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Assessing the altitude and dispersion of volcanic plumes using MISR multi-angle imaging from space: Sixteen years of volcanic activity in the Kamchatka Peninsula, Russia

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ABSTRACT

Volcanic eruptions represent a significant source of atmospheric aerosols and can display local, regional and global effects, impacting earth systems and human populations. In order to assess the relative impacts of these events, accurate plume injection altitude measurements are needed. In this work, volcanic plumes generated from seven Kamchatka Peninsula volcanoes (Shiveluch, Kliuchevskoi, Bezymianny, Tolbachik, Kizimen, Karymsky and Zhupanovsky), were identified using over 16 years of Multi-angle Imaging SpectroRadiometer (MISR) measurements. Eighty-eight volcanic plumes were observed by MISR, capturing 3–25% of reported events at individual volcanoes. Retrievals were most successful where eruptive events persisted over a period of weeks to months. Compared with existing ground and airborne observations, and alternative satellite-based reports compiled by the Global Volcanism Program (GVP), MISR plume height retrievals show general consistency; the comparison reports appear to be skewed towards the region of highest concentration observed in MISR-constrained plume vertical extent. The report observations display less discrepancy with MISR toward the end of the analysis period (2013–2016), with improvements in the suborbital data likely the result of the deployment of new instrumentation. Conversely, the general consistency of MISR plume heights with conventionally reported observations supports the use of MISR in the ongoing assessment of volcanic activity globally, especially where ground-based observations are unavailable. Differences between the northern (Shiveluch, Kliuchevskoi, Bezymianny and Tolbachik) and southern (Kizimen, Karymsky and Zhupanovsky) volcanoes broadly corresponding to the Central Kamchatka Depression (CKD) and Eastern Volcanic Front (EVF) geological sub-regions of Kamchatka, respectively, are distinguished by varying magma composition. For example, by comparison with reanalysis-model simulations of local meteorological conditions, CKD plumes were generally less constrained by mid-tropospheric (<6 km) layers of vertical stability above the boundary layer, suggesting that these eruptions were more energetic than those in the EVF region.

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1. Introduction

Satellite observations represent a valuable resource for observing volcanic eruptions, and are increasingly used in near-real-time monitoring efforts due to their frequent, global coverage (Wright et al., 2002; Brenot et al., 2013). Additionally, they can aid in the assessment of volcanic system dynamics (Murphy et al., 2013; Flower and Carn, 2015). Unlike surface-based instruments, space-borne ones are unencumbered by local contamination or damage from the volcanic eruptive products themselves, but generally at the expense of temporal and spatial resolution. Greater spatial coverage makes satellite-based instruments especially useful for monitoring volcanic activity where eruptions are violent (Carn, 2015) or for observing remote regions such as Kamchatka (van Manen et al., 2010; 2012). Following the initial investment, these instruments provide ongoing data at minimal incremental cost.

The quantification of aerosolized volcanic products from satellite-based remote sensing data have utilized both infrared (IR) (e.g. Prata, 1989; Ellrod et al., 2003; Pergola et al., 2004; Prata and Kerkmann, 2007; Corradini et al., 2010; Clarisse et al., 2010) and ultraviolet (UV) (e.g. Krueger, 1983; Bluth et al., 1992; Yang et al., 2007; Carn et al., 2009; Krotkov et al., 2010) techniques. These methods commonly rely on accurate plume height estimates to calculate the concentration of emitted material present in suspension. Despite the importance of accurate plume height determination, this remains a key challenge in the field of volcanology, with typical uncertainties of ~20% (Bonadonna et al., 2015). Satellite multi-angle imagery can be used to deduce volcanic

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plume height based on the observed parallax of plume features (e.g., Moroney et al., 2002; Kahn et al., 2007; Nelson et al., 2008, 2013). The vertical profiles and horizontal extent gleaned from multi-angle imagery can also elucidate details of eruptive style, and is the primary tool applied in the current study.

1.1. Kamchatka volcanological setting

The Kamchatka Peninsula is a complex geological region influenced by the subduction of the Pacific plate and Emperor Sea Mounts beneath the Okhotsk Plate (Churikova et al., 2007; Ponomareva et al., 2007a, 2007b). The southeast part of the peninsula, referred to as the Eastern Volcanic Front (EVF), is affected by the subducting Pacific plate, and displays similar composition to volcanoes in the Kuril island chain to the south of the peninsula (Ishikawa et al., 2001; Ponomareva et al., 2007b). In contrast, the northern volcanoes, located within a region known as the Central Kamchatka Depression (CKD), display variations in trace element composition influencing the properties of the erupted products (Ishikawa et al., 2001; Portnyagin et al., 2007), attributed to the additional influence of the subducting Emperor Sea Mounts.

These differences, observed over a relatively compact geographic region that is also monitored at ground stations, make the Kamchatka Peninsula an especially good target for exploring the ability of satellite observations to distinguish volcano properties. Variations in source magma can significantly impact the eruptive processes observed at volcanoes, which could manifest in the variation of ejection altitude identified between the CKD and EVF. The differences in magma composition, driving variations in eruption dynamics, might also result in the generation of particles with different microphysical properties (e.g., Scollo et al., 2012; Kahn and Limbacher, 2012). This is the focus of continuing work, entailing a detailed investigation of plume microphysical properties across Kamchatka, aimed at distinguishing any differences that could result from the complex geological setting of this location. Characteristics of the seven volcanoes studied here are given in Table 1, along with a general summary of activity observed at each one during the analysis period (2000–2016). Where activity is sporadic or short-lived, the years with registered activity are also noted.

1.2. Multi-angle Imaging SpectroRadiometer (MISR)

The Multi-angle Imaging SpectroRadiometer (MISR) instrument, deployed onboard NASA's Terra satellite in December 1999, is a visible-near-infrared (NIR) passive sensor measuring upwelling shortwave radiation in four spectral bands (446, 558, 672 and 866 nm). Although other satellite-based instruments cover this spectral range, MISR is unique in providing near-simultaneous coverage at multiple viewing angles. The instrument consists of nine cameras positioned at nadir plus four steeper angles (26.1°, 45.6°, 60°, 70.5°), in both the forward (F) and aft (A) viewing directions (Diner et al., 1998). Through stereo matching of these images, plume altitude can be calculated from the observed parallax (Moroney et al., 2002; Muller et al., 2002; Kahn et al., 2007; Scollo et al., 2010; Nelson et al., 2013). In addition to yielding accurate plume heights, MISR data have been used to provide the microphysical properties of volcanic plumes at Eyjafjallajökull (Kahn and

Table 1
Summary of activity and MISR retrieval success at Kamchatka volcanoes.

Volcano (Location) (Altitude)	Activity	Magma composition	Eruptive characteristics (active periods)	MISR plume observations	Plume heights characteristics (MINX median)
Shiveluch 56.65°N, 161.36°E 3283 m	Periods of dome growth terminating in explosive collapse events (Belousov et al., 1999; Dirksen et al., 2006).	High magnesium andesite (Ponomareva et al., 2007a)	Ongoing (1999–present)	Significant atmospheric injection that is clearly identifiable in the MISR record. Highest number of retrievals from a single volcano within this analysis.	Mean ~4 km Larger events and ash remobilization events were sporadic throughout time-series.
Kliuchevskoi 56.06°N, 160.64°E 4754 m	Eruptions occur every 1–2 years, lasting from months to a year (Ozerov et al., 1997).	Basaltic andesite (Fedotov and Zharinov, 2007; Ozerov et al., 1997)	Summit eruptions ~1–2 years (Rose and Ramsey, 2009) (2000, 2002–2005, 2007–2013, 2015–2016)	Plumes observed in only 6 years (2001, 2005, 2007, 2008, 2014 and 2016). Most successful mid-2007 with the high intensity, short-lived eruption.	Mean - 5.4 km Plume height varied throughout time-series. Prior to 2006 ~4.1 km. In mid-2007 ~8.8 km. Returned to ~4.4 km after September 2007.
Bezymianny 55.97°N, 160.6°E 2882 m	Ongoing dome growth accompanied by periodic eruptions and collapse events, occurring at a rate of 1–2 per year (Belousov et al., 2002; van Manen et al., 2010).	Basaltic andesite (Global Volcanism Program, 2013)	Ongoing 1–2 eruptions per year (Carter et al., 2008) (1999–present)	Sporadic short-lived nature of eruptions limited observation with MISR.	Mean - 4.4 km Consistent throughout time-series.
Tolbachik 55.83°N, 160.33°E 3611 m	A single yearlong fissure eruption beginning on the 27 November 2012 and continuing through August 2013 (Belousov et al., 2015).	High alumina basaltic trachyandesites (Volynets et al., 2015)	High intensity eruption with repose of decades. (November 2012–August 2013)	Persistent cloud cover limited MISR observations.	Mean – 3.8 km Consistent throughout time-series.
Kizimen 55.13°N, 160.32°E 2334 m	The single eruptive phase began on 10 December 2010 (Senyukov, 2013), preceded by a period of intense seismicity (Senyukov, 2013) and deformation (Ji et al., 2013).	Basalt and Basaltic andesite (Churikova et al., 2007)	High-intensity eruption with repose of decades. (December 2010–September 2013)	Persistent high-intensity plumes at moderate altitude, timing conducive to observation by MISR.	Mean – 3.1 km. Plume height varied throughout time-series. First month ~3 km. January to mid-February ~4.5 km. Returned to ~3 km for continuing activity.
Karymsky 54.05°N, 159.44°E 1513 m	Typically displayed moderate Strombolian-Vulcanian activity (van Manen et al., 2012) characterized by small plumes with rapid particle deposition on a scale of minutes to hours (Sigurdsson et al., 2015).	Andesite (Lopez et al., 2013	Ongoing (1999–present)	The short residence period of pulsatory plumes limited observation with MISR. Only larger eruption plumes or fortuitously timed events identified.	Mean – 2.7 km. Relatively consistent throughout time-series. Two larger plumes in 2006 and 2011.
Zhupanovsky 53.59°N, 159.15°E 2899 m	Began erupting in 2014 with some ash-producing events. However, the plumes were comprised primarily of gas and steam (Global Volcanism Program, 2014).	Basalt (Plechova et al., 2011)	Two periods of activity (October 2013, June 2014–March 2016) Global Volcanism Program, 2016)	Pulsatory activity limited observations with MISR. Cloud cover and data outages restricted observations during 2014.	Mean – 2.3 km. Single plume identified in September 2014.

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