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Ground-based weather radar remote sensing of volcanic ash explosive eruptions

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The explosive eruptions of active volcanoes with a consequent formation of ash clouds represent a severe threat in several regions of the urbanized world. During a Plinian or a sub-Plinian eruption the injection of large amounts of fine and coarse rock fragments and corrosive gases into the troposphere and lower stratosphere is usually followed by a long lasting ashfall which can cause a variety of damages. Volcanic ash clouds are an increasing hazard to aviation safety because of growing air traffic volumes that use more efficient and susceptible jet engines. Real-time and areal monitoring of a volcano eruption, in terms of its intensity and dynamics, is not always possible by conventional visual inspections, especially during worse visibility periods which are quite common during eruption activity. Remote sensing techniques both from ground and from space represent unique tools to be exploited. In this respect, microwave weather radars can gather three-dimensional information of atmospheric scattering volumes up several hundreds of kilometers, in all weather conditions, at a fairly high spatial resolution (less than a kilometer) and with a repetition cycle of few minutes.

Ground-based radar systems represent one of the best methods for determining the height and volume of volcanic eruption clouds. Single-polarization Doppler radars can measure horizontally-polarized power echo and Doppler shift from which ash content and radial velocity can be, in principle, extracted. In spite of these potentials, there are still several open issues about microwave weather radar capabilities to detect and quantitatively retrieve ash cloud parameters. A major issue is related to the aggregation of volcanic ash particles within the eruption column of explosive eruptions which has been observed at many volcanoes. It influences the residence time of ash in the atmosphere and the radiative properties of the "umbrella" cloud. Numerical experiments are helpful to explore processes occurring in the eruption column. In this study we use the plume model ATHAM (Active Tracer High Resolution Atmospheric Model) to investigate, in both time and space, processes leading to particle aggregation in the eruption column.

In this work a set of numerical simulations of radar reflectivity is performed with the ATHAM model, under the same experimental conditions except for the initial size distribution, i.e. varying the radii of average mass of the two particle dimension modes. A sensitivity analysis is carried out to evaluate the possible impact of aggregate particles on microwave radar reflectivity. It is shown how dimension, composition, temperature and mass concentration are the main characteristics of eruptive cloud particles that contribute to determine different radar reflectivity responses. In order to evaluate Rayleigh scattering approximation accuracy, the ATHAM simulations of radar reflectivity are used to compare in a detailed way the Mie and Rayleigh scattering regimes at S-, C- and X-band. The relationship between radar reflectivity factor and ash concentration has been statistically derived for the various particle classes by applying a new radar reflectivity microphysical model, which was developed starting from results of numerical experiments performed with plume model ATHAM. The ash retrieval physical-statistical algorithm is based on the backscattering microphysical model of volcanic cloud particles, used within a Bayesian classification and optimal regression algorithm.

In order to illustrate the potential of this microwave active remote sensing technique, the case study of the eruption of Augustine volcano in Alaska in January 2006 is described. This event was the first time that a significant volcanic eruption was observed within the nominal range of a WSR-88D. The radar data, in conjunction with pilot reports, proved to be crucial in analyzing the height and movement of volcanic ash clouds during and immediately following each eruptive event. This data greatly aided National Weather Service meteorologists in the issuance of timely and accurate warning and advisory products to aviation, public, and marine interests. An application of the retrieval technique has been shown, taking into consideration the eruption of the Augustine volcano. Volume scan data from the NEXRAD WSR-88D S-band radar, which are located 190 km from the volcano vent, are processed to identify and estimate the particles concentration in an automatic fashion. The evolution of the Augustine Vulcanian eruption is discussed in terms of radar measurements products, pointing out the unique features, the current limitations and future improvements of radar remote sensing of volcanic plumes.