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Lidar Detection of Hunga Tonga Volcanic Aerosols in Antarctica

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Abstract: Atmospheric lidar operating from McMurdo Station, Antarctica captured observations in late 2022 through 2023 which show unique signals of stratospheric aerosols injected by the Hunga Tonga volcanic eruption from January 2022. The aerosols observed show strong atmospheric circulation features, have several different appearance forms throughout the year such as diffuse layers and concentrated clusters, and are observed throughout the entire season of observations. These features appear suddenly in the data about 10 months after the eruption when the polar vortex started to break up above Antarctica, bringing up questions about their transport mechanism that we will use these lidar observations to answer. This study presents sample cases of these observations and lays out a plan of study which will further assess these unique aerosol measurements.

1. Introduction

The Hunga Tonga–Hunga Ha'apai volcanic eruptions in late-December 2021 to mid-January 2022 were among the most powerful modern observed explosions and also one of the largest injections of water vapor into the stratosphere in recorded history [1, 2]. The seismic, Lamb, and atmospheric waves induced by the eruption have allowed for a host of studies and the global scale of these disturbances allowed for stunning visualizations of the scope of such an event [3]. In addition to these dynamics, the stratospheric injection of water, sulfates, and other aerosols made for a particularly interesting case study for atmospheric scientists, especially as the stratosphere is generally a relatively dry region of the atmosphere [4].

Such eruptions introduce aerosols in the form of dust and water vapor into the atmosphere which can circulate for months or years, affecting both the climate and human activities. Though the eruption occurred at ~20^{o} S, the injected constituents were expected to "ride" global circulation patterns and distribute themselves across a wide range of latitudes and longitudes, as well as interact with features like the polar vortices and local atmospheric waves. While it is likely that the strong wind shear of the southern polar vortex would keep the pole isolated from these aerosols, the vortex in the Southern hemisphere annually weakens from July to Oct and breaks down in November to December [5] which could allow the aerosol to enter the vortex and make its way into the McMurdo lidar data. However, unique sightings of glowing pink skies observed over McMurdo Station, Antarctica for a few days in July 2022, which have been theorized to be caused by stratospheric aerosols from the volcano, bring up interesting questions about the interaction between the vortex and the aerosols.

During daytime operations from 27 November to 1 December 2022, the McMurdo lidar team noticed an anomalous spike in photon return, centered around an altitude of 15 km, which had not been present in the data in weeks and months prior. In winter months, it is expected to observe polar stratospheric clouds (PSCs) anywhere from 15-25 km, but in December (summer in Antarctica), the stratosphere should be far too warm for PSCs to form. The signals were observed on both co-located lidar systems, so we could easily rule out instrumentation issues, and a visual inspection of the skies did not reveal any abnormalities. When processed, this data revealed incredibly dynamic structures ranging from 12-25 km which show clear atmospheric circulation patterns and large-scale waves. Additionally, throughout the remainder of the season, these aerosol layers were observed regularly during lidar operation in a variety of forms.

This preliminary study explores these observations using simultaneous data from both lidar systems and comparisons to other datasets such as satellites and high-altitude balloons. We will use these lidar observations to study the onset, structure, composition, and evolution of the volcanic aerosol layers throughout the entire 2022-2023 season of McMurdo lidar observations.

2. Instrumentation and Processing

This lidar project has been operating out of McMurdo Station, Antarctica since 2010, and currently takes observations using two lidar systems, an iron (Fe) Boltzmann system and a sodium (Na) Doppler system [5,6] both primarily probing mesosphere and lower-thermospheric (MLT) Fe and Na metal layers from 80-110 km, but also collecting temperature and neutral density from ~30-70 km. These lidar are able to collect year-round measurements, including polar day, thanks to powerful filters in their receiver systems and careful data handling. This daytime operation capability allowed the lidar to capture the aerosol layers upon their arrival during the austral summer and to continue tracking them throughout the entire year. The systems can resolve altitudes down to nearly 10 km, though in standard data processing procedure these lower altitudes are not processed alongside the standard data products as it is impossible to guarantee that the data is free of aerosols. However, for this study, we decrease the lowest altitude of our processing in order to introduce the aerosols to our observed window. Generally, the systems are run by graduate students and technicians year-round, collecting data any time there is no cloud-cover above the station. Annually, anywhere from 1500-2500 hrs are collected across all seasons including the polar daytime, but unfortunately, the systems were not in operation during the duration of the eruption due to pandemic-related restrictions in accessing McMurdo Station, so we did not collect data after the eruption until September 2022.

The data in Figures 1 and 2 are presented as normalized photon counts. No further parameters have been derived from the counts thus far, but this approach easily reveals the structures seen in Figures 1 and 2. The lidar systems are fitted with a chopper that blanks out the lowest regions of the atmosphere to prevent detector blinding by strong low-altitude aerosol return, so in the processing of this data, care was taken that the chopper's blanking function was accurately applied to the data to prevent any effect on this data by the chopper.

3. Observations

The observations from early December were some of the earliest and strongest we have found in the lidar data thus far. Throughout the entire observation, there are coherent wave structures which have a period of ~70hrs. In addition to the major wave feature, we can see different, smaller circulation structures, with an especially strong feature around 44 hrs UT. This is somewhat surprising, as it was expected that these aerosol layers would be far more static than they are in this December observation. These features are large, coherent, and likely showcase typical atmospheric patterns in this region, though we cannot typically observe these from our lidar systems this easily without a tracer such as the aerosols. It is possible that we may be able to derive some conclusions about the type/size of aerosol we are seeing based on the features of this atmospheric circulation and how it interacts with the aerosol.

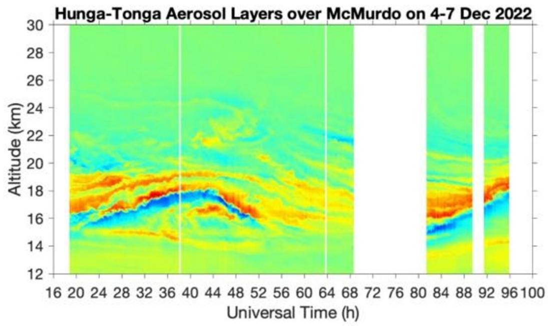

Figure 1. Stratospheric aerosol layers at their onset in Dec 2022, from the Na Doppler lidar.

As a comparison, we see distinctly different features in the May plot. The beginning of the run shows a strong concentrated feature of aerosols around 20 km descending to 18 km before fading out, while the rest of the run features a diffuse pattern of aerosols that looks more like we saw in December but without the coherent waves. Small pockets of stronger concentrated aerosols appear in clusters throughout the duration of the run, especially around 88 hrs UT. The grouping of these events suggests driving by a similar physical mechanism as opposed to just coincidental strong concentrations of aerosol, though that mechanism is not yet known. It is not clear exactly what the aerosol composition is from this data thus far, but there are distinctly different features in this May observation as compared to December's observations which may lend hints to understanding the composition.

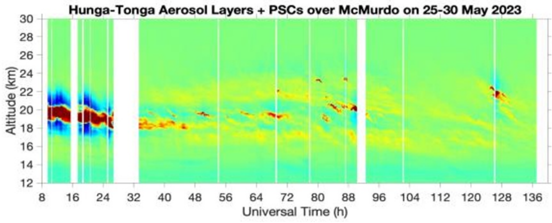

Figure 2. Stratospheric aerosols and possible PSC in May 2023, from the Na Doppler Lidar.

4. Ongoing and Planned Analysis

A major feature of this stratospheric region at the poles is the occurrence of PSCs. While it can be difficult to distinguish between PSCs and other aerosols, the PSCs can generally only form in winter, making the December observations definitively not PSCs. The May observations are more difficult to conclude upon. Two distinctly different return strengths and structures hint at two independent phenomena occurring in our data. The more diffuse aerosols dominating the majority of the measurement are present throughout most of the seasons winter observations, while the strong concentrated features were more intermittent. This supports the theory that the strong feature is a PSC, like those that could be seen in any season, and that the weaker features are volcanic aerosols, most likely water vapor.

Figure 3. Sun and PSCs above McMurdo in the austral spring (photographer: Jack Iribarren)

It is likely that the elevated levels of water vapor affected the PSCs during the 2022-2023 season. The presence of increased water vapor and other aerosol particles should allow for easier and more frequent PSC formation by providing nucleation sites and water vapor to use in the formation of the clouds. While this relation has yet to be explored from our data, it is likely that the PSC occurrence rate and brightness will be higher in this 2023 season than in prior ones, and there will likely be a change in the PSC season start-end dates from a standard year. As we have collected 10+ years of data from this location, this is a relation which will be explored further in upcoming studies.

Additionally, the arrival of the aerosol layers in our lidar data coincided with the expected timing of a typical polar vortex breakdown. Using this lidar data, we have already documented effects on the McMurdo stratosphere which are linked to vortex parameters (in the form of gravity wave modulation [7]). We plan an extensive study into the relation between aerosol transport and the vortex to determine how it affects these aerosols and their appearance/occurrence rate in our data. We aim to relate these factors to vortex strength and breakdown time. In addition to this, we plan to incorporate available satellite data to track the aerosols on their journey south, as well as compare with the many studies specifically modeling transport of these volcanic aerosols.

It is fortuitous that McMurdo is a busy scientific outpost because there are daily weather balloon and even high-altitude balloon launches coincident with these lidar observations of the stratospheric aerosol. The daily meteorological weather balloons took temperature, wind, and humidity measurements, and the high-altitude balloon took in-situ spectrometer measurements of these aerosols. We plan a collaboration with these teams and hope to combine our data in order to characterize these observed aerosol layers.

The McMurdo lidar project is unique in that it operates two different wavelengths probing the same space in order to measure both Fe and Na layers in the MLT. As both lidar observed these aerosols, there is a possibility that we can utilize the different return characteristics from each system in order to make some certain determinations about the aerosol layer, along the lines of DIAL or other multi-beam type measurements.

5. Conclusions

This work is an opportunity to use our lidar data in order to contribute a unique view of the Hunga Tonga volcanic eruption and its impact on the global atmosphere. Initial observations are incredibly intriguing, and many further studies are planned. From this investigation and future publication of these results, we aim to not to contribute these results to the wealth of science that has followed this eruption, but also as a chance to demonstrate the capability of this lidar to study aerosols and to highlight the proficiencies of such high-resolution data.

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