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Volcanic plumes and wind: Jetstream interaction examples and implications for air traffic

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ABSTRACT

Volcanic plumes interact with the wind at all scales. On smaller scales, wind affects local eddy structure; on larger scales, wind shapes the entire plume trajectory. The polar jets or jetstreams are regions of high [generally eastbound] winds that span the globe from 30 to 60° in latitude, centered at an altitude of about 10 km. They can be hundreds of kilometers wide, but as little as 1 km in thickness. Core windspeeds are up to 130 m/s. Modern transcontinental and transoceanic air routes are configured to take advantage of the jetstream. Eastbound commercial jets can save both time and fuel by flying within it; westbound aircraft generally seek to avoid it.

Using both an integral model of plume motion that is formulated within a plume-centered coordinate system (BENT) as well as the Active Tracer High-resolution Atmospheric Model (ATHAM), we have calculated plume trajectories and rise heights under different wind conditions. Model plume trajectories compare well with the observed plume trajectory of the Sept 30/Oct 1, 1994, eruption of Kliuchevskoi Volcano, Kamchatka, Russia, for which measured maximum windspeed was 30–40 m/s at about 12 km. Tephra fall patterns for some prehistoric eruptions of Avachinsky Volcano, Kamchatka, and Inyo Craters, CA, USA, are anomalously elongated and inconsistent with simple models of tephra dispersal in a constant windfield. The Avachinsky deposit is modeled well by BENT using a windspeed that varies with height.

Two potentially useful conclusions can be made about air routes and volcanic eruption plumes under jetstream conditions. The first is that by taking advantage of the jetstream, aircraft are flying within an airspace that is also preferentially occupied by volcanic eruption clouds and particles. The second is that, because eruptions with highly variable mass eruption rate pump volcanic particles into the jetstream under these conditions, it is difficult to constrain the tephra grain size distribution and mass loading present within a downwind volcanic plume or cloud that has interacted with the jetstream. Furthermore, anomalously large particles and high mass loadings could be present within the cloud, if it was in fact formed by an eruption with a high mass eruption rate. In terms of interpretation of tephra dispersal patterns, the results suggest that extremely elongated isopach or isopleth patterns may often be the result of eruption into the jetstream, and that estimation of the mass eruption rate from these elongated patterns should be considered cautiously.

1. Introduction

The polar jets or jetstreams are regions of high windspeed that span the globe at latitudes from 30° to 60°. The jets mark the convergence zone between warm subtropical air and cold polar air. They are geostrophic winds and therefore are associated with a rapid change in vertical pressure gradient and tropopause height. The height of the tropopause is considerably lower on the poleward side of the jet than it is in lower latitudes, averaging 9 km in winter (occasionally as low as 5 km in tropospheric folding events) and 10 km in summer, as opposed to 16 km at the equator (Glaze and Baloga, 1996). Windspeeds within the jets average 40 m/s in winter, and 10 m/s in summer. Maximum speeds estimated in the core of the strongest jets are as high as 130 m/s. In cross section, windspeed decreases with height and horizontal distance from the core. Jet width (in planform) varies up to hundreds of kilometers, whereas jet thickness is as little as 1 km.

Even large volcanic plumes that are injected into the atmosphere at mid- and high latitudes can be expected to sometimes show profound effects caused by the interaction of the plume with the jet. In fact, jet speeds can approach and even surpass local plume speeds,

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resulting in ingestion of unusual amounts of air during plume rise, bending over of the plume in the windfield, and subsequent effects on maximum plume height and tephra dispersal. Oddly enough, modern transcontinental and transoceanic air routes are configured to take advantage of the jetstream. Eastbound jets can save both time and fuel by flying within it. The congruence of strong effects on volcanic plumes by the jetstream and the tendency of air traffic to use the jetstream poses an interesting volcanological problem.

Avachinsky volcano (53.3° N, 158.8° E, 2741 masl), 30 km north of Petropavlovsk–Kamchatskiy, Russia, poses the greatest risk to life and property of any volcano of the Kamchatkan peninsula. Past sector collapse eruptions have inundated the area now occupied by Petropavlovsk with over 100 m of flow debris (Melekestsev et al., 1991). The explosive eruption of 1945 resulted in the formation of a substantial atmospheric plume, which, if it occurred today, could pose a serious hazard to aviation (Casadevall and Thompson, 1995).

The Inyo Craters (37.7° N, 119.0° W, 2629 masl), eastern California, USA, last erupted explosively approximately 1450 A.D., with four distinct eruptions from three vents ejecting about 0.32 km^3 DRE of rhyolitic–rhyodacitic pyroclastic material (Miller, 1985). Tephra from these eruptions is dispersed widely over the Sierra Nevada (Wood, 1977), suggesting that a modern eruption would halt transcontinental air traffic into the San Francisco Bay area.

On September 8, 1994, Kliuchevskoi volcano (56.1° N, 160.6° E, 4835 masl), Kamchatka, Russia, began to erupt with minor explosions inside the volcanic crater. The activity gradually intensified, so that by September 20 the volcano was producing a plume that rose to between 1.5 and 2 km above the summit and extended over 100 km southeast (KVERT, 1994). The eruption greatly intensified on the afternoon of September 30. The plume rose to over 10 km above MSL. The paroxysmal stage happened at 0600 local time the next morning (October 1) when the top of the plume was reportedly elevated to approximately 18 km above MSL. Pilots reported the maximum height to be closer to 12 to 13 km. This large plume persisted for about 10 h. Over the next 12 h the plume height reduced to between 8 and 10 km, then to 6 to 7 km by 1100 October 2. During October 3 the volcano was obscured by clouds, but volcanic tremors indicated that the eruption intensity was reducing. By October 4 only fumarolic activity was present. The plume was photographed numerous times from the space shuttle (STS-68), and from the ground.

In this contribution, we present tephra dispersal data for eruptions from Avachinsky and Inyo Craters that show extreme elongation of isopach patterns. We hypothesize that the elongation is caused by transport of the ash within the jetstream. We test this hypothesis with two numerical volcanic plume models that are capable of handling a complex wind structure: the integral model BENT (Bursik, 2001) and the Active Tracer High-resolution Atmospheric Model (ATHAM; Oberhuber et al., 1998). The hypothesis is first tested using photographic data on plume shape from the Kliuchevskoi eruption given the known wind profile. Dispersal data for an eruption from Avachinsky are then fit, allowing us to test for injection into the polar jet for past eruptions. We conclude by examining implications of the volcanic plume-polar jet interaction for air traffic.

2. Data

2.1. Deposits and eruptions of Avachinsky Volcano, Kamchatka, Russia

Discussion of the tephrostratigraphy of Avachinsky is given in Melekestsev et al. (1994), Braitseva et al. (1995), Braitseva et al. (1998) and Bazanova et al. (2003).

The Avachinsky volcano-2 eruption (AV2) occurred in 2409–2850 cal B.C., with the large range in calibrated age resulting from the complexity of the radiocarbon calibration curve in this time

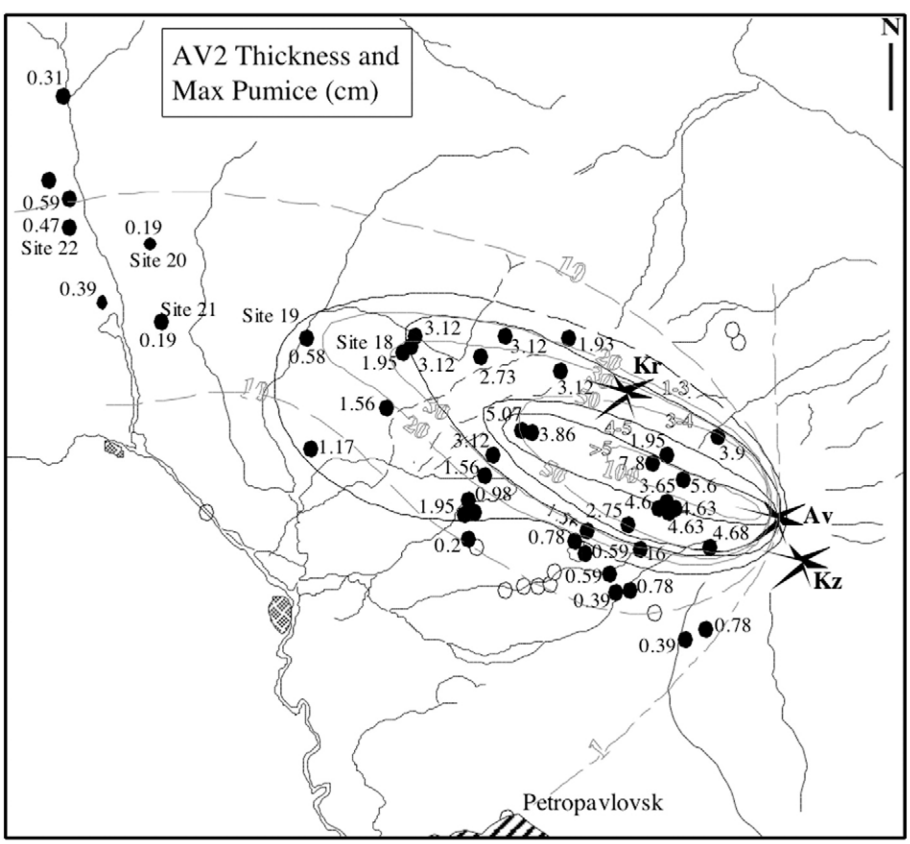

Fig. 1. Isopach map for the Avachinsky-2 eruption. Thickness isopachs shown with light gray lines and numerals. Grain-size isopleths with black lines and numerals. Values at sites are for grain size. Open circles denote observations without measurements. Kr, Koryaksky; Av, Avachinsky; Kz, Kozelsky volcanoes.