Learning Science Through Research
Published by the Keck Geology Consortium
Short Contributions
Keck Geology Consortium
Volume 38
May 2026
doi: 10.18277/AKRSG.2026.38.05

INVESTIGATING VOLCANICALLY FORCED SHIFTS IN NORTH PACIFIC CLIMATE IN MODEL SIMULATIONS AND ALASKA TREE RING RECORDS

LEV SUGERMAN-BROZAN, Colorado College
Project Advisors: Allison Lawman

INTRODUCTION

Volcanic eruptions can have long-lasting effects on climate. Eruptions inject sulfate aerosols into the atmosphere, reducing incoming shortwave radiation to the ocean-atmosphere system. This often has a large-scale cooling effect on the global ocean-atmosphere system (Cole-Dai, 2010). However, recent work has shown that volcanic eruptions can also have longer-lasting effects on key aspects of ocean-atmosphere circulation (e.g., Pausata et al., 2015; McGregor et al., 2020). For example, modelling has suggested that shifts in the Pacific Decadal Oscillation (PDO) include volcanically triggered 50-70-year PDO cycles (Sun et al., 2022). Despite an abundance of recent research on persisting climatic responses to volcanic forcings, the response of North Pacific climate variability remains unclear.

Here we use the Community Earth System Model Last Millenium Ensemble (CESM-LME, Otto-Bliesner et al., 2016) and a selection of mountain hemlock tree-ring chronologies from Alaska to investigate the North Pacific temperature and hydroclimate responses to volcanic forcing. A reconstruction based on the mountain hemlock chronologies show regional temperature changes following volcanic eruptions in 1258, 1452, 1697-1698 and 1809 CE.

We then use superposed epoch analysis to investigate the magnitude and duration of both the proxy-inferred and simulated surface temperature responses at the sites of the tree-ring chronologies during known volcanic events. This comparison helps identify both similarities and discrepancies between the model and data, therefore providing insights into the response of North Pacific climate to volcanic forcings. These findings will provide much-needed context for better understanding current and future changes in the North Pacific ocean-atmosphere system, and its response to external climate forcings.

BACKGROUND

The North Pacific is a region influenced by high internal variability, driven by the Pacific Decadal Oscillation (PDO), a long-lived El Niño Southern Oscillation (ENSO)-like pattern of ocean-atmosphere variability. The PDO is linked to North American climate variability, and typically occurs on 10-30 year cycles. Similar to ENSO, end-member phases of the PDO are characterized by anomalous sea surface temperatures (SSTs) and sea level pressure (SLP) in the North Pacific. The PDO also drives variability of the Aleutian Low (AL), a semipermanent low-pressure system in the Gulf of Alaska. The multiple overlapping modes of internal variability in the North Pacific is often difficult to disentangle from responses to volcanic forcings, making proxy records and multi-ensemble modeled datasets crucial for robust analysis.

The use of tree rings as climatic, ecological, hydrologic, and cultural proxies, called dendrochronology, has been a popular scientific method since the early twentieth century (e.g., Douglass, 1914). Tree rings have been found to be sensitive to a number of important climatic phenomena, including winter and summer temperatures, hydroclimate, and winter storminess (Wiles et al., 2014; Wilson et al., 2016; Gaglioti, 2019). Trees at high latitudes, such as those in the North Pacific, are primarily temperature-limited, and therefore are excellent proxies for growing season temperatures (e.g., Raspopov, 2004; Wiles et al., 2014) and associated internal climate variability (D'Arrigo et al., 2001; Davi et al., 2003). Dendrochronology also allows for annual resolution through cross-dating, the process of cross-referencing chronologies to obtain exact calendar year dates (Douglass, 1941). This process allows for exact correlation of chronologies to abrupt, year-scale temperature anomalies (e.g., volcanic eruption dates), making dendrochronological proxies an important record of volcanically-forced shifts in climate.

A mountain hemlock chronology from Wiles et al. (2014) reconstructs surface air temperature in the Gulf of Alaska (GOA) for the past 1200 years. The reconstruction displays internal variability on interannual and centennial timescales, suggested to correspond to solar/lunar tidal forcings and solar variability, respectively. The reconstruction also demonstrates prolonged cooling signals that correspond to multiple major volcanic events. These suggest not only well-documented externally-forced cooling signals, but also potentially coupled ocean-atmosphere responses to such forcings. The coastal location of the GOA temperature reconstruction suggests this proxy record may be sensitive to more prolonged, ocean-atmosphere coupled shifts in response to external forcings.

Though proxy-inferred responses are valuable records of climatic responses to external forcings, they often contain unwanted noise or internal variability. Multi-ensemble modeled datasets, such as the Community Earth System Model Last Millennium Ensemble (CESM-LME) allow for the reduction of such internal variability through multiple model runs (Otto-Bliesner et al., 2016). Each ensemble member begins with slightly different starting conditions, designed to replicate internal variability on both short and long timescales. The combination of such ensemble members (thirteen for the CESM-LME) allows for the approximate removal of internal variability; the ensemble mean thus isolates the forced signal. This effectively separates internal variability from the volcanically-forced cooling signal. Superposed epoch analysis (SEA) is a technique that isolates the specific time-window of an external forcing, aligning multiple events and separating coherent signals from noisier climate records.

Model-proxy comparisons are therefore powerful tools to test whether modeled mechanisms replicate real-world (e.g., proxy-inferred) responses to volcanic forcings. Though proxy records and climate models are inherently related (the CESM-LME uses forcing reconstructions based on proxy records; see Gao et al. (2008)), the comparison of controlled models (i.e., the removal of internal variability and isolation of external forcings) to the real-world proxy response often reveals valuable agreements or discrepancies. Proxy-model agreement can confirm proxy-inferred responses to volcanic eruptions and validate model accuracy, while discrepancies reveal limitations of proxy records or shortcomings of climate models. Proxy-model comparisons are therefore an effective methodology for evaluating proxy-inferred responses to external forcings.

METHODS

We performed a superposed epoch analysis (SEA) using growing season (January-September) surface air temperature reconstructed from tree rings (Wiles et al., 2014) and 2-meter air temperature modeled by the full-forcing member of the Community Earth System Model Last Millennium Ensemble (CESM-LME, Otto-Bliesner et al., 2016). We focus on the Gulf of Alaska (GOA) region, here subset to 50-60°N, 130-170°W (see Figure 1). The eruption events were selected for magnitude (as inferred from ice cores in Gao et al., 2008), well-constrained eruption dates, and existing literature (Gao et al., 2008; Leland et al., 2023). Here we use the 1258, 1452, 1697-1698, and 1809 events to facilitate comparison across the proxy record and the model.

The CESM-LME 2-meter air temperature data is subset to January-September. Area-weighted spatial means were calculated over the GOA region to ensure comparability with the entire proxy record. The time series are annually averaged for each growing season (Jan-Sep) and all thirteen ensemble members are averaged to reduce internal variability. The surface air temperature chronology, inferred from mountain hemlock trees in the GOA, was calculated by Wiles

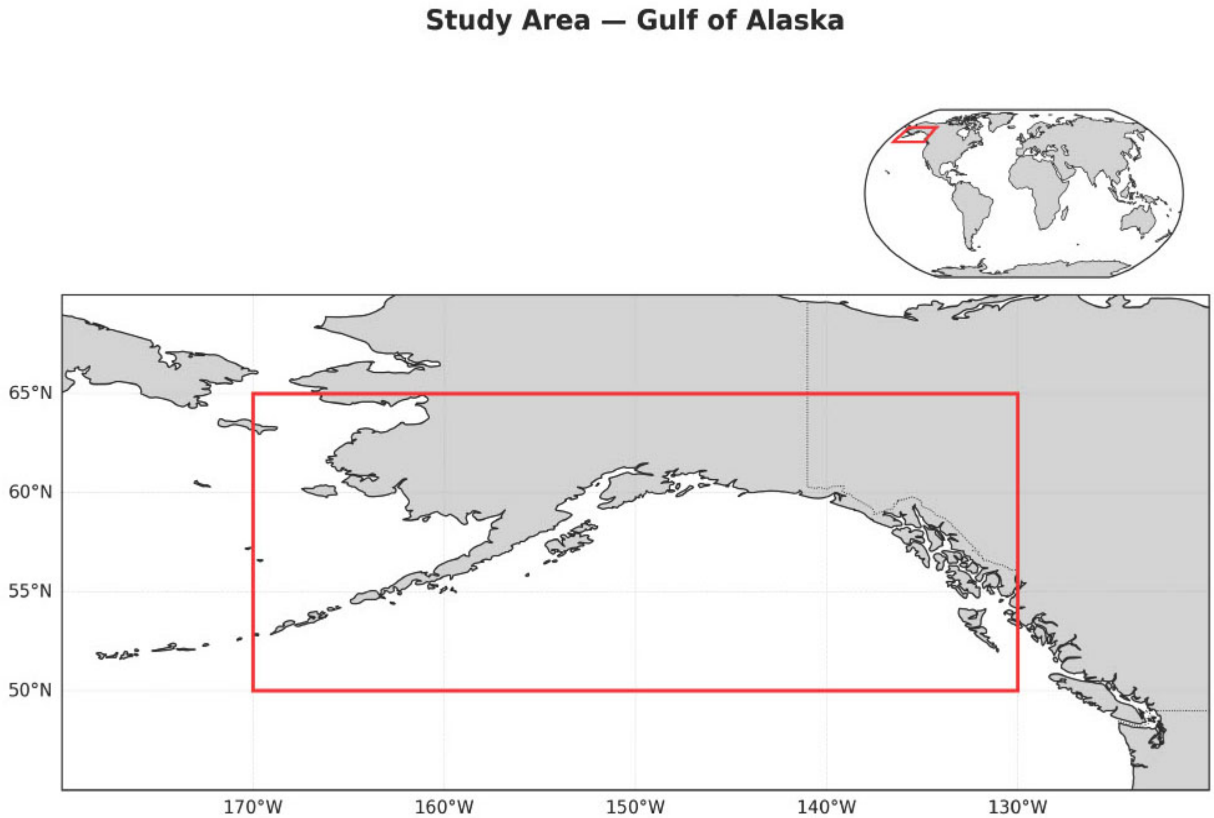

Figure 1. The study site in the Gulf of Alaska (GOA), 50°-60° N and 130°-170° W.

et al. (2014) according to their methods section. Mountain hemlock trees are sensitive to growing season temperature; the chronology therefore reflects January-September temperatures.

The SEA analysis aligned the time series for both the tree-ring chronology and the CESM-LME around the eruption year (e.g., Year 0), and extended Year -5 to Year +10 relative to each eruption. We calculated absolute temperature anomalies (°C) for ten years post-eruption compared to a five-year pre-eruption baseline. For the CESM-LME, the ensemble mean was calculated and compared to the thirteen individual ensemble members (Figure 2). Spatial, year-by-year anomalies were then calculated for the model data and displayed for the 1809 eruption (Figure 3) to investigate spatial cooling trends. Methodological consistency across the proxy record and model simulations allows for the investigation of post-eruption cooling magnitude, duration and spatial coherence, as well as proxy-model agreement or discrepancy.

RESULTS

Both the CESM-LME and the tree-ring chronology display cooling signals following major eruptions (1258, 1452, 1697-1698, 1809) compared to a five-year pre-eruption baseline. The modeled cooling response reaches a maximum of 1.7°C. The CESM-LME approaches pre-eruption baselines between 4 and 7 years post-eruption, and models spatially coherent cooling signals within the GOA (Figure 3). The magnitude of the cooling signal varies considerably across ensemble members. In contrast, the proxy-inferred cooling response has a higher maximum than the modeled at 2°C, and persists for between 5 and 8 years post-eruption.

The timing and the sign of the modeled and proxy-inferred post-eruption responses are therefore in agreement. However, there are significant discrepancies in the duration, amplitude, and variability of cooling signals between the modeled and proxy-inferred responses. The mechanisms for such discrepancies will be discussed in the following section.

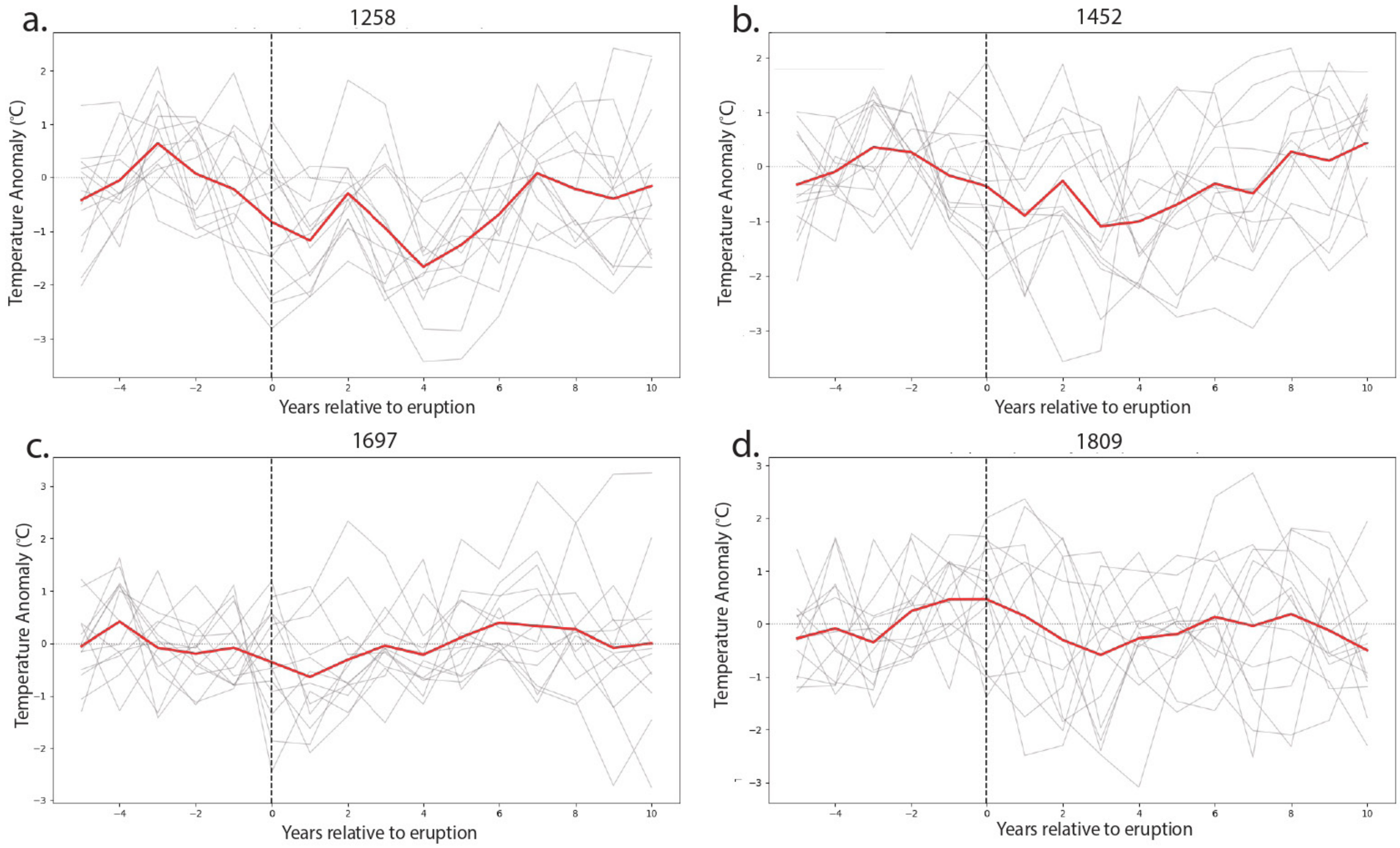

Figure 2. Superposed epoch analysis (SEA) for the 1258, 1452, 1697 and 1809 eruptions in the CESM-LME. Gray lines show the 13 individual ensemble members. The bolded red line shows the ensemble mean. Post-volcanic temperature changes are calculated relative to the 5-year pre-eruption baseline.

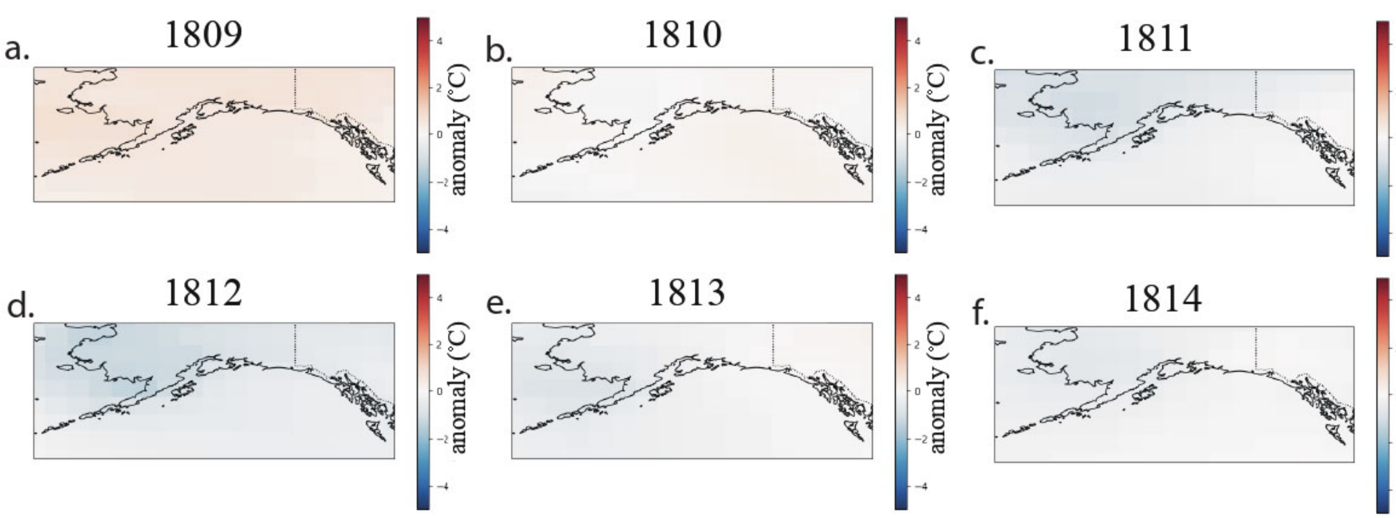

Figure 3. Spatial cooling trends in the GOA following the 1809 "mystery" eruption, as simulated in the 13 ensemble members of the full-forcing CESM-LME. Anomalies are calculated compared to the five-year pre-eruption baseline.

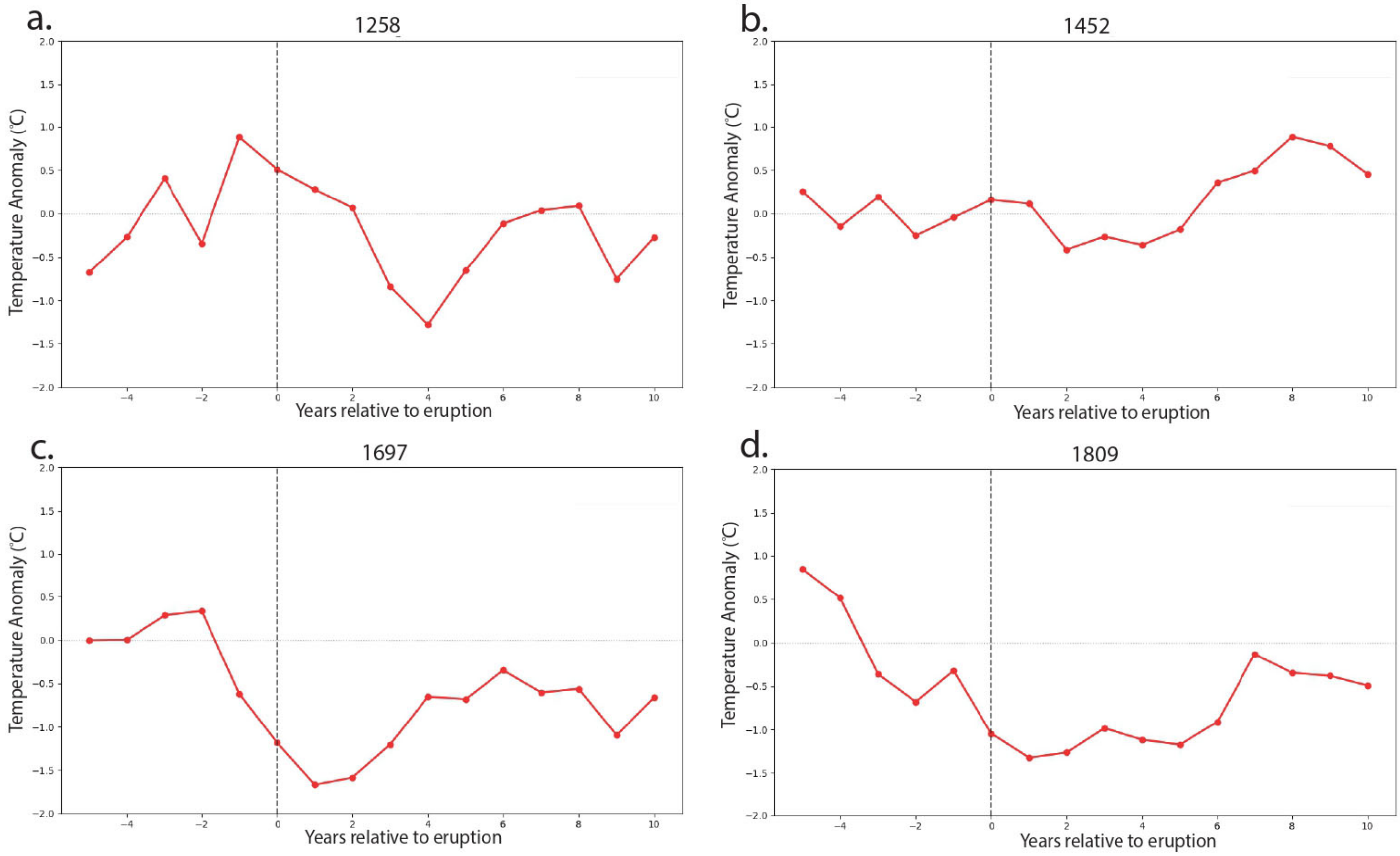

Figure 4. SEA for the Alaskan mountain hemlock temperature reconstruction for the same eruptions in Figure 2. Post-volcanic temperature changes are calculated relative to the 5-year pre-eruption baseline.

DISCUSSION

Our results replicate previous studies that show near-global cooling signals in response to large volcanic events (e.g., Cole-Dai, 2010). However, the considerable variability between ensemble members (Figure 2) in the modeled cooling response suggests that interannual variability plays a key role in modulating responses to external forcings in the North Pacific. Such variability may reflect ENSO or PDO phase, and therefore exerts controls on the magnitude, duration, and amplitude of forced responses to volcanic eruptions. The proxy-inferred cooling signals reflect the combined effects of forced responses and regional ocean-atmosphere circulation shifts. That these signals are longer-lasting and higher in magnitude (Figure 4) indicates the possible enhancement or dampening of forced signals by ocean-atmosphere coupled circulations and internal variability.

Specifically, the observed climatic response is dependent on the phase of climatic oscillations pre-eruption (Predybaylo et al., 2017), but more work is needed to determine the specific effects of pre-eruption phase on post-eruption responses. Volcanically-forced shifts in PDO phase have been proposed in previous work (Sun et al., 2022), as well as shifts in ENSO variability and magnitude (McGregor et al., 2020; Pausata et al., 2020), yet the exact effects on climatic oscillations similarly remain unclear. Such changes could feasibly produce changes in global teleconnections (Zhang et al., 2025), leading to truly global climatic changes. Post-volcanic cooling also alters the ocean's heat budget, mixed layer depth, and mixing capacity (Church et al., 2005), which exerts controls on the persistence and recovery time of post-eruption cooling. The discrepancies between ensemble members, as well as between the proxies and the model, show that these complex ocean-atmosphere interactions mask post-eruption temperature signals, highlighting the need for further work on responses of such interactions in the North Pacific to external forcings to better understand the mechanisms behind volcanically-forced shifts in climate.

Though the proxy-inferred cooling signals are sensitive to both external forcings (e.g., volcanic eruptions) and internal variability, they are also sensitive to a number of other non-climatic factors, including biological and ecological influences on growth, seasonal bias (January-September), and other local dynamics. These factors, similar to internal variability, can amplify or dampen forced signals. As such, caution must be exercised when utilizing proxy-inferred responses to volcanic forcings. Climate models have similar limitations in evaluating volcanic cooling signals, namely that many existing models, including the CESM-LME, often underestimate certain modes of internal variability. The CESM-LME may also not fully capture regional dynamics and ocean-atmosphere coupled interactions due to its relatively coarse resolution (1.9° x 2.5°).

Despite these limitations, our results demonstrate modeled and proxy-inferred post-volcanic cooling signals in the GOA. There is proxy-model agreement on the timing and sign of such responses. However, our results identify discrepancies between proxy data, model data and ensemble members, revealing that interannual ocean-atmosphere variability exerts key controls over the persistence and magnitude of volcanically forced shifts in climate. Understanding the specific mechanisms of such controls will aid in the interpretation of both past and future regional climate shifts in response to external forcing.

CONCLUSIONS

We found spatially coherent, persistent cooling signals in both the proxy-inferred and modeled responses to major volcanic eruptions in the Gulf of Alaska, as well as important discrepancies in the persistence and magnitude of such signals. Based on these results, we draw the following conclusions:

- Proxy and model data support a post-volcanic cooling signal in the Gulf of Alaska in response to major volcanic eruptions.

- Ocean-atmosphere coupled oscillations modulate the persistence and magnitude of the climatic response to such forcings.

Further work will investigate interannual to decadal changes as well as potential ocean-atmosphere oscillation phase shifts in response to volcanic forcings.

ACKNOWLEDGEMENTS

This material is based upon work supported by the Keck Geology Consortium and the National Science Foundation under Grant No. 2050697. Funding was provided to this project by a 2025-2026 Keck Geology Consortium Advanced Research Grant. We would like to thank Alaska Youth Stewards for their indispensable help in collecting samples.

REFERENCES

Brad Adams, J., Mann, M. E., & Ammann, C. M. (2003). Proxy evidence for an El Niño-like response to volcanic forcing. Nature, 426(6964), 274-278.

Church, J. A., White, N. J., & Arblaster, J. M. (2005). Significant decadal-scale impact of volcanic eruptions on sea level and ocean heat content. Nature, 438(7064), 74-77.

Cole-Dai, J. (2010). Volcanoes and climate. Wiley Interdisciplinary Reviews: Climate Change, 1(6), 824-839.

D'Arrigo, R., Villalba, R., & Wiles, G. (2001). Tree-ring estimates of Pacific decadal climate variability. Climate Dynamics, 18(3), 219-224.

Davi, N. K., Jacoby, G. C., & Wiles, G. C. (2003). Boreal temperature variability inferred from maximum latewood density and tree-ring width data, Wrangell Mountain region, Alaska. Quaternary Research, 60(3), 252-262.

Dee, S. G., Cobb, K. M., Emile-Geay, J., Ault, T. R., Edwards, R. L., Cheng, H., & Charles, C. D. (2020). No consistent ENSO response to volcanic forcing over the last millennium. Science, 367(6485), 1477-1481.

Douglass, A. E. (1914). A method of estimating rainfall by the growth of trees. Bulletin of the American Geographical Society, 46(5), 321-335.

Douglass, A. E. (1941). Crossdating in dendrochronology. Journal of Forestry, 39(10), 825-831.

Gaglioti, B. V., Mann, D. H., Williams, A. P., Wiles, G. C., Stoffel, M., Oelkers, R., ... & Andreu-Hayles,

L. (2019). Traumatic resin ducts in Alaska mountain hemlock trees provide a new proxy for winter storminess. Journal of Geophysical Research: Biogeosciences, 124(7), 1923-1938.

Gao, C., Robock, A., & Ammann, C. (2008). Volcanic forcing of climate over the past 1500 years: An improved ice core-based index for climate models. Journal of Geophysical Research: Atmospheres, 113(D23).

Latif, M., & Barnett, T. P. (1996). Decadal climate variability over the North Pacific and North America: Dynamics and predictability. Journal of Climate, 9(10), 2407-2423.

Leland, C. et al., 2023, A Spatiotemporal Assessment of Extreme Cold in Northwestern North America Following the Unidentified 1809 CE Volcanic Eruption: Paleoceanography and Paleoclimatology, v. 38, p. e2022PA004581, doi:10.1029/2022PA004581.

McGregor, S., Khodri, M., Maher, N., Ohba, M., Pausata, F. S., & Stevenson, S. (2020). The effect of strong volcanic eruptions on ENSO. El Niño Southern Oscillation in a changing climate, 267-287.

Nakamura, H., Lin, G., & Yamagata, T. (1997). Decadal climate variability in the North Pacific during the recent decades. Bulletin of the American Meteorological Society, 78(10), 2215-2226.

Otto-Bliesner, B. L., Brady, E. C., Fasullo, J., Jahn, A., Landrum, L., Stevenson, S., ... & Strand, G. (2016). Climate variability and change since 850 CE: An ensemble approach with the Community Earth System Model. Bulletin of the American Meteorological Society, 97(5), 735-754.

Pausata, F. S., Chafik, L., Caballero, R., & Battisti, D. S. (2015). Impacts of high-latitude volcanic eruptions on ENSO and AMOC. Proceedings of the National Academy of Sciences, 112(45), 13784-13788.

Pausata, F. S., Zanchettin, D., Karamperidou, C., Caballero, R., & Battisti, D. S. (2020). ITCZ shift and extratropical teleconnections drive ENSO response to volcanic eruptions. Science Advances, 6(23), eaaz5006.

Predybaylo, E., Stenchikov, G. L., Wittenberg, A. T., & Zeng, F. (2017). Impacts of a Pinatubo-size volcanic eruption on ENSO. Journal of Geophysical Research: Atmospheres, 122(2), 925-947.

Raspopov, O. M., Dergachev, V. A., & Kolström, T. (2004). Periodicity of climate conditions and solar variability derived from dendrochronological and other palaeoclimatic data in high latitudes. Palaeogeography, Palaeoclimatology, Palaeoecology, 209(1-4), 127-139.

Sun, W., Liu, J., Wang, B., Chen, D., & Gao, C. (2022). Pacific multidecadal (50–70 year) variability instigated by volcanic forcing during the Little Ice Age (1250–1850). Climate dynamics, 59(1), 231-244.

Wang, T., Otterå, O. H., Gao, Y., & Wang, H. (2012). The response of the North Pacific Decadal Variability to strong tropical volcanic eruptions. Climate Dynamics, 39(12), 2917-2936.

Wiles, G. C., D'Arrigo, R. D., Barclay, D., Wilson, R. S., Jarvis, S. K., Vargo, L., & Frank, D. (2014). Surface air temperature variability reconstructed with tree rings for the Gulf of Alaska over the past 1200 years. The Holocene, 24(2), 198-208.

Wilson, R., Anchukaitis, K., Briffa, K. R., Büntgen, U., Cook, E., D'Arrigo, R., ... & Zorita, E. (2016). Last millennium northern hemisphere summer temperatures from tree rings: Part I: The long term context. Quaternary Science Reviews, 134, 1-18.

Wu, C. H., Lee, S. Y., Tsai, I. C., Shiu, C. J., & Chen, Y. Y. (2023). Volcanic contribution to the 1990s North Pacific climate shift in winter. Scientific Reports, 13(1), 5672.

Zhang, X., Li, J., Xie, S. P., Liu, F., Shi, F., Gao, C., ... & Dong, Q. (2025). Volcanic eruptions disrupt ENSO teleconnections with land summer temperature. Nature Communications, 16(1), 9882.