students have to be aware of the impact that volcanic ash could have on flight safety. Navigation and communication systems of aircraft may be affected in different ways during an encounter with volcanic ash: abrasion of aircraft antennas, attenuation or refraction of waves in volcanic ash clouds, electrostatic discharges following exogenous charging or triboelectric charging, contamination, clogging and plugging pitot-static system, ash deposit on avionics, electrical or computer failure, problems with speed indication, are the most common incidents involving electrical and avionics systems of aircraft (Prata and Rose 2015; Lechner *et al.* 2017). The highest severity incidents are, however, when volcanic ash enters jet engines and the glass may melt when they encounter temperatures in excess of about 800 °C, which causes engine failures (Prata and Rose 2015). The vitric components of volcanic ash become "sticky" as they pass through their glass transition temperatures where their properties change from brittle to plastic at temperatures ranging from about 700 to 1100 °C, depending on various factors, including impurities and the proportion of minerals that require higher temperatures to melt the silicate (Prata and Rose 2015). The combustion region of modern jet turbine engines is maintained at temperatures of 1200/1500 °C and so if volcanic ash finds its way into the hot parts of the engines, glass and a small fraction of the minerals may also melt. When engine temperatures are lower, as when the engine is powered off, the glass will cross the transition temperature back to brittle behavior and may fracture, thus clearing the metal surfaces (Prata and Rose 2015). These exact mechanisms of deposition depend on the mineralogical composition and the size distribution. Needless to say, many of these effects can lead to catastrophic consequences for jet aircraft, with loss of engine power and potentially loss of aircraft.

3. The complexity of a natural system

Although volcanic eruptions are the most exciting, awe-inspiring phenomena of all the Earth's dynamic processes, and have always aroused human curiosity and/or fear. Volcanoes and volcanic eruptions come in many varieties, however, and to begin to understand them one must absorb a great amount of information (Lockwood and Hazlett 2010).

Volcanoes produce multiple primary and secondary hazards that must each be recognized in order to mitigate their impacts. In particular, the most frequent, and often widespread, volcanic hazard is tephra, occurring in more than 90% of all eruptions (Loughlin *et al.* 2015). Tephra comprises fragments of rock produced when magma or vent material is explosively disintegrated during an eruption. Tephra consists of glass and minerals. The mineralogical composition of tephra can be primarily of a silicate nature, and according to origin could be *juvenile*, *cognate*, and *accidental* (Fisher and Schmincke 1984).

The very finest fragments from 2 mm down to nanoparticles are known as "volcanic ash" and can be produced in huge volumes and convected upwards within the eruption column or convective plume and dispersed away from the volcano by winds or buoyancy forces (Prata and Rose 2015). The physical and chemical characteristics of volcanic ash are highly variable and this has implications for impacts on health, environment, critical infrastructures, and economy (Jenkins *et al.* 2015).

Another key concept to take into consideration is the Volcanic Explosivity Index, or VEI, that correlates the volume of volcanic ejecta and various other observed physical criteria, such as eruption column height and eruption duration. It was developed by Newhall and Self (1982) in order to determine the impact of volcanic ash impact on civil aviation, the acquisition of information at the source is needed in order to establish the amount and height of ash (and gas) emissions into the atmosphere as a function of time. Also, the total size distribution and mass eruption rate are of primary interest.

4. Attempts to mitigate a complex system

Even though the regulatory environment for the ash-aviation problem is complex, involving many national and international agencies and authorities, after the eruptions of Mt. Pinatubo, the Philippines, in June-July 1991, the International Civil Aviation Organization (ICAO) established a network of nine Volcanic Ash Advisory Centers (VAACs) to provide advice and timely warnings for aviation concerning volcanic clouds (Prata and Rose 2015). In addition, VAACs are informed by the latest scientific developments through a mechanism established under the auspices of ICAO and WMO (World Meteorological Organization). The Volcanic Ash Scientific Advisory Group (VASAG) is an *ad hoc* group of scientists working within academia that meet periodically with representatives of the VAACs, volcanologists, and aviation meteorologists to discuss activities related to the ash-aviation problem (Prata and Rose 2015). During the Eyjafjallajökull crisis, the International Volcanic Ash Task Force (IVATF) was also established to quickly advise governments and industry on ways to mitigate the hazard and provide information on better ways to designate safe airspace during ash cloud events (Prata and Rose 2015).

5. The dynamics of volcanic eruptions

Knowing the potential effects on aviation, students can now explore the complexity of the causes that generate the mentioned effects. The main problem for aviation is that ash and other volcanic emissions, notably SO_2 gas, can reach high into the atmosphere and intersect airspace at all flight levels (Prata and Rose 2015). At this stage, it is important to understand some basic concepts of volcanic plume dynamics. As already mentioned, volcanic plumes are typically associated with explosive activity, which whether generated from a point source or from an extended source, eventually develops into a turbulent buoyant current whose dynamics are strongly controlled by the degree of interaction with the atmosphere.

Bonadonna and Costa (2013) explain the concept of volcanic plume dynamics: if the plume upward velocity is much stronger than the wind velocity, the initial jet phase evolves into a vertical buoyant column that then eventually spreads laterally as a gravity current. In contrast, if the wind velocity is much stronger than the plume upward velocity, the turbulent current will be bent over above the basal jet before spreading laterally. It is important to distinguish between vigorous and low-energy weak plumes: both plumes are bent over by the wind but they are characterized by different energetics. The same authors affirm, also, that vigorous weak plumes characterize the beginning of low-intensity sustained eruptions, whereas low-energy weak plumes characterize the last phase of an eruption when wind eventually dominates and the cloud starts propagating as a lens of aerosol. Volcanic clasts are carried up within the turbulent current according to their settling velocity, which depends on both particle and atmospheric characteristics. When particle settling velocities are larger than the upwards component of the turbulent current, they fall out and are advected by local winds. Particles that are sufficiently small will typically aggregate into micron- to millimeter-sized clusters having greater settling velocities.

According to Prata and Rose (2015), commercial aircraft at cruise altitude often fly just below the tropopause, and violent eruptions are able to reach the tropopause and even penetrate into the stratosphere. If SO_2 is present in the violent eruption, then at least some of it will reach the tropopause or higher, and form stable layers where it will be chemically transformed into sulfate. At lower levels, there may be mixtures of ash and SO_2, or separated ash and SO_2 layers, transported in thin layers by the wind field. At the lowest levels, ash will fall out or rain out, most prominently close to the volcano. A particularly insidious problem is the presence of ice in volcanic clouds, and ice-coated ash particles. These almost always occur in vigorous tropical eruptions, which reach high into a cold, moist atmosphere. Ash coated with ice is very difficult to discriminate from ice-only clouds. While ice clouds themselves pose a threat to aviation, ash coated in ice is likely to be just as hazardous. Volcanic emissions remain in the atmosphere for different amounts of time, depending mostly on the height they initially reach. In the stratosphere, volcanic aerosols may have lifetimes of a few years, whereas, in the lower atmosphere, ash and SO2 are removed quickly, within a few hours, by gravitational settling, wet, and dry aggregation that enhance fallout and by atmospheric processes such as rainout (Prata and Rose 2015).

The shape of the ash reflects the fragmentation mechanism of the eruption, usually either explosive vesiculation (bursting gas bubbles), water-magma (phreatomagmatic or fuel-coolant) interactions, or comminution within a pyroclastic flow or volcano conduit. The volcanic ash size distribution may include a wide range of diameters, and is typically sorted during its atmospheric residence by gravitational settling (Prata and Rose 2015; Bagheri and Bonadonna 2016). Particle Size and shape are both influencing factors for determining their aerodynamic behavior such as terminal velocity, and their residence time in the atmosphere (Bagheri and Bonadonna 2016). They are also important parameters in remote sensing applications. As an example, many remote sensing retrieval algorithms are based on the conventional Lorenz-Mie theory or its modifications, in which the particle shape is assumed to be spherical. However, the scattering properties of non-spherical particles can differ dramatically from those of equivalent Mie spheres, which affect estimations of sizes and mass concentrations within an eruption cloud (Prata and Rose 2015). In fact, the assumption of spherical shapes for volcanic particles can overestimate mass concentration and optical depth of the ash cloud and underestimate particle effective diameter. Thus, fine (atmospheric residence > 30 min) and especially very fine ash (atmospheric residence from three hours to several days) are agents for volcanic cloud aircraft hazards. Because very fine ash that is often dispersed at large distances from the source volcano can fall out in low, sometimes barely detectable amounts, estimates of the actual amount of ash produced are unreliable. Fine and very fine ash fallout is apparently controlled largely by meteorological processes, where very fine ash acts as cloud condensation and ice nuclei and becomes part of the hydrometeors (Prata and Rose 2015).

Models for tephra dispersal are based on the mass conservation equation with different degrees of simplicity, following either Eulerian or Lagrangian formulations. The Eulerian approach describes changes in the fluid at fixed points, whereas the Lagrangian approach describes changes by following a fluid parcel along its trajectory (Aloisi *et al.* 2002).

According to Prata and Rose (2015), IR methods of direct volcanic ash detection grew out of applications using weather satellites. Direct detection of ash is related to the reststrahlen effect, where semiconductor materials (in this case silicates) of small scale (in the Mie region where IR wavelength is similar to ash particle size) show changes in refractive index concurrent with absorption bands. These standard tools are being supplemented by sophisticated remote sensing technologies, including ground-based UV and IR cameras to measure gases and particles and also ground-based radars, normally used for meteorological purposes. In the early stages of the eruption, radar is very useful because the microwave energy can penetrate the optically thick plume and provide estimates of the column height and the mass eruption rate. These instruments operate at millimeter wavelengths, so their sensitivity to micron-size particles is low, but radar observations have become increasingly important at volcanoes because the waves penetrate clouds and provide height estimates.

It should be noted that there has not yet been a satellite instrument developed for the purpose of ash detection and retrieval, and researchers have relied on suboptimal measurements, at least until the arrival of the high-spectral resolution spectrometers (*e.g.*, AIRS) and interferometers (*e.g.*, IASI). The most advanced algorithms use optimal estimation schemes that incorporate spectral databases on the scattering properties of volcanic ash particles and retrieve effective particle radii, column mass loading, and cloud-top height simultaneously.

The unpredictable nature of volcanic activity, the global distribution of active volcanoes, and the potentially far-reaching spread of ash clouds in the atmosphere make satellites ideal for monitoring them. These factors also mean that continuous observation is needed (day and night) and at relatively high temporal frequency. Spatial resolution is not too much of a demand because modern satellite instruments have 1- to 10-km^2 footprints, which are adequate for monitoring dispersing ash in the atmosphere (Prata and Rose 2015).

The difficulties associated with discriminating ash from ice and water in infrared satellite data are compounded by the lack of high spatial resolution and the lack of any vertical resolution. On occasion, satellite data can be rendered less useful because the ash can be obscured from view by the meteorological cloud above the ash or because the opacity of the cloud is so great that the IR methods (Magazù *et al.* 2013; Caccamo and Magazù 2016) can no longer discriminate them from meteorological clouds (Prata and Rose 2015). These models have been used for many years and were originally developed for pollution forecasting, especially for nuclear accidents.

A theoretical infrared spectroscopic study has been carried out on the volcanic ash. Starting from the overview of the various spectroscopic methodologies (Caccamo and Magazù 2017b; Caccamo *et al.* 2018b), students went on to study the mineralogical characteristics for silica polymorphs, vitreous nature of silica and silicate particles that are identified by the infrared spectroscopy (Magazù *et al.* 2018; Malek *et al.* 2018). In Figure 1, a spectrum of volcanic ash (collected on Etna Volcano) is reported.

Students learned that experimental spectra are often affected by noise. This is due to various causes, such as interference from chemical and physical processes, limitations in the experimental device, or abnormal oscillations of the signal sent to the detector (Satish and Nazneen 2003; Caccamo *et al.* 2018a). It was important to identify that, among the different methods for leveling and denoising the signal, Wavelet Transform (WT) is the

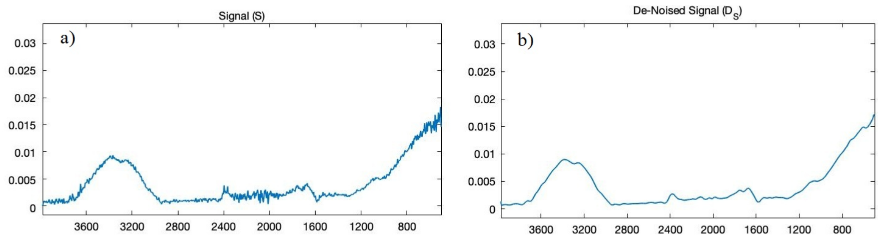

FIGURE 1. Spectrum of volcanic ash of Etna Volcano.

most performing method. In fact, it converts the signal into terms of basic functions, which are small waves (Pasti *et al.* 1999; Caccamo and Magazù 2018). WT is invertible, and the set of basic functions is orthogonal and is localized in both the frequency and time domains. In general, the orthogonal basis functions are obtained from the mother function by means of shifts on the time variable and of dilations on the frequency variable (Caccamo and Magazù 2017a; Dautov and Ozerdem 2018). In literature, exist a large number of mother function, in the present work, the Haar wavelets is used. The choice of this mother wavelet is due to its speed, compression, and dynamic response (Zainuddin Lubis *et al.* 2016; Caccamo and Magazù 2017c). More precisely, Figure 1 reports the spectrum of volcanic ash (collected on Etna Volcano) before (a) and after (b) the application of the wavelet procedure. What emerges is that, due to the wavelet procedure, it is possible to suppress the spurious components evidently.

6. Conclusion

Despite many efforts, there is still a list of compelling scientific challenges that have to be won. For instance, science is still unable to predict catastrophic events on our planet, like volcanic eruptions, which, unfortunately, may cause many victims and damages every time they occur. The reason why this happens is that whenever science faces these challenges, science itself deals with complex systems. Studying volcanic ash hazards to aviation itself can surely be considered as a complex system considering the complexity and the large number of variables involved. A complex system consists of many elements, often diverse, if not unique. The elements of a complex system are also highly interconnected (Gentili 2019).

Students need, thus, to learn to untangle a complex system as volcanic ash hazards to aviation through a vast range of scientific disciplines, ranging from various branches of physics to aeronautical engineering, chemistry, mathematics, volcanology, mineralogy, and management engineering.

The flipped classroom approach used during the course has enabled students to increase both their interactive period within the classroom and their motivation.

Students can now deal with the study of how a natural phenomenon – although spectacular – could have a profound impact on society. In the face of considerable efforts to try to predict the most likely hazards and the magnitude of eruptions, Students will also learn that a superficial and simplistic approach to problems related to eruptions can become a poorly constrained guesswork.

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