Advances in Atmospheric Sciences
Impact Factor: 5.8
E-alert
ISSN 0256-1530
CN 11-1925/O4

Southern Hemisphere Volcanism Triggered Multi–year La Nias during the Last Millennium

Shangrong ZHOU, Fei LIU

Citation: Zhang, S. R., and F. Liu 2024: Southern Hemisphere Volcanism Triggered Multi–year La Nias during the Last Millennium, *Adv. Atmos. Sci.*, 41, 587–592. doi: 10.1007/s00376-023-3254-8.

View online: https://doi.org/10.1007/s00376-023-3254-8

Related articles that may interest you

Roles of Wind Stress and Subsurface Cold Water in the Second–Year Cooling of the 2017/18 La Nia Event

Advances in Atmospheric Sciences. 2020, 37(8), 847 https://doi.org/10.1007/s00376-020-0028-4

Interannual Climate Variability Change during the Medieval Climate Anomaly and Little Ice Age in PMIP3 Last Millennium Simulations

Advances in Atmospheric Sciences. 2017, 34(4), 497 https://doi.org/10.1007/s00376-016-6075-1

Influence of Intraseasonal Oscillation on the Asymmetric Decays of El Nio and La Nia

Advances in Atmospheric Sciences. 2019(8), 779 https://doi.org/10.1007/s00376-019-9029-6

Decadal Variation of the Impact of La Nia on the Winter Arctic Stratosphere

Advances in Atmospheric Sciences. 2017, 34(5), 679 https://doi.org/10.1007/s00376-016-6184-x

A 38–Year Climatology of Explosive Cyclones over the Northern Hemisphere

Advances in Atmospheric Sciences. 2020, 37(2), 143 https://doi.org/10.1007/s00376-019-9106-x

Influence of the Preceding Austral Summer Southern Hemisphere Annular Mode on the Amplitude of ENSO Decay

Advances in Atmospheric Sciences. 2017, 34(11), 1358 https://doi.org/10.1007/s00376-017-6339-4

AAS Website AAS Weibo AAS WeChat

Follow AAS public account for more information

ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 41, APRIL 2024, 587–592

• News & Views •

Southern Hemisphere Volcanism Triggered Multi-year La Niñas during the Last Millennium

Shangrong ZHOU[1,2] and Fei LIU*[1,2]

[1]*School of Atmospheric Sciences Sun Yat-Sen University*, *Key Laboratory of Tropical Atmosphere-Ocean System Ministry of Education*, *and Southern Marine Science and Engineering Guangdong Laboratory*, *Zhuhai* 519082, *China*

[2]*Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD)*, *Nanjing University of Information Science and Technology*, *Nanjing* 210044, *China*

(Received 10 October 2023; revised 12 November 2023; accepted 17 November 2023)

ABSTRACT

To explain the recent three-year La Niña event from 2020 to 2022, which has caused catastrophic weather events worldwide, Fasullo et al. (2023) demonstrated that the increase in biomass aerosol resulting from the 2019–20 Australian wildfire season could have triggered this multi-year La Niña. Here, we present compelling evidence from paleo-proxies, utilizing a substantial sample size of 26 volcanic eruptions in the Southern Hemisphere (SH), to support the hypothesis that ocean cooling in the SH can lead to a multi-year La Niña event. This research highlights the importance of focusing on the Southern Ocean, as current climate models struggle to accurately simulate the Pacific response driven by the Southern Ocean.

Key words: volcanic eruptions, multi-year La Niñas, Australian wildfire, southern ocean cooling

Citation: Zhang, S. R., and F. Liu, 2024: Southern Hemisphere volcanism triggered multi-year La Niñas during the last millennium. *Adv. Atmos. Sci.*, **41**(4), 587−592, https://doi.org/10.1007/s00376-023-3254-8.

1. Introduction

The worldwide catastrophic weather events caused by the recent three-year La Niña from 2020 to 2022 have garnered significant attention (Jones, 2022). Compared to a single-year La Niña, a multi-year La Niña is more likely to cause severe droughts, heatwaves, and wildfires in the southwestern United States (Cole et al., 2002; Williams et al., 2020). It also leads to floods in Australia and Southeast Asia and deadly hurricanes over the North Atlantic (Raj Deepak et al., 2019; Jones, 2022), primarily due to its stronger cumulative impact (Wang et al., 2023).

The occurrence of multi-year La Niña events was previously attributed to several factors, including significant upper-ocean heat discharge induced by a preceding extreme El Niño (Wu et al., 2019; Iwakiri and Watanabe, 2021), influences from higher latitudes of the North Pacific that cause meridionally broad easterly wind anomalies slowing the heat recharge of the equatorial Pacific (Park et al., 2021; Geng et al., 2023; Zhang, 2023), the negative phase of the North Pacific Meridional mode (Kim et al., 2023), and tropical inter-basin interactions involving the Indian Ocean Dipole and/or Atlantic Niño (Okumura et al., 2011; McPhaden, 2023). A recent study has also indicated that the prevailing multi-year La Niña events since 1970 have primarily been triggered by rapid onsets following extreme or central-Pacific El Niños (Wang et al., 2023).

Since 1920, there have been ten instances of multi-year La Niña events, with eight of them occurring after 1970 (Wang et al., 2023). The frequent occurrence of multi-year La Niñas after 1970 is likely associated with a faster warming of the western Pacific, particularly a strengthened sea surface temperature (SST) gradient towards the west. This warming contrast between the western and eastern equatorial Pacific enhances the zonal advective feedback for central-Pacific El Niño to multi-year La Niña events and the thermocline feedback for super El Niño to multi-year La Niña events. Whether this strengthened SST gradient towards the west is a result of internal variability or a response to external forcing remains an open question (Power et al., 2021; Hartmann, 2022; Lee et al., 2022; Heede and Fedorov, 2023).

In the future, anthropogenic forcing–induced global warming will intensify the maximum warming in the subtropical northeastern Pacific, enhancing the regional thermodynamic response to perturbations. As a result, anomalous easterlies of

---

* Corresponding author: Fei LIU
Email: liufei26@mail.sysu.edu.cn

the first-year La Niña will be generated further northward compared with the present-day climate, leading to a slower heat recharge of the equatorial Pacific and therefore an increased frequency of multi-year La Niña events. Under a low-emission scenario, the projected frequency is expected to range from 19%±11%, while under a high-emission scenario, it is expected to range from 33%±13% Geng et al. (2023).

These studies have primarily focused on investigating the internal variability of air–sea interaction and its potential influences from climate change. However, an intriguing question to explore is whether external forcing can directly impact the occurrence of multi-year La Niña events, rather than solely altering the mean state. Investigating this aspect can provide valuable insights into the dynamics of multi-year La Niña events.

2. Southern Ocean cooling-induced multi-year La Niñas

In a recent study by Fasullo et al. (2023), it was simulated that following the largest 2019 Indian Ocean Dipole, the increase in biomass aerosol from the 2019–20 Australian wildfire season could lead to an increase in cloud albedo and cooling of the southeastern subtropical Pacific Ocean. This cooling tendency resulted in a northward shift of the intertropical convergence zone, which favored the occurrence of strong La Niña events from 2020 to 2022. This work suggests that the sudden cooling in the Southern Hemisphere (SH) caused by biomass aerosol can trigger multi-year La Niña events. On longer time scales, a cooling trend in the eastern tropical Pacific was also simulated due to cooler temperatures over the Southern Ocean near Antarctica (Kang et al., 2023a, b, c). One of the factors contributing to this cooling trend was the onset of the Antarctic ozone hole since about 1980 (Hartmann, 2022).

All these simulations have demonstrated that a cold SH can lead to a drying of the boundary in the SH Pacific and a decrease in moist static energy. Consequently, this leads to a northward shift of the intertropical convergence zone and triggers a multi-year La Niña event or a La Niña-like trend (Fasullo et al., 2023; Kang et al., 2023a, b, c). However, it is worth noting that this mechanism currently lacks support from observations due to the limited number of available samples from wildfires or ozone holes. Therefore, it is important to seek evidence from paleo-proxies, which can provide valuable insights into past climate conditions.

3. SH volcanic eruption-triggered multi-year La Niñas

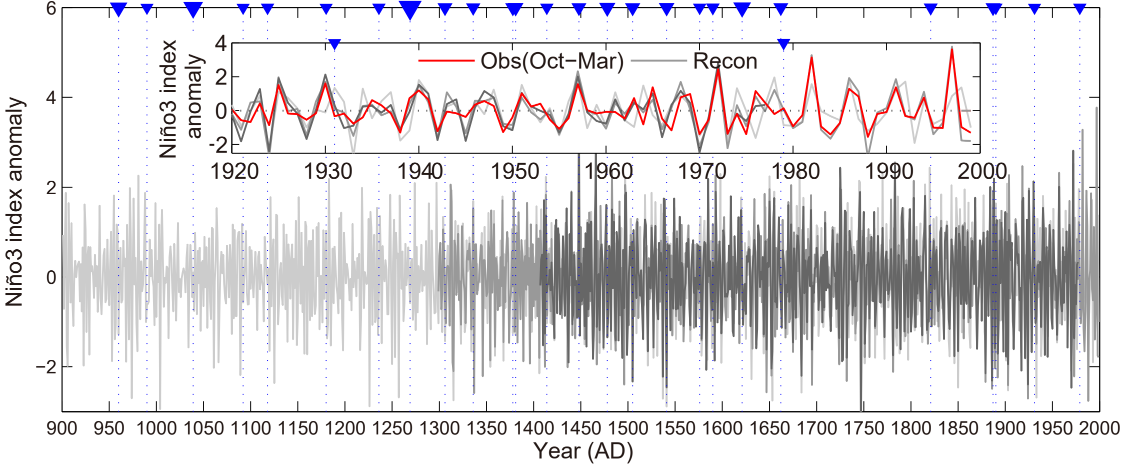
Volcanic eruptions, as natural external forcings, have the potential to alter our climate on various time scales, ranging from subseasonal (Xing and Liu, 2023), interannual (Adams et al., 2003), multidecadal (Mann et al., 2021), and centennial (Miller et al., 2012) time scales. This is achieved through the injection of sulfur dioxide into the stratosphere (Robock, 2000). The formation of volcanic sulfate aerosols occurs through the reaction between sulfur dioxide and hydroxide or water vapor, and these aerosols persist in the stratosphere for approximately one to two years (Timmreck, 2012). They have a significant impact on global climate by scattering incoming solar radiation, ultimately resulting in global surface cooling and monsoon changes (Iles and Hegerl, 2014; Paik et al., 2020; Singh et al., 2020; Liu et al., 2022b). Frequently erupting volcanoes offer us an opportunity to study the response of multi-year La Niñas to the Southern Ocean cooling. In comparison to the extensively researched El Niño response to tropical volcanic eruptions caused by the suppression of the African monsoon and the resultant tropical westerly anomaly (Khodri et al., 2017; Liu et al., 2022a; Pausata et al., 2023), the El Niño–Southern Oscillation (ENSO) response to high-latitude volcanic eruptions has received less attention.

To investigate the response of ENSO to volcanic eruptions in the tropics, Northern Hemisphere, and SH, our previous work conducted a reconstruction analysis covering the period from 900 to 2000 AD (Liu et al., 2018b). In this analysis, the focus was on the SH eruptions that could cool the SH rather than the tropics and Northern Hemisphere (Haywood et al., 2013; Pausata et al., 2015; Colose et al., 2016; Stevenson et al., 2016; Liu et al., 2018b; Erez and Adam, 2021), and multiproxy data were used. Specifically, tree ring records in southwestern North America were utilized as reliable indicators of ENSO variability, due to the stable Pacific–North American teleconnection over the last millennium (Li et al., 2011; Han et al., 2023).

During the period 900–2000 AD, for which ENSO reconstructions were available (Fig. 1a), a total of 26 SH volcanic eruptions were recorded in the newest volcanic reconstruction (Sigl et al., 2015). The two most recent eruptions for which reliable observations were available occurred in 1931 and 1979 (Fig. 1a). By conducting a superposed epoch analysis (SEA; Haurwitz and Brier, 1981) on all available reconstructions for these 26 eruptions, a three-year negative anomaly in the boreal-winter Niño-3 index was observed (Fig. 1b). Notably, a significant anomaly (at the 90% confidence level) was observed during the eruption winter and the third winter following the eruptions.

High-latitude volcanic eruptions, which are known for their significant cooling effect in the hemisphere of eruption, can induce a migration of the intertropical convergence zone towards the comparatively warmer hemisphere (Haywood et al., 2013; Pausata et al., 2015; Liu et al., 2016; Colose et al., 2016; Stevenson et al., 2016; Liu et al., 2018b; Erez and Adam, 2021). This migration is primarily driven by the atmospheric energy balance (Schneider et al., 2014). Simulations

(a) Reconstructed ENSO



(b) Response to SH eruptions

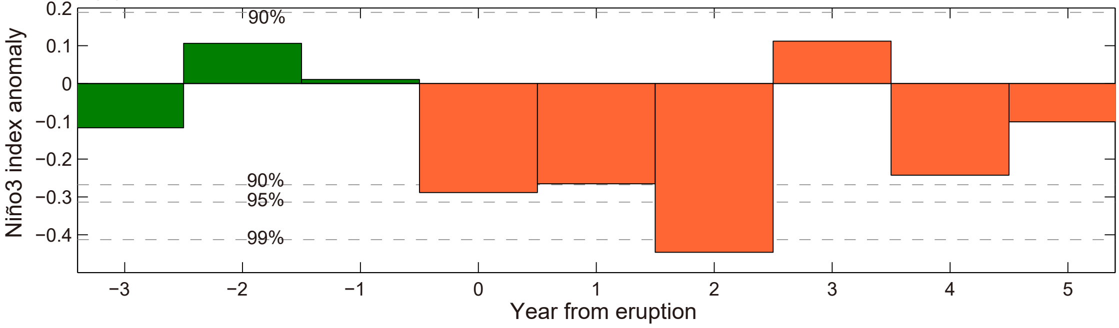


Fig. 1. Three-year La Niña response to SH volcanic eruptions in paleo-proxies: (a) Three sets of long-term ENSO indices reconstructed based on tree rings from southwestern North America covering the periods 1408–1978 AD, 1300–2000 AD, and 900–2000 AD (gray lines), as well as instrumental October–March Niño-3 index from 1920–2000 AD (red line). Blue triangles and dotted vertical lines denote cold seasons (defined by the beginning year of the cold season of the NH) following 26 SH eruptions back to 900 AD. In the inset, the 1931 and 1979 SH eruptions are also marked. (b) Composite response of three Niño-3 reconstructions to 26 SH volcanic eruptions. Green and orange colors mark the pre- and post-eruption composites, respectively. "0" denotes the first cold season following the eruptions. Confidence intervals (90%, 95%, 99%) are marked by horizontal dashed lines.

have shown that volcanic eruptions in the SH can cause a northward shift in the intertropical convergence zone (Haywood et al., 2013; Liu et al., 2016; Stevenson et al., 2016). As a result, this northward migration of the intertropical convergence zone leads to the occurrence of a multi-year La Niña event, as simulated by Fasullo et al. (2023).

The analysis of paleo-reconstructions provides evidence that volcanic eruptions in the SH can induce a multi-year La Niña event through the ocean cooling effects. However, it is crucial to note that, for a specific event, the ENSO anomaly can be influenced by both internal variability and external forcing (Liu et al., 2018a; Zanchettin et al., 2019). For instance, after the eruption in the SH in 1931, a cooling signal persisted for three years, whereas no discernible signal was observed during the winter of 1979 eruption (Fig. 1a). The most powerful SH volcanic eruption in recent decades, known as the Hunga Tonga-Hunga Ha'apai eruption on 15 January 2022, had a volcanic explosivity index of five, comparable to the Krakatoa eruption in 1883 (Carn et al., 2022). However, this eruption only released 0.5–1.5 Tg of SO_2 into the stratosphere, even though it injected 146 Tg or approximately 10% of the total stratospheric water vapor prior to the eruption (Millán et al., 2022). As a result, the decrease in SH SST was relatively small (Zuo et al., 2022; Schoeberl et al., 2023).

Our results were primarily derived from ENSO reconstruction using tree rings in southwestern North America. However, it is important to note that different paleoclimate reconstructions can yield divergent responses. For example, ENSO reconstructions based on coral records did not exhibit a significant multi-year La Niña response (not shown), similar to their inability to capture an El Niño response following tropical volcanic eruptions (Dee et al., 2020), against other reconstructions (Adams et al., 2003; Robock, 2020). This raises an interesting yet challenging issue of identifying which reconstructions are more reliable, and further research in this area is warranted.

Although both wildfires (Fasullo et al., 2023) and SH volcanic eruptions (Fig. 1) can contribute to the occurrence of a multi-year La Niña, they cool the Southern Ocean through different processes. For the Australian wildfires, tropospheric processes—specifically, the aerosol–cloud feedback—was identified as the mechanism responsible for cooling the Southern Ocean. On the other hand, for SH volcanic eruptions, the stratospheric aerosols play a role in cooling the Southern Ocean through the reflection of solar radiation. The strong zonal winds in the stratosphere result in a uniform distribution of volcanic aerosols, independent of the longitude of the eruption location. However, it is crucial to investigate the impact of the eruption season on the evolution of ENSO, as discussed by Stevenson et al. (2017). Unfortunately, the Last-Millennium volcanic reconstruction cannot provide information about the specific season of volcanic eruptions.

4. Conclusion

In this study, we present compelling evidence from paleo-proxies, utilizing a substantial sample size of 26 SH volcanic eruptions, to support the hypothesis that ocean cooling in the SH can lead to a multi-year La Niña event (Fasullo et al., 2023). Moreover, these findings emphasize the importance of incorporating the biomass aerosol process as a crucial component of the new ENSO cycle, in addition to the traditional air–sea interaction (Jin, 1997). Furthermore, this study highlights the necessity for greater focus on the Southern Ocean, as most climate models currently struggle to accurately simulate the Pacific response driven by the Southern Ocean. This can primarily be attributed to excessively weak stratocumulus cloud feedback in these models (Kang et al., 2023a).

Data and methods

The long-term volcanic eruption reconstruction, covering the period from 500 BC to 2000 AD, was utilized to expand the sample size for SH volcanic eruptions (Sigl et al., 2015). Additionally, ENSO indices reconstructed mainly from tree rings in southwestern North America were used, which covered the periods of 1408–1978 AD (D'Arrigo et al., 2005), 1300–2006 AD (Cook et al., 2008), and 900–2002 AD (Li et al., 2011), respectively. Instrumental SST data from the HadISST1 dataset were also used as a reference (Rayner et al., 2003). These ENSO reconstructions primarily capture boreal-winter Niño-3 SST changes and exhibit a high correlation with the instrumental Niño-3 index (Liu et al., 2018b).

In order to assess the impact of volcanic forcing, SEA (Haurwitz and Brier (1981) was employed to composite the ENSO response to volcanic eruptions. For the composite analysis, an 11-year window was utilized, including five years before and five years after the eruptions. To determine the significance, we employed the bootstrapped resampling method. The SEA was repeated 10 000 times using random draws from the studied period.

Acknowledgements. We acknowledge the useful discussion with Tao GENG and Yonggang LIU on an early version of the manuscript. The work was supported by the National Key Research and Development Program of China (Grant No. 2020YFA0608803) and the National Natural Science Foundation of China (Grant Nos. 41975107, 41875092 and 42005020).

REFERENCES

Adams, J. B., M. E. Mann, and C. M. Ammann, 2003: Proxy evidence for an El Niño-like response to volcanic forcing. *Nature*, **426**, 274–278, https://doi.org/10.1038/nature02101.

Carn, S. A., N. A. Krotkov, B. L. Fisher, and C. Li, 2022: Out of the blue: Volcanic SO_2 emissions during the 2021–2022 eruptions of Hunga Tonga—Hunga Ha'apai (Tonga). *Frontiers in Earth Science*, **10**, 976962, https://doi.org/10.3389/feart.2022.976962.

Cole, J. E., J. T. Overpeck, and E. R. Cook, 2002: Multiyear La Niña events and persistent drought in the contiguous United States. *Geophys. Res. Lett.*, **29**, 1647, https://doi.org/10.1029/2001GL013561.

Colose, C. M., A. N. LeGrande, and M. Vuille, 2016: Hemispherically asymmetric volcanic forcing of tropical hydroclimate during the last millennium. *Earth System Dynamics*, **7**, 681–696, https://doi.org/10.5194/esd-7-681-2016.

Cook, E. R., R. D. D'Arrigo, and K. J. Anchukaitis, 2008: ENSO reconstructions from long tree-ring chronologies: Unifying the differences. In Talk presented at a special workshop on Reconciling ENSO Chronologies for the Past, **500**, 15.

D'Arrigo, R., E. R. Cook, R. J. Wilson, R. Allan, and M. E. Mann, 2005: On the variability of ENSO over the past six centuries. *Geophys. Res. Lett.*, **32**, L03711, https://doi.org/10.1029/2004GL022055.

Dee, S. G., K. M. Cobb, J. Emile-Geay, T. R. Ault, R. L. Edwards, H. Cheng, and C. D. Charles, 2020: No consistent ENSO response to volcanic forcing over the last millennium. *Science*, **367**, 1477–1481, https://doi.org/10.1126/science.aax2Cook000.

Erez, M., and O. Adam, 2021: Energetic constraints on the time-dependent response of the ITCZ to volcanic eruptions. *J. Climate*, **34**, 9989–10 006, https://doi.org/10.1175/JCLI-D-21-0146.1.

Fasullo, J. T., N. Rosenbloom, and R. Buchholz, 2023: A multiyear tropical Pacific cooling response to recent Australian wildfires in CESM2. *Science Advances*, **9**, eadg1213, https://doi.org/10.1126/sciadv.adg1213.

Geng, T., F. Jia, W. J. Cai, L. X. Wu, B. L. Gan, Z. Jing, S. J. Li, and M. J. McPhaden, 2023: Increased occurrences of consecutive La Niña events under global warming. *Nature*, **619**, 774–781, https://doi.org/10.1038/s41586-023-06236-9.

Han, X., Y. J. Li, F. Liu, J. B. Li, X. T. Zheng, Y. Li, and L. C. Feng, 2023: Stability of ENSO teleconnections during the last millennium in CESM. *Climate Dyn.*, **61**, 5699–5714, https://doi.org/10.1007/s00382-023-06878-5.

Hartmann, D. L., 2022: The Antarctic ozone hole and the pattern effect on climate sensitivity. *Proceedings of the National Academy of*

Sciences of the United States of America, **119**, e2207889119, https://doi.org/10.1073/pnas.2207889119.

Haurwitz, M. W., and G. W. Brier, 1981: A critique of the superposed epoch analysis method: Its application to solar–weather relations. *Mon. Wea. Rev.*, **109**, 2074–2079, https://doi.org/10.1175/1520-0493(1981)109<2074:Acotse>2.0.Co;2.

Haywood, J. M., A. Jones, N. Bellouin, and D. Stephenson, 2013: Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. *Nature Climate Change*, **3**, 660–665, https://doi.org/10.1038/nclimate1857.

Heede, U. K., and A. V. Fedorov, 2023: Colder eastern equatorial pacific and stronger walker circulation in the early 21st century: Separating the forced response to global warming from natural variability. *Geophys. Res. Lett.*, **50**, e2022GL101020, https://doi.org/10.1029/2022GL101020.

Iles, C. E., and G. C. Hegerl, 2014: The global precipitation response to volcanic eruptions in the CMIP5 models. *Environmental Research Letters*, **9**, 104012, https://doi.org/10.1088/1748-9326/9/10/104012.

Iwakiri, T., and M. Watanabe, 2021: Mechanisms linking multi-year La Niña with preceding strong El Niño. *Scientific Reports*, **11**, 17465, https://doi.org/10.1038/s41598-021-96056-6.

Jin, F.-F., 1997: An equatorial ocean recharge paradigm for ENSO. Part I: Conceptual model. *J. Atmos. Sci.*, **54**, 811–829, https://doi.org/10.1175/1520-0469(1997)054<0811:AEORPF>2.0.CO;2.

Jones, N., 2022: Rare 'triple' La Niña climate event looks likely-what does the future hold. *Nature*, **607**, 21, https://doi.org/10.1038/d41586-022-01668-1.

Kang, S. M., P. Ceppi, Y. Yu, and I.-S. Kang, 2023a: Recent global climate feedback controlled by Southern Ocean cooling. *Nature Geoscience*, **16**, 775–780, https://doi.org/10.1038/s41561-023-01256-6.

Kang, S. M., Y. Shin, H. Kim, S.-P. Xie, and S. N. Hu, 2023b: Disentangling the mechanisms of equatorial Pacific climate change. *Science Advances*, **9**, eadf5059, https://doi.org/10.1126/sciadv.adf5059.

Kang, S. M., Y. Yu, C. Deser, X. Y. Zhang, I.-S. Kang, S.-S. Lee, K. B. Rodgers, and P. Ceppi, 2023c: Global impacts of recent Southern Ocean cooling. *Proceedings of the National Academy of Sciences of the United States of America*, **120**, e2300881120, https://doi.org/10.1073/pnas.2300881120.

Khodri, M., and Coauthors, 2017: Tropical explosive volcanic eruptions can trigger El Niño by cooling tropical Africa. *Nature Communications*, **8**, 778, https://doi.org/10.1038/s41467-017-00755-6.

Kim, J.-W., J.-Y. Yu, and B. J. Tian, 2023: Overemphasized role of preceding strong El Niño in generating multi-year La Niña events. *Nature Communications*, **14**, 6790, https://doi.org/10.1038/s41467-023-42373-5.

Lee, S., M. L'Heureux, A. T. Wittenberg, R. Seager, P. A. O'Gorman, and N. C. Johnson, 2022: On the future zonal contrasts of equatorial Pacific climate: Perspectives from Observations, Simulations, and Theories. *npj Climate and Atmospheric Science*, **5**, 82, https://doi.org/10.1038/s41612-022-00301-2.

Li, J. B., S.-P. Xie, E. R. Cook, G. Huang, R. D'arrigo, F. Liu, J. Ma, and X.-T. Zheng, 2011: Interdecadal modulation of El Niño amplitude during the past millennium. *Nature Climate Change*, **1**, 114–118, https://doi.org/10.1038/nclimate1086.

Liu, F., J. Chai, B. Wang, J. Liu, X. Zhang, and Z. Y. Wang, 2016: Global monsoon precipitation responses to large volcanic eruptions. *Scientific Reports*, **6**, 24331. https://doi.org/10.1038/srep24331.

Liu, F., J. B. Li, B. Wang, J. Liu, T. Li, G. Huang, and Z. Y. Wang, 2018b: Divergent El Niño responses to volcanic eruptions at different latitudes over the past millennium. *Climate Dyn.*, **50**, 3799–3812, https://doi.org/10.1007/s00382-017-3846-z.

Liu, F., C. Xing, L. Y. Sun, B. Wang, D. L. Chen, and J. Liu, 2018a: How do tropical, northern hemispheric, and southern hemispheric volcanic eruptions affect ENSO under different initial ocean conditions? *Geophys. Res. Lett.*, **45**, 13 041--13 049, https://doi.org/10.1029/2018GL080315.

Liu, F., and Coauthors, 2022a: Relative roles of land and ocean cooling in triggering an El Niño following tropical volcanic eruptions. *Geophys. Res. Lett.*, **49**, e2022GL100609. https://doi.org/10.1029/2022GL100609.

Liu, F., and Coauthors, 2022b: Tropical volcanism enhanced the east asian summer monsoon during the last millennium. *Nature Communications*, **13**, 3429. https://doi.org/10.1038/s41467-022-31108-7.

Mann, M. E., B. A. Steinman, D. J. Brouillette, and S. K. Miller, 2021: Multidecadal climate oscillations during the past millennium driven by volcanic forcing. *Science*, **371**, 1014–1019, https://doi.org/10.1126/science.abc5810.

McPhaden, M. J., 2023: The 2020-23 triple-dip La Niña. [In "State of the Climate in 2022"]. *Bull. Amer. Meteor. Soc.*, **104** (9), S157–S158, https://doi.org/10.1175/BAMS-D-23-0076.2.

Millán, L., and Coauthors, 2022: The hunga tonga-hunga ha'apai hydration of the stratosphere. *Geophys. Res. Lett.*, **49**, e2022GL099381. https://doi.org/10.1029/2022GL099381.

Miller, G. H., and Coauthors, 2012: Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. *Geophys. Res. Lett.*, **39**, L02708. https://doi.org/10.1029/2011GL050168.

Okumura, Y. M., M. Ohba, C. Deser, and H. Ueda, 2011: A proposed mechanism for the asymmetric duration of El Niño and La Niña. *J. Climate*, **24**, 3822–3829, https://doi.org/10.1175/2011JCLI3999.1.

Paik, S., S.-K. Min, C. E. Iles, E. M. Fischer, and A. P. Schurer, 2020: Volcanic-induced global monsoon drying modulated by diverse El Niño responses. *Science Advances*, **6**, eaba1212. https://doi.org/10.1126/sciadv.aba1212.

Park, J.-H., S.-I. An, J.-S. Kug, Y.-M. Yang, T. Li, and H.-S. Jo, 2021: Mid-latitude leading double-dip La Niña. *International Journal of Climatology*, **41**, E1353–E1370, https://doi.org/10.1002/joc.6772.

Pausata, F. S. R., L. Chafik, R. Caballero, and D. S. Battisti, 2015: Impacts of high-latitude volcanic eruptions on ENSO and AMOC. *Proceedings of the National Academy of Sciences of the United States of America*, **112**, 13 784–13 788, https://doi.org/10.1073/pnas.1509153112.

Pausata, F. S. R., Y. Zhao, D. Zanchettin, R. Caballero, and D. S. Battisti, 2023: Revisiting the mechanisms of ENSO response to tropical volcanic eruptions. *Geophys. Res. Lett.*, **50**, e2022GL102183, https://doi.org/10.1029/2022GL102183.

Power, S., and Coauthors, 2021: Decadal climate variability in the tropical Pacific: Characteristics, causes, predictability, and prospects. *Science*, **374**, eaay9165, https://doi.org/10.1126/science.aay9165.

Raj Deepak, S. N., J. S. Chowdary, A. R. Dandi, G. Srinivas, A. Parekh, C. Gnanaseelan, and R. K. Yadav, 2019: Impact of multiyear La Niña events on the South and East Asian summer monsoon rainfall in observations and CMIP5 models. *Climate Dyn.*, **52**, 6989−7011, https://doi.org/10.1007/s00382-018-4561-0.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.*, **108**, 4407, https://doi.org/10.1029/2002JD002670.

Robock, A., 2000: Volcanic eruptions and climate. *Rev. Geophys.*, **38**, 191−219, https://doi.org/10.1029/1998RG000054.

Robock, A., 2020: Comment on “No consistent ENSO response to volcanic forcing over the last millennium”. *Science*, **369**(6509), eabc0502.

Schneider, T., T. Bischoff, and G. H. Haug, 2014: Migrations and dynamics of the intertropical convergence zone. *Nature*, **513**, 45−53, https://doi.org/10.1038/nature13636.

Schoeberl, M. R., Y. Wang, R. Ueyama, A. Dessler, G. Taha, and W. Yu, 2023: The estimated climate impact of the hunga tonga-hunga ha'apai eruption plume. *Geophys. Res. Lett.*, **50**, e2023GL104634, https://doi.org/10.1029/2023GL104634.

Sigl, M., and Coauthors, 2015: Timing and climate forcing of volcanic eruptions for the past 2,500 years. *Nature*, **523**, 543−549, https://doi.org/10.1038/nature14565.

Singh, M., and Coauthors, 2020: Fingerprint of volcanic forcing on the ENSO-Indian monsoon coupling. *Science Advances*, **6**, eaba8164, https://doi.org/10.1126/sciadv.aba8164.

Stevenson, S., B. Otto-Bliesner, J. Fasullo, and E. Brady, 2016: “El Niño Like” hydroclimate responses to last millennium volcanic eruptions. *J. Climate*, **29**, 2907−2921, https://doi.org/10.1175/jcli-d-15-0239.1.

Stevenson, S., J. T. Fasullo, B. L. Otto-Bliesner, R. A. Tomas, and C. C. Gao, 2017: Role of eruption season in reconciling model and proxy responses to tropical volcanism. *Proceedings of the National Academy of Sciences of the United States of America*, **114**, 1822−1826, https://doi.org/10.1073/pnas.1612505114.

Timmreck, C., 2012: Modeling the climatic effects of large explosive volcanic eruptions. *WIREs Climate Change*, **3**, 545−564, https://doi.org/10.1002/wcc.192.

Wang, B., and Coauthors, 2023: Understanding the recent increase in multiyear La Niñas. *Nature Climate Change*, **13**, 1075−1081, https://doi.org/10.1038/s41558-023-01801-6.

Williams, A. P., and Coauthors, 2020: Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, **368**, 314−318, https://doi.org/10.1126/science.aaz9600.

Wu, X., Y. M. Okumura, and P. N. DiNezio, 2019: What controls the duration of El Niño and La Niña Events?. *J. Climate*, **32**, 5941−5965, https://doi.org/10.1175/JCLI-D-18-0681.1.

Xing, C., and F. Liu, 2023: Mount Pinatubo eruption caused the major East China flood in 1991. *The Innovation Geoscience*, **1(3)**, https://doi.org/10.59717/j.xinn-geo.2023.100032.

Zanchettin, D., C. Timmreck, M. Toohey, J. H. Jungclaus, M. Bittner, S. J. Lorenz, and A. Rubino, 2019: Clarifying the relative role of forcing uncertainties and initial-condition unknowns in spreading the climate response to volcanic eruptions. *Geophys. Res. Lett.*, **46**, 1602−1611, https://doi.org/10.1029/2018GL081018.

Zhang, R., 2023: Greenhouse warming facilitates multi-year La Niña events. *Science Bulletin*, S2095-9273.

Zuo, M., T. J. Zhou, W. M. Man, X. L. Chen, J. Liu, F. Liu, and C. C. Gao, 2022: Volcanoes and climate: Sizing up the impact of the recent hunga tonga-hunga ha’apai volcanic eruption from a historical perspective. *Adv. Atmos. Sci.*, **39**, 1986−1993, https://doi.org/10.1007/s00376-022-2034-1.