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Using Tree-Ring Data to Analyze the Effects of Volcanic Eruptions on Climate in Inner Asia from 500 BCE to Present

Jennie Zhu

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Amy Hessl, Ph.D., Chair
Eungul Lee, Ph.D.
Jaime Toro, Ph.D.

Department of Geography

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ABSTRACT

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Volcanic eruptions have influenced regional and global climate on annual, interannual, decadal, and multi-decadal time scales. However, past studies have largely focused on the response of global temperature to modern eruptions with the aid of satellite records. This approach limits the number of eruptions that can be studied and restricts our knowledge to relatively small events when compared to the volcanic history of the late Holocene. I used modern climate records to evaluate the effect of recent eruptions on Mongolian climate. I then extended my analysis to the last 2500 years by examining existing and new tree-ring data from Mongolia to understand how volcanic eruptions influence different climatic variables (temperature, moisture, and solar irradiance) in Inner Asia. This study, part of a larger research project on human ecology in Inner Asia, focuses on past volcanic eruptions (600 BCE to 2013 CE) at three sites in north central Mongolia: Solongotyn Davaa (48.3°N, 98.93°E), a temperature-limited site, Khorgo lava (48.17°N, 99.87°E), and Urgaat lava (46.40°N, 101.46°E), both moisture-limited sites. To test how modern eruptions (1959-2012) influenced temperature and precipitation regimes in Mongolia, I used the Grid Analysis and Display System to run composite analyses using Climatic Research Unit 3.21 temperature and 3.21 scPDSI data. Three eruptions were analyzed and both composite analyses suggest that, at each location, temperature and moisture variabilities are statistically insignificant during the year of the eruption. I then used superposed epoch analysis to evaluate how past eruptions affected regional climate by separating temperature, moisture, and solar irradiance variables. Again, the results fell within the 95% confidence limits for years zero to three, suggesting that these large eruptions do not affect temperature, moisture, and solar irradiance as much as once thought. Lastly, I looked at the tree-ring anatomy of individual samples to see if there was any anatomical evidence of an eruption event. Select eruption events are evidenced in tree-rings by the presence of narrow ring-width, false rings, and absent rings without any clear pattern as to why certain events affected tree growth at Khorgo lava and Urgaat lava. Chi-square tests comparing non-eruption years with eruption years show that the number of false rings and absent rings at Khorgo lava, and absent rings at Urgaat lava, is statistically significantly higher in the second year following the eruption, showing some effect on tree-ring growth but not necessarily tree-ring-width. The study calls into question the process of studying volcanic eruptions using tree-rings by showing that the atmosphere may be an intransitive cycle where the effects of volcanic eruptions can be variable and uncertain.

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INTRODUCTION

Volcanic eruptions have a strong influence on regional and global climate from interannual to century-long time scales (Stothers 2000, Salzer and Hughes 2006). Singular large tropical eruptions can produce global or hemispheric cooling for two to three years (Robock and Mao 1995, Kelly et al. 1996). In the Northern Hemisphere, the winter following a large tropical eruption is typically warmer due to cold season shifts in the Arctic Oscillation (Kelly and Jones 1996). Following eruptions of multiple large volcanoes, cooler temperatures have been experienced for 100-year periods (Crowley 2000, Robock 2000). For example, the massive Samalas eruption of 1258 CE (previously thought to be 1257) in Indonesia may have contributed to the onset of the Little Ice Age (LIA), a period spanning approximately 1400 to 1800 CE when sea surface temperatures were 1°C cooler (Miller et al. 2012, Bradley and Jonest 1993, Keigwin 1996, Lavigne et al. 2013). These major eruptions and their associated climate forcing have had serious consequences for society. The 1258 CE eruption, along with other eruptions such as Laki in 1783 CE and an eruption of unknown location in 536 CE and 540 CE, are both associated with cooler temperatures as well as poor harvests and famine (Stothers 1999, Sigl et al. 2015).

Studies of eruptions that occurred within the last 30 years have been aided by the availability of satellite records (Robock 2000). As a result, there is a large body of literature focusing on the 1991 CE eruption of Mount Pinatubo in the Philippines including Kirchner et al. (1999), McCormick et al. (1995), and Minnis et al. (1993). The available satellite data, along with its tropical location and high intensity, provide insights into the effects of large eruptions on climate. Volcanic material from Mount Pinatubo was studied using modern instruments, therefore, we have a more complete understanding on how aerosols travel through the atmosphere, at what pace, and how eruptions affect the climate system, particularly Earth's radiative processes and stratospheric chemical processes (McCormick et al. 1995). However, volcanic eruptions of this magnitude, which have a global impact, are relatively rare events. There is an urgent need to study eruptions of varying magnitudes using a variety of data sources, including tree-rings, to improve the records on the effects of eruptions on past climate change. Due to the

rarity of large modern eruptions, researchers have attempted to study several past eruptions of similar magnitude using model simulations (Oman et al. 2005, Mann et al. 2012). Oman et al. (2005) studied the Katmai eruptions of 1912 using the Goddard Institute for Space Studies ModelE GCM and stratospheric aerosol optical depth data showing a maximum cooling effect over Asia of about 1°C to 1.5°C. Mann et al. (2012) modelled mean surface temperatures in the Northern Hemisphere using an energy-balance climate model and the US National Center for Atmospheric Research CSM 1.4 coupled ocean-atmosphere general circulation model that showed about a 2°C decline in temperature following the 1258 eruption and then compared it to a tree-ring reconstruction that shows a decrease of only about 0.6°C. There has been disagreement regarding the severity of temperature forcing (from 0.1°C to up to 2.5°C surface temperature cooling) between model simulations and proxy records due to the inherent uncertainties contained in simulation models and proxy data. These uncertainties include weak correlation between instrumental temperatures and proxies, the detrending process and how proxy records can be affected by other climate and non-climatic influences, and incorrectly incorporating errors in the proxy data (IPCC 2013). There are also uncertainties in using the proxy themselves, including micro-site characteristics not detected while calibrating proxy against instrumental data and the amount of sulfate aerosols found in ice cores and if they're an accurate representation of the size of volcanic eruptions.

Tree-rings have long been used to study eruptions (Lawrence 1939, Lough and Fritts 1987, LaMarche and Hirschboeck 1984, Briffa et al. 1998, Salzer and Hughes 2007, Anchukaitis et al. 2012, D'Arrigo et al. 2013). Tree-rings are invaluable in this setting because they are annually resolved proxies of climate variability, are commonly found throughout the world, and their chronology dates as far back as 10,000 BCE. Radial tree growth is influenced by the most limiting environmental variable at a site. For example, trees growing at high elevations or high latitudes tend to be limited by temperature, thus, they act as a proxy for past temperature. As the result, temperature-sensitive trees have been used extensively to study temperature variability due to past volcanic eruptions (Briffa et al. 1998, D'Arrigo 2001, Anchukaitis 2012, Gennaretti et al. 2014). However, several studies suggest that major volcanic eruptions

may influence irradiance and moisture availability, in addition to temperature (Wexler 1951, McCracken and Luther 1984, Handler 1984, Mass and Portman 1988, Dutton and Christy 1992, Roderick et al. 2001). By combining tree-ring data from a variety of sites that are either temperature or moisture-limited, it may be possible to attain a more complete understanding of the climatic effects of large eruptions.

I studied how past volcanic eruptions from 500 BCE to 2013 CE influenced Inner Asia climate using tree-ring chronologies of Siberian pine (Pinus sibirica) from three locations in north central Mongolia. The three sites are relatively near one another (within 300 km), but are located in different topographic positions and thus are constrained by different growth-limiting factors. Khorgo lava (KLP) and Urgaat lava (ULP) are low elevation, moisture-limited sites, while Solongotyn Davaa (Sol Dav) is a high elevation temperature-limited site. D'Arrigo and others (2001) used the tree-ring record at Sol Dav to demonstrate that some tropical eruptions, such as the 536 CE eruption, produced low temperatures in central Mongolia for one year (indicated by the presence of a frost ring), followed by a brief recovery in radial growth and then another decline in growth. Here I propose that tree-ring records from the three study sites may allow me to isolate different climatic effects of the eruption events beyond temperature.

This study will contribute to the scientific understanding of how historic volcanic eruptions influenced temperature, moisture, and irradiance regimes, by extending the available data and corresponding analysis back by 2,500 years and covering a unique range of geographic and climate variability, particularly on moisture-sensitive response at high latitudes. The objectives of this study are to:

1. Evaluate the effect of recent eruptions on the climate of central Mongolia using spatial fields of gridded temperature, moisture availability, and irradiance.
2. Expand the temporal window of volcanic effects on climate in central Mongolia by analyzing the effects of volcanic eruptions on tree growth over 2,500 years on three different sites in central Mongolia.

I analyzed the different responses of moisture and temperature-sensitive trees to refine what we know about how eruptions alter climate in central Mongolia. I hypothesize that volcanic eruptions change key climate attributes (temperature, moisture availability, and solar irradiance), and influence the tree-ring data. If the dominant climatic effect is a decrease in temperature, this effect will be most apparent at temperature-limited sites such as Sol Dav. I expect to see a decrease in ring-width at Sol Dav and increase in ring-width at Khorgo lava and Urgaat lava. If the dominant climatic effect is an increase in moisture availability, then I expect to see an increase in ring-width and little changes in tree-ring anatomy in the samples from Khorgo lava and Urgaat lava. Lastly, if the dominant effect is an increase diffuse light, then I expect to see all sites experience an increase in tree productivity and thus an increase in ring-width.

LITERATURE REVIEW

Volcanic Eruptions Influencing Climate

Volcanic eruptions influence climate by emitting sulfur dioxide which is then transformed into sulfate aerosols in the atmosphere (Devine et al. 1984, Zhao et al. 1995). These aerosols increase the optical thickness of the stratosphere, which decreases the amount of solar radiation reaching the earth's surface. These aerosols also absorb infrared energy radiated by the planet, reducing the average temperature of the troposphere (Hansen et al. 1978, Toon and Pollack 1980, Minnis et al. 1993, McMormick et al. 1995). There have been major eruptions during the last 2,500 years that have caused hemispheric and global cooling due to the amount of aerosols emitted (Kelly and Sear 1984). Since the advent of remote sensing, most of the recent research on the effects of volcanic activity on climate has focused on only a few eruptions, such as the 1991 eruption of Mount Pinatubo. In these studies, they found year 1992 to have an increase in diffuse radiation (and thus an increase in photosynthesis), summer cooling and winter warming patterns in January, and a mean tropospheric temperature 0.2°C below normal when compared to a base period of 1958 to 1991 (Gu et al. 2003, Kirchner et al. 1999, McCormick et al. 1995). Adjusted to take into the account the 1992 El Niño-Southern Oscillation (ENSO), there would have been a decrease of -0.4°C in 1992, which is a decrease of more than 0.7°C from 1991 (McCormick et al. 1995).

With only Mount Pinatubo as a modern reference for large eruptions, scientists have used a combination of model simulations and proxies to study older eruptions. However, there is disagreement between model simulations and reconstructions from proxies such as tree-rings. Simulations tend to overestimate surface temperature cooling resulting from major eruptions when compared to proxies (IPCC 2013). Model simulations show a decrease in mean surface temperature of approximately 1.0°C to 2.5°C for two to three years following large eruptions such as the 1258 CE eruption (Oman et al. 2005, Mann et al. 2012). However, empirical reconstructions using tree-ring data with simulated climate models estimate only a 0.6°C to 2°C cooling for the 1258 CE eruption in the Northern Hemisphere (Anchukaitis

et al. 2012). Other empirical studies using volcanic dust effects and temperature records show a cooling of only a few tenths of a degree Celsius (Mass and Schneider 1977, Taylor et al. 1980, Self et al. 1981). This disagreement on the severity of cooling between models, tree-rings, and empirical studies is important because it shows the uncertainties present in relating model simulations, proxy records, and instrumental data, and a need to better understand these relationships.

In addition to temperature and precipitation effects, volcanic eruptions may also affect solar irradiance (Gu et al. 2003, Minnis et al. 1993, Dutton and Christy 1992). Solar radiation is observed to decrease by as much as 25 to 30% due to the backscattering of radiation by sulfate aerosols in the stratosphere, creating a global dimming effect (Dutton and Christy 1992). The solar radiation that is forward scattered to earth is enhanced diffuse radiation and somewhat compensates for the radiation that is backscattered into space (Robock 2000). Enhanced diffuse radiation can have a major effect on plant growth. Roderick et al. (2001) proposed that the enhanced diffuse radiation caused by eruptions increase photosynthesis. Gu et al. (2003) also studied the relationship between diffuse radiation and photosynthesis, concluding that the increase in diffuse radiation enhanced photosynthesis for two years following the Mount Pinatubo eruption. This concept is important to consider when using tree-rings as proxies because the enhanced diffuse radiation may help offset effects of cooler temperatures (Robock 2005).

Using Tree-Rings to Study Past Volcanic Eruptions

Tree-rings have been used to reconstruct and analyze past temperature (Briffa et al. 1998). In temperature-sensitive trees, the effects of volcanic eruptions on tree growth can be detected through the presence of narrow rings, frost rings (cellular growth differences due to freeze damage during the growth season), and rings with low maximum latewood density (LaMarche and Hirschboeck 1984, Salzer and Hughes 2007). Maximum latewood density is a measure based on the high density of cells formed at the end of each growing season, and is mostly limited by the cold temperature of late growing season (Parker and Jozsa 1973). However, studying this parameter is expensive and time consuming and not realistic for

inclusion in this project. Frost rings may be present from eruptions and they typically show a more immediate response to temperature (D'Arrigo 1999). At Sol Dav, two out of the three samples that date to year 536 CE show frost damage in the latewood of that year, signifying cooler temperatures during the year of the 536 CE eruption. There were five frost rings out of 11 samples that corresponded to the 1258 CE eruption at Sol Dav. Other factors however, such as false rings, have been rarely studied, if at all. Sudden changes in the limiting factor during the growing season, such as moisture availability, can possibly produce false rings (Stokes and Smiley 1996).

Tree-ring reconstructions have been used to study temperature regimes in the years during and immediately following eruptions. Cooling caused by volcanic eruptions can appear for several years within temperature reconstructions based on ring width and frost ring data (D'Arrigo et al. 2013). However, along with the delay in surface cooling due to atmospheric circulation, there may also be a biological lag response in tree growth, shown as ring width (D'Arrigo et al. 2001). Narrow rings due to volcanic eruptions may be seen a few years after the occurrence of the eruption. Along with detecting individual volcanic eruptions, there are low-growth intervals that may be a result of several eruptions closely spaced in time (Salzer and Hughes 2007).

Temperature is commonly studied in bodies of literature involving the use of tree-rings to analyze the effects of volcanic eruptions on climate. Mann et al. (2012) used simulated data that predict a climate cooling of about 2°C during the modern period (1850-1999) and pre-instrumental period (1200-1980). He concluded that this effect is largely absent from tree-ring reconstructions of temperature (resulting in missing rings for the years coinciding with large eruptions such as the 1258 CE Samalas eruption). However, it is rare for more than 5-10% of samples from trees at northern latitude sites to have a missing ring per year (St. George et al. 2013). Anchukaitis et al. (2012) responded to Mann et al. highlighting problems with their tree-ring model including a lack of consideration for the amplitude and spatial pattern of volcanic forcing and climate responses and a lack of empirical evidence for misdating tree-ring chronologies. Their empirical models, along with other studies, showed cooling coinciding with volcanic

eruptions, but with a one-year lag in narrow tree-rings and with only a cooling of approximately 0.5°C to 1°C (Anchukaitis et al. 2012, IPCC 2013, D'Arrigo et al. 2013, Gennaretti et al. 2014). Thus there is evidence that tree-ring chronologies are correctly dated and show surface temperature cooling, albeit less than the model projections.

There is less conclusive evidence regarding volcanic eruptions' influence on precipitation and irradiance in the tree-ring data. This is perhaps due to the low statistical significance found in connecting precipitation and eruptions, even while using modern instrumental and satellite data. Work performed by Wexler (1951), Mass and Portman (1988), Fischer et al. (2007), and Anchukaitis et al. (2010) show conflicting results on how eruptions influence precipitation. While it is hypothesized that eruptions may increase precipitation (Wexler 1951, McCracken and Luther 1984, Mass and Portman 1988), Anchukaitis et al. (2010) used tree-ring based drought reconstructions and the Superposed Epoch Analysis (SEA) to show that Inner Asia became drier following large eruptions. If the models by Anchukaitis et al. (2010) are accurate, then I expect to see drier conditions in Mongolia following large eruptions by analyzing moisture-sensitive tree-ring samples from Khorgo lava. Breitenmoser et al. (2012) analyzed the effects of volcanic eruptions on climate using a variety of time-series, including the temperature-sensitive chronologies (from Tornetrask, Central Europe, Yamal, Taimyr, Sol Dav, Indigirka, Puerto Café, and La Esperanza) and precipitation and drought chronologies (Prec. Qinghai, Drought Princeton, Drought El Malpais). They found that volcanic activities may mask the solar signal spatially and temporally, causing a decrease in temperature, but the results for precipitation and drought are less straightforward showing a negative volcanic effect in some areas but a positive effect in others. My research took this further by analyzing three sites one being temperature-sensitive and two being moisture-sensitive to research how volcanic eruptions influence temperature, precipitation, and irradiance regimes relative to one another.

Data and Methods

Study Area

Mongolia is a landlocked country in inner Asia, with Russia on its northern border and China to the south, east, and west. The country has a land area of 1,564,116 km^2 and human population estimated at 2,953,190 in 2014 (United Nations). The country is arid and semi-arid with pastoralism, mining, and agriculture as its main economic and cultural drivers (Johnson et al. 2006). Because of this, large natural events like volcanic eruptions and droughts can have major impacts on Mongolia's food supply, economy, and culture.

My first research site is Khorgo lava, which is located on a Holocene lava flow (48.17°N, 99.87°E) at an elevation of 2,060 m (Figure 1, Table 1). The site is moisture-stressed (Pederson et al. 2014). There are currently 191 samples dated in the master chronology that range from 668 BCE to 2013 CE. The second site is Urgaat lava (46.70°N, 101.79°E) at an elevation of 2,016 m. Moisture is also the limiting growth factor. Urgaat lava dates between 416 BCE to 2013 CE, with 105 processed and analyzed samples. The last site is Solongotyn Davaa (Sol Dav), a nearby high elevation site at 2,420 m (48.3°N, 98.93°E) in the Tarvagatay Mountains (D'Arrigo et al. 2001). Temperature is the dominant control of tree growth due to the high elevation and mesic setting. Ninety total samples were collected from Sol Dav that date from 558 CE to 1999 CE. Because the available chronology from Sol Dav does not date as far back as the moisture-limited sites, temperature information and analysis is limited to 558 CE to 1999 CE. There has been some tree-ring anatomy analysis performed at Sol Dav from previous studies that go back to the 536 eruption (noted in the literature review) but the available chronology only dates to 558 CE (D'Arrigo et al. 2001). These three sites act as proxies to reconstruct past temperature and moisture data that are used to analyze the effect of volcanic eruptions on local climate between 500 BCE and 2013 CE. For high elevation high latitude trees, narrow rings are typically produced in response to volcanic cooling (D'Arrigo et al. 1999). Less is known about climatic effects and tree response at low elevation moisture-limited sites.

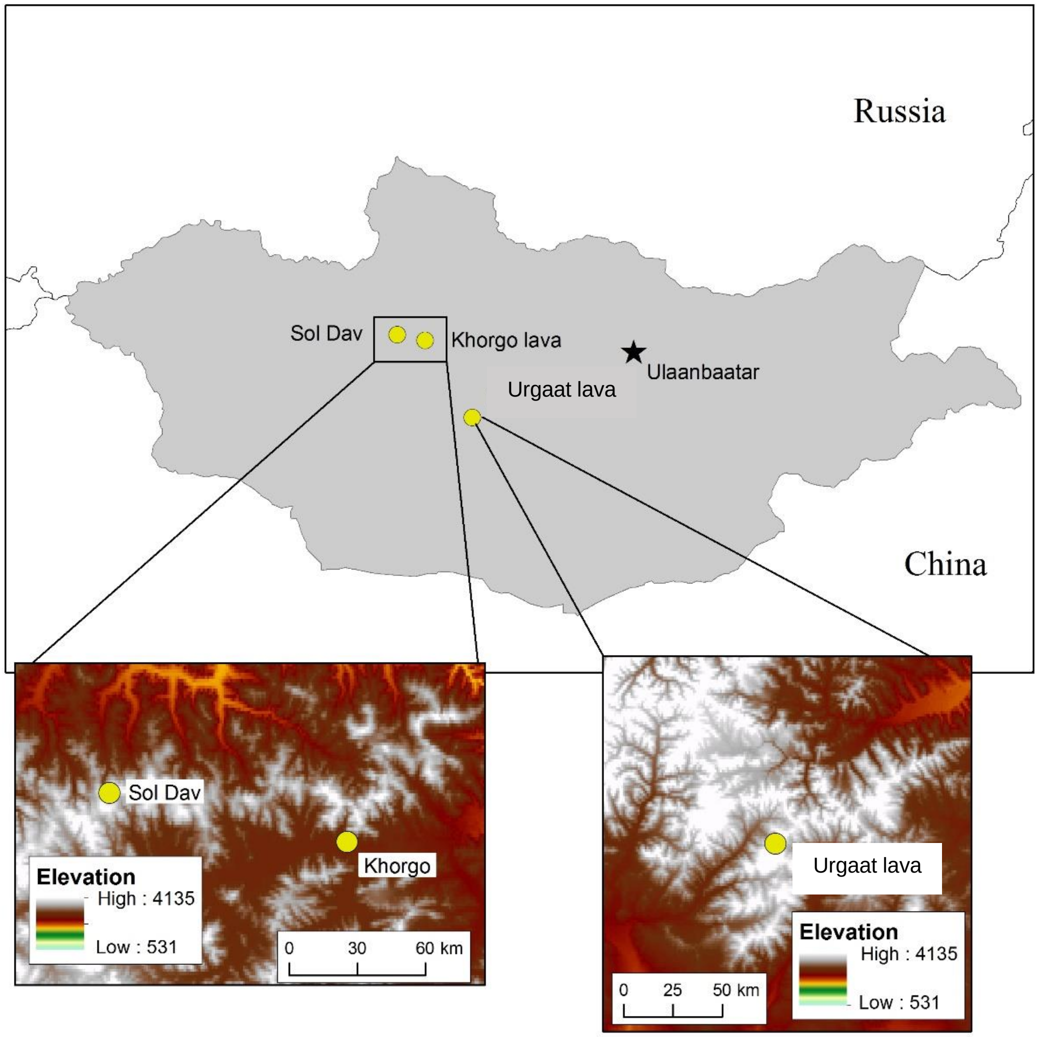


Figure 1: Study sites in Mongolia including elevation

Table 1: Site descriptions

Site	Elevation	Limiting Factor	Inner Ring	Outer Ring	# of Samples
Khorgo lava	2060 m	Moisture	668 BCE	2013 CE	191
Urgaat lava	2016 m	Moisture	416 BCE	2013 CE	105
Solongotyn Davaa	2420 m	Temperature	558 CE	1998 CE	90

Sample Preparation and Processing

The samples from Khorgo lava and Urgaat lava were dried, mounted, and sanded according to standard dendrochronological techniques by several other technicians and myself (Stokes and Smiley 1996). Next, we crossdated and measured the ring widths of the samples to 0.01 mm precision using a measuring standard and microscope. The crossdating was checked using the computer program COFECHA to validate its accuracy against an existing master chronology (Holmes 1983). The existing master chronology for Khorgo lava has a sample depth of over 60 samples spanning 1140 CE to 1770 CE and a series intercorrelation of 0.71. Urgaat lava has a series intercorrelation of 0.77. The raw ring widths are standardized by Pederson et al. (2014) using a detrending method using the program ARSTAN to remove growth-related trends (Cook and Holmes 1986). Pederson et al. calibrated the standardized raw ring widths with soil moisture using a linear regression model relating June to September scPDSI to the ring width chronology from 1959 to 2009 and then validated the calibration using a split-period cross-validation approach.

I attained the dataset for Sol Dav from the International Tree-Ring Data Bank (ITRDB) on the National Oceanic and Atmospheric Administration (NOAA) website. D'Arrigo et al. (2001) collected and processed the tree-ring samples from Sol Dav using basic dendrochronological techniques and then I standardized the data using ARSTAN to remove growth-related trends. However, Sol Dav cannot be used to generate calibrated and validated reconstructions due to limits of nearby meteorological station records (Davi et al. 2015). Thus, analyses of Sol Dav will use uncalibrated ring-width indices. Due to the high elevation and mesic setting, temperature is the dominant control of tree growth at Sol Dav (D'Arrigo et al. 2001).

Past Eruptions to Analyze

Sea surface temperatures, aerosol estimations, historical reports, radiation measurements, and ice cores have been used in previous studies to help create different indices of eruptions (Lamb 1970, Newhall and Self 1982, Robock and Free 1995). An ideal index conveys the radiative forcing associated

with each explosive eruption, but indices of past eruptions are either incomplete spatially, temporally, or measure a single property (Briffa et al. 1998, Robock 2000). This research uses the years obtained from the Sigl et al. (2015) paper, a recent study that uses a combination of volcanic aerosol loadings from ice cores (from Greenland and Antarctica), tree-ring data from Central Europe, northern Siberia, and the United States, to obtain volcanic eruption events for the past 2,500 years (Tables 2 – 4, Figure 2)). The list contains and ranks the 25 largest eruptions during this time period based on total global aerosol forcing. The accuracy of these ice core chronologies were evaluated by comparing their volcanic aerosol loadings to an extensive database of the historical volcanic dust veil observations, ice core tephra evidence, and the 994 CE event, and are accurate to within less than five years during the past 2,500 years (see more at Sigl et al. 2015). Just with all proxies, ice cores should be researched carefully and their uncertainties should be taken into consideration, such as how aerosols become deposited, by how much, and if all this is possibly by chance. This may come to explain if some eruptions are experienced elsewhere on the global context, or just near the poles where the ice cores are extracted.

In order to analyze these eruptions, I used the Climate Research Unit (CRU) high resolution monthly mean time series 3.21 global temperature data on a 0.5° by 0.5° grid that spans from 1901 to 2012 (Jones et al. 1999) and the CRU self-calibrating PDSI 3.21 global data on a 0.5° by 0.5° grid that spans from 1901 to 2012 (van der Schrier et al. 2013). The scPDSI is a calibrated index of PDSI by Palmer that calculates the moisture availability at any location derived from CRU 3.20 precipitation and evapotranspiration fields. It improves upon the PDSI in that the sensitivity of the index is based on the local climate. Tree-ring data for Sol Dav and Khorgo lava is provided by ITRDB. Siberian pine data at Sol Dav was originally collected by Jacoby et al. while the Siberian pine data at Khorgo lava was contributed by Hessl et al. The Urgaat lava Siberian pine data, although not yet available on the ITRDB, was also provided by Hessl et al. (2016).

Table 2: Complete list of volcanic eruptions to be analyzed provided by Sigl et al. 2015. Edited to include only pertaining information
**Total global aerosol forcing was estimated by scaling the total sulfate flux from both polar ice sheets to the reconstructed total (that is, time integrated) aerosol forcing for Tambora 1815. For more detailed information, see Sigl et al. 2015.*
± Unattributed volcanic events (UE) and tentative attributions for non-documented historic eruptions (?) are marked.

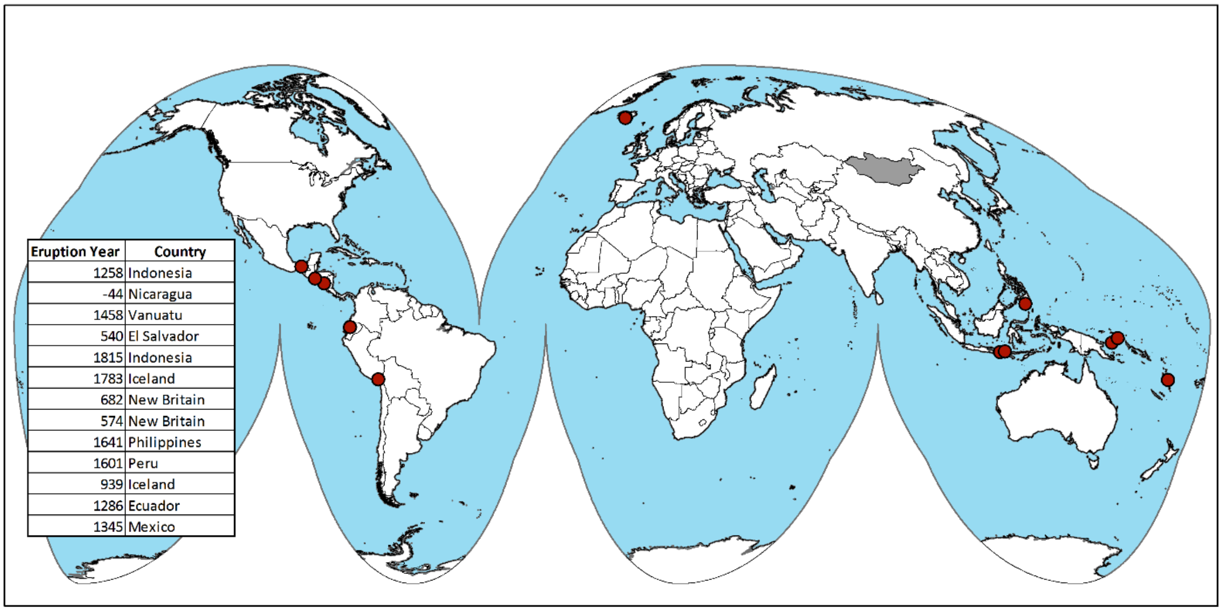
Rank	Year	Volc. SO_4^{2-} Greenland (kg km^{-2})	Volc. SO_4^{2-} Antarctica (kg km^{-2})	Global forcing* (W m^{-2})	Volcano±/Region
1	-426	99.8	78.2	-35.6	UE
2	1258	90.4	73.4	-32.8	Samalas/Indonesia
3	-44	100.6	15.4	-23.2	Chiltepe?/Nicaragua
4	1458	39	63.6	-20.5	Kuwae/Vanuatu
5	540	61.2	34.4	-19.1	Ilopango?/El Salvador
6	1815	39.7	45.8	-17.1	Tambora/Indonesia
7	1230	56.4	23.1	-15.9	UE
8	1783	135.8		-15.5	Laki/Iceland
9	682	38.4	38.7	-15.4	Pago?/New Britain
10	574	38.3	34.1	-14.5	Rabaul?/New Britain
11	266	61	11.3	-14.5	UE
12	1809	34.6	25.4	-12	UE
13	1108	48.3	11.6	-12	UE
14	1641	44.2	14.9	-11.8	Parker/Philippines
15	1601	39.2	18.7	-11.6	Huaynaputina/Peru
16	169	39.1	18.4	-11.5	UE
17	1171	37	19.5	-11.3	UE
18	536	99		-11.3	UE
19	1695	28.6	22.5	-10.2	UE
20	939	88.7		-10.1	Eldgja/Iceland
21	1286	27.6	20.8	-9.7	Quilotoa?/Ecuador
22	433	20.6	27.2	-9.6	UE
23	87	83.1		-9.5	UE
24	1345	27.9	19.1	-9.4	El Chichon?/Mexico
25	626	72.2		-8.2	UE

Table 3: Known timing of eruptions at Khorgo lava along with which year the narrow ring-width was recorded in the chronology, and location of eruptions

Khorgo Lava Pine - Timing of Eruption							
Eruption Event	**Narrow Eruption Year**	**Narrow Year After Eruption**	**Before Growing Season?**	**After Growing Season?**	**Date of Eruption**	**Source**	**Location**
-426	x		-	-	-	-	-
-44	x		x		March	Stothers 1999	Nicaragua
87		x	-	-	-	-	-
169	x		-	-	-	-	-
266		x	-	-	-	-	-
433		x	-	-	-	-	-
536	x		x		March	Stothers 1999	-
540		x	-	-	-	-	El Salvador
574	x		-	-	-	-	New Britain
626		x		x	October	Stothers 1999	-
682	x		-	-	-	-	New Britain
939	x		x		Summer	Stothers 1999	Iceland
1108		x	-	-	-	-	-
1171	x		-	-	-	-	-
1230		x	-	-	-	-	-
1258		x	x		January	Stothers 1999	Indonesia
1286	x		-	-	-	-	Ecuador
1345		x	-	-	-	-	Mexico
1458		x	-	-	-	-	Vanuatu
1601	x		x		February 1600	Thouret et al. 1999	Peru
1641	x		x		January?		Philippines
1695		x	-	-	-	-	-
1783	x		x		June	Stothers 1999	Iceland
1809	x		x		December 1808?	Guevara-Murua et al. 2014	-
1815	x		x		April	Stothers 1984	Indonesia

Table 4: Known timing of eruptions at Urgaat lava along with which year the narrow ring-width was recorded in the chronology, and location of eruptions

Urgaat Lava Pine - Timing of Eruption							
Eruption Event	**Narrow Eruption Year**	**Narrow Year After Eruption**	**Before Growing Season?**	**After Growing Season?**	**Date of Eruption**	**Source**	**Location**
-426	NA	NA	NA	NA	-	-	-
-44		x	x		March	Stothers 1999	Nicaragua
87	x		-	-	-	-	-
169		x	-	-	-	-	-
266	x		-	-	-	-	-
433	x		-	-	-	-	-
536	x		x		March	Stothers 1999	-
540		x	-	-	-	-	El Salvador
574	x		-	-	-	-	New Britain
626		x		x	October	Stothers 1999	-
682		x	-	-	-	-	New Britain
939	x		x		Summer	Stothers 1999	Iceland
1108		x	-	-	-	-	-
1171	x		-	-	-	-	-
1230		x	-	-	-	-	-
1258	x		x		January	Stothers 1999	Indonesia
1286	x		-	-	-	-	Ecuador
1345		x	-	-	-	-	Mexico
1458		x	-	-	-	-	Vanuatu
1601	x		x		February 1600	Thouret et al. 1999	Peru
1641		x	x		January?		Philippines
1695		x	-	-	-	-	-
1783		x	x		June	Stothers 1999	Iceland
1809	x		x		December 1808?	Guevara-Murua et al. 2014	-
1815	x		x		April	Stothers 1984	Indonesia



Eruption Year	Country
1258	Indonesia
-44	Nicaragua
1458	Vanuatu
540	El Salvador
1815	Indonesia
1783	Iceland
682	New Britain
574	New Britain
1641	Philippines
1601	Peru
939	Iceland
1286	Ecuador
1345	Mexico

Figure 2: Locations of eruptions at known locations from Sigl et al. (2015) table

Modern Climatic Effects of Eruptions on Central Mongolia

I performed a preliminary analysis to test the influence of eruptions on temperature and moisture availability regimes in Mongolia during the modern instrumental period. The goal was to see if there were any climatic effects in Mongolia using available instrumental data. I used the Grid Analysis and Display System (GrADS; Doty 1995) to run composite analyses using CRU 3.21 temperature and CRU scPDSI 3.21 data. I examined large (Volcanic Explosivity Index (VEI) of 5 or greater) tropical volcanic eruptions between 1959 and 2012 (Table 5).

Table 5: Volcanic eruptions chosen for composite analysis during the modern period (1959-2012)

Volcanic Event Year	Name	Location	VEI
1963	Mount Agung	Bali, Indonesia	5
1982	El Chichón	Francisco León, Mexico	5
1991	Mount Pinatubo	Luzon, Philippines	6

Because the three eruptions happened before my sites' general growing season (growing season of June, July, August, September), I analyzed only the year of the eruption because it would have impacted the current year's climatic variable. The composite, with n being year of eruption, is

$$composite = \left(\frac{n1 + n2 + n3}{3}\right) - 54\ year\ average$$

for both CRU temperature and CRU scPDSI analyses. I repeated the same process using only the 1991 Mount Pinatubo eruption since it is the largest eruption that has occurred during the instrumental period and might show a less muted effect. Significance levels ($p \leq 0.05$) were calculated using a t-test on GrADS and were contoured in composite maps for the three eruptions. The composite maps including only Mount Pinatubo did not have significance levels calculated because the sample size is only one.

Superposed Epoch Analysis

Superposed epoch analysis (SEA) is commonly used in studies involving the effects of volcanic eruptions on climate (Kelly and Sear 1984). The objective of SEA is to help clarify volcanic signals not common to individual events (noise) by identifying weak signals present in noisy data from the effects of a particular sequence of events (Taylor et al. 1980). For this project, I conducted SEA for each site to attempt to separate moisture, temperature, and irradiance influences.

To conduct SEA, first I selected event dates from the volcanic eruption time series (Table 2) (Sigl et al. 2015). I averaged the variables of these dates (i.e. reconstructed scPDSI data from tree-rings) in the statistical program R to produce pre- and post- volcanic signals over a nine-year window centered on the eruption year (year 0). The superposition clarifies the volcanic signals by averaging out features not common to individual events, which are believed to be caused by non-volcanic factors (Kelly and Sear 1984). I derived statistical significance from 10,000 Monte Carlo simulations of windows of the same length selected at random from the entire time series of the climate variable (Haurwitz and Brier 1981, Mooney and Duval 1993).

I ran SEA four times for each three sites: 1) all available eruption years, 2) eruption years with corresponding sample depth of 10 or greater, 3) top 10 largest eruptions according to the Sigl et al. paper (that also have a sample depth of 10 or greater), and 4) top five largest eruption with a sample depth of 10 or greater (Tables 6 - 8). For the first run, all 25 eruptions are used when performing SEA at Khorgo lava. However, only 24 eruptions are used for Urgaat lava and 17 eruptions at Sol Dav due to shorter chronologies.

Table 6: Events used for SEA at Khorgo lava

	Khorgo Lava Pine – Eruption Event Years Used for SEA Analysis			
	All Eruption Events	**At Least 10 Sample Depth**	**Top 10 Largest Eruption Events**	**Top 5 Largest Eruption Events**
	-426	-44	-44	-44
	-44	87	266	540
	87	169	540	1258
	169	266	574	1458
	266	433	682	1815
	433	536	1230	
	536	540	1258	
	540	574	1458	
	574	626	1783	
	626	682	1815	
	682	939		
	939	1108		
	1108	1171		
	1171	1230		
	1230	1258		
	1258	1286		
	1286	1345		
	1345	1458		
	1458	1601		
	1601	1641		
	1641	1695		
	1695	1783		
	1783	1809		
	1809	1815		
	1815			
Total Events:	25	24	10	5

Table 7: Events used for SEA at Urgaat lava

	Urgaat Lava Pine – Eruption Event Years Used for SEA Analysis			
	All Eruption Events	**At Least 10 Sample Depth**	**Top 10 Largest Eruption Events**	**Top 5 Largest Eruption Events**
	-44	536	266	540
	87	540	540	1230
	169	574	574	1258
	266	626	682	1458
	433	682	1230	1815
	536	939	1258	
	540	1108	1458	
	574	1171	1783	
	626	1230	1809	
	682	1258	1815	
	939	1286		
	1108	1345		
	1171	1458		
	1230	1601		
	1258	1641		
	1286	1695		
	1345	1783		
	1458	1809		
	1601	1815		
	1641			
	1695			
	1783			
	1809			
	1815			
Total Events:	24	19	10	5

Table 8: Events used for SEA at Sol Dav

	Sol Dav – Eruption Event Years Used for SEA Analysis			
	All Eruption Events	**At Least 10 Sample Depth**	**Top 10 Largest Eruption Events**	**Top 5 Largest Eruption Events**
	574	939	574	1230
	626	1108	682	1258
	682	1171	1108	1458
	939	1230	1230	1783
	1108	1258	1258	1815
	1171	1286	1458	
	1230	1345	1641	
	1258	1458	1783	
	1286	1601	1809	
	1345	1641	1815	
	1458	1695		
	1601	1783		
	1641	1809		
	1695	1815		
	1783			
	1809			
	1815			
Total Events:	17	14	10	5

Tree-ring Anatomy Due to Droughts

In addition to the SEA statistical analysis, I looked for anatomical evidence (ring width, frost rings, false rings, locally absent rings, and completely absent rings) (Table 9) of volcanic eruptions from the Khorgo lava and Urgaat lava tree samples (Tables 10 - 11). Like SEA, I examined 9-year windows centered on each eruption year. Observed and total sample depths are listed under Table 12. Observed samples are what I found while examining cross-sections from the list of samples under Table 10 and Table 11 (for false rings and absent rings) while the total sample depth (only available for absent rings) includes values from the entire chronology. Sol Dav is excluded from this analysis since we do not have the cross-sections.

Each anatomical feature of a tree-ring is important in studying if tree-growth is affected by large events such as volcanic eruptions. Ring width, or the size of each ring measured to 0.01 mm precision, is important because it shows the general growth pattern of a tree and if there were any anomalies (especially large or small rings) that may have been caused by the limiting factor during that year of the growing season. Frost rings are annual growth increments that have cellular irregularities caused by freeze damage during the growing season that signify cold conditions related to volcanic and other large events that cause colder than average temperatures (D'Arrigo et al. 2001, LaMarche and Hirschboeck 1984). False rings, or "double rings", are where a dark-colored latewood band appears in the light-colored earlywood of the ring. Frequently the last-formed latewood of a false ring is not clearly delineated because it gradually blends in with the earlywood on either side (Stokes and Smiley 1996). This suggests that there may have been an onset of a decrease in limiting factor (cooler temperatures or drier growing season) before the end of the growing season. Locally absent rings and completely absent rings are similar. The locally absent ring is the absence of an annual ring from some portion of the sample. A completely absent ring is when the ring is not visible at any location of the cross-section. Both these features are caused by a decrease in the limiting factor (such as a decrease in temperature or a decrease in moisture availability) at each location.

Table 9: Tree-ring anatomy features to examine

Ring Anatomy Feature
Ring-width
Frost Ring
False Ring
Locally Absent Ring
Completely Absent Ring

Table 10: Samples analyzed from Khorgo lava, including the inside ring year, outside ring year, and total number of rings

Khorgo Lava Pine			
Sample ID	**Inside**	**Outside**	**Rings**
KLP3023x	562	1472	911
KLP3036x	1434	1840	407
KLP3040x	984	1399	416
KLP3067x	497	1090	594
KLP3079x	105	736	632
KLP3087x	31	854	824
KLP3110x	345	878	534
KLP3118	1130	1456	327
KLP3156x	155	755	601
KLP4061x	450	993	544
KLP5002x	299	1109	811
KLP5006x	670	1343	674
KLP6007x	474	1028	555
KLP6019x	785	1698	914
KLP6020x	1070	1310	241
KLP6020y	1046	1301	256
KLP6031x	153	716	564
KLP6031y	-731	-210	512
KLP6035	-364	449	814
KLP7010x	1044	1417	374
KLP7012x	1089	1692	604
KLP7019x	1200	1574	375
KLP7025x	1105	1307	203
KLP8007x	493	880	388
KLP8017x	688	1314	627
KLP8022x	465	945	481
KLP9026	196	877	682

Table 11: Samples analyzed from Urgaat lava including the inside ring year, outside ring year, and number of years the sample covers

Urgaat Lava Pine			
Sample ID	**Inside**	**Outside**	**Years**
ULP3002x	362	1080	719
ULP3002Y	345	855	511
ULP3002z	51	329	279
ULP4003x	920	1310	391
ULP4010x	591	1517	927
ULP4018x	508	1200	693
ULP4020x	230	766	537
ULP4028x	-179	725	905
ULP5008x	1596	1839	244
ULP5018x	328	955	628
ULP5028x	528	1150	623
ULP6005x	528	880	353
ULP6011x	1471	1980	510
ULP6013x	1196	1535	340
ULP6013y	869	1454	586
ULP6021x	480	871	392
ULP6023x	1118	1762	645
ULP6035x	1173	1494	322
ULP6045x	1047	1661	615
ULP6049x	1023	1418	396
ULP6053x	257	946	690
ULP6059x	1128	1667	540
ULP6063x	171	766	596
ULP7020x	491	1044	554
ULP7026x	768	1624	857

Table 12: Observed and total sample depth for Khorgo lava and Urgaat lava

Year	Khorgo Observed Sample Depth	Khorgo Total Sample Depth	Urgaat Observed Sample Depth	Urgaat Total Sample Depth
-426	1	3	NA	NA
-44	1	10	1	2
87	2	15	2	2
169	4	18	2	3
266	5	25	5	6
433	9	36	7	9
536	12	43	12	16
540	12	45	12	16
574	13	46	12	18
626	13	47	13	21
682	14	48	13	22
939	9	56	10	26
1108	11	60	9	22
1171	11	65	9	25
1230	13	68	12	26
1258	13	89	12	28
1286	13	72	12	28
1345	8	65	11	29
1458	6	61	8	30
1601	2	51	6	31
1641	2	55	6	32
1695	2	59	3	28
1783	1	50	2	25
1809	1	42	2	25
1815	1	42	2	25

I computed the statistical significance of receiving a false ring and absent ring using a chi-square test for each anatomy at each location. For false rings, I counted the observed false rings and total number of samples observed for the four years before the eruption, the year of the eruption, and four years after the eruption for each eruption event (the same nine-year window as SEA). The chi-square test compared the false rings before the eruptions (four years before) to the year of the eruption and four years after (five-year window). I compared the frequency of events during the years preceding the eruptions and the years following the eruptions (presumably influenced by the eruptions).

For absent rings, I used the COFECHA output that reports the total number of absent rings in the chronology along with the total number of rings for each calendar year in the chronology. Due to this, the sample size will not be the same as the false rings analysis. I analyzed the same nine-year window as the false rings analysis for each of the eruptions. This provided me with the observed values used to calculate the chi-square value.

Results

Volcanic Eruptions During the Instrumental Period in Mongolia

The composite analyses performed in GrADS using CRU temperature and CRU scPDSI show little change in climate following volcanic eruptions during the modern instrumental period in Mongolia (Figures 3 - 6). The composite analyses following the three tropical eruptions show an increase of up to an scPDSI value of two in central and northern Mongolia. A small region in central Mongolia was found to be statistically significantly wetter ($p \leq 0.05$). In terms of temperature, the composite analyses show that most of Mongolia, especially central Mongolia, experienced a ~0.1° - 0.3°C cooling in the year of the eruption though results were not statistically significant (significance set at $p \leq 0.05$). Southeast and southwest Mongolia experienced a statistically insignificant 0.2°C warming. Results of the composite analysis following just the 1991 Mount Pinatubo eruption show the majority of Mongolia being wetter by scPDSI values of one to three. Only small regions of Mongolia were drier following the eruption by scPDSI value of negative one including southeast Mongolia and small patches in southern, central, and western Mongolia. We found a warming trend in the majority of Mongolia of up to 1.0°C with only a small region in eastern Mongolia experiencing a cooling of about 0.8°C. Significance testing was not performed while analyzing the Mount Pinatubo eruption due to the sample size.

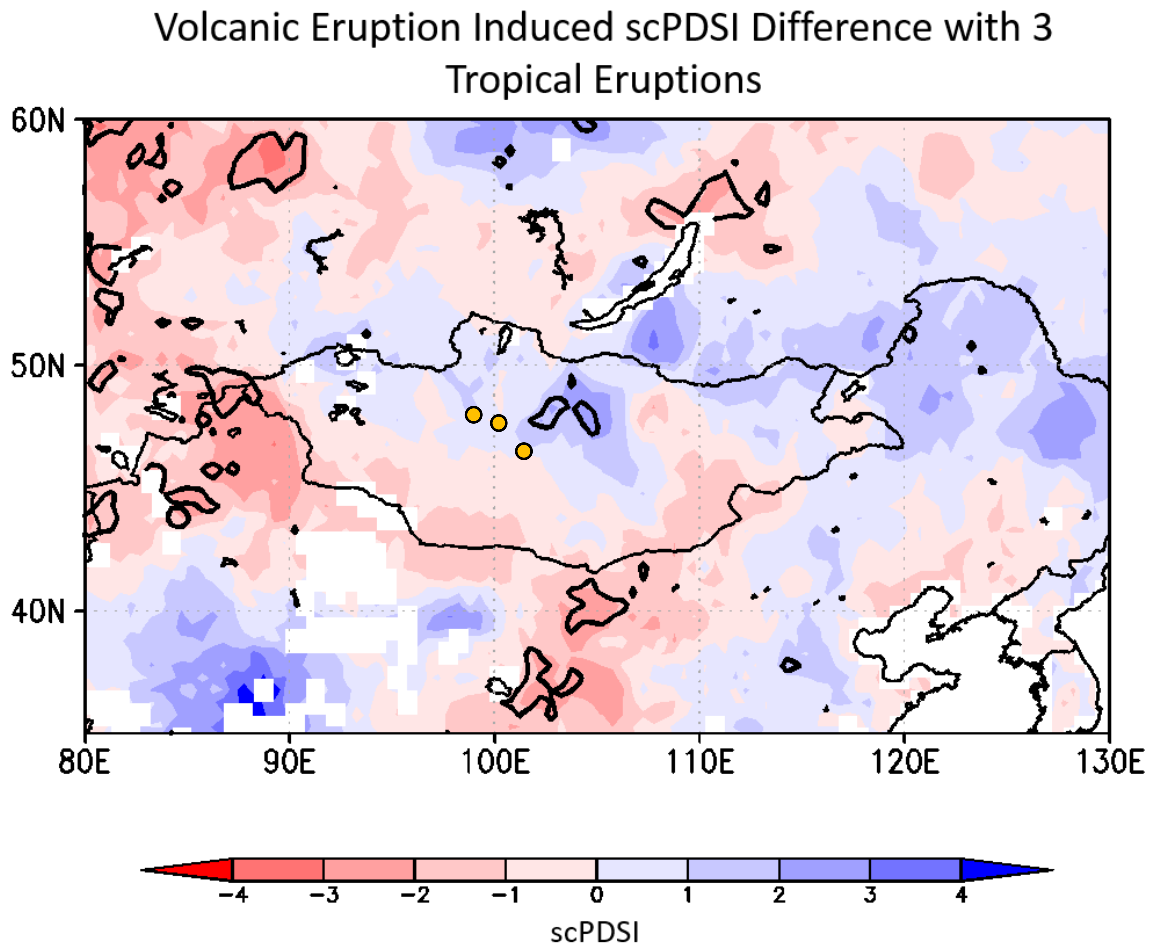


Figure 3: scPDSI composite difference using the 1963, 1982, and 1991 eruptions with a 54-year mean. Yellow dots represent the approximate locations of the three study sites

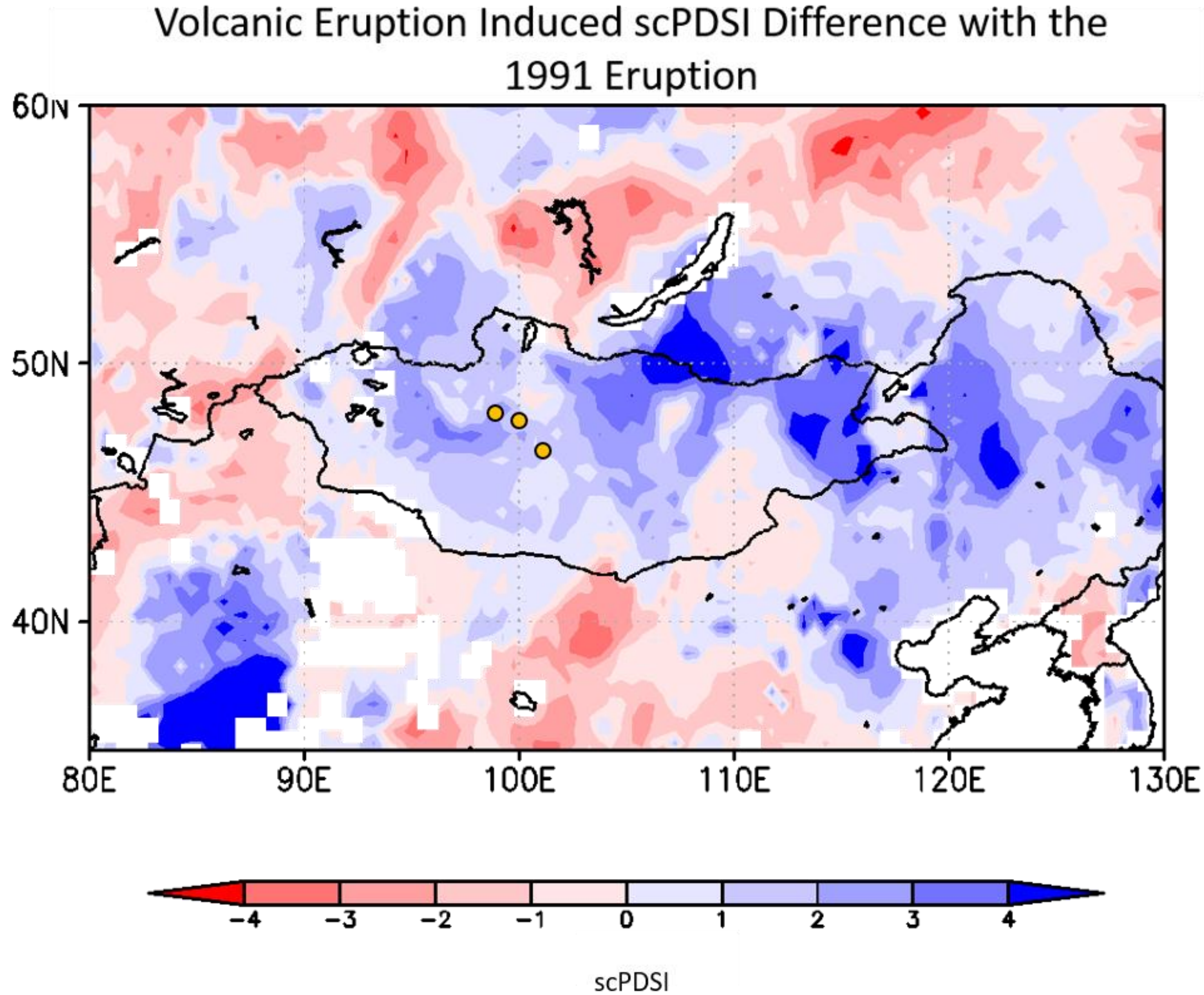


Figure 4: scPDSI composite difference comparing the 1991 eruption with a 54-year mean. Yellow dots represent the approximate locations of the three study sites

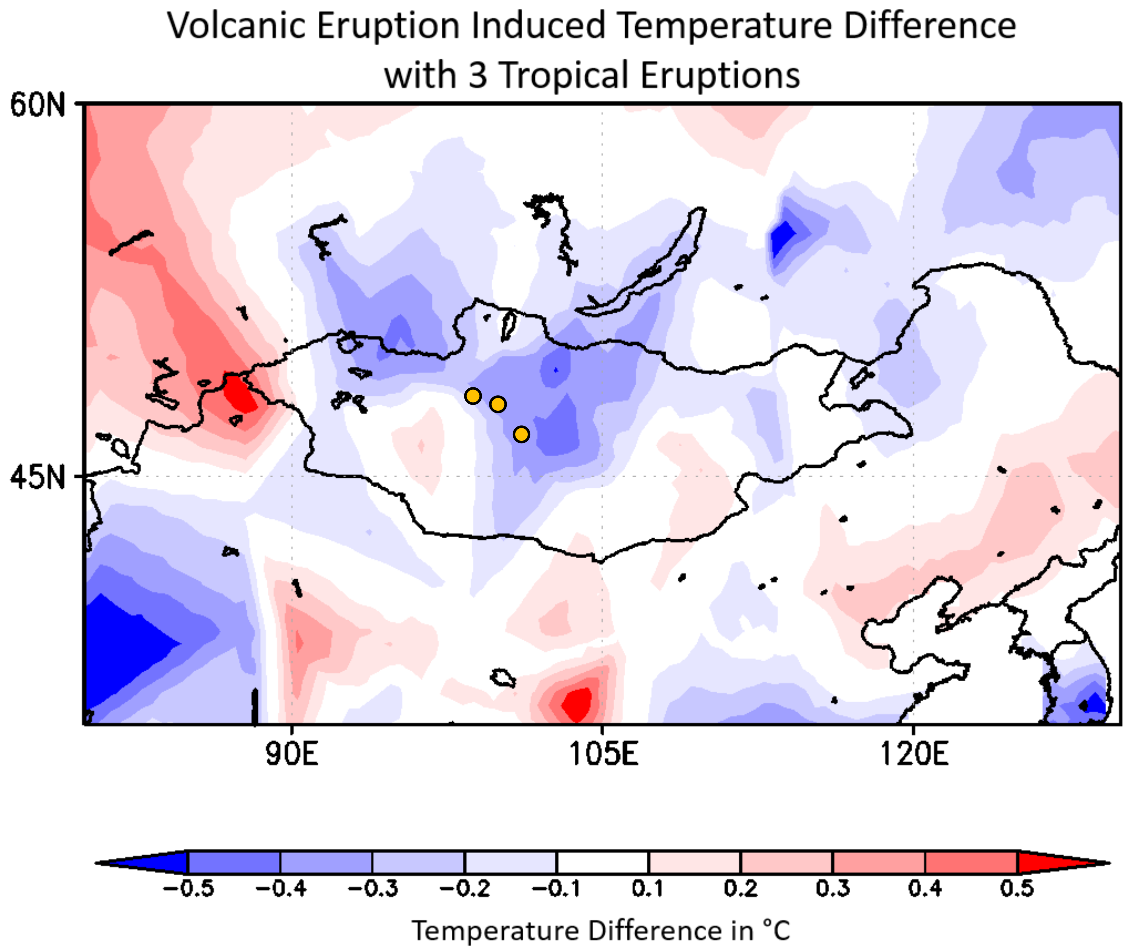


Figure 5: Temperature difference between the 1963, 1982, and 1991 eruptions with a 54-year average. Yellow dots represent the approximate locations of the three study sites

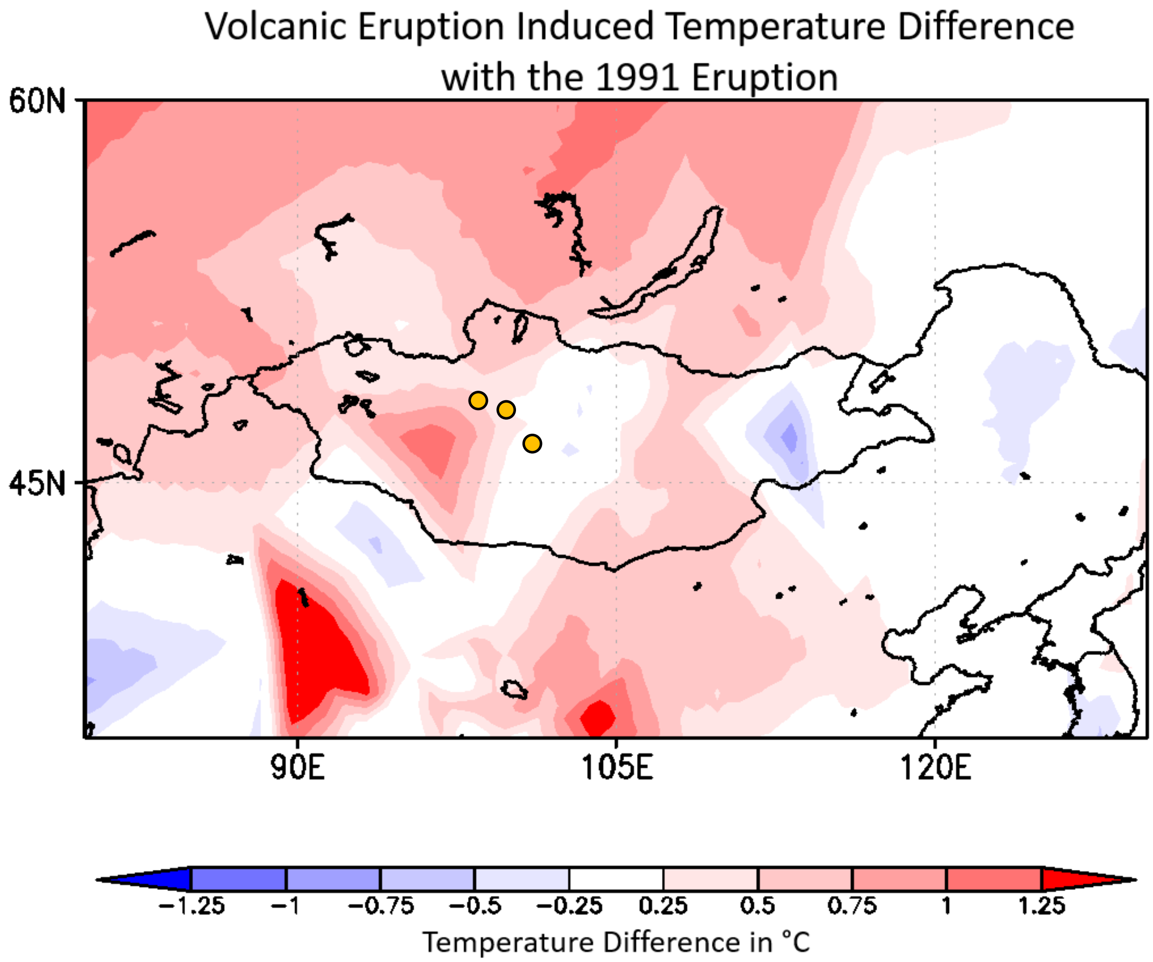


Figure 6: Temperature difference between the 1991 eruption and 54-year average. Yellow dots represent the approximate locations of the three study sites

SEA Results

I observed no clear evidence of volcanic eruption induced temperature or moisture availability differences at Sol Dav, Khorgo lava, and Urgaat lava during the four SEA runs (Figures 7 - 18). During run one, (the complete volcanic eruption series) reconstructed scPDSI values at Khorgo lava and Urgaat lava are slightly lower the year after the eruption. At Khorgo lava, the second year after the eruption scPDSI values return to near average while Urgaat lava continues to become drier. Year three is slightly wetter than average at Khorgo lava and Urgaat lava. All these fell within the 95% confidence levels. I observed no statistically significant differences in index values at Sol Dav (temperature-sensitive location) except for in year four. However, based on previous literature, we would consider year four to be outside the realm of volcanic-induced climate variation. Years negative three to one show in increase in index value, thus an increase in ring width. Years zero to two hover slightly below the mean index value of 0.0 with a gradual decrease from year three to year four with an index value of about -0.5. The following three runs resulted in similar patterns of climate variability during the nine-year window. Most notably, results for the top 10 largest eruptions for both Khorgo lava and Urgaat lava were not significant at the 95% level. Results for the top five largest eruptions were also statistically insignificant at the 95% level but showed slightly more volcanic eruption induced moisture differences. They show recovery and decline patterns similar to the other SEA runs. SEA performed at Sol Dav during the top 10 and top five largest eruptions runs still fell within the 95% confidence levels, however, those values are close to being statistically significant while performing SEA with the top five largest eruptions.

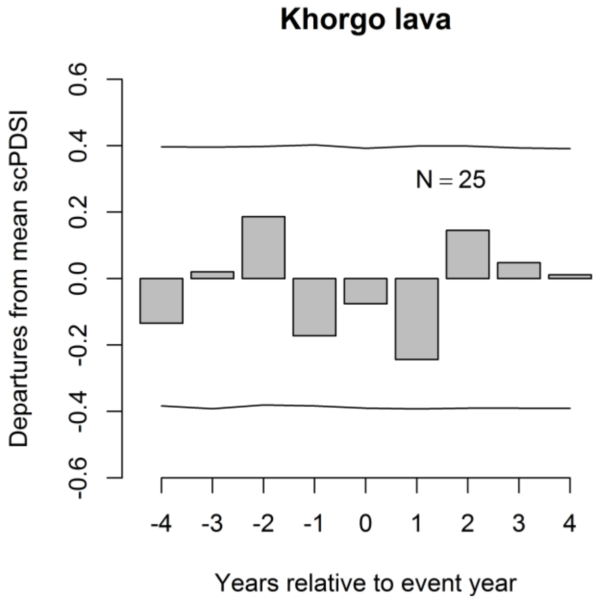


Figure 7: SEA results at Khorgo lava using all 25 eruptions. The lower and upper lines represent the 95% confidence limits

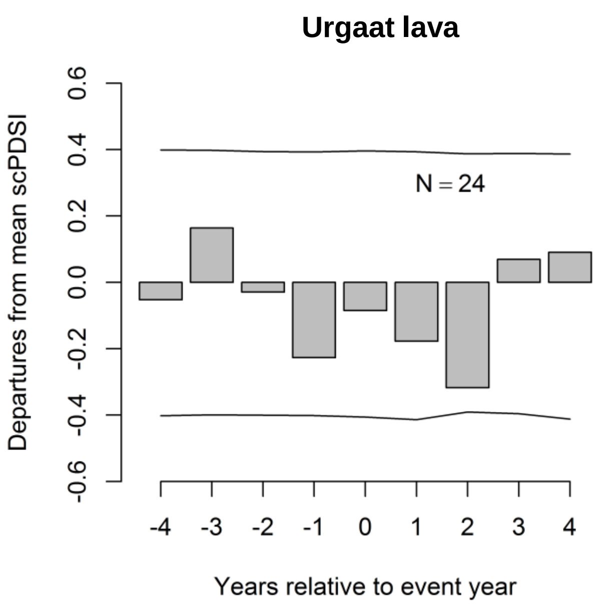


Figure 8: SEA results at Urgaat lava using 24 eruptions due to length of reconstruction. The lower and upper lines represent the 95% confidence limits

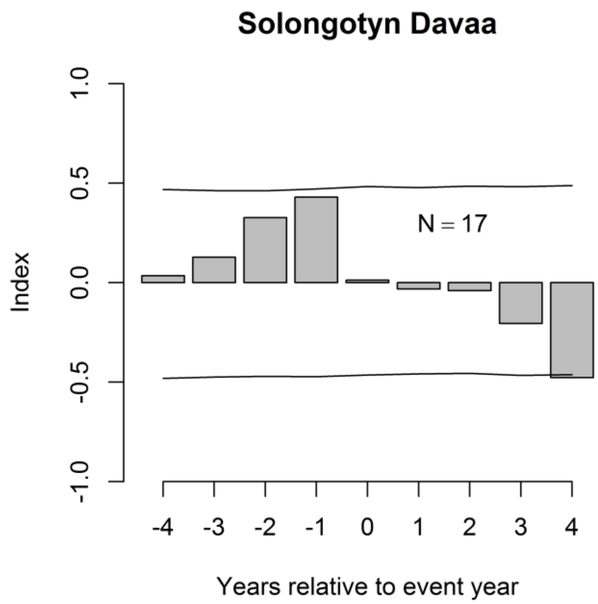


Figure 9: SEA results at Sol Dav using 17 eruptions due to length of chronology. The lower and upper lines represent the 95% confidence limits

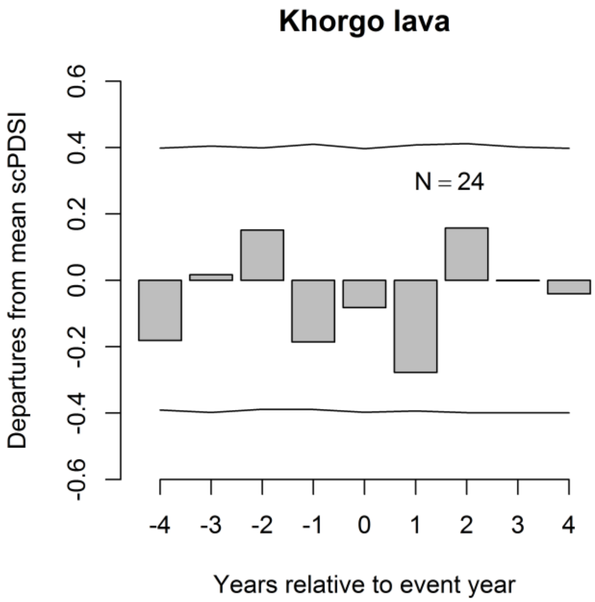
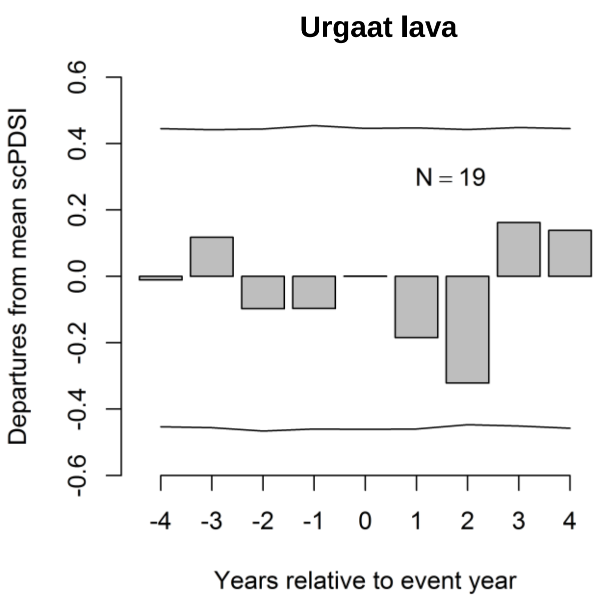


Figure 10: SEA performed at Khorgo lava using years in the reconstruction that has a sample depth of 10 or greater. The lower and upper lines represent the 95% confidence limits



reconstruction that has a sample depth of 10 or greater. The lower and upper lines represent the 95% confidence limits

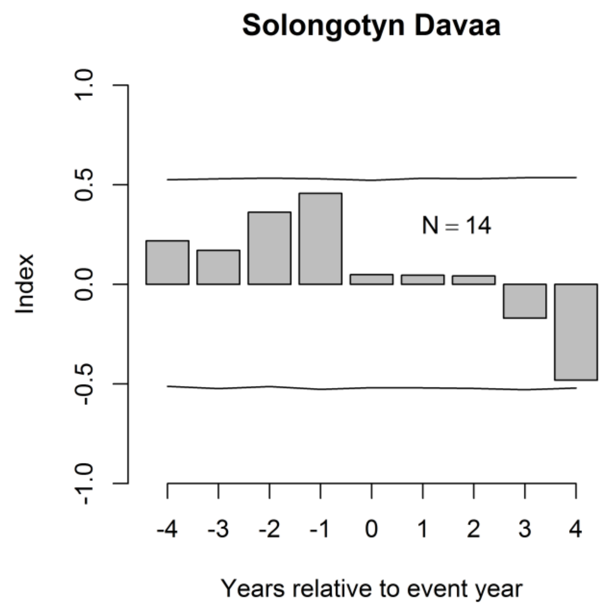


Figure 12: SEA performed at Sol Dav using years in the chronology that has a sample depth of 10 or greater. The lower and upper lines represent the 95% confidence limits

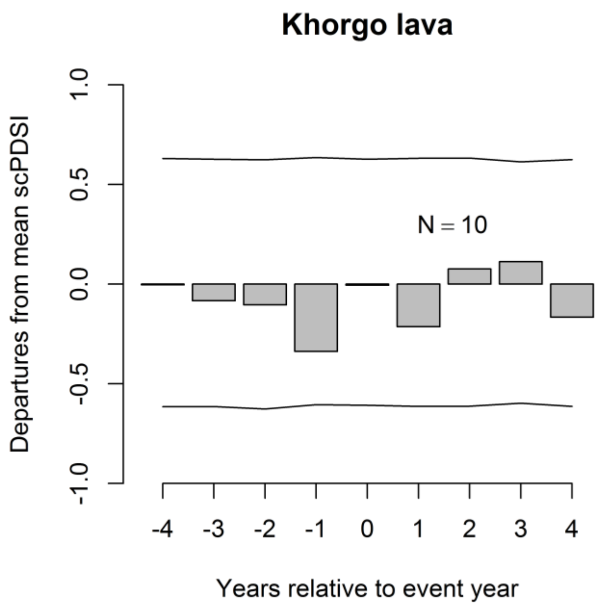


Figure 13: SEA using the 10 largest eruptions on the Sigl et al. (2015) table that also have at least 10 sample depth at Khorgo lava. The lower and upper lines represent the 95% confidence limits

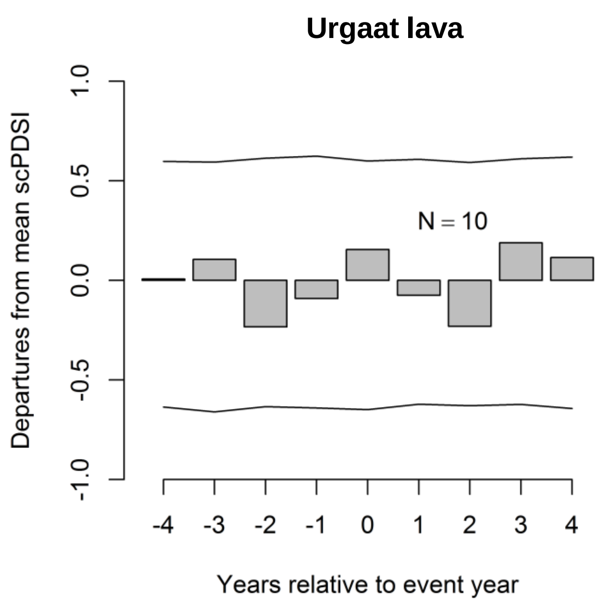


Figure 14: SEA using the 10 largest eruptions on the Sigl et al. (2015) table that also have at least 10 sample depth at Urgaat lava. The lower and upper lines represent the 95% confidence limits

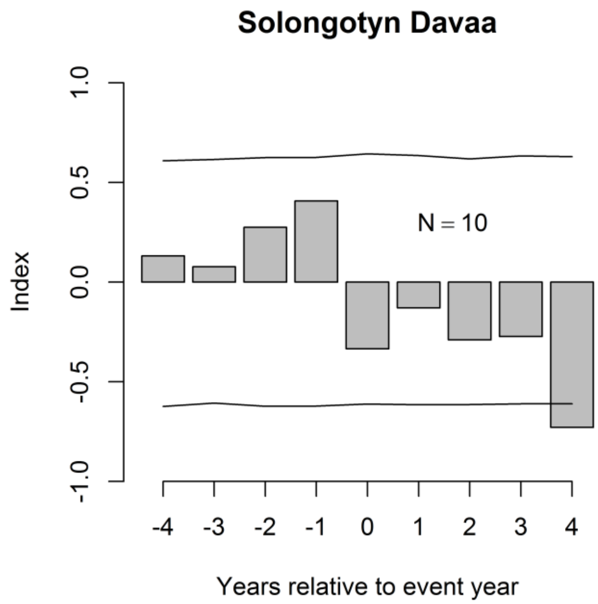


Figure 15: SEA using the 10 largest eruptions on the Sigl et al. (2015) table that also have at least 10 sample depth at Sol Dav. The lower and upper lines represent the 95% confidence limits

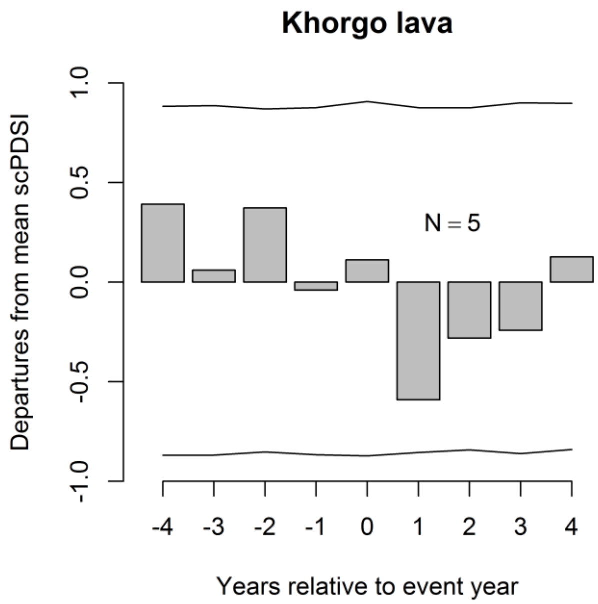


Figure 16: SEA using the 5 largest eruptions on the Sigl et al. (2015) table that also have at least 10 sample depth at Khorgo lava. The lower and upper lines represent the 95% confidence limits

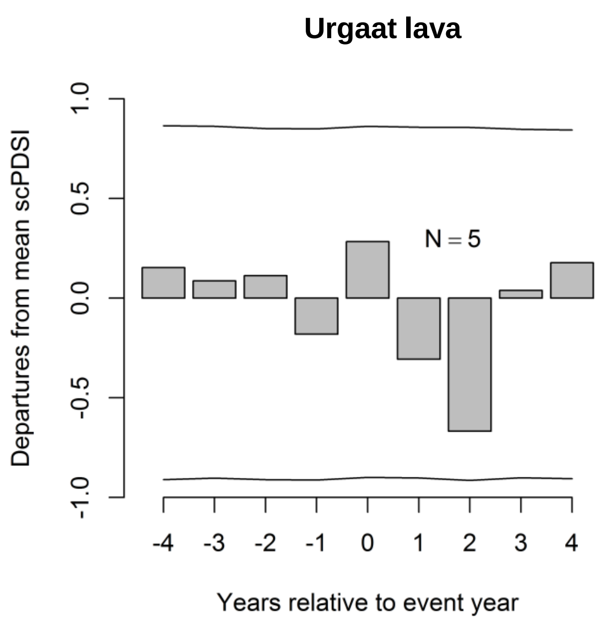


Figure 17: SEA using the 5 largest eruptions on the Sigl et al. (2015) table that also have at least 10 sample depth at Urgaat lava. The lower and upper lines represent the 95% confidence limits

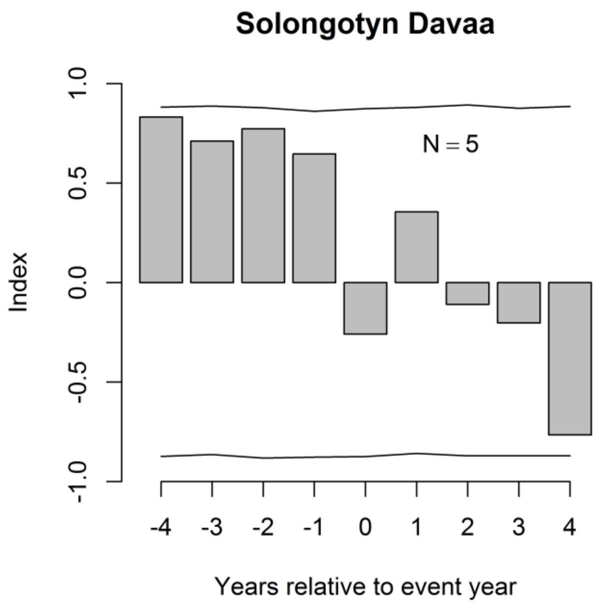


Figure 18: SEA using the 5 largest eruptions on the Sigl et al. (2015) table that also have at least 10 sample depth at Sol Dav. The lower and upper lines represent the 95% confidence limits

Tree-ring Anatomy Results

I found that during the tree-ring anatomy analysis, Khorgo lava and Urgaat lava tree growth were affected by select eruption events (Tables 13 – 16, Figures 19 - 20). False rings were detected at Khorgo lava for eruption event years -426, 87,169, 433, 536, 540, 574, 626, 682, 939, 1108, 1230, 1258, 1345, and 1458 and at Urgaat lava for years 87, 540, 939, 1258, and 1345. A chi-square test shows that year two at Khorgo lava has a statistically significant difference in false rings when compared to non-eruption induced years (p-value =0.013) (Table 17). All years following an eruption at Urgaat lava have p-values of greater than 0.05, thus we do not have enough evidence to say that it is statistically different from non-eruption induced years.

Along with false rings, absent rings were detected for eruption event years 87, 1230, 1258, 1286, 1345, 1641, 1695, 1809, and 1815 at Khorgo lava (Table 15). At Urgaat lava the event years that showed absent rings during the five-year post-eruption period include years 939 and 1258 (Table 16). All other eruption event years that were available during this chronology did not have any missing rings present. Chi-square test showed that the second year following the eruption have statistically significant difference in absent rings when compared to the rest of the chronology (p-value at Khorgo lava = 0.019 and p-value at Urgaat lava = 0.033) (Table 17).

*Table 13: Percent of observed samples showing false rings at Khorgo lava during the year of the eruption and four years after. * resembles year of eruption*

Khorgo Lava Pine False Rings

Year	% Showing	Year	% Showing	Year	% Showing	Year	% Showing	Year	% Showing
*-426	0%	*433	0%	*682	7%	*1258	0%	*1641	0%
-425	0%	434	0%	683	0%	1259	15%	1642	0%
-424	100%	435	0%	684	0%	1260	0%	1643	0%
-423	0%	436	22%	685	0%	1261	8%	1644	0%
-422	0%	437	11%	686	0%	1262	8%	1645	0%
*-44	0%	*536	0%	*939	0%	*1286	0%	*1695	0%
-43	0%	537	8%	940	0%	1287	0%	1696	0%
-42	0%	538	0%	941	22%	1288	0%	1697	0%
-41	0%	639	0%	942	11%	1289	0%	1698	0%
-40	0%	*540	0%	943	0%	1290	0%	1699	0%
*87	50%	541	0%	*1108	0%	*1345	0%	*1783	0%
88	0%	542	42%	1109	0%	1346	0%	1784	0%
89	0%	543	8%	1110	27%	1347	63%	1785	0%
90	0%	544	0%	1111	0%	1348	0%	1786	0%
91	0%	*574	0%	1112	0%	1349	38%	1787	0%
*169	25%	575	0%	*1171	0%	*1458	0%	*1809	0%
170	25%	576	0%	1172	0%	1459	0%	1810	0%
171	0%	577	0%	1173	0%	1460	0%	1811	0%
172	0%	578	38%	1174	0%	1461	0%	1812	0%
173	0%	*626	0%	1175	0%	1462	17%	1813	0%
*266	0%	627	0%	*1230	0%	*1601	0%	*1815	0%
267	0%	628	0%	1231	23%	1602	0%	1816	0%
268	0%	629	0%	1232	0%	1603	0%	1817	0%
269	0%	630	8%	1233	0%	1604	0%	1818	0%
270	0%			1234	0%	1605	0%	1819	0%

*Table 14: Percent of observed samples showing false rings at Urgaat lava during the year of the eruption and four years after. * resembles year of eruption*

Urgaat Lava Pine False Rings

Year	% Showing	Year	% Showing	Year	% Showing	Year	% Showing	Year	% Showing
*-426	NA	*433	0%	*682	0%	*1258	0%	*1641	0%
-425	NA	434	0%	683	0%	1259	0%	1642	0%
-424	NA	435	0%	684	0%	1260	8%	1643	0%
-423	NA	436	0%	685	0%	1261	0%	1644	0%
-422	NA	437	0%	686	0%	1262	0%	1645	0%
*-44	0%	*536	0%	*939	0%	*1286	0%	*1695	0%
-43	0%	537	0%	940	0%	1287	0%	1696	0%
-42	0%	538	0%	941	11%	1288	0%	1697	0%
-41	0%	639	0%	942	0%	1289	0%	1698	0%
-40	0%	*540	0%	943	0%	1290	0%	1699	0%
*87	50%	541	0%	*1108	0%	*1345	0%	*1783	0%
88	0%	542	8%	1109	0%	1346	0%	1784	0%
89	0%	543	0%	1110	0%	1347	9%	1785	0%
90	0%	544	0%	1111	0%	1348	0%	1786	0%
91	0%	*574	0%	1112	0%	1349	0%	1787	0%
*169	0%	575	0%	*1171	0%	*1458	0%	*1809	0%
170	0%	576	0%	1172	0%	1459	0%	1810	0%
171	0%	577	0%	1173	0%	1460	0%	1811	0%
172	0%	578	0%	1174	0%	1461	0%	1812	0%
173	0%	*626	0%	1175	0%	1462	0%	1813	0%
*266	0%	627	0%	*1230	0%	*1601	0%	*1815	0%
267	0%	628	0%	1231	0%	1602	0%	1816	0%
268	0%	629	0%	1232	0%	1603	0%	1817	0%
269	0%	630	0%	1233	0%	1604	0%	1818	0%
270	0%			1234	0%	1605	0%	1819	0%

Table 15: Percent of total samples in chronology showing absent rings at Khorgo lava during the year of the eruption and four years after.
** resembles year of eruption*

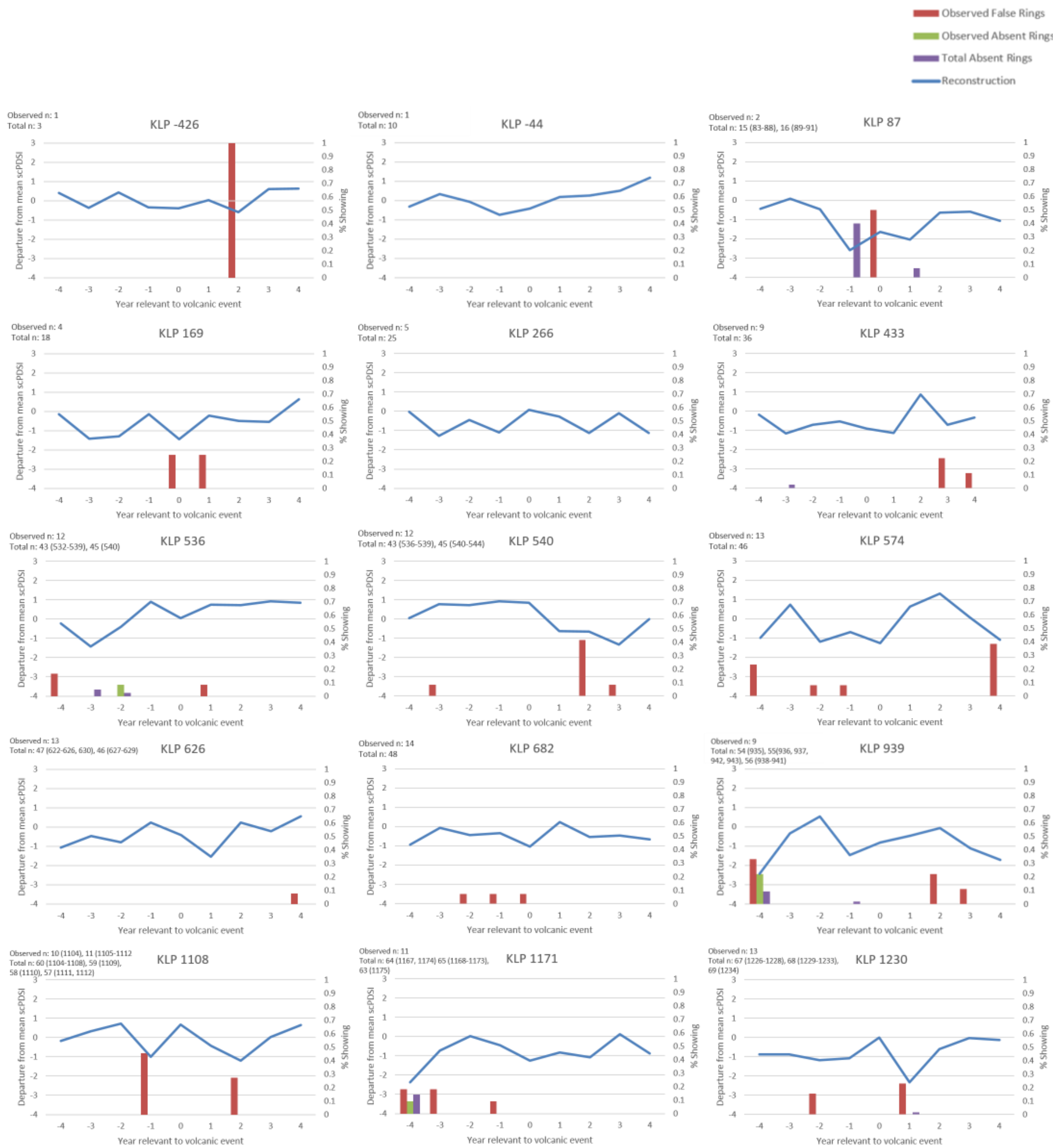
Khorgo Lava Pine Absent Rings

Year	% Showing	Year	% Showing	Year	% Showing	Year	% Showing	Year	% Showing
*-426	0%	*433	0%	*682	0%	*1258	0%	*1641	5.5%
-425	0%	434	0%	683	0%	1259	14.5%	1642	1.8%
-424	0%	435	0%	684	0%	1260	1.4%	1643	0%
-423	0%	436	0%	685	0%	1261	0%	1644	0%
-422	0%	437	0%	686	0%	1262	0%	1645	0%
*-44	0%	*536	0%	*939	0%	*1286	0%	*1695	0%
-43	0%	537	0%	940	0%	1287	0%	1696	0%
-42	0%	538	0%	941	0%	1288	0%	1697	0%
-41	0%	639	0%	942	0%	1289	0%	1698	1.7%
-40	0%	*540	0%	943	0%	1290	1.4%	1699	0%
*87	0%	541	0%	*1108	0%	*1345	0%	*1783	0%
88	6.7%	542	0%	1109	0%	1346	0%	1784	0%
89	0%	543	0%	1110	0%	1347	0%	1785	0%
90	0%	544	0%	1111	0%	1348	0%	1786	0%
91	0%	*574	0%	1112	0%	1349	0%	1787	0%
*169	0%	575	0%	*1171	0%	*1458	0%	*1809	0%
170	0%	576	0%	1172	0%	1459	0%	1810	0%
171	0%	577	0%	1173	0%	1460	0%	1811	0%
172	0%	578	0%	1174	0%	1461	0%	1812	2.4%
173	0%	*626	0%	1175	0%	1462	0%	1813	0%
*266	0%	627	0%	*1230	0%	*1601	0%	*1815	0%
267	0%	628	0%	1231	1.5%	1602	0%	1816	0%
268	0%	629	0%	1232	0%	1603	0%	1817	0%
269	0%	630	0%	1233	0%	1604	0%	1818	0%
270	0%			1234	0%	1605	0%	1819	2.4%

Table 16: Percent of total samples in chronology showing absent rings at Urgaat lava during the year of the eruption and four years after.
** resembles year of eruption*

Urgaat Lava Pine Absent Rings

Year	% Showing	Year	% Showing	Year	% Showing	Year	% Showing	Year	% Showing
*-426	NA	*433	0%	*682	0%	*1258	0%	*1641	0%
-425	NA	434	0%	683	0%	1259	0%	1642	0%
-424	NA	435	0%	684	0%	1260	17.9%	1643	0%
-423	NA	436	0%	685	0%	1261	0%	1644	0%
-422	NA	437	0%	686	0%	1262	0%	1645	0%
*-44	0%	*536	0%	*939	0%	*1286	0%	*1695	0%
-43	0%	537	0%	940	0%	1287	0%	1696	0%
-42	0%	538	0%	941	3.8%	1288	0%	1697	0%
-41	0%	639	0%	942	0%	1289	0%	1698	0%
-40	0%	*540	0%	943	0%	1290	0%	1699	0%
*87	0%	541	0%	*1108	0%	*1345	0%	*1783	0%
88	0%	542	0%	1109	0%	1346	0%	1784	0%
89	0%	543	0%	1110	0%	1347	0%	1785	0%
90	0%	544	0%	1111	0%	1348	0%	1786	0%
91	0%	*574	0%	1112	0%	1349	0%	1787	0%
*169	0%	575	0%	*1171	0%	*1458	0%	*1809	0%
170	0%	576	0%	1172	0%	1459	0%	1810	0%
171	0%	577	0%	1173	0%	1460	0%	1811	0%
172	0%	578	0%	1174	0%	1461	0%	1812	0%
173	0%	*626	0%	1175	0%	1462	0%	1813	0%
*266	0%	627	0%	*1230	0%	*1601	0%	*1815	0%
267	0%	628	0%	1231	0%	1602	0%	1816	0%
268	0%	629	0%	1232	0%	1603	0%	1817	0%
269	0%	630	0%	1233	0%	1604	0%	1818	0%
270	0%			1234	0%	1605	0%	1819	0%


Observed False Rings
Observed Absent Rings
Total Absent Rings
Reconstruction
Observed n: 1
Total n: 3
KLP -426
Observed n: 1
Total n: 10
KLP -44
Observed n: 2
Total n: 15 (83-88), 16 (89-91)
KLP 87
Observed n: 4
Total n: 18
KLP 169
Observed n: 5
Total n: 25
KLP 266
Observed n: 9
Total n: 36
KLP 433
Observed n: 12
Total n: 43 (532-539), 45 (540)
KLP 536
Observed n: 12
Total n: 43 (536-539), 45 (540-544)
KLP 540
Observed n: 13
Total n: 46
KLP 574
Observed n: 13
Total n: 47 (622-626, 630), 46 (627-629)
KLP 626
Observed n: 14
Total n: 48
KLP 682
Observed n: 9
Total n: 54 (935), 55(936, 937, 942, 943), 56 (938-941)
KLP 939
Observed n: 10 (1104), 11 (1105-1112
Total n: 60 (1104-1108), 59 (1109), 58 (1110), 57 (1111, 1112)
KLP 1108
Observed n: 11
Total n: 64 (1167, 1174) 65 (1168-1173), 63 (1175)
KLP 1171
Observed n: 13
Total n: 67 (1226-1228), 68 (1229-1233), 69 (1234)
KLP 1230
Departure from mean scPDSI
% Showing
Year relevant to volcanic event

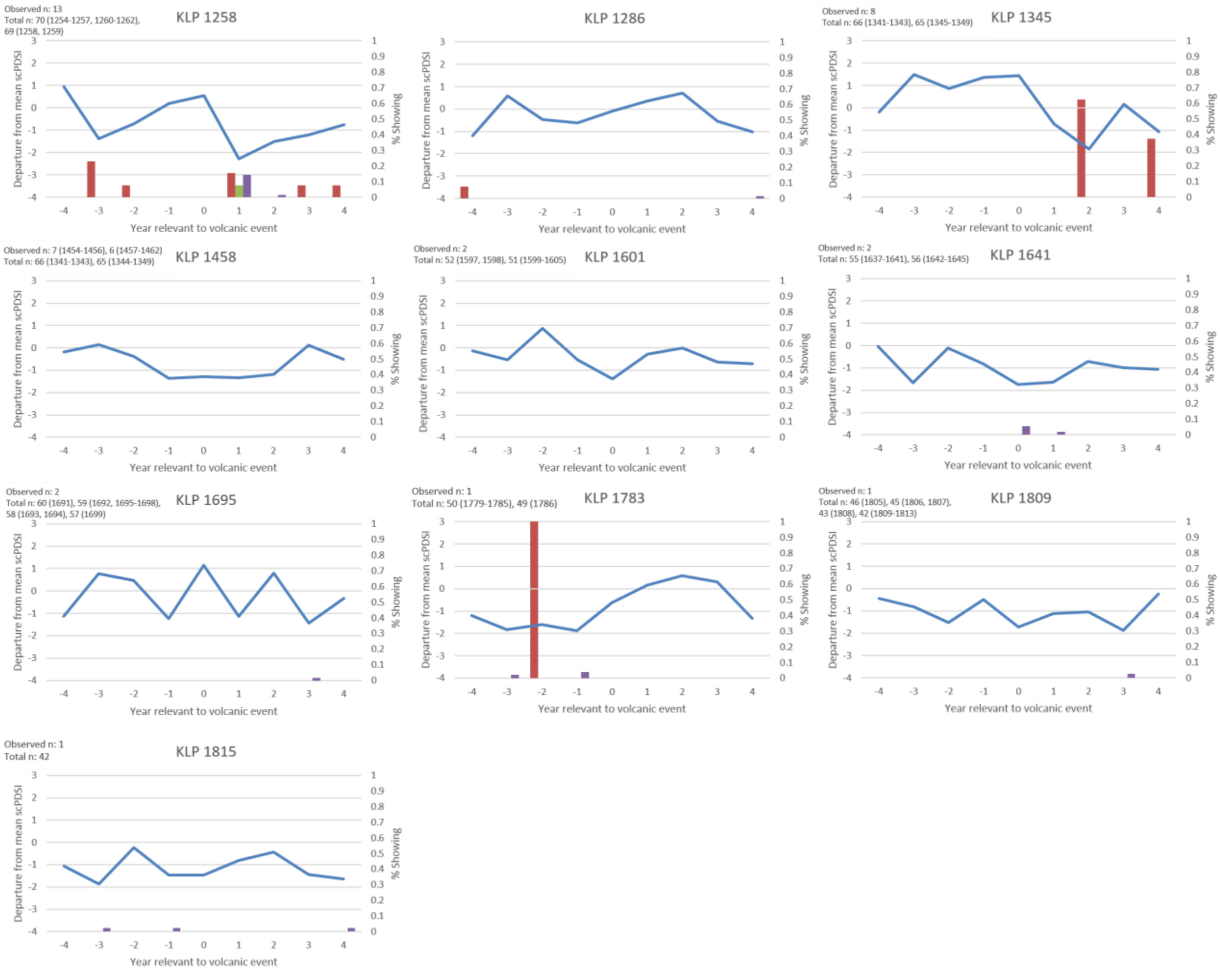
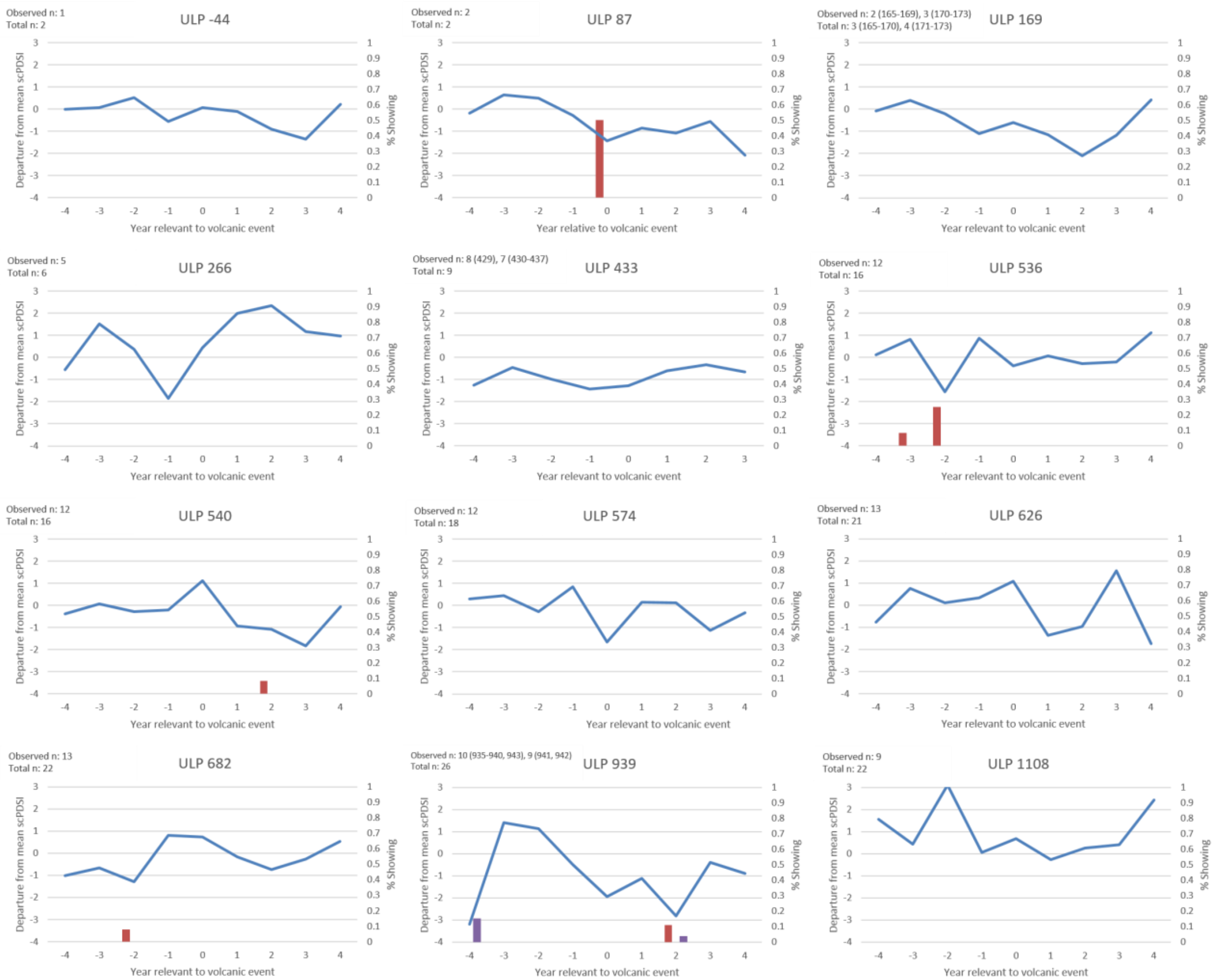


Figure 19: Plotting reconstruction values against percent observed false rings, percent observed absent rings, and percent total absent rings at Khorgo lava


Observed n: 1
Total n: 2
ULP -44
Departure from mean scPDSI
% Showing
Year relevant to volcanic event
Observed n: 2
Total n: 2
ULP 87
Year relative to volcanic event
Observed n: 2 (165-169), 3 (170-173)
Total n: 3 (165-170), 4 (171-173)
ULP 169
Observed n: 5
Total n: 6
ULP 266
Observed n: 8 (429), 7 (430-437)
Total n: 9
ULP 433
Observed n: 12
Total n: 16
ULP 536
Observed n: 12
Total n: 16
ULP 540
Observed n: 12
Total n: 18
ULP 574
Observed n: 13
Total n: 21
ULP 626
Observed n: 13
Total n: 22
ULP 682
Observed n: 10 (935-940, 943), 9 (941, 942)
Total n: 26
ULP 939
Observed n: 9
Total n: 22
ULP 1108

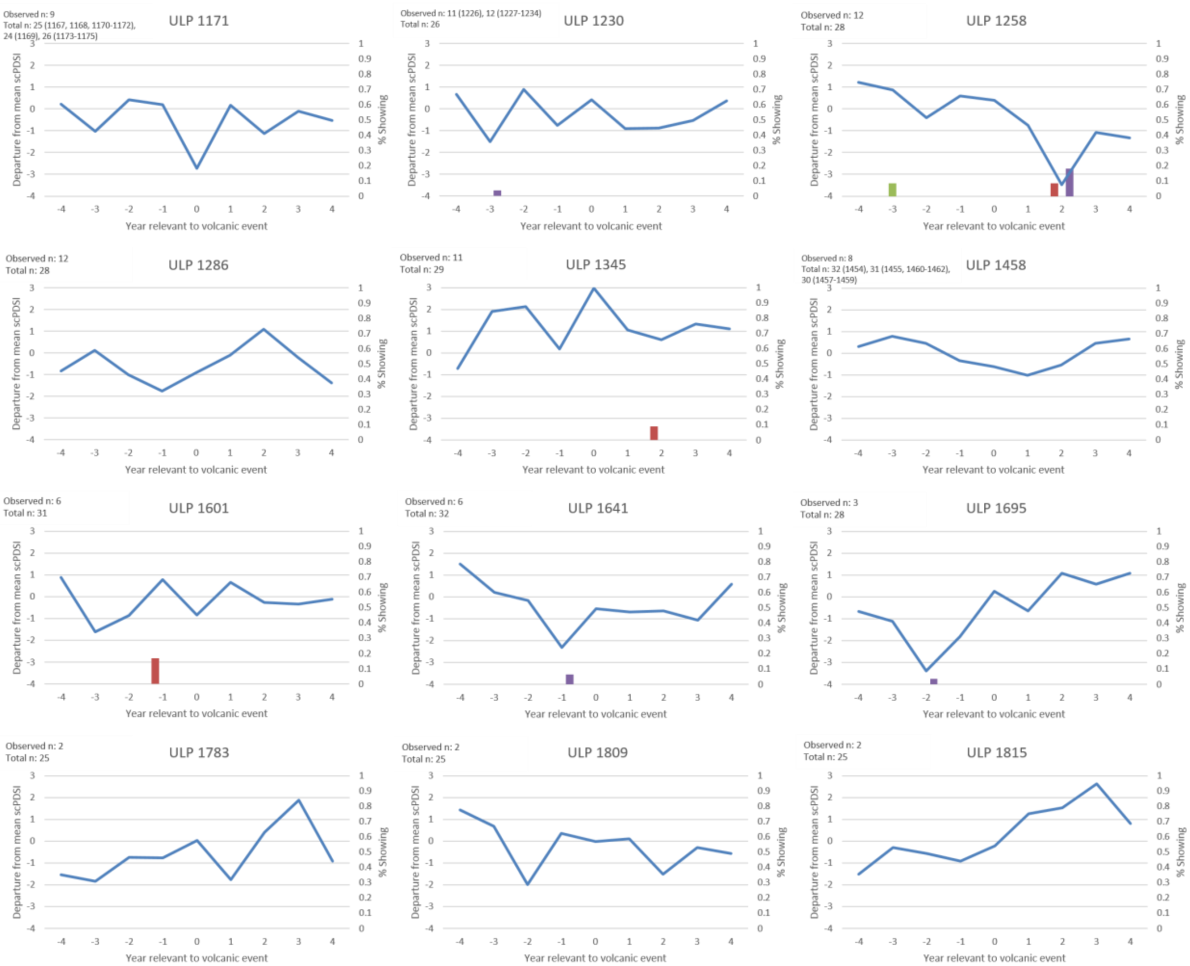


Figure 20: Plotting reconstruction values against percent observed false rings, percent observed absent rings, and percent total absent rings at Urgaat lava

Table 17: Chi-square results at Khorgo lava (KLP) and Urgaat lava (ULP) for false rings and absent rings

chi-square test
Khorgo False Rings

Year	**p-value**
0	0.098
1	0.809
2	0.013
3	0.353
4	0.429
Total, 0-4	0.458

chi-square test
Khorgo Absent Rings

Year	**p-value**
0	0.117
1	0.090
2	0.019
3	0.052
4	0.052
Total, 0-4	0.039

chi-square test
Urgaat False Rings

Year	**p-value**
0	0.704
1	0.218
2	0.112
3	0.219
4	0.218
Total, 0-4	0.496

chi-square test
Urgaat Absent Rings

Year	**p-value**
0	0.157
1	0.157
2	0.033
3	0.156
4	0.156
Total, 0-4	0.336

Discussion

The hypothesis of this study is that historical volcanic eruptions would alter key climate attributes (temperature, moisture availability, and solar irradiance) that would be recorded in tree-ring data. We found there to be no statistical significance in the influence of volcanic eruptions but tree-ring anatomy analysis suggests that we do in fact see the effect of some eruption events at Khogo lava and Urgaat lava. Composite analysis performed during the instrumental period and SEA analysis show that there is slightly lower than average growth at all three sites following volcanic eruptions but none were statistically significant from the mean. This suggests that there is in fact little change in the tree-growth at the three sites. This is evidence for little decline in temperature and moisture availability following eruptions, and thus little change in solar irradiance.

Instrumental Period Composite Analysis and SEA Analysis

We observed no statistically significant departures in instrumental climate during eruption years. The analyses using instrumental data and tree-ring chronologies reflect the uncertainties highlighted by the IPCC (2013) in that eruptions may not be as influential to climate as once believed. If looking at only the Mount Pinatubo eruption, Mongolia is wetter. Most of Mongolia is cooler after the three eruptions but by only ~0.1°-0.3°C of degrees. However, after the 1991 Mount Pinatubo eruption, most of Mongolia is just slightly warmer by up to 1.0°C. The eruptions used to construct the composite analysis during the instrumental period were some of the largest during the modern times. However, on the larger time scale, none of the three eruptions are on the list of top 25 largest eruptions. Thus the eruptions may not have been large enough to influence global climate. Other global forcing such as ENSO may have the potential to mask the effects of smaller volcanic eruptions (Robock and Mao 1994).

A recent similar study was done using a Siberian larch chronology from a nearby temperature-sensitive site, OZN (Davi et al. 2015) using a different set of eruption events. Figure 21 shows the results of her temperature-sensitive site with two different sets of eruptions running SEA. The year after the eruption is significant at the 99% confidence levels for the events listed by Crowley et al. (2008) while

the year of the eruptions was significant at the 95% confidence levels for the events listed by Gao et al. (2008). We had expected Sol Dav to display similar results as OZN since both are temperature-sensitive chronologies but they did not. This may be because: 1) Sol Dav may not be as sensitive to temperature as OZN or 2) the events used to perform SEA influenced the results more than anticipated. Sol Dav could not be used to generate a calibrated and validated reconstruction. The events under the Sigl et al. (2015) paper may be the most recent and complete list of volcanic eruptions for the past 2500 years, but there will always be some degree of uncertainty in the dating accuracy and in the proxy methods.

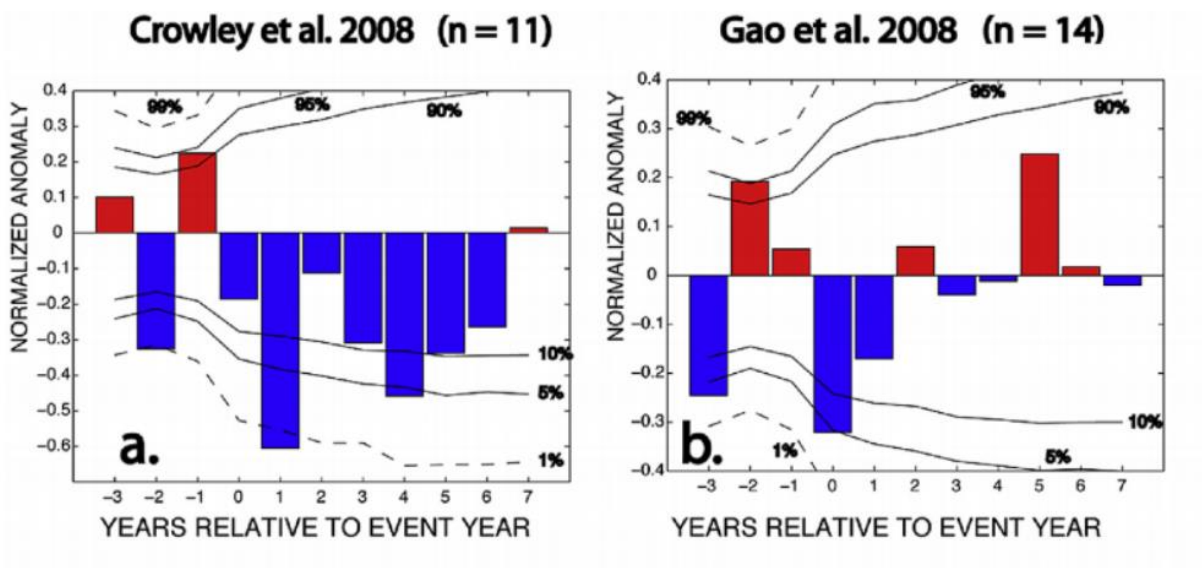


Figure 21: SEA performed using Siberian larch at OZN (Davi et al. 2015)

Wood Anatomy Discussion

While there were no significant moisture availability changes due to volcanic eruptions found during the instrumental period composite analysis and from the statistical SEA analysis, the tree-ring anatomy hinted that we see a volcanic effect at Khorgo lava and Urgaat lava for certain eruptions. Overall, more volcanic signals showed up at Khorgo lava than at Urgaat lava.

There were higher percentages of false and absent rings during the years analyzed and a greater number of potentially related volcanic events corresponding to the signals at Khorgo lava. However, many of these recorded false rings and absent rings occurred during the third or fourth year after the eruption event. According to previous literature, these events would be outside the realm of being influenced by a volcanic eruption (influence typically being only one to two years following the event). Thus the years that show a false ring or absent ring at Khorgo lava that may have been volcanically-induced are years 87, 169, 536, 540, 682, 939, 1108, 1230, 1258, 1345, and 1641.

For those years that showed a false ring or absent rings, there was no consistency in which year the false rings or absent rings tended to show up. Eruption event 1641 produced no false rings from the observed samples however had 5.5% of the eruption year showing total absent rings, and 1.8% of the following year's total rings showing absent rings. Years 169, 536, 540, 682, 939, 1108, and 1345 only produced false rings (thus no absent rings present) during the eruption event and following two years. Eruption events 1230 and 1258 have a high amount of false rings and absent rings present and may be the eruptions that influenced Khorgo lava moisture regimes the most. Year 1259 has 14.5% missing rings in the samples that were looked at, which is out of the ordinary since it is rare for more than 5-10% of samples from trees at northern latitude sites to have a missing ring per year (St. George et al. 2013). Year two is statistically significantly different in showing false rings and absent rings according to chi-square testing. At Khorgo lava, absent rings and false rings were present between years zero to two.

At Urgaat lava however, most of the absent rings and false rings had a two-year lag after the eruption. Year two for absent rings were statistically significant according to chi-square testing. Fewer

eruptions were evidenced at Urgaat lava. There were no observed false rings or absent rings present during the third and fourth year following an eruption. For eruption event year 87 the observed false rings fell on the eruption year. However, there was a sample depth of two at this location thus this information should not be considered as a reliable representative of the eruption event. Eruption event 540 had a false ring show up with a two-year lag. Eruption events 939 and 1258 had both false rings and absent rings present, both ring characteristics have a two-year lag following the eruption. Lastly eruption event 1345 had 9% observed false rings present with a two-year lag. Urgaat lava was relatively consistent with a decline in tree-ring growth and moisture availability by a two-year lag due to eruptions for the events that were experienced at this site location. The decline in moisture availability that showed up as false and absent rings following the 939 and 1258 eruption events hint that these two eruptions were detected at Urgaat lava and were also the strongest eruptions due to the amount of false rings and absent rings. Year 1260 has 17.9% missing rings in the samples that were looked at, which is also out of the ordinary (St. George et al. 2013). Volcanic eruption event 1258 is the only eruption that shows signs of both false rings and absent rings at Khorgo lava and Urgaat lava.

For eruption events that have sequential years showing either false rings or absent rings, it is hypothesized that there should be a decline in the ring characteristics in the following year due to the restabilization of the atmosphere from sulfate aerosols and other effects of volcanic eruptions. Tables 13 to 16 show these results. For example, it suggests that the 1258 eruption may have influenced moisture regimes greatly for 1259 while the site slowly recovers for the next three years.

The eruption events noted so far are not consistent with the global aerosol ranking calculated by Sigl et al. (2015). For the large eruptions, I observed no significant departures in climate during or after eruptions. The volcanic eruptions rankings may be based on the global aerosol forcing, but the eruptions may not have been the most influential volcanoes to impact Mongolian climate. For example, wood anatomy analysis hinted that some of the higher ranked eruptions such as 1345 (ranked 24th), 87 (ranked 23rd), 939 (ranked 20th), 1695 (ranked 19th), and 536 (ranked 18th) were found to be influential to tree

growth at Khorgo lava and Urgaat lava but are considered as having not as great of global aerosol forcing as many other eruptions. Years 1230 and 1258 were detected at Khorgo lava, however 1230 is ranked 7th on the list while 1258 is ranked 2nd. Some large eruptions such as -44, 1458, and 1815 (ranked 3rd, 4th, and 6th respectively) do not show up in the Khorgo lava samples. At Urgaat lava, eruption events 939 (ranked 20th) and 1258 show up in the samples. Very few of the largest eruptions show up. A couple ideas are suggested to influence the magnitude of the eruptions experienced at Khorgo lava and Urgaat lava including the timing of the eruptions (was it before or after growing season?) and the location of eruptions taking in account of global wind patterns. It is also risky to attribute these tree-ring characteristics to a decline in moisture availability. There is a possibility that it could be temperature causing them.

Timing of Eruptions

The timing of volcanic events could influence when the climatic effects due to eruptions are experienced at each location. It is hypothesized that if eruptions happened before the growing season (for Khorgo lava and Urgaat lava growing season is June, July, August, and September) then the effects may be experienced that year or later. However, if the eruptions happened in the latter half of the year or towards the end of the growing season, then the effects may be experienced the following year or later. A limitation to this study however would be the lack of knowledge on when the eruptions occurred. For more recent eruptions there may be historical evidence of when they occurred. However, it may be possible to date some eruptions from the dry fogs (deposited by volcanic eruptions) that appear in ice cores (Stothers 1999).

Table 3 and table 4 show the timing of the eruptions and which year the small ring was found (either the year of the eruption or the year after). The ring-widths were based on the reconstruction values. At Khorgo lava, eight out of the nine eruptions followed what we hypothesized. The year of the eruptions were small when the eruptions occurred before growing season or right at the beginning of growing season, or the year following the eruptions were small when the eruptions occurred after growing season.

There was one eruption that is listed as occurring in December of 1808. This is considered as late enough in the season to effect the 1809 growing season. There is some uncertainty in the timing of the 1601 eruption based on various sources. It is listed as occurring in 1600 by various sources such as Breitenmoser et al. (2012) and Fischer et al. (2007) even though Sigl et al. has it erupting in 1601. Due to this uncertainty, the 1600/1601 eruption was not considered during this analysis. At Urgaat lava, six out of the nine eruptions follow the hypothesis. The lower probability at Urgaat lava may be due to the two-year lag that we experience with false rings and absent rings and this analysis only considered the year of the eruption and the year after. Potential reasoning for the two-year lag include a biological response time in trees and time it takes for the atmosphere to transport sulfate aerosols.

The timing of eruptions influences when the eruptions are possibly experienced at each location. There was an almost immediate response at Khorgo lava and Urgaat lava from eruptions. This also hints that aerosols from eruptions can travel through the atmosphere at a quick pace where it would influence tree growth within a few weeks to months. There is consistent data showing that if the eruption happened before growing season or at the beginning of growing season, then it will more likely influence tree growth the same year (Tables 3-4). If it occurred at the end of growing season or towards the end of the year, then it influenced the following year’s growth. Although this might explain for why some eruptions are experienced the year of the eruption while others the year or two after, this does not explain why only certain eruptions are experienced that are not necessarily the largest.

Location of Eruptions and Wind Patterns

Figure 2 shows the locations of the known eruptions that were analyzed during this study. Only 12 total eruptions showed up at Khorgo lava and Urgaat lava during the wood anatomy analysis: 1258, 540, 1230, 682, 1108, 1641, 169, 536, 1695, 939, 87, and 1345 (ranked from largest to smallest). Of those eruptions, we only know the location to 6 of the eruptions: 1258 (Samalas, Indonesia), 540 (Ilopango, El Salvador), 682 (Pago, New Britain), 1641 (Parker, Philippines), 939 (Eldgja, Iceland), and 1345 (El Chichon, Mexico). Five out of the six of these volcanoes are tropical. Three of them are located in

southeast Asia and two in Mexico/Central America. Samalas, Indonesia and Pago, New Britain are located south of the equator.

There does not seem to be a pattern in the location of volcanoes that have erupted and show up in our samples. There have been other eruptions in similar areas that do not show up. For example, the 1783 eruption in Laki, Iceland (ranked 8th on the list) is near the 939 eruption of Eldgja, Iceland (ranked 20th on the list), but only the 939 eruption has a strong appearance in the samples. Global atmospheric circulation patterns in the lower latitudes (Hadley and Walker Cells) help with dispersing the aerosols into the atmosphere, but there does not seem to be any pattern in the location of the volcanoes and if those aerosols may reach the two sites in Mongolia. There is evidence of eruptions from high latitudes and the tropics at Khorgo lava and Urgaat lava, along with eruptions from the western hemisphere and eastern hemisphere. Again there is uncertainty in the location of some of the eruptions and thus analysis is limited.

Conclusion

Results of this study suggest that the volcanic eruptions analyzed in Mongolia did not yield statistically significant influences on temperature, moisture availability, and solar irradiance as seen through the tree-ring chronologies, CRU temperature, and CRU scPDSI. However, the study also called into question the process of studying volcanic eruptions using tree-rings and the climate system, showing that the atmosphere may be an intransitive cycle where the effects of volcanic eruptions may be variable and uncertain. There were no instrumental data significance and no statistical significance based on calibrations and ring-widths found at the three sites. However, an analysis of wood anatomy hinted that some eruptions were experienced at Khorgo lava and Urgaat lava.

The Effects of Recent Eruptions on Climate of Central Mongolia

The composite analysis performed in GrADS provided conflicting but statistically insignificant results when comparing three large eruptions during the instrumental period with a 54-year average in terms of CRU temperature and scPDSI.

The Effects of Volcanic Eruptions on Tree Growth Over the Past 2,500 years

SEA analysis showed statistically insignificant results for the three sites, however, wood-anatomy analysis suggested that we do see the effects of certain volcanic eruptions on tree growth. SEA showed insignificant results for Khorgo lava, Urgaat lava, and Sol Dav for the 25 eruptions that span the past 2,500 years when we ran it four different times. We are uncertain as to why some eruptions show up while others do not. However, for the eruptions that show up (in the wood anatomy analysis), there is a slight decline in ring-width within a zero to two-year window of the eruption and occasionally the presence of a false ring or the absence of a ring. This suggests that there were periods of low moisture availability during this time window. The most notable eruption events in the past 2,500 years at Khorgo lava and Urgaat lava are years 1258, 540, 1230, 682, 1108, 1641, 169, 536, 1695, 939, 87, and 1345.

How Eruptions Influence Climate in Central Mongolia

Results indicate that past volcanic eruptions do not alter climate as extremely as once believed. Sol Dav had statistically insignificant SEA results indicating that there was not much temperature change following eruptions. SEA results at Khorgo lava and Urgaat lava were similar in that there was not much moisture variability following eruptions. All SEA results fell within the 95% confidence levels. However, we do see evidence of certain volcanic eruptions in the wood anatomy at Khorgo lava and Urgaat lava through the presence of narrower rings, false rings, and absent rings. This suggests that volcanic eruptions have some influence on moisture regimes. More specifically, a decline in moisture availability following certain eruptions. It is risky to attribute all of what we see during those time periods to volcanic eruptions as there may be other global forcing or micro-site forcing that was not focused on for this research (Robock and Mao 1995).

Future Research

There are some improvements that can be made for future research. A thorough analysis on the timing of eruptions based on proxies and historical records would help clean up the analysis. It would help with statistical analysis, such as SEA, if the timing of the eruptions were accurate and it would also help with identifying a pattern of when eruptions show up at each location if there were a more extended list of precise dating to the month of the eruption. Identifying the location of eruptions may be beneficial to locating this pattern as well, but proved to be difficult due to how quickly and vastly volcanic aerosols can travel. Again, more in-depth research using historical documents may be helpful. Improving on the uncertainties with using proxy records would also benefit future research. Ring width may not be the most appropriate parameter to study the abruptness or severity of eruptions at the interannual scale (D'Arrigo et al. 2009, Anchukaitis et al. 2012). An alternative, and potentially stronger parameter for temperature-sensitive trees using tree-rings is the maximum latewood density (MXD) (D'Arrigo et al. 2013). MXD can show a clear response to volcanically induced summer cooling without the lag or dampened after-effects seen in ring width (Frank et al. 2007). This parameter is expensive and time consuming and thus

not realistic for the project. Additionally, my main focus is on the low elevation, moisture-sensitive trees (Khorgo lava and Urgaat lava) where ring width may be a suitable proxy. There may be potential to perform MXD on moisture-sensitive trees to see if there is a temperature signal following eruptions. Lastly, this research can be strengthened if there were a greater sample depth for the wood anatomy analysis. For this research, 52 samples were analyzed between Khorgo lava and Urgaat lava. There are another 59 samples available at the Montane Forest Dynamics Lab that have not been analyzed, and many more samples at the Lamont-Doherty Earth Observatory lab at Columbia University. Overall, this research showed that tree-rings are an invaluable proxy to volcanic eruption and climate studies. While many studies have used ring-width parameters to study volcanic eruptions via statistical methods, tree-ring anatomy should also be considered.

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