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Volcanic lightning as a monitoring tool during the 2016-2017 eruption of Bogoslof Volcano, AK

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***Abstract*— Volcanic lightning commonly occurs during powerful, ash-producing eruptions. Bogoslof Volcano in the Aleutian Islands of Alaska erupted from December 12th 2016 to August 30th 2017. There were 64 explosive events generating ash clouds, some of which impacted aviation and local communities. Approximately half of the eruptions produced volcanic lightning detectable by the World Wide Lightning Location Network (WWLLN). Detections were provided in near-real-time to the U.S. Geological Survey (USGS), representing the first time volcanic lightning has been used in operational monitoring efforts nationwide. Lightning activity was later verified in post-analysis by the Vaisala Global Lightning Dataset (GLD360). In this study, we examine volcanic lightning detected by both networks, and analyze the travel direction of the lightning. Our analysis shows that lightning azimuths matched the ash dispersal direction from satellite 64% of the time, and Ash3d model trajectories 78% of the time. This suggests that lightning travel direction can be a useful proxy for ash cloud dispersal in the early stages of eruption detection.**

Keywords — Bogoslof Volcano, Volcanic Lightning, WWLLN, GLD360

I. Introduction

Lightning has long been observed during volcanic eruptions. However, it was not until recent developments in lightning detection such as the Lightning Mapping Array [Behnke et al., 2014; Behnke and McNutt, 2014; Behnke et al., 2013], and volcanic alerts from WWLLN [Ewert et al, 2009, Shevtsov et al, 2016, Van Eaton et al., 2016] that detailed studies of volcanic lightning have become possible. The near-real time detection of volcanic lightning can work in tandem with other monitoring data, allowing rapid confirmation of an ash-producing eruption. It is has become a valuable component of comprehensive volcanic monitoring [Behnke and McNutt, 2014, McNutt and Thomas, 2015]. Volcanic lightning is particularly useful for remote Alaskan volcanoes with sparse instrumentation and little background thunderstorm activity. Bogoslof Volcano, located in the Aleutian Islands of Alaska, is mostly submerged beneath the Bering Sea. Its 2016–2017 eruption led to shifts between wet and dry volcanism as the edifice periodically built up, blocking off the vent from seawater access, and then breached to create an inlet. This water involvement is significant because it increases water entrainment into the volcanic plume, which is thought to influence lightning. As a small, remote island volcano, Bogoslof has no in-situ monitoring sensors. Therefore, the response effort relied on distant seismic and infrasound stations as well as satellite imagery and automated volcanic lightning alerts from WWLLN.

Volcanic plumes can inject volcanic ash into the atmosphere, threatening aviation and downwind communities. By understanding how volcanic lightning is related to plume dynamics, we aim to improve its value as a near-real-time monitoring resource for indicating the dispersal direction of hazardous volcanic ash [Arason et al., 2013]. This development will be especially useful in

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situations with limited in-situ monitoring networks, abundant cloud cover, and satellite data latency.

II. Data and Methods

In order to gain an understanding of Bogoslof's volcanic lightning we used the twenty-three explosive events detected by both WWLLN and GLD360 to calculate: (1) the time of first reported stroke, (2) the peak and average stroke rate, calculated as number of strokes per one minute interval, (3) the total number of strokes recorded, and (4) the duration of lightning from first to last stroke (Table I).

TABLE I. Volcanic Lightning Parameters from Bogoslof Volcano, Alaska

Date of eruptive event (UTC)	**WWLLN**					**GLD360**				
	First Stroke Time (UTC)	***Total Strokes***	***Average Stroke Rate (min^{-1})***	***Peak Stroke Rate (min^{-1})***	***Duration of lightning (min)***	***First Stroke Time (UTC)***	***Total Strokes***	***Average Stroke Rate (min^{-1})***	***Peak Stroke Rate (min^{-1})***	***Duration of lightning (min)***
12/16/16	18:36:11.399	6	0.41	2	14.60	18:36:11.399	41	2.81	5	14.60
12/19/16	15:49:13.480	21	0.47	5	44.80	15:49:13.576	35	0.78	5	44.80
12/22/16	01:27:41.543	60	2.17	17	27.68	01:30:09.354	114	5.57	26	20.48
12/23/16	18:43:51.579	9	2.38	4	3.78	18:43:09.014	18	3.47	7	5.19
12/26/16	23:32:47.376	35	1.26	6	27.84	23:32:47.376	58	1.39	8	41.58
12/31/16	07:30:43.005	32	1.02	6	31.38	07:30:24.917	56	1.77	9	31.68
1/4/17	06:24:17.439	11	1.78	5	6.17	06:19:37.659	154	8.33	35	18.48
1/5/17	22:25:01.971	26	1.67	8	15.53	22:25:01.971	41	2.54	11	16.13
1/9/17	08:01:53.775	20	2.60	4	7.70	08:00:00.968	157	9.94	23	15.80
1/15/17	07:19:49.614	3	0.26	2	11.53	07:15:33.764	4	0.16	1	25.41
1/18/17	22:26:04.175	6	0.74	1	8.16	22:26:04.175	14	1.05	3	13.39
1/20/17	22:18:10.841	1	1.00	1	0.00	22:24:44.971	2	1.17	1	1.16
1/22/17	23:08:05.246	6	0.87	1	6.88	23:02:10.924	30	2.23	5	13.45
1/24/17	13:58:38.694	13	0.31	4	42.12	13:57:04.201	68	1.56	10	43.70
1/26/17	15:49:35.360	7	1.02	4	6.87	15:50:54.046	24	1.07	9	22.52
1/27/17	17:42:10.456	1	1.00	1	0.00	17:38:04.551	2	0.49	1	4.10
1/31/17	08:59:55.113	54	0.35	6	153.66	06:38:25.507	190	0.58	15	327.05
2/17/17	19:28:46.808	35	0.57	4	61.05	19:22:28.340	91	1.35	10	67.36
2/18/17	14:03:51.535	13	2.94	5	4.43	14:03:12.060	92	9.08	29	10.13
2/20/17	02:19:52.413	2	0.28	1	7.12	02:12:58.811	20	1.43	6	14.02
3/8/17	08:06:49.344	200	1.36	9	146.90	08:00:27.103	1437	9.11	43	157.68
5/28/17	22:40:40.324	66	2.59	8	25.52	22:37:07.717	719	20.43	61	35.19
6/10/17	12:18:20.664	7	0.13	2	54.03	12:16:16.814	31	0.55	5	56.10

We also calculated the azimuth of the lightning locations, from the vent, reported as degrees 0-360 degrees from geographic north, for each eruptive event. The change in the azimuthal direction of the strokes was investigated through time. The azimuths were averaged using both an overall cumulative average and an average of just the most recent three strokes (Fig. 1B). These results were compared to ash plume trajectories as derived from the Ash3D numerical model [Schwaiger et al., 2012] and, where available, satellite imagery (GOES, AVHRR, and MODIS). The Ash3D model uses the 2.5-degree NCEP reanalysis wind model and gives projected tracks for a modeled ash plume at different altitudes as well as projected ashfall deposit thicknesses at the ground.

III. Results

Of the 64 eruptive events, 32 (50%) produced lightning detectable by one or more of the networks. Fifty-nine events were analyzed for this study, with 23 events (39%) detected by both WWLLN and GLD360. Among these, WWLLN had an earlier initial stroke time for 4 events, GLD360 had an earlier initial stroke time for 15 events, and there were 4 events where times were the same (within 0.001s). Across all events WWLLN had a mean average stroke rate of 1.2 strokes per minute and a mean peak stroke rate of 4.6 strokes per minute. The GLD360 had a mean average stroke rate of

3.8 strokes per minute and a mean peak stroke rate of 14.2 strokes per minute. The mean lightning duration per event for WWLLN was 30 minutes (min <1 minute, max 154 minutes) and for GLD360 was 43 minutes (min 1 minute, max 327 minutes).

The azimuthal analysis shows 78% of events (18 of 23 events) where the cumulative average azimuth of the lightning was in the same (8-point, 45°) cardinal direction as the plume motion modeled by Ash3D. Of the 59 analyzed events 23 had recorded lightning (39%). Of these 23 events only 17 had useable satellite imagery to determine plume directions from (74%). Measured lightning azimuths agreed with plume azimuths 64% of the time (Table II). Therefore the ability to calculate lighting azimuths in near-real-time would have increased knowledge of plume direction by approximately 17% when lightning was present but satellite views were not (due to cloud cover or data latency). This assumes 64% match accuracy for the 26% of the time where satellite views were not available.

TABLE II. RESULTS OF PLUME TRAJECTORY ANALYSIS

Date of eruptive event (UTC)	**Lightning Locations Visibly Match with:**				**Lightning Azimuths Match with:**		
	Ash cloud in satellite	***Ash3D modeled cloud***	***Ash3D dispersal axis of deposit isopach***	***Wind trajectory at altitude (feet)***	***Ash cloud in satellite***	***Ash3D modeled cloud***	***Wind trajectory at altitude of visual match***
12/16/16	No Data	Yes	0.3mm	5000–40,000	No Data	Yes	Yes
12/19/16	No Data	Yes	3mm–1cm	5000–20000, 40000–50000	No Data	Yes	Yes
12/22/16	No Data	Yes	3mm	20000–30000	No Data	Yes	Yes
12/23/16	No Data	Yes	0.1mm	5000–15000	No Data	Yes	Yes
12/26/16	Yes	Yes	0.3–1mm	5000–50000	Yes	Yes	Yes
12/31/16	No Data	Yes	0.3mm	5000–20000	No Data	Yes	Yes
1/4/17	Yes	Yes	1mm–3mm	10000–50000	Yes	Yes	Yes
1/5/17	No	Yes	1mm	5000–30000	No	Yes	Yes
1/9/17	Yes	Yes	1mm	5000–40000	Yes	Yes	Yes
1/15/17	No Data	No	edge (0–3mm)	No	No Data	No	No
1/18/17	Yes	Yes	3mm	5000–15000	Yes	Yes	Yes
1/20/17	No	No	edge (0–0.3mm)	No	No	No	No
1/22/17	Yes	Yes	0.3mm–1mm	5000–10000	No	Yes	Yes
1/24/17	No	Yes	0.3mm–1mm	10000–50000	Yes	Yes	Yes
1/26/17	Yes	Yes	1mm	5000–50000	Yes	Yes	Yes
1/27/17	Yes	Yes	1cm	5000–30000	No	No	No
1/31/17	Yes	Yes	1cm	5000–50000	Yes	Yes	Yes
2/17/17	Yes	No	edge(0.1mm–1cm)	Close 15000–30000	Yes	No	No
2/18/17	Yes	Yes	3mm	30000-50000–WWLLN 5000-50000–GLD360	No	No	No
2/20/17	Yes	Yes	3mm–1cm	5000–50000	Yes	Yes	Yes
3/8/17	Yes	Yes	1cm–3cm	10000–50000	Yes	Yes	Yes
5/28/17	Yes	Yes	1cm	5000–20000	Yes	Yes	Yes
6/10/17	Yes	Yes	edge (1cm)	5000–10000	No	Yes	Yes

IV. DISCUSSION

The regional detection efficiency for each network near individual volcanoes is important to characterize in order to develop a baseline for these networks as volcanic lightning becomes more integrated into overall volcanic monitoring schemes. The timing of the first lightning stroke is an important validation of seismic and infrasound data, and provides confirmation that ash was ejected into the atmosphere. Bogoslof is unique in that its high latitude precludes much natural thunderstorm lightning, making it an ideal candidate to study how global lightning detection systems record volcanic lightning. Analysis of volcanic lightning using near-field detection systems, such as the New Mexico Institute of Technology’s Lightning Mapping Array (LMA), has shown that near-vent volcanic lightning typically has shorter flash lengths and lower power than the larger lightning events that occur in the upper plume [Thomas et al., 2010]. Therefore, in order to best utilize long-range networks their detection efficiencies with relation to volcanic lightning must be recorded and analyzed.

The ability to look at the azimuthal spread of the lightning around the vent gives information on the developing plume. If the azimuths are radially distributed throughout the 360° range then it is likely that the charge carriers in the plume are likely spreading radially in the atmosphere, creating an umbrella cloud that spreads out at the level of neutral buoyancy (akin to the sheared top of a towering cumulonimbus). This would indicate a high-energy, sustained eruption that is not yet being controlled by the local wind field. Conversely, if the lightning is confined within a narrow azimuthal band then the plume was likely generated by a shorter-lived, explosive pulse and has bent over and is being highly directed by the local wind fields.

The 78% agreement with lightning azimuth and Ash3D modeled cloud direction also opens another avenue for potential investigation. The Ash3D model gives plume tracks at a variety of altitudes based on the wind field. If there is enough variance in the track at difference altitudes it may be possible to determine the altitude of the charged layer of the plume from the combination of lightning and wind model data. This would give some additional constraints on plume height, which is important for aviation warnings.

There are several possibilities to explain why the lightning stroke locations and the Ash3D models or satellite images may not match. For example, parallax from low-angle geostationary satellite views (i.e. GOES) can displace the apparent plume tens of kilometers away from its actual location. For lightning strokes that occur near the vent, this discrepancy may result in a location mismatch. Some of the ash may be also obscured by meteorological cloud cover in satellite images. Discrepancies between lightning trajectories and the Ash3D modeled cloud direction may result from two possibilities: (1) charge-carriers below the minimum modeled wind field in Ash3D causing lightning, and (2) errors in the model wind field, transporting ash to unrealistic locations.

Fig. 1 shows the utility of lightning as validation that significant production of volcanic ash has occurred. Fig. 1A shows the located lightning as detected from both global networks GLD360 and WWLLN for an explosive event on January 9, 2017 (eruption start time of 07:36 UTC). We can see that all of the lightning is located to the northwest of the volcano. In contrast, the only satellite image where the plume was visible (Fig. 1C) shows noticeable displacement from the vent, consistent with about a 30 minute lapse in time between the start of the eruption and the satellite pass at 8:10 UTC. Fig. 1B shows the 3-stroke average azimuth of the lightning as well as the distance of the lightning from the vent through time. Fig. 1D shows the Ash3d modeled plume direction based on NCEP reanalysis winds at varying altitude.

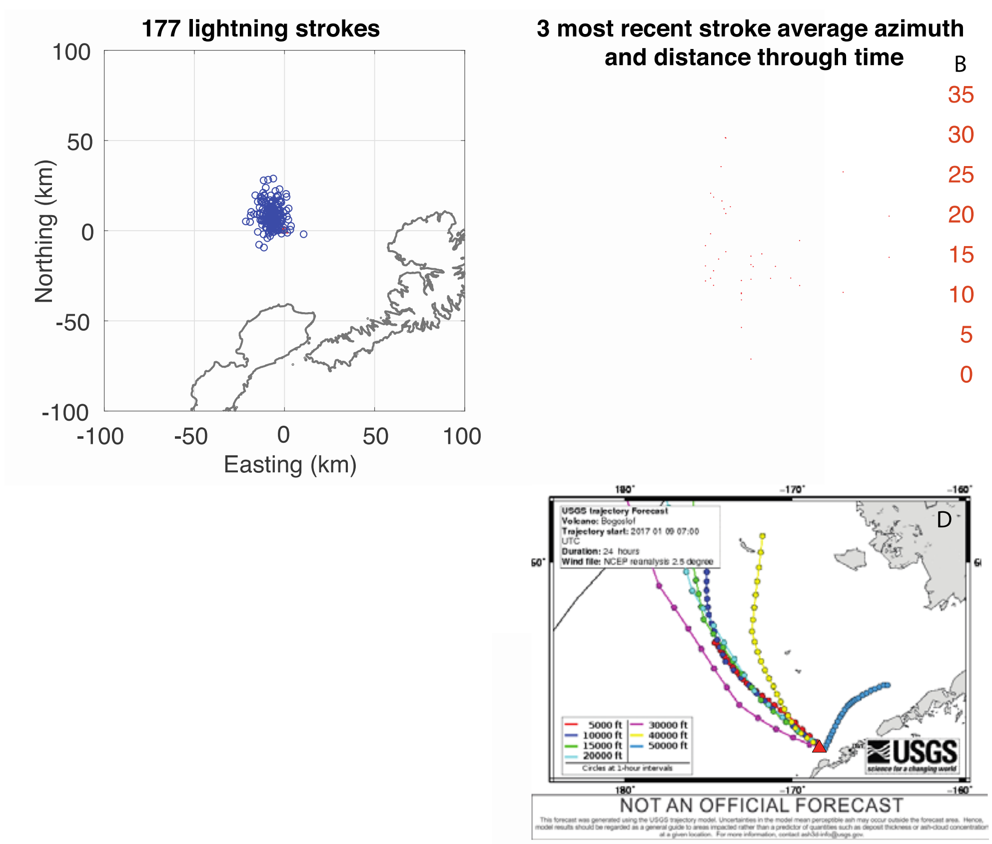

Fig. 1. Bogoslof's eruptive event on January 9, 2017. In panels A, C, and D the location of Bogoslof is indicated by a red triangle. Panel A shows the location of the lightning detected by the WWLLN and GLD360 networks. Panel B shows the averaged 3-stroke lightning azimuth (blue) and the distance of the lightning from the volcano (red) for the GLD360 and WWLLN strokes. Panel C shows the thermal infrared brightness temperature difference (in Celsius) from the MODIS satellite. The red arrow is pointing to the ash plume. Panel D shows the modeled travel paths of an ash plume at this time. The different colored lines refer to the path taken by the plume at different altitudes from 5,000-50,000 ft.

By combining the lightning data with the Ash3D models it is possible to conclude that: (1) a plume did form, (2) it traveled northwest, and (3) it is likely less than 50,000 ft. in altitude, based on wind directions. In this way it is possible to estimate where the plume is located during the crucial early minutes of eruption—before satellite images are available—and estimate its maximum plume height. The wind model is a limiting factor in this analysis, as any error in this wind data will be propagated into the Ash3D model plume trajectories.

I. Conclusions

Volcanic lightning is a valuable addition to the current suite of monitoring methods at volcanic observatories, such as seismic and infrasound sensors. Use of global networks like WWLLN and GLD360 does not require in situ equipment, so it is ideal for remote volcanoes such as those in the Aleutian Arc.

Our work at Bogoslof shows that globally detectable volcanic lighting occurred during approximately half of the explosive events of this eruption. We have shown that the cumulative azimuth of lightning strokes can help estimate where the plume is located and what direction it is travelling, even before satellite imagery can provide visual confirmation. By tracking the location of lightning in reference to the volcanic vent, it may be possible in some cases to combine lightning with model results and better estimate plume direction and height.

Lightning stroke rates and durations may hold additional information on physical processes, such as eruption rate, plume height, ash content, and ice formation in the plume, all of which influence the plume dynamics, and therefore aviation warnings. Our findings suggest that analysis of lightning trajectories may assist the detection and forecasting of ash-related hazards. If volcanic lightning is present it is highly probable that an ash-containing plume has developed. Every volcano is different and the trends seen at Bogoslof may not be representative of volcanic lightning at other volcanoes. The near-instantaneous detection of volcanic lightning, its many possible uses, and its variability between volcanoes makes it an important avenue for ongoing volcanic monitoring research.

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