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Operational dispersion modeling of 2023 Shishaldin Volcano eruption: complications from unknown granularity and mafic co-PDC plumes

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Abstract

The 2023 eruption of Shishaldin Volcano consisted of 13 explosive events, each resulting in drifting ash clouds that disrupted aviation and fallout that affected Aleutian communities and mariners. Shishaldin Volcano is monitored by the Alaska Volcano Observatory (AVO) with a local seismic network, regional infrasound stations, lightning detection networks, web cameras, and low-latency geostationary satellite data. These data streams allow a rapid estimation of critical eruption source parameters for operational ash dispersion modeling, such as the onset time of ash emissions and estimates of plume height. Although most of these dispersion model forecasts were consistent with subsequent reported fallout and satellite observations, ash plumes generated by syn-eruptive pyroclastic density currents (PDC) sometimes diverged from model forecasts. These co-PDC plumes had broad sources along the flanks of the volcano with lower plume heights than vent-derived plumes. Additionally, vent-derived plumes had coarse grain size distributions that led to inconsistencies with fallout model forecasts due to the more rapid settling of particles from the eruption cloud. Due to the remote location of Shishaldin Volcano, sampling tephra fallout to determine the typical grainsize was not typically possible, however combining a single field visit and community provided samples during the eruption provided data to develop a model for vent and co-PDC derived plumes. In this study, we present a reanalysis of the sequence of explosive events using the Ash3d dispersion/sedimentation model and the implications of this reanalysis on operational modeling of explosive mafic eruptions.

1. Introduction

In July 2023, Shishaldin Volcano, located on Unimak Island along the Aleutian arc (Figure 1), began an eruptive sequence that produced 13 explosive events over approximately five months. The Alaska

Volcano Observatory (AVO) monitors activity at Shishaldin Volcano through several real-time data streams, including from a local network of seismometers, GNSS stations, infrasound sensors, and web-cameras (Coombs et al. 2024). Additional low latency lightning detection services (latency of minutes) and geostationary satellite images (latency of minutes to tens of minutes) augment the AVO monitoring effort. As there are no communities in the immediate vicinity of Shishaldin Volcano, the primary hazards from eruptions are from drifting ash clouds affecting local and transpacific air routes, fishing and other marine ships, and nearby communities including False Pass (38 km or 23 mi northeast) Cold Bay (93 km or 58 mi northeast), King Cove (111 km or 69 mi), and Sand Point (230 km or 140 mi) , all of which have experienced ashfall during historic Shishaldin Volcano eruptions.

AVO reports on volcanic activity using Volcanic Activity Notices (VAN) and Volcanic Observatory Notice to Aviation (VONA), and coordinates with partner agencies who issue the formal products advising the public of ashfall and aviation hazards. During the 2023 eruption of Shishaldin Volcano, AVO operated with a rotational operations team with specific on-call positions covering expertise in seismology, remote sensing (satellite data), and ash dispersion and fallout modelling (Coombs et al., this issue). The role of the response ash modeler is to provide forecasts of fallout from a range of eruption scenarios and updating the forecasts as conditions change. The USGS uses the dispersion model, Ash3d (Schwaiger et al, 2012), primarily through a web-based interface for operational needs (Mastin et al. 2013). This web-based interface simplifies the source term to a single plume at the vent with a pre-determined grainsize distribution. Operationally, these simplifications often suffice, however when co-PDC plumes contribute to the ash cloud, the model deviates from the observation as the co-PDC plumes effectively insert ash laterally offset and at a different height than the vent-derived plume, typically with a finer grainsize distribution.

In this manuscript, we review the use of Ash3d in supporting response efforts for the sequence of eruptive events and document ways to improve forecasts by accounting for an additional co-PDC ash plume and variations in grainsize distribution of eruption products.

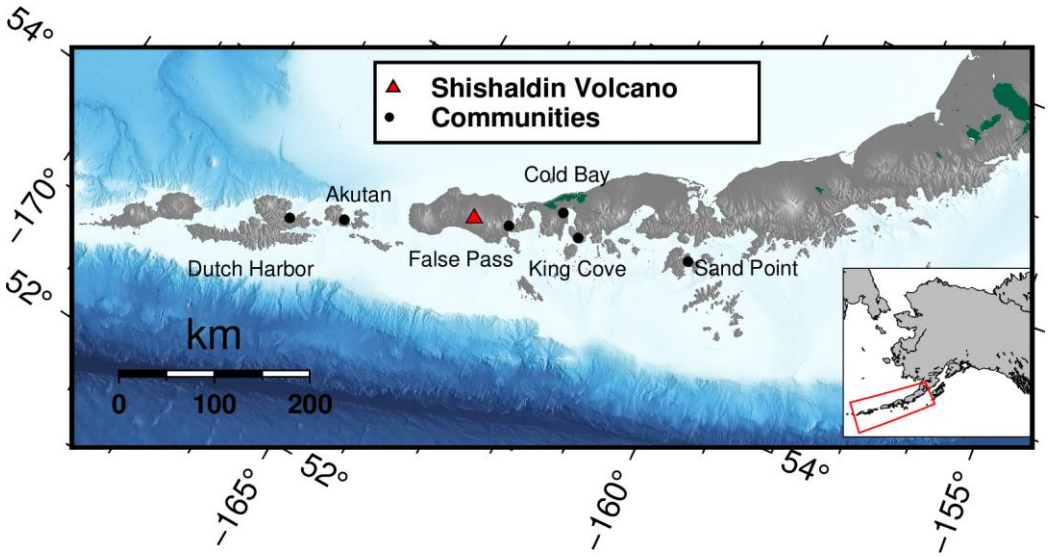


Figure 1*. Location map showing Shishaldin Volcano (red triangle) and nearby communities (black dots).*

2. Forecasting tephra fallout: the operational use of dispersion models at the AVO

For volcanoes that are frequently active or showing signs of unrest, AVO uses a web-based interface to the Ash3d software to simulate hypothetical explosive eruptions. These models generate ash cloud dispersal and ashfall thickness maps that are linked to the AVO public webpage. These simulations are automatically run twice daily as numerical weather prediction (NWP) forecast data become available and provide situational awareness for AVO staff, partner agencies, and the general public. These hypothetical events use eruption source parameters designed to reflect the expected plume height and duration based on past events. For Shishaldin Volcano, two representative scenarios were selected to bracket a reasonable range of outcomes: one with a plume height of 30,000 feet (9.1 km) above mean sea level (asl) and another with a height of 15,000 feet (4.6 km) asl, each with a 1-hour eruption duration. The simplified web-interface allows the on-call Ash3d response scientist to easily initiate or update simulations while off-site, including mobile devices if necessary. The automatic hypothetical modeling generates separate ash cloud dispersal and the ash fallout products. To reduce the computational burden, the simulation for the distal ash cloud uses a single 10 μm particle size as a tracer with 5% of the total expected erupted volume and is run over a large domain to capture the trajectory of the drifting ash cloud. The paired fallout simulation, in contrast, considers the full expected erupted volume (based on plume height and eruption duration), and incorporates a seven-bin particle size distribution representing particle sizes from 2 mm and 88 μm, with fine particles represented in low-density aggregate bins (Mastin et al., 2016). In both simulations, the source is

represented in the model's column of grid cells containing the vent by a vertical mass distribution profile that has a peak mass loading at 75% of the plume height (Suzuki profile with a constant of 4.0).

During actual eruption events, the response ash modeler can update the start time as needed to match the observed onset of explosive activity. In cloudy conditions, the onset of explosive activity may only be inferred from seismic, infrasound and/or lightning detections. Because plume height is often not immediately observable, early estimates are typically based on similarities between the real-time geophysical data (such as seismic thresholding with RSAM or the presence or absence of volcanic lightning detections) and past events of known plume heights. If the ash cloud is visible, AVO determines a plume height estimate by synthesizing observed cloud trajectories and wind from weather forecast models, cloud top and atmospheric temperature profiles, parallax offset from oblique views in geostationary satellite images, webcam images, and pilot reports.

When an event is confirmed, the model output is flagged as an 'actual' rather than 'hypothetical' eruption, which updates downstream messaging displayed on the AVO webpage. At this stage, the model runs are also shared with partner agencies, such as the National Weather Service (NWS), who may use them to inform their hazard-response products, including ashfall forecasts and warning products. If impacts to communities are anticipated, the response ash modeler can prepare predicted fallout maps for different eruption durations and communicate expected onset times and the potential range of ash-deposit thicknesses to the NWS Weather Forecast Office (WFO), who is responsible for issuing the ashfall warnings. Once there is a cessation or marked decrease in activity, the eruption duration can be updated with the final model output remaining flagged as an 'actual' eruption until the event ends and the ash plume drifts away from the volcano, at which point the model state is returned to 'hypothetical'.

To support and refine the operational modeling described above, community observations play an essential role in validating and constraining ashfall forecasts. During the period of gradually increasing activity prior to the explosive events, AVO encourages community members to submit observations through the "Is Ash Falling?" reporting tool on the AVO webpage (Wallace et al., 2015). Once an explosive eruption occurs, and if ashfall reaches communities or mariners, AVO often receives photographs and additional reports from the affected communities. These ground-based observations help the response ash modeler to better constrain the timing, duration, and thickness of the forecast ashfall.

While the simplified web-interface to the Ash3d model facilitates ease-of-use and enables the on-call ash modeler to rapidly respond, it necessarily reduces complexity that may be important for the variable behavior we observe in actual volcanic plumes. In the next section, we describe the chronology of the response for each of the 13 explosive events of the 2023 Shishaldin Volcano eruption, highlighting when there was an alignment of model output with observations and what issues led to the occasional misalignment.

3. Summary of explosive events

Below is a summary of the sequence of events, taken from AVO communication logs where critical observations are posted and shared, with an emphasis on how the dispersion/fallout model was updated. For a full accounting of the eruption chronology, see Loewen et al (this issue). For each of these 13 explosive events, trajectory analysis using the ERA5 (0.25-degree, 1-hourly) reanalysis data (Hersbach et al. 2020n) as well as the North American Regional Reanalysis (45 km, 3-hourly) are shown in the Supplemental Data. Also provided in the Supplemental Data are the key initial and updated Ash3d model output for both the ash cloud and deposit simulations for each event along with corresponding GOES-18 satellite views. Since the real-time numerical weather prediction products used for the operational Ash3d simulations (Global Forecast System) were not archived, Ash3d results presented in the Supplemental Data section used the ERA5 reanalysis product.

Event 1: 2023-07-14

Winds during the event were relatively uniform from the northwest, and cloudy conditions limited visibility. Because the onset occurred at night and only triggered a regional infrasound alarm, it was initially missed by AVO. The NWS Alaska Aviation Weather Unit (AAWU) detected the volcanic cloud approximately 6 hours after the event and issued a SIGMET for volcanic ash (VA) at 25,000 feet asl (FL250) for the detached plume. Retrospective analysis showed that emissions began at 8:50 UTC and ended at 10:20 UTC, and parallax profiles of the plume (Gomez-Patron et al., this issue) indicated that it reached 38,000 feet (11.6 km) asl (Loewen et al., 2026a). Ash3d remained in a ‘hypothetical’ state at 17,000 feet (5.18 km) asl, 1-hour duration, and an erupted volume of 1.0×10^{-4} km^3 (DRE). High-resolution satellite imagery reviewed in the days following the event suggested that pyroclastic density currents (PDC’s) likely occurred (Waythomas and Loewen, this issue). Trace amounts of ashfall were reported by a Canadian Coast Guard ship south of Unimak Island in the Pacific Ocean.

Event 2: 2023-07-16

Winds during this event were relatively uniform from the north-northwest. As volcanic unrest intensified, the response ash modeler updated the model start time once the eruption onset was confirmed, flagging the simulation as an ‘actual’ event. The AAWU reported satellite observation of ash cloud at 15,000 feet (4.6 km) asl, close to the retrospective maximum cloud height determined from cloud top temperature profiles of 17,000 feet (5.2 km) asl. The Ash3d output indicated an ash fallout forecast to the southwest over the Gulf of Alaska and the WFO subsequently issued a Marine Weather Statement warning mariners of possible trace (< 0.8 mm or 1/32 in) ashfall along the Alaska Peninsula coastal waters south of Shishaldin. The eruption continued beyond the initially estimated duration, and the plume height was updated periodically. No ashfall accounts or subsequent impacts were reported.

Event 3: 2023-07-18

Winds during this event were relatively uniform from the north, and conditions were fairly clear. Although the onset of the eruption was visible in web camera views, plume heights were difficult to determine from web camera data alone. Given the increasing volcanic unrest and indications of a stronger event, Ash3d was set to an ‘actual’ status using an estimated plume height of 40,000 feet asl. Once satellite data became available, cloud top temperatures supported a revised ash-cloud height of 30,000 (9.1 km) feet asl. Retrospective parallax profiles of the plume ultimately determined the maximum plume height reached 26,000 feet (7.9 km) asl. Ash3d predicted a narrow fallout swath to the south and the WFO issued Marine Weather Statement warning mariners of possible trace (< 0.8 mm or 1/32 in) ashfall. Pilot reports indicated ash at 24,000 feet asl initially, and later at 20,000, 24,000, and 33,000 feet (6.1, 7.3, and 10 km) asl; the model plume height remained at 30,000 feet while the duration was extended from 1 to 2 hours. The model was returned to ‘hypothetical’ status after the plume detached from the vent later in the day. There were likely PDC’s during this event, but there were no inconsistencies between the Ash3d cloud model output and observations. No ashfall accounts or subsequent impacts were reported.

Event 4: 2023-07-23

Winds during this event showed mild shear, with surface winds from the south shifting to southwesterly flow at higher altitudes. Meteorological clouds between 20,000-30,000 feet asl obscured the vent, but AVO issued a VAN/VONA stating ash emission were likely based on seismic intensity. Given the wind direction, the WFO issued a Special Weather Statement warning of trace (< 0.8 mm) ashfall for communities to the northeast in anticipation of an ash-producing event. A small plume was

first observed at 15,000 feet (4.6 km) asl but it was an hour later, when a new plume reached an initial estimate of 30,000 feet (9.1 km) asl, that Ash3d was set to 'actual' status. A pilot report promptly confirmed the 30,000 feet asl plume height. Subsequent colder cloud-top temperatures and the presence of volcanogenic lightning suggested the ash cloud could have reached 40,000 feet asl and Ash3d was updated to 40,000 feet (12.2 km) asl to be consistent with the active SIGMET at the time. Retrospective parallax profiles of the plume ultimately determined the maximum plume height reached 45,000 feet (13.7 km) asl. The WFO issued a Marine Weather Statement and a Special Weather Statement warning of trace (< 0.8 mm or 1/32 in) ashfall along the Alaska Peninsula and waters to the north as well as, an Ashfall Advisory for False Pass warning of minor (up to 6.4 mm or ¼ in) ashfall. Satellite imagery showed the ash cloud tracking along the Alaska Peninsula, while Ash3d predicted a more northerly fallout axis. The model remained in 'actual' status until the following morning when it is returned to 'hypothetical'. Trace amounts of ashfall were reported from a fishing vessel approximately 46 km northeast of False Pass in the Bering Sea. No other ashfall accounts or impacts were reported.

Event 5: 2023-07-26

Winds during this event showed significant shear, with low-level winds from the south, mid-level from the southwest and high-level winds shifting back to southerly flow. Conditions were overcast with meteorological clouds at 15,000–20,000 feet asl. The onset of this event was first identified from infrasound detections of explosions. The hypothetical Ash3d run used an initial plume height of 15,000 (4.6 km) feet asl, forecasting an ash cloud drifting northeast along the Alaska Peninsula, with a more northerly fallout axis. Retrospective parallax plume heights were similar, with a maximum height determined of 17,000 feet (5.2 km) asl. The WFO issued a Marine Weather Statement and a Special Weather Statement warning of trace (< 0.8 mm or 1/32 in) ashfall, for surrounding waters and nearby communities of False Pass, Cold Bay, and King Cove. The AAWU issued a SIGMET due to likely ash emissions. The SIGMET for the ash cloud differs from the ashfall model due to strong vertical wind shear. The Ash3d model duration was updated as additional observations became available. No ashfall accounts or subsequent impacts were reported.

Event 6: 2023-08-04

Wind shear during this event was significant, with surface winds from the south shifting to northwesterly flow at higher altitudes. Low-level ash emissions were observed and the hypothetical Ash3d run set at 15,000 feet asl forecasted a cloud dispersal toward the community of False Pass. The AAWU issued a SIGMET to 15,000 feet asl and the Ash3d model was toggled to 'actual' status.

Satellite cloud top temperatures and VOLCAT (Pavolonis et al. 2018) analysis supported a cloud height near 20,000 feet asl, while solicited pilot reports indicated ash at 24,000 and 25,000 feet asl. The AAWU updated the SIGMET accordingly, and Ash3d was updated to 30,000 feet asl. Matching the modeled cloud to observations proved challenging due to variability in the source height. The WFO issued a Marine Weather Statement warning of trace (< 0.8 mm or 1/32 in) ashfall. The cloud appeared bifurcated in satellite views. Ash3d was subsequently updated with a slightly higher altitude, and both the WFO and AAWU issued additional updates, including a Special Weather Statement warning of trace (< 0.8 mm or 1/32 in) ashfall for False Pass and a revised SIGMET to 31,000 feet (9.4 km) asl. This revised SIGMET matched the retrospective plume height determination. Community reporting confirmed that only trace ashfall was observed in False Pass.

Event 7: 2023-08-15

Wind shear during this event was modest, with surface winds from the southeast and stronger southwesterly flow aloft. The hypothetical Ash3d run initially used the plume height from the previous event (30,000 feet asl). The AAWU reported lightning detections, and AVO detected infrasound, although meteorological clouds obscured the volcano. The AAWU issued a SIGMET at 25,000 feet asl, and AVO issued a VAN/VONA. Ash3d was updated accordingly, forecasting fallout to the north. The WFO issued a Marine Weather Statement warning of trace (< 0.8 mm or 1/32 in) ashfall. The SIGMET was later raised to 36,000 feet asl following satellite observations of SO_2 at that altitude. Parallax cloud height estimates from satellite observations indicated a height near 25,000 feet asl, and additional pilot reports indicate ash at 25,000 and 29,000 feet asl. Ash3d over-predicted fallout on False Pass (1 mm), and no fallout was reported. The model duration was subsequently reduced. No ashfall accounts or subsequent ground-based impacts were reported, although two aircraft encounters were reported, one of a sulfur smell and a second observing St. Elmo's Fire. The final retrospective plume height determination ultimately indicated the plume reached 42,000 feet (12.8 km) asl.

Event 8: 2023-08-25

Wind shear during this event was minimal, with winds primarily from the south, although surface wind directions appeared more easterly in some reanalysis products. Meteorological clouds at 27,000–33,000 feet asl obscured views of the volcano. Infrasound detections indicated low-level explosive activity, and several pilot reports confirmed ash at 20,000, 25,000 and 28,000 feet asl. Ash3d model was toggled to 'actual' status, and the plume height was updated to 30,000 feet asl. Parallax-based cloud height estimates suggested a lower altitude, and AVO issued a VAN/VONA consistent with the

SIGMET at 21,000 feet asl. The final retrospective plume height determination ultimately indicated the plume reached 29,000 feet (8.8 km) asl. Trace amounts of ashfall were reported from a vessel in the Bering Sea, and a dusting of ash was reported from False Pass. The ship in the Bering Sea collected some of the ash and sent it to AVO for further analysis.

Event 9: 2023-09-05

Wind directions during this event were fairly consistent from the west with minimal wind shear. AVO was drafting a notice to alert to increasing activity when a pilot reported ash at 24,000 feet asl, coincident with heightened seismicity and lighting detections. Ash3d was toggled to 'actual' status and updated to a plume height of 30,000 feet asl. Satellite-derived cloud-top temperatures of the ash cloud suggested a height of 32,000 feet asl, consistent with parallax calculations. The AAWU issued a SIGMET at 32,000 feet. The eruption appeared to intensify, with cloud-top temperatures indicating a rising to 37,000–38,000 feet asl. The WFO issued a Marine Weather Statement and a Special Weather Statement warning of trace (< 0.8 mm or 1/32 in) ashfall for the communities of Cold Bay and Sand Point and surrounding waters. No ashfall accounts or subsequent impacts were reported. The final retrospective plume height determination ultimately indicated the plume reached 42,000 feet (12.8 km) asl.

Event 10: 2023-09-16

Wind shear during this event was moderate, with surface winds from the southwest shifting to the west-northwest at higher altitudes. Meteorological clouds at 25,000–30,000 feet asl obscured direct views of the volcano. Ash emissions were visible in web camera imagery, and lightning was detected near the vent. The Ash3d plume height was updated to 42,000 feet asl to be consistent with an active VAN/VONA, although cloud-displacement calculations suggested a lower altitude. The model forecasted fallout to the east prompting the WFO to issue a Special Weather Statement and Marine Weather Statement, warning of trace (< 0.8 mm or 1/32 in) ashfall for False Pass and surrounding waters. Social-media reports subsequently confirmed minor ashfall occurring in False Pass. Later satellite imagery showed the plume detached from the vent, indicating a duration of 1.75 hours. Reports submitted through the "Is Ash Falling?" tool continued after the anticipated end of activity, including observations from False Pass, Stonewall, Ikatan—a fishing vessel near Cape Pankof, southeast of False Pass, and King Cove. Community members collected samples from 2 locations in False Pass which were subsequently sent to AVO for further analysis. The final retrospective plume height determination ultimately indicated the plume reached 37,000 feet (11.3 km) asl.

Event 11: 2023-09-25

Wind shear during this event was a moderate, with upper-level winds from the west and low-level winds from the south, while low-level clouds obscured satellite views of the volcano's summit. In response to increasing seismicity, AVO was preparing to issue a notice, when a pilot reported ash at 12,000 feet asl, prompting the WFO to request an Ash3d forecast to assess potential community impacts. Although initial duration estimates suggested minimal effects, irregular, low-level ash emissions persisted for hours. Cloud-cover at 18,000–20,000 feet asl continued to obscure satellite detection of the low-level plume. Several hours later, lightning detections and an alert from the AAWU regarding a plume observation triggered an updated Ash3d model run with a new start time for a larger event using a 30,000 feet asl plume height. The model indicated ashfall to impact the community of Cold Bay. Parallax calculations from satellite imagery suggested cloud heights as high as 48,000–50,000 feet asl, and Ash3d was updated accordingly, forecasting minor (up to 6.4 mm or ¼ in) ashfall extending to King Cove. The WFO issued an Ashfall Advisory warning of minor ashfall for False Pass and a Special Weather Statement and Marine Weather Statement warning of trace (< 0.8 mm or 1/32 in) ashfall for communities of Cold Bay, King Cove and Sand Point and surrounding waters. The high-level ash emissions continued for about 40 minutes before dropping to 20,000–24,000 feet asl. The high-plume height Ash3d model run, using a 1-hour duration, was retained. Ashfall was ultimately reported in False Pass, Cold Bay, King Cove, and Sand Point. As forecast by the model, minor ashfall up to 2 mm occurred in False Pass, while only trace amounts (< 0.8 mm or 1/32 in) were reported in the more distal communities of Cold Bay, King Cove, and Sand Point. The Ash3d model provided the basis for WFO ashfall warnings, resulting in warnings being issued to the exact communities that later confirmed ashfall. As with Event 10, community collected samples at 2 locations in False Pass and from Cold Bay were provided to AVO for further analysis. The retrospective plume height determination indicated the plume reached 46,000 feet (14 km) asl.

Event 12: 2023-10-03

Wind shear was significant during this event, with surface winds from the northeast, mid-level winds from the north, and high-level winds from the southwest. During the initial period of increasing unrest, minor ash emissions were suspected based on fresh pyroclastic material visible on the flanks of the volcano. A SIGMET was issued for 15,000 feet asl, although the Ash3d model remained in its 'hypothetical' state. A sudden increase in seismicity, coincident with lightning detections, elevated infrasound, and a cloud-growth alert, prompted Ash3d to be set to 'actual' status using a plume height

estimated from past events. Minutes later, the model was updated to 40,000 feet asl based on parallax-derived plume height of 38,000 feet (11.6 km) from GOES satellite imagery. Because of pronounced wind shear, the observed and forecast ash cloud drifted eastward, while the fallout model predicted ashfall primarily to the south. The WFO issued a Special Weather Statement for all of Unimak Island warning of possible trace (< 0.8 mm or 1/32 in) ashfall. After a few hours, seismicity indicated that continuous ash emissions might be waning. Satellite imagery showed a high-level plume (30,000–40,000 feet asl) drifting northeast, while finer-grained, low-level (surface to 30,000 feet asl) ash was carried southwest. A photo from a local pilot showed a low-level (10,000 feet asl) ash plume rising from the lower eastern flank, interpreted as a co-PDC plume, and web camera views confirmed continued PDC activity over the next several hours. Once the high plume detached, these low-level PDC-related emissions became the primary source of ash, with the resulting ash cloud drifting south and west as far as Unalaska, where a very fine dusting of ash was reported. Trace ash was also reported in Cold Bay. Ash3d was reinitialized with a 10,000 feet asl source with limited success.

Event 13: 2023-11-03
Winds during this event were primarily from the East. An increase in seismicity prompted the AVO to issue an alert minutes before an ash cloud became visible in satellite imagery. Ash3d was set to 'actual' using a plume height of 30,000 feet asl based on a parallax estimate and consistent with an initial SIGMET issued from the AAWU, but subsequent cloud-top temperatures suggested a lower altitude. The AAWU issued a revised SIGMET for 20,000 feet and the model was subsequently updated to 20,000 feet. There were no reported ashfall occurrences in communities or on nearby ships.

4. Tephra characterization
Shishaldin Volcano's remote location limited event-specific sampling during and after the eruption. A collection of proximal samples was collected by field crews after Event 7 in August 2023. Samples were also collected by community members after ashfall in False Pass and Cold Bay, Alaska, following Events 10 and 11, and on board a ship in the Bering Sea after Event 8. Bulk samples were analyzed for grain size distributions (GSD) by a combination of wet sieving and laser diffraction size analysis (results and methods reported in Loewen et al., 2026 TBD).

All four measured GSD distributions are very poorly sorted with a size mode of 88 μm (3.5 ϕ; Figure 2). Three of the four samples have a secondary coarse mode > 1 mm (-0.5 to -3.5 ϕ). Satellite images following these early paroxysms showed distinct vent-derived deposits directly downwind from the

summit crater—SE for Events 1–3 and NE for events 4–7. More diffuse deposits were seen near the volcano offset from the summit but aligned with the toe of PDC deposits, especially those extending upwind on the northern flank of the volcano (see Loewen et al. 2026b Figure 9). Samples collected in August 2023 were all off the axis of primary vent-derived plumes during Events 1–7 (Figure 2).

Event 10 and 11 produced ashfalls on the communities of False Pass and Cold Bay. Samples were collected form two different locations 4–5 km apart in False Pass (Figure 3). For Event 10, these two locations captured distinct GSDs. The southern location was moderately well-sorted with a median size of 643 μm (0.6 ϕ). The northern location was poorly sorted with a finer median grainsize of 177 μm (2.5 ϕ). While these samples were separated only by a few kilometers, strong wind shear during Event 10 would have bimodal ash distributions from different plume heights, with <3 km winds skewed to the north and >3 km winds skewed south.

During event 11, all samples from False Pass had a similar GSD, with moderate sorting and median grainsize of 677 to 650 μm (0.6 ϕ), similar to the well-sorted Event 10 sample from south False Pass. The more distal Cold Bay samples were also moderately sorted but finer grained, with median size of 95 μm (3.4 ϕ).

We also note the GSD of a sample collected during Event 8 290 km NE of Shishaldin Volcano on a ship was moderately sorted with a median size of 65 μm (4 ϕ).

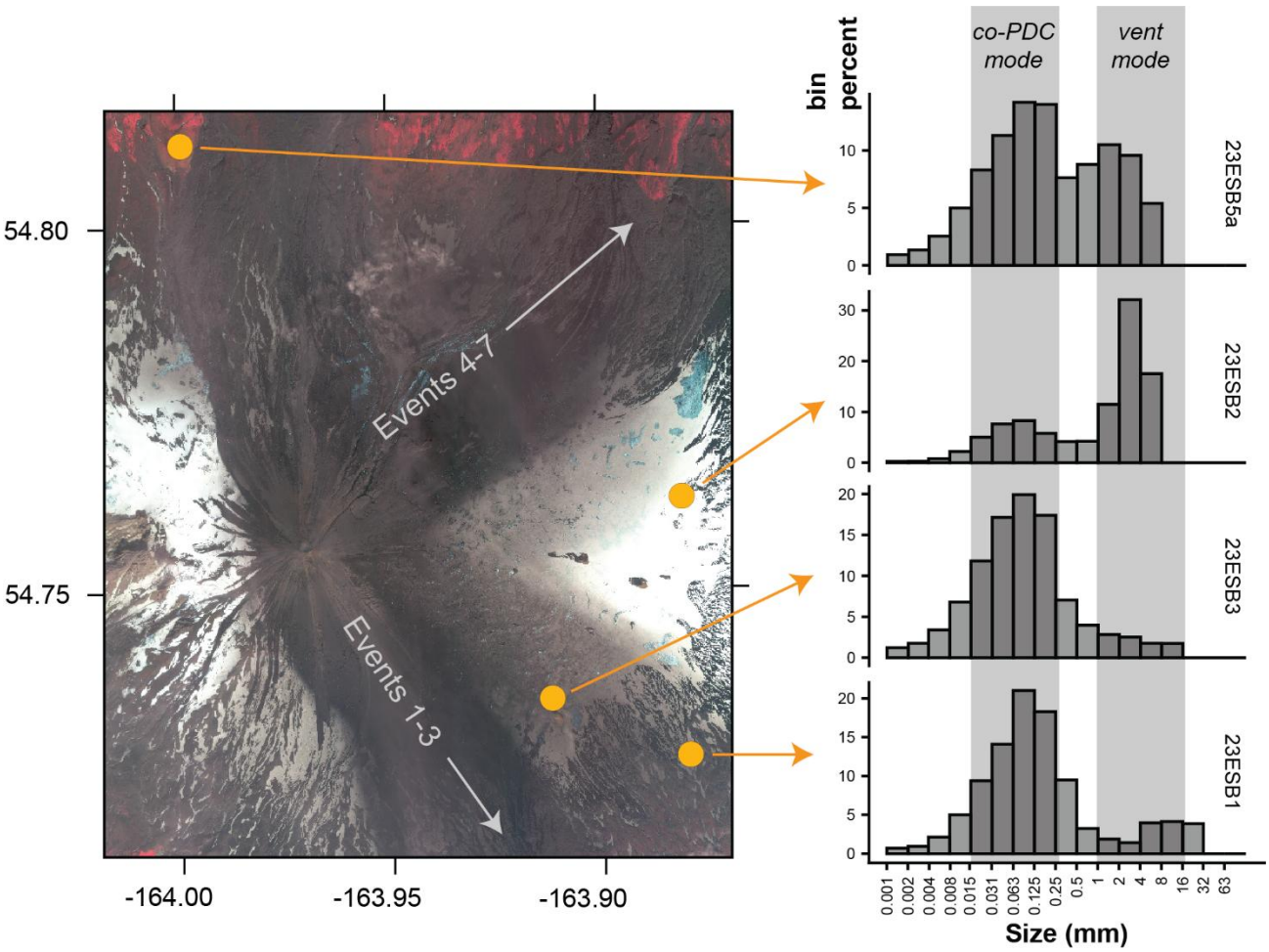


Figure 2. *Proximal samples collected in August 2023 following Event 7. Sample locations are shown on a near-infrared WorldView-3 satellite image captured August 1, 2023. Sample locations miss the southeast and northeast plume axis from these early events but capture off-axis co-PDC deposits likely mixed with some vent-derived material falling outside the primary plume direction. Grain size distributions for these samples capture a fine-grained co-PCD size mode and a secondary coarse mode inferred to be from the vent-derived plume. Satellite image ©2023 Maxar, USG Plus.*

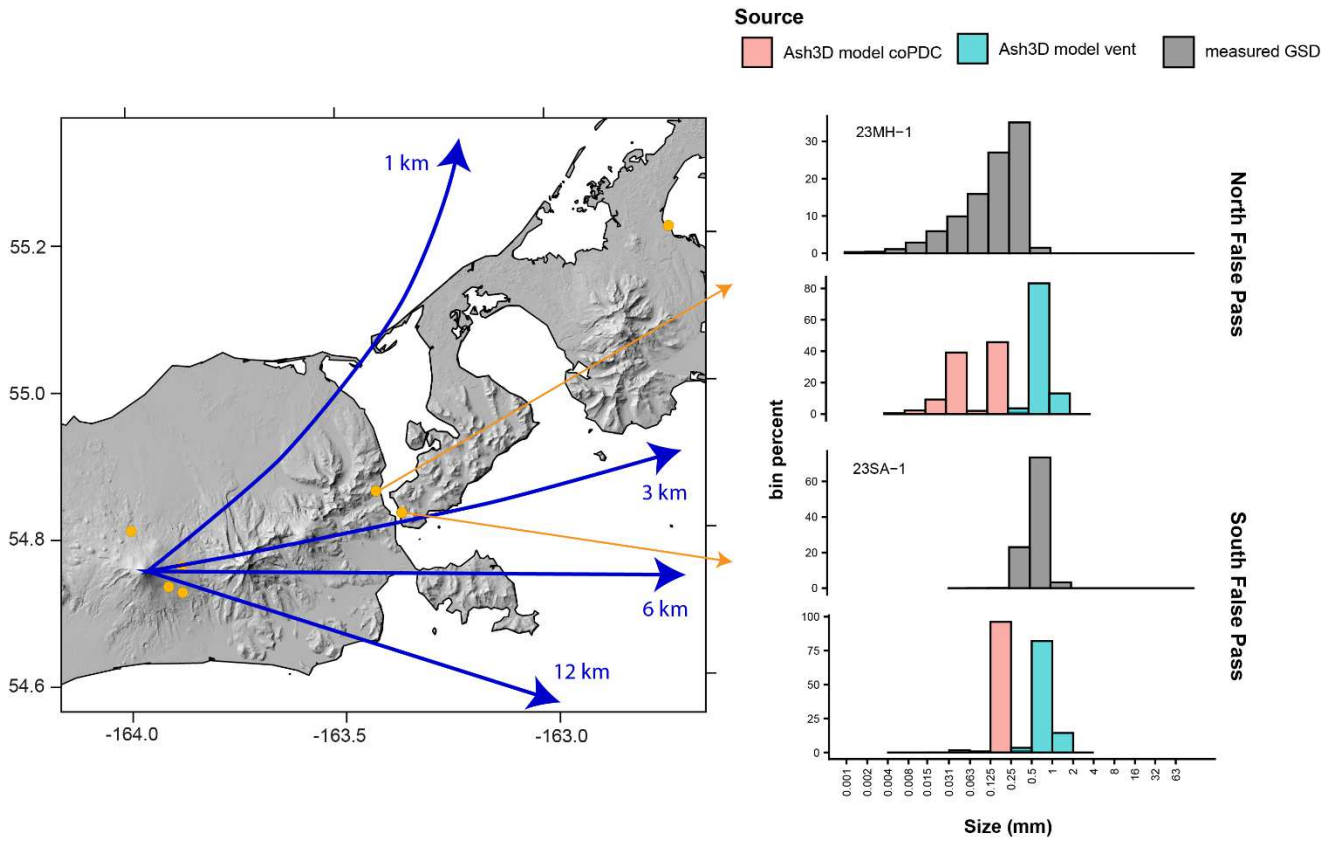


Figure 3. *Community collected samples from False Pass and Cold Bay, collected from Event 10, are shown and compared to Ash3D model grainsize distributions for a vent and co-PDC plume source. Map shows approximate wind directions at different altitudes during Event 10 (blue arrows). False Pass samples from 2 locations 4-5 km apart all captured a consistent 0.6 ϕ* size *mode, however, the southern False Pass site captured a fine-grained tail during Event 10, Grain size distributions for the northern False Pass site captured a fine-grained tail during Event 10 which we interpret to reflect the more northerly trajectory of the lower-altitude co-PDC plumes from this event. Ash3D model results are consistent with the fine-skewed tail from the northern False Pass location originating from a co-PDC plume source distributed further north due to low altitude wind shear.*

5. Discussion and Operational Implications

In general, the dispersion modeling provided useful ashfall forecasts for all cases in which the wind shear was minor. This includes events 1 (though only retrospectively), 2, 3, 8, 9, 10, 11, and 13. This performance is particularly important because, although AVO is responsible for evaluating volcanic activity and communicating associated hazards, the formal authority for issuing ash-related warnings in the Unites States lies with NOAA and the National Weather Service (NWS). Close coordination between AVO scientists and the NWS forecasters, especially around interpretation of Ash3D results, plume behavior, and real-time volcanic conditions, is therefore essential for ensuring that accurate, consistent messaging is delivered to populations and aviation interests at risk.

Due to the remote location of Shishaldin Volcano, few communities are situated close enough for significant ashfall impacts, and most events were expected to produce only trace to minor accumulations (up to a several millimeters or about ¼ in). A notable exception occurred during Event 11, when trace ashfall (< 0.8 mm or 1/36 in) reached Cold Bay. Even this small amount caused immediate operational impacts at the airport. Ash deposition on the runway triggered issuance of a NOTAM and a temporary runway close until inspection and clean up could occur (Figure 4). Cold Bay's main runway (CDB/PACD) is the fifth largest in Alaska and supports scheduled passenger and cargo operations, US. Coast Guard activities, and private medevac flights. It also serves as a critical emergency alternate aerodrome for trans-Pacific twin-engine aircraft. Its temporary loss due to ashfall and the associated drifting ash cloud forced multiple flight diversion and cancellations. Because of the runways' strategic importance, even minor ash accumulation resulted in disproportionate region and international aviation disruptions, underscoring the value of accurate and timely ash-hazard information to help mitigate impacts such as these.



Figure 4. *Photographs showing clean-up operations on the Cold Bay airport runway after trace amounts of ashfall (< 0.8 mm or 1/32 in) from the September 25, 2023 eruption of Shishaldin Volcano, 93 km (58 mi) southwest of Cold Bay. Photos courtesy of the Alaska Department of Transportation.*

For the events with significant wind shear, namely events 4, 5, 6, 7 and 12, there was often a misalignment between the ash cloud trajectory and the primary axis of the deposit. This is to be expected; however, this visual incongruence was frequently a point of discussion when questioning if the model parameters are appropriate. For event 4, for example, the modeled fallout footprint was slightly north of the Alaska Peninsula, missing most communities, but the ash cloud drifted along the full length of the Alaska Peninsula. Given all uncertainties in the source parameters, the WFO issued a Special Weather Statement for regions beneath the cloud. Similarly for event 5 which also had a forecasted fallout footprint more northerly than the observed ash cloud.

A second challenge associated with strong wind shear is that the fixed vertical mass distribution used in operational models (Suzuki profile with constant =4) typically insert ash over a broad range of altitudes, with peak loading at 75% of the plume height. This often produces a drifting ash cloud that is more laterally extensive than what is observed in satellite imagery. For many of the Shishaldin Volcano events, however, the ash that contributed to the drifting cloud was likely confined to a narrower vertical interval. Such a narrow insertion band is not suitable for fallout simulations because it produces a deposit footprint that becomes disconnected from the vent. Moreover, when a cloud was observed at a specific altitude, the dispersion modeler would need to assign a higher plume height so that the modelled peak ash loading would align with the drifting cloud. Adjusting plume height in this way can lead to over-predict fallout thicknesses. In the absence of real-time information on the vertical mass distribution, the plume height thus serves as the assumed vertical profile for initial forecasts, with parameters adjusted as fallout reports are received.

Some discrepancy in fallout simulations can be attributed to grain size variations that are not represented in the operational ash models. Proximal deposit GSDs and satellite images show 2 distinct plume characteristics. The vent-derived plume produced a narrow, downwind deposit extending from the summit crater. While bulk samples were not collected from the plume axis, photographs of deposits 13 km northeast of the vent show the tundra vegetation that was blanketed by a well-sorted, coarse scoria deposit (Figure 5), with the median size of the 20 largest clasts measuring 2.3 cm. In contrast, off-axis samples collected on the volcano flanks, were poorly sorting with abundant fine-grained

material (Figure 2). Satellite images collected shortly after the events showed that diffuse ash-deposits extended downwind of the toe of PDC deposits and upwind of the vent. We interpret the fine-grained mode seen in these proximal samples as elutriated material derived from PDC during transport and deposition, a process documented in many eruptions including the 1996 Soufriere Hills eruption (Bonadonna et al., 2002), the 2006 Tungurahua eruption (Eychenne et al., 2012), and larger eruptions such as the 1980 Mount St. Helens eruption (Eychenne et al., 2015), the 1991 Mount Pinatubo eruption (Wiesner et al., 2004), and older large-volume deposits such as the Campanian and Minoan ignimbrites (e.g., Sparks and Huang, 1980).



Figure 5*. Scoria deposited on top of tundra vegetation northeast of Shishaldin Volcano on August 21, 2023, documenting plume-axis deposits from Events 4–7. No ash was seen at this and other sites but abundant lapilli-sized scoria litter the surface. Photo location is next to AVO monitoring site ISNN. Photo courtesy of Darren Tan, UAF-GI (AVO image id 197214).*

An illustrative example of grain-size variability appears in Event 10, where two False Pass samples collected only 4 km apart show distinctly different GSD characteristics. The sample to the north exhibits a finer-skewed GSD, a pattern consistent with the strong wind shear documented during the event. A similar spatial offset in fine-grained modes was described by Eychenne et al. (2015) for the May 18, 1980, Mount St. Helens deposits, where they attributed the northward shift of fine material to

lateral displacement associated with the directed lateral blast. In that case, the co-blast plume likely rose higher than the vent-derived plume. In contrast, for the 2023 Shishaldin Volcano events, we infer that co-PDC plumes did not reach as high as the vent-derived column. This vertical separation is evident in satellite imagery from Event 12 where fine grained ash is clearly seen in both visible and multispectral data, following a low-level westerly trajectory, whereas the higher vent-derived plume, gas rich and poor in fine ash, drifts east to southeast. For Event 10, satellite views of the vent were obscured by low meteorological clouds but web camera images showed syn-eruptive PDC clouds rising off the north flank. Under the strong wind shear at the time, these low-altitude plumes would have been transported toward the northeast, while the higher vent-derived plume, clearly see in satellite images above the cloud deck, would have tracked toward the southeast. This interpretation aligns well with the contrasting GSD measured at the two False Pass sample locations.

These observations of vertically and spatially complex plume behaviors highlight broader challenges in modeling several of the Shishaldin Volcano events, particularly those with rapidly evolving plume heights. For several events, especially Event 12, modeling was further complicated by rapid, transient variations in plume height. Initially, ash emissions were confined to low altitudes only a few kilometers above the vent. Although such emissions pose a localized aviation hazard, the operational Ash3d configuration does not account for topography and is not well suited for simulating fallout from these low-level events. The main explosive pulse of Event 12 was modeled adequately, however, within a few hours, PDCs were generated and produced co-PDC plumes that contributed additional low-level ash emissions. Later in this event, the co-PDC plumes were the primary source of ash emissions. Multi-spectral satellite imagery indicates that this material was finer-grained than the primary plume. Attempts at the time to model this low-level source were ultimately unsuccessful, reflecting the limitations of operational modeling under a rapid evolving plume structure.

6. Model improvements

Although the operational Ash3d forecasts were generally consistent with observed fallout and provided reliable guidance for ashfall warnings and advisories, the model performed poorly when simulating the co-PDC plumes identified in satellite imagery during Events 6 and 12. Additionally, Event 10 also highlighted limitations, despite being obscured by meteorological clouds, deposit samples showed had spatial variability in grain size that could not be reproduced using a single, vent-based source. To address these shortcomings, three improvements were incorporated into the software to improve the retrospective model simulations.

First, the advection, diffusion and source insertion routines were modified to optionally account for topography using a terrain-following (sigma-altitude) coordinate system (Slordal, 2002). The GEBCO 2023 topographic data were smoothed with a weighted filter over a specified radius and the base of the computational grid was deformed to follow this filtered terrain, transitioning to undeformed grid at higher altitudes. Second, because ash from low-level sources must be transported upward to levels where it is observed, we implemented a vertical diffusivity scheme that responds to local atmospheric instability. When using the ERA5 (0.25-degree) or North America Regional Reanalysis (NARR) (32-km) reanalysis datasets, the model applies a vertical diffusivity proportional to the vertical gradient in horizontal wind speed. If higher-resolution meteorological models are available, Ash3d can also incorporate enhanced vertical mixing in the planetary boundary layer.

Ash3d already supported transient plume height through multiple sequential eruptive pulses, however, each pulse used the same grainsize distribution and the same vertical mass loading profile. The co-PDC plumes do not fit into this framework as they occur simultaneously to the primary eruption, originate away from the vent, and likely have different grain-size characteristics. To address this, we modified Ash3d to allow multiple, concurrent source types. We added a new source category ("copdc") was introduced to represent a wedge-shaped volume extending from the vent to a specified radius and height. All computational nodes from the surface to a specified height are activated for source insertion within this wedge. The vertical mass loading profile is constant by default but may be adjusted as needed. Because co-PDC plumes are generally finer-grained, this source includes additional parameters specifying a log-normal grain-size distribution (mean phi, standard deviation).

In practice, this source has limitations at both the high and coarse grid resolutions. High-resolution grids that incorporate topography can introduce spatial structures, not supported by the underlying meteorological datasets. Interpolating 0.25/0.5-degree global data used operationally onto a finer grid will not adequately resolve valley-scale micro-meteorology. At coarse resolution, the azimuth and positional offset of the source zone become less important, but the key advantage remains, the ability to represents simultaneous or overlapping source types with differing grain-size distributions.

We applied this new source in a reanalysis of Event 12. For these simulations, ERA5 reanalysis data provided the atmospheric fields, and GEBCO 2023 topography was smoothed using a 4-km filter. Web-camera imagery and photographs sent to AVO from pilots showed ash emissions from both the

primary event plume as well as low-level co-PDC plume (Figure 6a). Using a plume height guided by pilot reports, the vent-derived cloud was successfully modeled operationally with a 1-hour source duration. However, low-level emissions continued for several hours after the primary plume dissipated (Figure 6b). With the model improvements described above and a grainsize distribution similar to the vent mode (Figure 3), a reanalysis of the primary volcanic cloud using a 13.7 km asl plume height and a narrower vertical mass-loading profile (Suzuki constant = 10), is shown in the Figure 6e-f at the times of the GOES-18 data scenes. Adding a second 5-hour, low-level (4-km) plume with one third of the volume of the primary plume was still insufficient to match observations (Figure 6g-h). The inclusion of the 2-km co-PDC source (Figure 6i-j), with nodes below the summit on the south flank of the and assigned a finer GSD, produced results that were far more consistent with satellite observations. The eruption source parameters used in the reanalysis of Events 10 and 12 are included in the Supplemental Data.

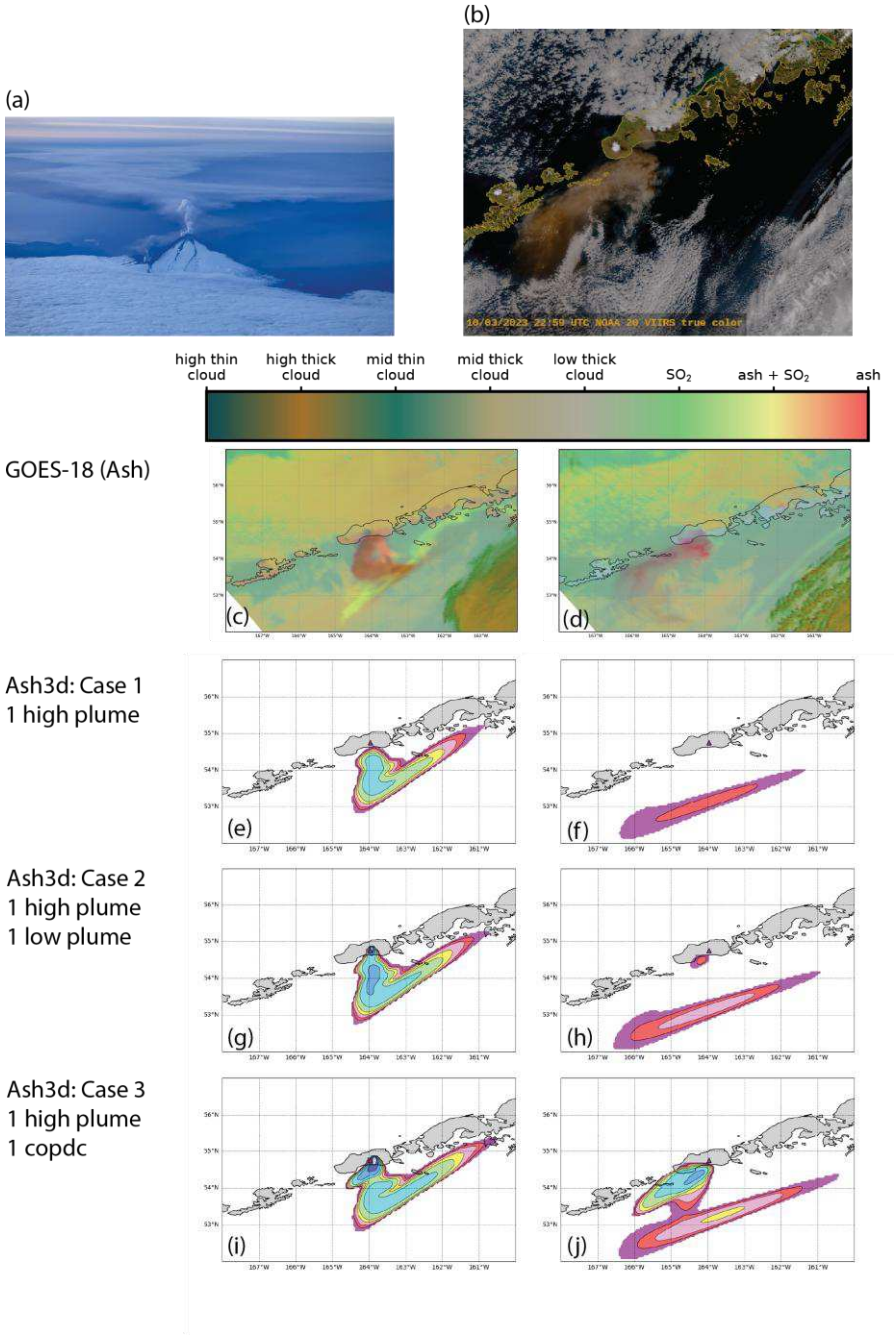


Figure 6. *Reanalysis of event 12. A photograph looking south (Chris Barnes) shows the primary plume from event 12 with low-level co-PDC plumes to the southeast of the vent. In (b) dark ash can be seen in true color satellite views after the vent plume detached (22:59 UTC). GOES-18 ash composite images are shown in (c) and (d) at 18:00 and 23:00 UTC respectively. Cloud load plots for three Ash3d cases are shown (e-j) at the times corresponding to the GOES images. Case 1 uses the ESP's from the operational run, but with a GSD as determined for vent-derived plumes (see Fig. 3). Case 2 uses a high plume as in Case 1 with an additional 4-km plume with 1/3 the volume. Case 3 uses the high plume, but*

supplements with a 2-km co-PDC source with a log-normal distribution centered on ϕ=4. Photo courtesy of C. Barns (AVO image id 194974)

For event 10, meteorological clouds obscured satellite views of the vent and co-PDC activity, however the high-level drifting ash cloud was clearly visible in satellite data. Inconsistencies in model forecasts due to the omission of co-PDC plumes were not recognized until deposit samples were provided by the community. Specifically, the spatial variation in grain size could not be reproduced without invoking a low-level, fine-grained source component. Although windshear present during the eruption (see Supplemental Data) resulted in sorting of the deposits GSD, the northern False Pass sample contained a significant fine-ash contribution that was inconsistent with a vent-only plume scenario. Using eruption source parameters for vent-derived plume tuned to match satellite observations produced the deposit shown in Figure 7a. When a co-PDC source with a height of 4 km asl and an eruptive volume equal to the of the primary plume was added, the resulting fallout pattern (Figure 7b) reproduced the observed GSD differences, providing a more consistent interpretation.

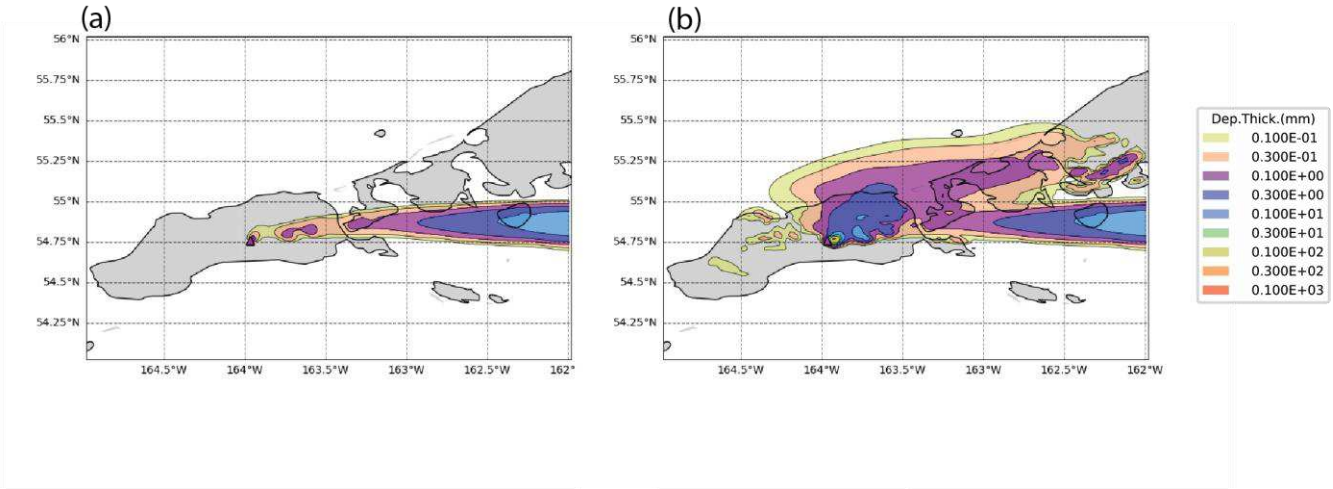


Figure 7. *Left plot (a) shows the deposit only considering a vent-derived plume using a GSD derived from South False Pass (Figure 3). The plot on the right (b) shows the additional contribution from a co-PDC plume with an equal eruptive volume, and with a log-normal GSD (mean ϕ=4 with a standard deviation of 2).*

7. Conclusions

The 2023 eruption of Shishaldin Volcano underscored the level of coordination required for the Alaska Volcano Observatory (AVO) to monitor a remote volcano, forecast tephra fallout, and relay

information to partner agencies responsible for public and aviation ash-hazard warnings. Although the dispersion model was originally tuned for operational use at andesitic, closed-vent systems such as Redoubt Volcano and Mount St. Helens, Ash3d nevertheless proved crucial during the Shishaldin Volcano eruption in guiding the National Weather Service (NWS) warnings of the expected extent and distribution of ashfall. In this operational context, AVO's rapid provision of eruption source parameters and plume assessments, coupled with NWS's formal authority to issue ash-related warning made close, continuous coordination indispensable for delivery of accurate, consistent and timely messaging to the communities and the aviation sector.

Given the volcano's remote location, real-time geologic sampling by AVO staff was not possible, and post-eruption field campaigns provided only limited special coverage of individual deposits. Even so, proximal samples collected during one field effort, supplemented by community-provided samples, revealed the coarse-grained nature of the tephra and provided essential insight into the contribution of co-PDC plumes during several events (Figures 2, 3). The coarse-grain size favored rapid deposition, produced relatively small fallout footprints with thickness maxima shifted closer to the vent. The coarse GSD also complicated hazard messaging, as areas forecast to receive only "trace" amounts of ash could experience scattered centimeter-scale clasts, an outcome with operational significance for communities and marine traffic even when areal ash thicknesses are minimal.

Despite these challenges, the dispersion model performed well for events with limited wind shear and only minor co-PDC contributions. While operational forecasts diverged from observations, targeted enhancements to Ash3d, including incorporation of surface topography, a more physically realistic representation of atmospheric diffusivity, and an updated source parameterization for co-PDC plumes, successfully addressed specific shortcomings. These improvements strengthen the model's ability to capture the complexity of explosive mafic eruptions and will improve operational forecasting during future Shishaldin Volcano activity and from other remote Alaska volcanoes.

More broadly, the Shishaldin Volcano response demonstrates that operational ash-hazard forecasting is as much an interagency workflow as it is modeling task. Reliable outcomes depend on: 1) prompt, iterative exchange of model output and observations between AVO and NWS; 2) shared interpretation of plume behavior (including vertical mass distribution) under variable wind shear; and 3) unified, risk appropriate messaging. Even trace ashfall can trigger disproportionate operational impacts at strategically important aerodromes, as seen during the 2023 sequence, reinforcing the need for

synchronized advisories, rapid verification from field reports and PIREPs, and clear thresholds for updates and cancellations. Continued investment in real-time atmospheric and volcanic monitoring—paired with routine, joint exercises to practice model-to-message workflows, will further enhance the reliability, clarity, and timeliness of ash hazard guidance across Alaska and the wider North Pacific aviation network.

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Declarations

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