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A multi-sensor plume height analysis of the 2009 Redoubt eruption

Angela L. Ekstrand [a,b,*], Peter W. Webley [a,b], Michael J. Garay [c], Jonathan Dehn [a,b], Anupma Prakash [a], David L. Nelson [d], Kenneson G. Dean [a,b], Torge Steensen [a,b]

[a] Geophysical Institute, University of Alaska Fairbanks, 903 Koyukuk Drive, Fairbanks, AK 99775, United States
[b] Alaska Volcano Observatory, University of Alaska Fairbanks, 903 Koyukuk Drive, Fairbanks, AK 99775, United States
[c] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, United States
[d] Raytheon Company, 299 N. Euclid Avenue, Pasadena, CA 91101, United States

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ABSTRACT

During an explosive volcanic eruption, accurately determining the height of a volcanic plume or cloud is essential to accurately forecast its motion because volcanic ash transport and dispersion models require the initial plume height as an input parameter. The direct use of satellite infrared temperatures for height determination, one of the most commonly employed methods at the Alaska Volcano Observatory, often does not yield unique solutions for height. This result is documented here for the 2009 eruption of Redoubt Volcano. Satellite temperature heights consistently underestimated the height of ash plumes in comparison to other methods such as ground-based radar and Multi-angle Imaging SpectroRadiometer (MISR) stereo heights. For ash plumes below the tropopause, increasing transparency of a plume begins to affect the accuracy of simple temperature height retrievals soon after eruption. With decreasing opacity, plume temperature heights become increasingly inaccurate. Comparison with dispersion models and aircraft gas flight data confirms that radar and MISR stereo heights are more accurate than basic satellite temperature heights. Even in the cases in which satellite temperature results appeared to be relatively accurate (e.g., for plumes below the tropopause), a mixed signal of plume and ground radiation still presented an issue for almost every event studied. This was true regardless of the fact that a band differencing method was used to remove presumably translucent pixels. The data presented here make a strong case for the use of data fusion in volcano monitoring, as there is a need to confirm satellite temperature heights with other height data. If only basic satellite temperature heights are available for a given eruption, then these heights must be considered with a significant margin of error.

1. Introduction and background

During an explosive volcanic eruption, a primary goal of volcano monitoring is to predict the regions that may be adversely affected by an ash cloud so that local populations and aviation agencies can be notified of impending hazards. In Alaska, volcano monitoring is performed by the Alaska Volcano Observatory (AVO), a joint program of the United States Geological Survey (USGS), the Geophysical Institute (GI) of the University of Alaska Fairbanks (UAF), and the Alaska Division of Geological and Geophysical Surveys (ADGGS). AVO relies heavily on volcanic ash transport and dispersion (VATD) models that allow scientists to predict the movement of an ash cloud based on wind field data (Webley et al., 2009). Plume height (i.e., altitude above mean sea level) information is used as an input parameter for VATD models, and because wind directions and speeds often vary with altitude (known as wind shear), accurate plume height information is necessary for making accurate cloud movement forecasts (Searcy et al., 1998).

Currently, discrepancies exist between methods for plume height retrieval. The basic satellite temperature method, which uses direct comparison of single band thermal infrared (TIR) temperatures to local temperature–altitude profiles to determine plume height (Kienle and Shaw, 1979; Sparks et al., 1997), tends to produce lower heights than methods such as satellite stereo and ground-based radar. While this discrepancy is not significant for all eruptions (e.g., the Augustine 2006 eruption, see Bailey et al., 2010), some recent eruptions in the North Pacific (NOPAC) have displayed discrepancies up to ~10 km. These discrepancies, in turn, greatly impact the ability of AVO to accurately constrain plume heights and effectively utilize VATD models.

Located in a region of heavy air traffic, the 100+ active volcanoes in the NOPAC between Alaska and Russia are potential threats to aircraft (Miller and Casadevall, 2000; Dean et al., in press), though most are in remote, difficult to monitor locations. Satellites provide frequent coverage of the entire NOPAC region, so the basic satellite temperature method is heavily used by AVO for volcano monitoring. Ground-based radar

* Corresponding author at: Geophysical Institute/Alaska Volcano Observatory, University of Alaska Fairbanks, 903 Koyukuk Drive, Fairbanks, AK 99775-7320, United States. Tel.: +1 907 474 7490.
E-mail address: angela.ekstrand@gi.alaska.edu (A.L. Ekstrand).

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and satellite stereo methods, as described in this manuscript, have greater limits on temporal and spatial coverage. Some volcanoes (e.g., Mt. Cleveland in the Aleutians; McGimsey et al., 2011) lack seismic networks, making satellite data sometimes the sole source of information about an active eruption. Because the basic satellite temperature method is heavily relied upon, it is necessary to understand its limitations. This study aims to fulfill that objective by comparing multiple plume height retrieval methods for the 2009 eruption of Redoubt Volcano in Alaska. Redoubt is an excellent case study because of its location in the Cook Inlet region (Fig. 1). At this location, ground-based radar and aircraft gas flight data are available for comparison with satellite stereo data, VATD models, and temperature method data.

1.1. The 2009 Redoubt eruption

Redoubt Volcano (60.485° N, 152.743° W; Fig. 1) erupted explosively on March 23, 2009 after nearly 20 years of repose, and continued erupting until April 4, 2009 (Schaefer, 2012). Nineteen events were recorded for which a Volcano Activity Notice (VAN) and Volcano Observatory Notice for Aviation (VONA) were issued by AVO (McNutt et al., 2013). Seismic analysis by AVO scientists revealed that there were actually over 30 explosive events (McNutt et al., 2013). After the eruptive phase of activity, the volcano transitioned to a lava dome building phase (Bull and Buurman, 2013).

Redoubt is located within a region of heavy air traffic about 175 km southwest of Alaska's largest city, Anchorage (Fig. 1), which has the fifth largest airport in the world for air cargo (Airports Council International, 2011). During the Redoubt eruption, commercial flights from area airports, as well as activity at Elmendorf Air Force Base in Anchorage, were interrupted (Riccardi and Glascock, 2009). Most plumes during this period were products of explosive eruptions, however, on April 4, 2009, an ash plume developed from lava dome collapse (Webley et al., 2013).

2. Methods of height determination, datasets, and sensors

In this study, four height retrieval methods are considered: (1) aircraft gas flight observations, (2) ground-based radar, (3) satellite-based stereo height analysis, and (4) the basic satellite temperature method. Of the above, all are used operationally for volcano monitoring purposes within AVO except stereo height analysis, with emphasis on satellite and radar methods. In addition, results from the Puff VATD model (Searcy et al., 1998) are included.

2.1. Gas flight heights

During the Redoubt 2009 eruption, gas observation flights were conducted in a fixed-wing aircraft at Redoubt Volcano by AVO and the USGS Cascades Volcano Observatory. Scientists used in-situ and remote instrumentation to measure the plume composition and calculate emission rates of carbon dioxide (CO_2), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S) gases (personal communication, T. Lopez). The gas flight observations described in this manuscript were obtained from Werner et al. (2013). Height information and position from gas flights were obtained from a Global Positioning System (GPS) receiver at 1-second intervals (1 Hz frequency; personal communication, P. Kelly).

2.2. Ground-based radar heights

Radar systems are able to provide information about volcanic plumes, including column height, in most weather conditions (Rose et al., 1995; Marzano et al., 2006a,b, 2010; Wood et al., 2007). Larger

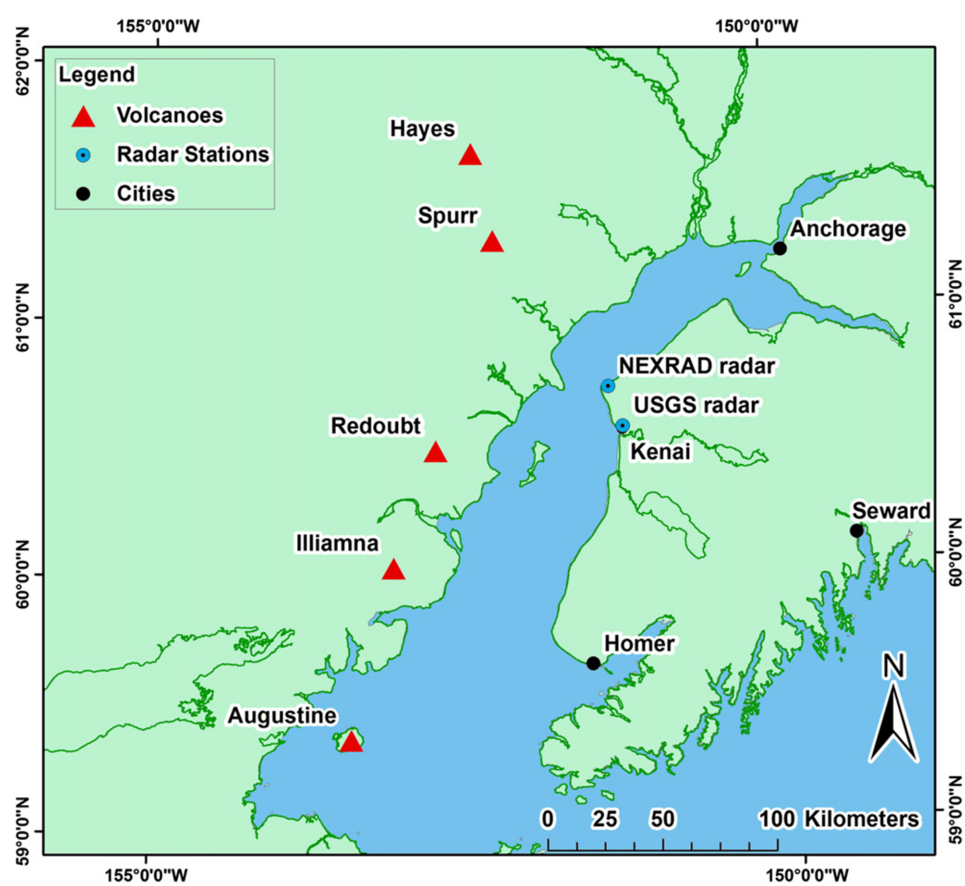

Fig. 1. Location of Redoubt Volcano relative to Anchorage and surrounding area. The summit of Redoubt is approximately 160 km from Anchorage, and 30 km from the Cook Inlet. Radar locations from Schneider and Hoblitt (2013).