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Satellite Observations and Numerical Simulation Results for the Comprehensive Analysis of Ash Cloud Transport during the Explosive Eruptions of Kamchatka Volcanoes

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Abstract—Ash clouds resulting from explosive volcanic eruptions pose a real threat to human life (for aircraft flights, airport operations, etc.); therefore, the detection, monitoring, and forecast of their movement is an urgent and important issue. The features and examples of application of the new tool developed on the basis of "Monitoring of Active Volcanoes of Kamchatka and the Kurile Islands" information system (VolSatView) are described. It allows the integrated monitoring and forecasting of ash cloud transport using the data of remote sensing and mathematical modeling as well as the assessment of the parameters of explosive events.

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1. INTRODUCTION

Explosive volcanic eruptions are the most dangerous due to the high energy of the volcanogenic process (catastrophic eruptions that release more than 1 km^3 of substances, the lift of eruptive clouds to 35 km above the sea level, pyroclastic flows moving with the speed of 150 km/hour for a distance of 30 km from the volcano). Depending on the explosive eruption strength (on its intensity and duration, on the eruptive matter volume, on the height it was lifted to, etc.) and on wind speed ash clouds of different strength are formed at different heights in the atmosphere. They can be transported for thousands of kilometers from the volcano during many days. The movement of the eruptive cloud depends on its initial height, concentration of ash particles in it, their deposition under the effect of gravity, on wind speed in the troposphere and stratosphere, atmospheric stability, precipitation, and other meteorological conditions.

Ash clouds pose a real threat to aircrafts and cause significant difficulties for airport operations [1, 5, 12, 18, 19]; therefore, their detection, monitoring, and forecasting are urgent and important. To join the efforts of different services dealing with the detection of volcanic ash and with the monitoring of its transport in the atmosphere, the International Civil Aviation Organization (ICAO, http://www.icao.int) set up nine specialized meteorological centers as Volcanic Ash Advisory Centers.

To improve the aviation safety in case of explosive volcanic eruptions on Kamchatka, the Kamchatka Volcanic Eruption Response Team (KVERT, http://www.kscnet.ru/ivs/kvert/) was established in 1993. Since 2010 the KVERT group being a part of the Institute of Volcanology and Seismology of Far Eastern Branch of Russian Academy of Sciences (IVS FEB RAS) has functioned as the Volcano Observatory of the Russian Federation; it provided the international air navigation community with information on the activity of the Far East volcanoes [1, 5, 18, 19]. The objective of KVERT is the mitigation of the risk of aircraft collision with ash clouds in the North Pacific based on the timely detection of volcanic activity increase, on the identification and tracking of volcanic ash clouds, and on the operational warning of aviation companies about the risk emergence for aircrafts.

Thirty active volcanoes are situated on the territory of Kamchatka. Every year two to eight of them erupt and release tonnes of volcanogenic products (ash, gas, and aerosol) to the atmosphere. During strong explosive events ash reaches the height of 8–15 km above the sea level and poses a threat to aviation [1, 5, 19]. It should be noted that due to the remoteness of most volcanoes from populated areas and due to the sparse network of ground-based observations, the continuous monitoring of volcanic activity is impossible without using the remote (first of all, satellite) observation systems.

In recent years, the rapid development of specialized mathematical models opens up new possibilities for the analysis and investigation of the processes of ash cloud transport and for the estimation of their parameters and related hazards. The usage of numerical simulation results jointly with the continuous remote monitoring data allows assessing the basic parameters of explosive eruptions (the start time and duration of ash emission, its height, etc.). This aim can be achieved by selecting the optimum initial data for the modeling of specific events via the minimization of the difference between preliminary simulation results and actual remote observations.

The present paper describes the possible approach for solving such problems, the tools and features of the joint analysis of satellite observations and numerical simulation data on the movement of ash clouds based on the "Monitoring of Active Volcanoes of Kamchatka and the Kurile Islands" information system (VolSatView, http://volcanoes.smislab.ru) [2–4] and on the "Signal" automated system [16, 23].

2. PECULIARITIES OF SIMULATION OF ASH CLOUD TRANSPORT DURING EXPLOSIVE ERUPTIONS

Nowadays there are many models of various complexity used for the prediction of ash cloud transport: from simple two-dimensional trajectory models to three-dimensional models of transport and dispersion of ash clouds. Such models are based on the Lagrangian or Eulerian statement of the problem of atmospheric transport of pollutants and on the usage of meteorological data from the forecast models by National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS). For example, the NOAA HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model computes wind speed and wind direction at different heights above the sea level but does not provide information on the amount of ash transported from volcanoes.

An example of the universal atmospheric pollution dispersion model is NAME (Numerical Atmospheric-dispersion Modeling Environment). This model can predict the transport, transformation, and deposition of different aerosol products including volcanic ash as well as the three-dimensional field of ash concentration in the cloud and the deposition of aerosol particles at the distance from one kilometer to many thousands kilometers from the volcano. It utilizes detailed three-dimensional meteorological data for northwestern Europe [12].

The complex forecast model ASH3D under specified conditions (the start time of eruption, ash column height, eruption duration, and erupted volume) includes the simple simulation of ash fall from the eruptive cloud as well as the three-dimensional modeling of variations in the ash cloud height and in the concentration of ash particles in it [17].

Another forecast model, PUFF, was proposed in [26] and was implemented in the form of the set of Puff-UAF computer programs at the University of Alaska Fairbanks Geophysical Institute [20–22]. It is somewhat similar to ASH3D (in terms of the set of initial parameters used for modeling meteorological fields, GFS NCEP/NOAA), but it is more attractive for operation due to the detailed description of the computer implementation of the model and its testing in the process of investigation of ash clouds from Alaska and Kamchatka volcanoes.

The PUFF model is based on the solution of the simplified equation of particle transport under the conditions of horizontally homogeneous wind field and spatially homogeneous turbulence field. It has been applied for studying explosive volcanic eruptions in different regions of the globe during more than 10 years and exhibited a rather high correlation between the simulated and observed (from satellites) trajectories of ash clouds [14, 21, 24]. In view of this, the PUFF model was chosen for numerical calculations and the further comparative analysis of the results with the data of satellite observations of Kamchatka volcanoes.

3. METHODS AND INSTRUMENTS

To solve the problems of comprehensive analysis of diverse information based on the results of modeling and satellite and ground-based observations, special tools are needed which provide the presentation of satellite and meteorological data, the simulation process control, and the synchronous analysis and comparison of different data. The VolSatView information system [2–4] was used as a technological base for the development of such tools. This system allows the integration of information received from different information systems and the creation of specialized user interfaces. The data sources for VolSatView are the integrated system of satellite data of Planeta Research Center for Space Hydrometeorology [8], the "Signal" automated information system [16, 23], the IKI-Monitoring Center for Collective Use [9], and "Volcanoes of Kurile-Kamchatka Island Arc" information system (VOKKIA) of the IVS FEB RAS Geoportal [10, 11]. To organize the cross-system coupling, the REST (Representational State Transfer) service was developed within the "Signal" system. It provides the mutual access to initial data and results of their processing for a wide range of the areas dealing with the study of Kamchatka volcanoes [13]. The numerical simulation is carried out using the modified Puff-UAF package in the "Signal" system. The mentioned works allowed pooling the resources of the most authoritative Russian thematic information systems in the area under study.

The system for the modeling of ash cloud transport is implemented within the "Signal" information system and has two operation modes: automatic and interactive. The base for the automatic modeling is the data of operational monitoring of volcanoes conducted by the KVERT group. If the ash cloud is detected in the volcano area, the VONA message (Volcano Observatory Notice for Aviation) is issued which contains the information (date and time of eruption, its duration, ash plume height, the distance and direction of ash cloud movement, etc.) obtained from the analysis of video-visual and satellite monitoring data. This information is recorded to the KVERT "Active Volcanoes of Kamchatka and the Northern Kurile Islands" database in the VOKKIA information system and becomes available in the "Signal" system. The used scheme of data exchange between the above systems allows the "Signal" system to receive the VONA message in real time and to provide the automatic computation of the ash cloud trajectory based on the information received.

The date and time of eruption are also used to retrieve the corresponding set of meteorological data representing the fields of zonal and meridional wind speed components (u and v) at different standard levels covering the simulation domain. The source of these data is the GFS forecast model products (NCEP/NOAA, USA) distributed in the form of GRIB Edition 2 files. The data of forecasts with the lead time of 0 and 3 hours are used first; if such data are absent, the data of forecasts with the longer lead time are used. The information from the formed set is recorded to the four-dimensional (time, level, latitude, longitude) NetCDF file which is subsequently used as initial meteorological data for the modeling.

The results of calculations are the coordinates and height of the model ash cloud particles recorded to the NetCDF files each corresponding to the cloud state at the certain moment of time. The number of these files is defined by the ratio of the simulation period to the results saving step and is specified as input parameters before the start of calculations. Numerical results are presented in the required graphic format (GIF, KML, Shape, etc.) and supplement the results reference in the "Signal" system.

To provide the transparent work with the results of the modeling in VolSatView, the special service REST was developed in the "Signal" system, which provides the list of all calculations with parameters and the list of results. It is retrieved by VolSatView by further visualization of simulation data for a specific explosive event and the comparative analysis of satellite and meteorological observations provided by VolSatView.

The calculations in the automatic mode imply that the system contains some predefined parameters for the PUFF model (for example, the time and step of modeling, formats of resultant files, etc.). By default, the values recommended in the Puff-UAF package documentation are used [20].

The interactive mode of the system operation is associated with the use of corresponding interfaces in VolSatView through which the researcher may initiate the execution of separate computing tasks using the above tools and technologies. For example, the specialized interface implemented within the "Signal" system can be used for modeling ash transport with the detailed prescription of all conditions. The modeling results are recorded to the database and are also available in VolSatView.

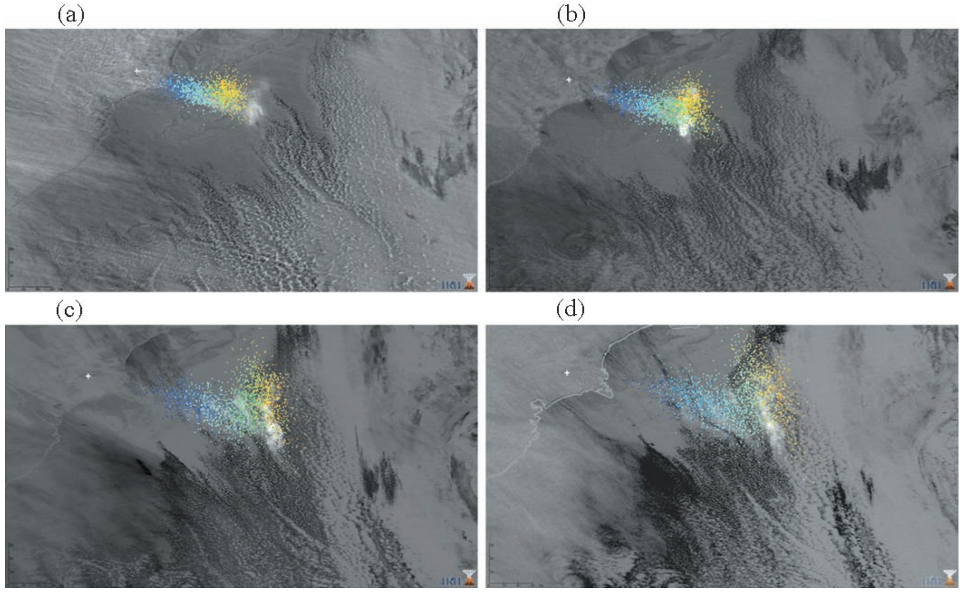

Fig. 1. The dynamics of ash cloud transport after the explosive eruption of Zhupanovsky volcano on February 12, 2016 based on satellite data and mathematical modeling results. Here and in Fig. 2: the white asterisk is the location of Zhupanovsky volcano; the black-and-white image is the difference in 11–12 μm channels from the data of satellite instruments; the color of ash particles corresponds to the height where they are situated (it varies from blue (1.5 km) to yellow (10 km)). (a) 23:40 on February 12, 2016, MSU-MR instrument, Meteor-M No. 2 satellite; (b) 23:55 on February 12, MODIS instrument, Terra satellite; (c) 01:45 on February 13, VIIRS instrument, Suomi NPP satellite; (d) 02:27 on February 13, AVHRR instrument, NOAA-19 satellite (hereinafter, the Coordinated Universal Time is given). The results of ash cloud simulation are presented for the respective moments of time: (a) 23:40 on February 12; (b) 24:00 on February 12; (c) 02:00 on February 13; (d) 03:00 on February 13.

The mapping interface of VolSatView contains special sections intended for the remote operation of the modeling system. They enable forming a task for the modeling of the concrete event for the volcano of interest, transmitting this task to the “Signal” system, tracking the status of its execution, and, upon completion, getting access to the modeling results. The modeling with different parameters may be carried out by subsequently choosing the variants which maximally coincide with satellite data.

The simulation results are presented in the mapping interface as the set of points whose color corresponds to the height of location of ash particles at the specified time moment. The interface has an option of viewing the results (the geographic position of particles and their height) for each simulation step and at the height of interest.

The results of computation may be visualized in the system jointly with different information products based on satellite data. The detailed description of VolSatView features is presented in [2–4, 6–9]. Some examples of the joint visualization of simulation results and satellite data are given in the next section.

4. THE EXAMPLES OF APPLICATION OF THE DEVELOPED METHODS AND TOOLS

The possibility of quality assessment for the modeling of the transport of ash clouds resulting from explosive volcanic eruptions is demonstrated in Fig. 1. It may be noted that the simulation results (if initial parameters describing an explosive event are correctly specified) coincide rather well with the general pattern of ash cloud transport that is observed from satellite data not only at a certain time moment but also during the time period comparable with the cloud lifetime (more than 5 hours). This means that the used model is applicable to short- and medium-range forecasting of ash cloud transport.

It should be noted that since VolSatView utilizes the data of the great number of satellites, it allows the detailed analysis of ash cloud dynamics. For example, Figure 1 presents the comparison of simulation results with observational data from four different satellites. It is noteworthy that such possibility may help to

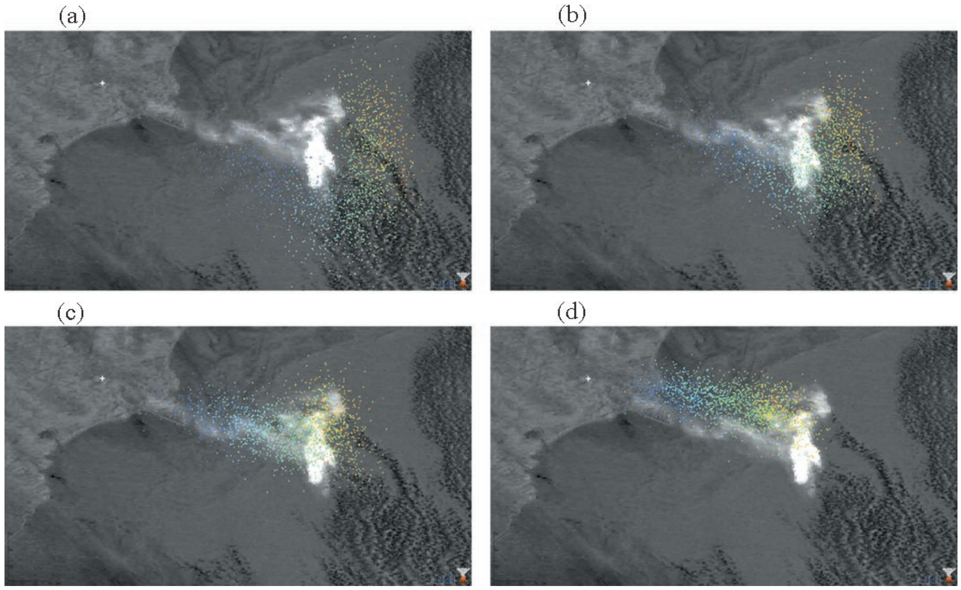

Fig. 2. The possibility of varying the time of explosive eruption of Zhupanovsky volcano on February 12, 2016 for the optimum coincidence of simulation results and satellite data (the image trom 23:55 on February 12, MODIS instrument, Terra satellite). The start time of ash release specified in the model: (a) 18:00; (b) 19:00; (c) 20:00; (d) 21:00.

develop the methods and tools for the automated correction of modeling parameters aimed at assessing the accuracy of obtained forecasts and the characteristics of observed explosive eruptions.

For example, it is sometimes impossible to determine even the basic parameters of eruptions of remote volcanoes at Kamchatka and the Kurile Islands such as the start time of an explosive event, ash plume height, eruption duration, etc. The comparison of the results of ash cloud transport simulation with satellite data may specify or partly retrieve these parameters.

Let us consider the explosive eruption of Zhupanovsky volcano on February 12, 2016. The comparison of simulation results for different eruption start times with the ash cloud state in satellite images allows selecting the time (about 20:00 UTC on February 12, 2016) of the maximum coincidence of simulation results and satellite data (Fig. 2). This is true not only for the basic zone where the ash cloud is located at the moment of comparison (24:00 UTC on February 12, 2016), but also for its shape and propagation trend. If the modeling uses the earlier and later eruption start time, the ash cloud is displaced to the south and north, respectively, as compared to satellite data (Fig. 2).

It should be noted that since VolSatView contains no single-moment observations, in the future it will be possible to construct the scheme which allows the synchronous specification of several initial parameters required for the correct simulation of ash clouds.

The approach that retrieves or specifies the parameters of explosive events based on the joint analysis of remote sensing data and mathematical modeling results, has been widely used. It has also provided additional information on eruptions [14, 24]. At the same time, each such investigation requires the extensive background work and the presence of proper infrastructure for the acquisition, storage, special processing, and analysis of heterogeneous data. The tool developed in the present paper allows almost the full automation of all stages of such work. So, it can be applied not only for the hindcasting of eruptions which occurred in recent years, but also for the operational monitoring of volcanic activity.

5. CONCLUSIONS

A new tool was developed for solving the problems of integrated monitoring of ash cloud transport from Kamchatka volcanoes. It has already been used by the scientists of the IVS FEB RAS KVERT group for aviation safety provision in that region (http://www.kscnet.ru/ivs/kvert/puff.php). The developed set of technologies and software tools may be used for studying Kamchatka volcanoes, in particular, for developing the method of specification of characteristics of volcanic eruptions. It can also be applied for assessing the effects of volcanoes on the environment, for example, the processes associated with the atmospheric transport of ash clouds.

In the future it is planned to develop the methods and algorithms of the automatic comparison of information based on simulation results and satellite observations in the VolSatView information system. Their implementation will improve the forecasts of ash cloud transport and the assessment of parameters of explosive events.

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