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

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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 geostrophic winds and therefore are associated with a rapid change in

Jetstream conditions. The polar jets or jetstreams are regions of high 

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.

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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 km³ 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...
interval. (Calibrated ages were calculated using the technique and software of Stuiver and Reimer, 1993.) At proximal localities along the dispersal axis, as on the pass between Avachinsky and Koryaksky volcanoes, the deposit is made up of three major sublayers including one prominent Plinian fall unit at top, and a thinner fall unit at base separated by a thick channel-forming subunit. At more distal localities near the dispersal axis the deposit is also characterized by three prominent sublayers, but the basal fall subunit tends to be of a thickness similar to that of the upper fall subunit. Both fall subunits are locally reversely graded, although the lower fall subunit is generally normally graded. The thickness of the intervening unit is variable as it is followed across the paleotopography, and the unit is composed of numerous discontinuous beds. These stratigraphic relationships suggest that there were two main Plinian phases, separated one from another by a blast or surge style event. The clasts comprising the deposit are large angular white and banded pumice fragments with a high proportion of accidental dunite fragments, as well as dark-gray, porous, juvenile basaltic-andesite.

The dispersal axis is somewhat unusual for a Kamchatkan eruption, as it is directed west–northwest. Its main feature however is exceptional elongation both in thickness and grain size isopleths, suggesting a mean windspeed >30 m/s (Figs. 1 and 2) (Carey and Sparks, 1986). Despite a relatively low estimated eruption column height of 17 km (Fig. 2), the volume was 1.4 km$^3$, based on the method of Pyle (1989), making the eruption VEI = 5. The combination of low column height and large volume would lead one to believe that the eruption persisted for a considerable time, perhaps on the order of 8 h, as obtained by dividing mass eruption rate calculated from column height by total deposit mass. However, given that the column height–windspeed nomogram suggests an unrealistic mean windspeed, one may wonder whether the ash was in fact transported within a strong (winter) polar jet. In the “Analysis and discussion” section, we will compare tephra dispersal from this eruption with the output from a numerical model that assumes transport within a strong jet.

2.2. 1470 A.D. eruption of South Deadman, Inyo Craters, California, USA

The first of the c. 1450 A.D. Inyo eruptions occurred at the South Deadman vent, producing the South Deadman–1 (SD1) fall deposit (Fig. 3). The SD1 tephra is an elongate, NNE trending fall deposit that covers more than 80 km$^2$ (Miller, 1985). Pumice dominates the fall unit, making up 70% or more of the deposit even at proximal locations. SD1 is composed of four thin subunits separated by resistant septa. These subunits are indicative of puffing or pulsating often associated with weak subplinian eruptions (Bursik, 1993).

The nomograms of Carey and Sparks (1986) indicate an 11 km-high eruption column in an ambient wind greater than 35 m/s (Fig. 4). While these results are in broad agreement with the expectation of a bent eruption plume in a strong crosswind, the actual values must be used with caution: the elongation of SD1 is so exaggerated that it does not fit properly into the Carey and Sparks nomogram and, as such, must be extrapolated. Extrapolation, as usual, yields an estimate that can be far from correct. In addition, we know that high wind speed values are not distributed with height in the troposphere, but are concentrated in the jetstream. Therefore a high, mean windspeed value may be somewhat misleading or at least oversimplified. Can we
formulate a more realistic approach to characterizing the interaction of a volcanic plume with the wind when a calculated mean windspeed would be unusually high?

2.3. 1994 eruption of Kliuchevskoi Volcano, Kamchatka, Russia

We can perhaps begin to explore another way of looking at the extreme elongation of the isopachs for the AV2 and SD1 deposits by considering a modern eruption plume that shows clear signs of wind advection, and for which we have photographs and wind profile data, in light of numerical modeling of the interaction of plumes with wind. One such eruption is the 30 Sept/1 Oct, 1994, eruption plume of Kliuchevskoi volcano, Kamchatka, Russia. The eruption was observed both from the space shuttle (Fig. 5) and from the ground, both of which show extensive interaction of the plume with the ambient windfield. The wind profile was measured by radiosonde on both 30 Sept 1994 and 1 Oct 1994 (V. Kirianov, personal communication, 1995), and is consistent with presence of the jet aloft based on windspeed value near the tropopause (Papp et al., 2005). The axial jet velocity, radius, and angle the plume makes with the horizon must be estimated at the vent to provide input for the plume models.

The mass eruption rate, $M$, can be estimated using results from the model of Sparks et al. (1997), who plotted mass eruption rate versus column height for typical volcanic plumes with a still wind profile and several other windspeeds. The model suggests that plume height is highly sensitive to the wind profile. Using this method, a mass eruption rate between $10^6$ and $3 \times 10^6$ kg/s is estimated. This estimate can be used to couple the axial jet velocity, $U$, with the vent radius, $b_0$, by the equation:

$$M = \pi b_0^2 \rho_0 U$$  \hspace{1cm} (1)

Where $\rho_0$ is the bulk density of the erupting mixture, assumed to be 5–10 kg/m$^3$ (e.g., Bursik et al., 1992a). The vent radius was estimated from photographs to be 75 m. Entering the estimated values for $M$, $\rho_0$ and $b_0$ into Eq. (1) and solving for $U$ yields a range for $U$ between 60 and 170 m/s. Multiple values of $U$ were tested, and a value of 100 m/s produced a reasonable fit to the observed plume.

The wind profiles on September 30 and October 1, 1994 were similar (V. Kirianov, pers. comm., 1995). Therefore since the climax of the eruption took place on October 1 the wind profile for this day was used in the models (Fig. 6). The two models, BENT and ATHAM have different methods of describing the wind field. ATHAM uses constant values for each kilometer of elevation. The average value for each kilometer was read directly off the wind profile and entered into

![Image of plume](image_url)

Fig. 5. The plume of the 30 Sept/1 Oct 1994 eruption of Kliuchevskoi Volcano, Kamchatka taken from the space shuttle STS-68 mission.
ATHAM. BENT uses a mathematical function to represent the wind field. A best-fit function was fit through the data, and this function was entered into BENT.

The observed axis of the Kliuchevskoi 1994 eruption plume was derived from ground-based photography. If the photographer was too close, high, low, or not perpendicular to the plume, the plume's axis will appear to be less curved than it actually is. This effect is greatly reduced as the photographer moves away from and perpendicular to the plume axis. The photograph used in the present contribution (traced in Fig. 6) was taken from a vantage point approximately 23 km away from and within 10° of perpendicular to the plume axis, which is acceptable to avoid any major distortion of the true bending in the plume axis.

The top of the plume is estimated to be at 12–13 km above MSL (7–8 km height above vent) (Fig. 6), which is consistent with pilot reports. Using the distance from the top of the plume to the top of the volcano, and the top of the volcano to its base, a scale for the picture was determined. The plume axis was plotted by fitting a continuous, smooth curve along the plume centerline from the vent to the point at which the plume becomes parallel with the horizon. Points on the plume axis were scaled off the picture. This plume axis will be compared in the next section to the plume axis calculated by the models.

3. Analysis and discussion

3.1. The Kliuchevskoi plume

In the present contribution, we use two numerical models that have been presented and are thoroughly discussed elsewhere: BENT (Bursik, 2001) and ATHAM (Oberhuber et al., 1998). Briefly, BENT is an integral model of steady plume motion that calculates properties in a plume-centered coordinate system that can be advected by the wind. ATHAM is a time-varying, large-eddy simulation in which the largescale flow field is directly calculated. One important outcome of the earlier work on BENT to which we will refer is that because of the nature of the interaction of volcanic plumes with the jet, over a wide range of mass eruption rates, plume height is limited by the jetstream (Figs. 7 and 8). A comparison of Fig. 8A and C most dramatically shows the rise-height limiting, shearing effects of the jetstream caused by extremely rapid entrainment of horizontal momentum within the jet.

![Fig. 6. Comparison of observed and modeled plume centerlines for the 30 Sept./1 Oct 1994 eruption of Kliuchevskoi. A) Using BENT, B) Using ATHAM. Colors in models are contours of particle concentration within the plume and are used to illustrate model plume shape. The outermost color can be taken to approximately represent the visible edge of the plume; the inner colors can be used to estimate the position of the model plume centerline. Color scale is not the same for both models. Horizontal spatial scale is the same as vertical. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image)

![Fig. 7. Eruption column height as a function of mass eruption rate for a number of windspeed models. The windspeed models that assume a jet at height are highlighted in red with maximum core jet speeds indicated. Note that over a range of mass eruption rates, column height remains nearly constant (From Bursik, 2001).](image)
Using the data described in the previous section, the plume model BENT was used to simulate the 1994 Kliuchevskoi eruption. The parameters used were: axial vent velocity, $U_0 = 100$ m/s, radius of the vent, $b_0 = 75$ m, and elevation of the vent, $H = 4880$ m.

The observed wind profile of the atmosphere is fit by the polynomials:

For $z<12.5$ km

$$V(z) = 0.71007 + 0.43989 z - 0.0019675 z^2 + 0.000042507 z^3 \text{ (m/s)}$$

For $z>12.5$ km

$$V(z) = 35 \text{ m/s}$$

where $z$ is the elevation above MSL. A constant value of 35 m/s was used for $V(z)$ for all elevations above 12.5 km as representative. The type of eruption, particle shape factor, and particle fraction values as required by BENT have no effect on the plume shape (Bursik, 2001). These other parameters are needed as input to BENT to calculate the amount and position of fallout from the plume. Standard values for these were used, as fallout is not important to the present calculation.

The model output fits the plume shape quite closely at distances less than 4000 m downwind from the vent (Fig. 6A). At just over 4000 m the angle the modeled axis makes with the horizon approaches zero. The model assumptions break down at this distance. Comparing the total rise height of the plume axis yields further information on model accuracy. The total rise height of the modeled axis is approximately 6400 m above the vent. The observed plume axis was at a maximum elevation of 7200 m above the vent. This represents an error in rise height on the order of 10%.

The 1994 Kliuchevskoi eruption plume was also modeled using ATHAM. The boundary condition values used in BENT constituted some of the initial condition values used in ATHAM. In terms of maximum rise height, the modeled plume extends slightly over 1 km higher than the observed plume (Fig. 6B). There are many possible causes for the difference in the observed and ATHAM modeled plume, and it may even be that this represents an acceptable amount of error, given uncertainties in initial conditions. However, the validity of the parametrization of sub-eddy scale entrainment by ATHAM is unknown, and the version of ATHAM used herein is two-dimensional, essentially being more appropriate to a line source rather than a point-source or central vent. A line source plume entrains air only on the windward and leeward sides of the plume. This is in contrast to the point source plume that entrains air around its entire circumference. This difference causes the point source plume to entrain significantly more air than the line source plume, which

![Fig. 8. Examples of plumes erupted into different windfields using model BENT. A, B, and C are for plumes of same mass eruption rate; D eruption rate is higher. In C, the jet is centered at 10 km. The combination of mass eruption rate and windspeed results in the different mean plume profiles.](image-url)
dilutes the plume more quickly, thus reaching a lower maximum rise height.

The horizontal distance the modeled plume propagated downwind does not agree well with the observed plume (Fig. 6B). The wind bends the modeled plume too much in the near-field. The modeled plume axis does not approach horizontality until about 15 km downwind. The observed plume was completely bent over in about half that distance. The centerline trajectory results for ATHAM again are probably related to the greater entrainment of the wind's horizontal momentum in the 2-D model.

The above analysis with BENT and ATHAM suggests that plume bending and rise height are roughly consistent with eruption into a jetstream. Furthermore, the results for the (3-D) BENT model suggest that the detailed centerline trajectory results from the lower wind-speeds closer to the surface and the high windspeed aloft within the jet. In the next section, we use BENT to fit the dispersal data for the AV2 eruption to invert for the wind profile, and discuss the nature of the profile. Although the maximum grain-size data for the SD1 eruption yield results similarly anomalous to those for the AV2 eruption on the Carey and Sparks (1986) nomogram and therefore support a contention that not all eruption deposits can be correctly characterized using these diagrams, an exercise to invert fallout data for the wind profile was not carried out for the SD1 eruption, due to the paucity of our data on mass deposited per unit area.

3.2. Dispersal of AV2 tephra

Cursory inspection of the dispersal data for the AV2 and SD1 tephras is suggestive of deposition from a bent-over plume (Fig. 1). For vertical eruption columns, the gradient at which deposition of larger clasts decreases with distance along the dispersal axis from vent is dependent only on mass eruption rate and pyroclast settling speed (Bursik et al., 1992a). Larger clasts will display a steeper negative gradient of sedimentation because of their greater settling speed. The larger pyroclasts do display this characteristic (Fig. 9), but the depositional patterns for smaller pyroclasts show a downwind peak in sedimentation at about 45 km, consistent with enhancement of deposition from the horizontally flowing downwind plume caused by a sudden decrease in vertical particle support (Fig. 9). This is thought to be consistent with a “corner” at the juncture of a roughly vertically directed eruption column and a roughly horizontal downwind plume (Bursik et al., 1992b). The amplitude of the secondary peak in deposition is small relative to that for the Mount St. Helens eruption (Bursik et al., 1992b). This may be because a large fraction of the pyroclasts had already been deposited from the bent-over plume.

As discussed above, the maximum clast dispersal data for the AV2 eruption are consistent with a windspeed of ~30 m/s using the model of Carey and Sparks (1986). To obtain a more realistic picture of the wind profile, we compare the dispersal axis sedimentation data (in kg/m²) for a variety of grain-size fractions with a number of possible models to estimate the wind speed as a function of height at the time of the eruption (output from the three best models is shown in Fig. 9). (Such sedimentation data for SD1 are not available.) The data are most consistent with a high speed jet centered at an altitude near 7 km above vent (10 km ASL), with a maximum wind speed of 40–50 m/s, as determined primarily from the anomalously extensive distribution of clasts in the 1 to −3 phi size classes (1/2–8 mm).

4. Conclusions

Some tephra deposits within the geological record exhibit extreme elongation of isopachs. Two examples are the AV2 tephra of Avachinsky volcano, Russia, and the SD1 tephra of the Inyo Craters, CA, USA. We hypothesized that perhaps the elongation is the result of eruption into the polar jet. Two models, BENT and ATHAM, were tested for their capability to perhaps model the interaction of a plume
with the jet. Each model has strengths and weaknesses, which are highlighted in comparisons of model output with photographic and radiosonde observations for the 30 Sept/1 Oct, 1994, eruption plume of Kliuchevskoi volcano, Russia.

Based on analysis of the dispersal data for the AV2 tephra with the numerical model BENT, we conclude that the plumes responsible for the AV2 and SD1 tephas may have been erupted into the polar jet.

If we combine the results from the present study with those from our earlier work (Bursik, 2001), we can make some potentially far-reaching conclusions. That is, we suspect that the presence of the jet causes anomalously low plume height at a given eruption rate (Bursik, 2001), and that the jet causes rapid downwind transport and thus anomalously distal deposition of tephra from the dramatically bent-over (in fact, sheared) eruption column. Extreme elongation of isopachs or grain-size isopleth contours may therefore be a sign of transport in the polar jet and peculiar to mid- and high-latitude eruptions. Inversion of such patterns to estimate mass eruption rate should be done with caution.

Furthermore, estimates of mass eruption rate from rise height measurements may be in considerable error in cases of high wind speed. Alternatively, changes in windspeed during a sustained eruption can alter plume height, even when there is no change in eruption strength at the vent. As a result of the shearing effect, eruptions with very different mass eruption rates pump volcanic particles into the jetstream, making it difficult to characterize the maximum size, grain size distribution and mass loading within a particular plume. If the effects of wind are not properly accounted for, high concentrations of large particles may persist to otherwise anomalous distances from the source.

Finally, and unfortunately, by taking advantage of the jetstream, aircraft are flying within an airspace that is preferentially occupied by volcanic eruption clouds and particles.

Acknowledgements

This research was supported in part by grants from the National Science Foundation (EAR0711464 and EAR0538227), National Aeronautics and Space Administration, the California Institute of Technology, and Science Applications International Corp. Part of the work (D. Pieri) was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the NASA Geology Program. The creators of ATHAM (H. Graf et al.) are thanked for sharing the source code and allowing its use by other researchers; A. Burns’ modeling of the Kliuchevskoi plume with ATHAM was completed following a stay at MPI, Hamburg, for which we are grateful. M. Melnyk assisted with particle analysis in the laboratory; V. Kirianov is thanked for the radiosonde wind profile for Kliuchevskoi. Larry Mastin, Amanda Clarke and an anonymous reviewer are thanked for numerous helpful comments.

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