Comment:
Marshall et al., Last Millennium Volcanic Forcing and Climate Response using SO_2 Emissions

Dear Lauren and others: This paper is a long awaited and important contribution. It is clearly structured and well written, but I do have few comments on aspects related to the volcanic forcing, the analysis of the climate response, and on the 1458 eruption widely assigned to Kuwae.

I would like to start with a more general comment in the beginning: I always thought that the idea of all MIPs (including PMIP, CMIP) is to explore the range different models respond to the same given forcing. For PMIP3, this was already hampered by having two different volcanic forcing datasets at the same time (Gao et al., 2008, Crowely & Unterman 2012). In this paper you randomized the eruption seasons for unidentified eruptions which are now different to those suggested for past1000 simulations in PMIP4 (Toohey & Sigl 2017). There may be good reasons as you outline in your paper to avoid bias or to explore the role of the season on the climate response specifically, but it makes the comparison across the model simulations more difficult.

Before **discussing the effects of the randomization of the dates** it is important to remind ourselves how these dates have been originally derived. All unidentified eruptions (UE) are based on ice-core records of sulfur or sulfate which are available from both Greenland and Antarctica. State-of-the art records are based on annual-layer counted chronologies, constrained to various extent with historical eruption dates (e.g. in 1362, 1477, 1600) and typically have sub-annual (i.e. nominal monthly to seasonal age resolution, so >4 to 12 samples per year). Toohey & Sigl (2017) made a conservative statement of dating uncertainty in the ice cores of better than ±2 years going back to 500 CE. Work published since has widely confirmed the accuracy of the ice core record for the past millennium using records of lunar eclipses (1100-1300 CE) or links to historic eruptions in Iceland (1300-1500 CE) next to new ice cores analyzed and dated since (Guillett et al., 2023; Plunkett et al., 2023; Stoffel et al., 2022; Abbott et al., 2021; Nardin et al., 2021; Sinnl et al. 2022; Burke et al., 2023). A more realistic estimate of the annual layer ice-core dating since 1200 CE would be +/-1 year at most, with the largest eruption signals in the 13th century and 15th century most likely being dated to the correct year.
In reconstructing volcanic sulfate, we can therefore make time estimates of when the volcanic sulfate deposition at the ice core site exceeded the sulfate deposition from other natural sources. For example, a large volcanic sulfate signal is recorded in the 1450s (let's call it Kuwae, more later) in the annual-layer counted chronologies from NGRIP in 1459.2 (Plummer et al., 2012), NEEM in 1459.1 (Sigl et al., 2013) both from Greenland and in Law Dome in 1458.5 (Plummer et al., 2012) and WDC in 1458.4 (Sigl et al., 2013) both from Antarctica. The seasonal timing information has uncertainties of about 1-3 months based on defining the annual-layer boundaries and the distribution of snowfall throughout the year. Next to the uncertainty in the ice-core layer dating and the seasonal age estimate there is also the uncertainty related to the unknown time lag between a large eruption somewhere in the tropics and the subsequent deposition of aerosols on the polar ice sheets. This time lag is difficult to assess empirically because well-dated large magnitude eruptions are scarce. For Tambora which erupted in April 1815 this time lag was about 6 months (Marshall et al., 2018), and the mean time lag for a number of other large eruptions is in the order of 6 +/-3 months (e.g. Wainman et al., 2024), with both studies using high snow accumulation ice-core sites.
Toohey & Sigl (2017) defined the UE eruption year in the PMIP4 aerosol forcing dataset as the year when the sulfate started to rise, so in the example above the eruption year for Kuwae was set

at 1458. Defining January as the default season was not only for simplicity, but it also made sure that the default eruption date always preceded the start of the volcanic sulfate deposition. A mean lag time between eruption and deposition of 6 months implies that about 50% of the UEs have occurred in the year before the initial volcanic sulfur rise defining the eruption year in Toohey 2017. This has consequences for randomizing dates from UE in the tropics. For example, an UE (or Kuwae) in July 1458 (as suggested in this study) is difficult (though not impossible given the uncertainties discussed above) to reconcile with the start of deposition observed in Antarctica in early summer 1458. But eruptions in October 1453 and October 1809 cannot be reconciled with the start of sulfate deposition in these years (nor with the JJA response in the proxies in 1453). So, in effect, by randomizing the eruption dates for tropical eruption dates without accounting for a time delay you have artificially introduced a seasonal dating bias (towards too young) which might also be reflected in the comparisons with some of the proxy reconstructions.

With the computationally expensive analyses already done, I don't see how to address this in hindsight, but I think a more critical discussion of what you mean with "dating uncertainty" in the eruption dates is warranted which you frequently refer to in the paper without going into much detail. Esper et al. (2017), for example, suggested that the ice-core chronologies are wrong and that the large sulfate signal in 1458 in Antarctica should be dated to 1453 to match the cooling in the Arctic, a suggestion which was widely rejected (Abbott et al., 2021; Nardin et al. 2021; Burke et al., 2023). Or do you mean the uncertainty of the eruption season? These are different aspects and clarity is needed what you mean exactly using this term.

I have another comment regarding your **superposed epoch analysis** (SEA) in Figure 3. In my view, the SEA should isolate the mean idealized climate response to a single large volcanic eruption. It is thus important to provide a representative background period and remove from the individual time segments potential effects from additional large subsequent eruptions, before compositing (i.e. remove all data after 1815 when analyzing 1809). If not, the SEA will underestimate the cooling magnitude and overestimate the persistency in the model and proxy responses (see e.g. Büntgen et al., 2020, their Figure 6 and Supplementary Table S3). You have adopted a volcano-free reference period for the SEA of the three largest eruptions in your Supplementary figure, but not for the other large eruptions included in your Figure 3 which also include some prominent clusters next to 1453/58, 1809/15 e.g. those in 1595/1600 and 1831/1835. The clustering of these likely contributes to the tailing and produces the secondary cooling minima visible in year +6.

Finally, a few words on **Kuwae**: The mid-15th century eruption of Kuwae, Vanuatu has for a long time been linked to the exceptionally large volcanic sulfate signal now dated to 1458 (Gao et al., 2006; and references therein; Newhall et al., 2018). I have no objections to being very conservative and calling the 1450s signals Unidentified 1453 and Unidentified 1458 as was also suggested by Toohey & Sigl (2017). No tephra has been identified in ice cores to geochemically link the signal to the Kuwae eruption. However, recent geochemical work have confirmed the date (as shown above), the correctness of the correlated sulfate signals between Greenland and Antarctica, a purely stratospheric formation of the respective sulfate aerosols (through S-isotope analyses; Burke et al., 2023), and thereby that the sulfur injection estimates are within error comparable to those of other caldera-forming VEI=7 eruptions in 1815 and 1257. The strong asymmetry of sulfate accumulating in the Southern Hemisphere as evidenced by ice cores, together with geochronological, volcanological (volume, caldera-size) and petrologic (sulfur yield) evidence from the source, all suggest that the 1458 ice-core signal remains the strongest contender for the Kuwae eruption (Burke et al 2023; Ballard 2023, Abbott et al., 2021). Using this combined evidence, Kuwae (Vanuatu) was used for the source and a latitude of 17°S for the latest evolv2k_v4 dataset update submitted to PANGAEA recently (Sigl & Toohey, PANGAEA, in review).

Specific comments:

Figure 2: L. 301-302: Tree-rings do not reflect eruption years either, but the years of cooling which can be in the year or in the years after an eruption.

L. 423-24: I would argue that the tree-ring proxy network is spatially biased towards the Arctic and thus underrepresents the cooling observed in 1458 in large areas of the mid-latitudes (e.g. Central Asia, Europe, N-America). NH summer temperature reductions in 1453 from the maximum latewood density (MXD) record from Esper et al. (2017), in particular, are dominated by tree-ring sites located north of 66°N (50% of all records) in proximity to the Arctic ocean with its seasonal sea-ice cover. Temperature reductions at sites below 66°N in Esper et al., (2017) are much smaller (-1.4 °C rel. to 1961-1990) in 1453 AD and almost as large as in 1458 AD (-1.1 °C rel. to 1961-1990). This is also reflected in proxy compilations and monthly reanalysis which assimilated >170 records in the 1450s including most of the tree-ring records discussed here (Valler et al., 2024) summarized in Figures 1 and 2 (below) showing large scale cooling over Northern Hemisphere land areas in the consecutive summers of 1453/1454 and 1458/1459.

L. 592-596: there is, however, no empirical evidence that would suggest that the Samalas 1257 the 1809 or the Tambora 1815 produced strong hemispheric asymmetries of sulfate aerosols. A large network of high-quality ice-core records can be used to benchmark the spatial distribution of sulfate across both hemispheres (Sigl et al., 2014; 2015). For 1458, the spatial spread of sulfate is the opposite to your emission-based simulation, with a much larger sulfate spread over the Southern Hemisphere as could be expected for a large eruption at 17°S such as Kuwae. As it stands now it appears you are giving more credit to an apparently improved match between models and tree rings while largely ignoring existing ice-core observations suggesting otherwise.

L. 706-707: The most direct evidence about the spatial distribution of aerosols from past volcanic eruption arguably comes from the ice cores.

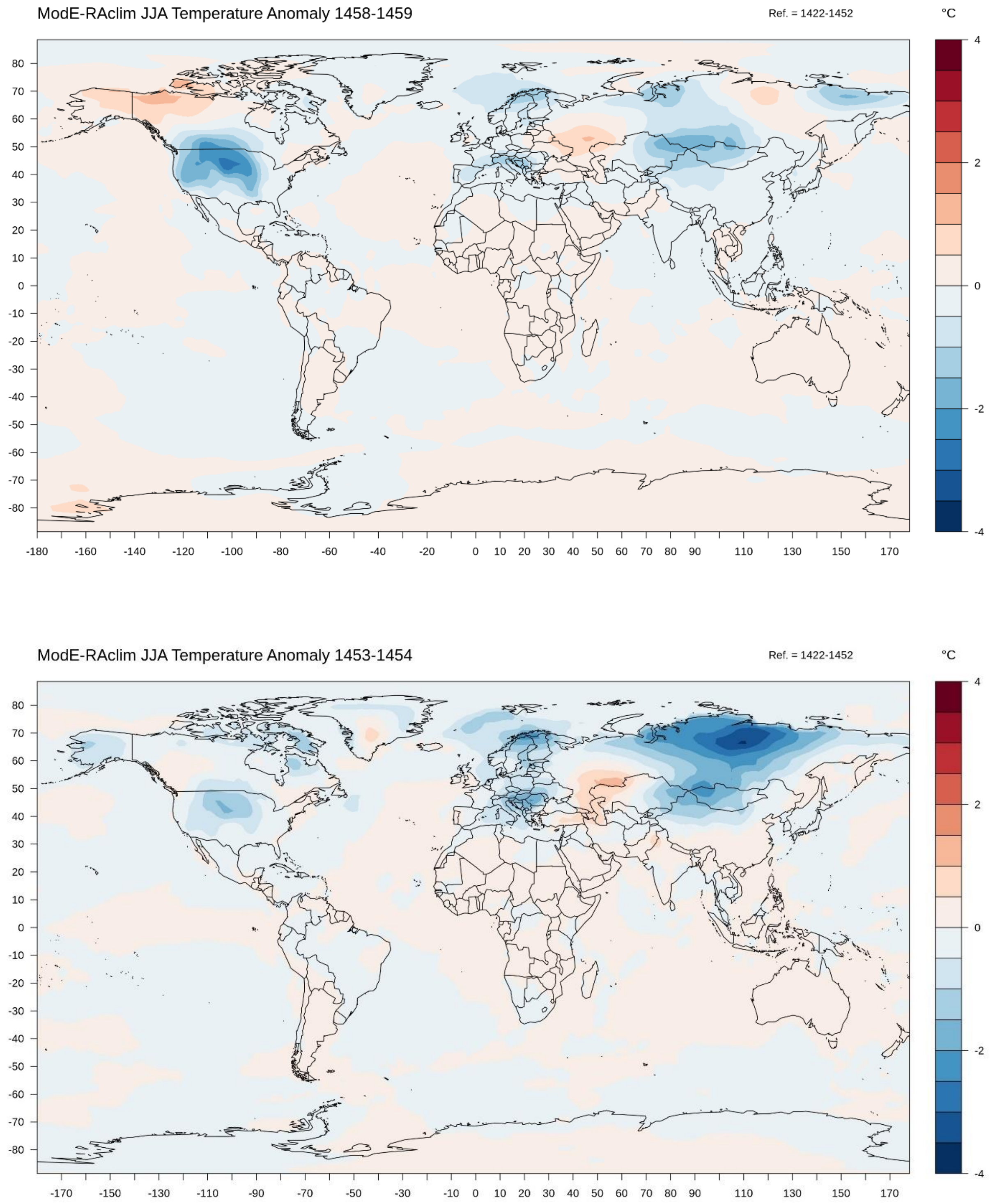
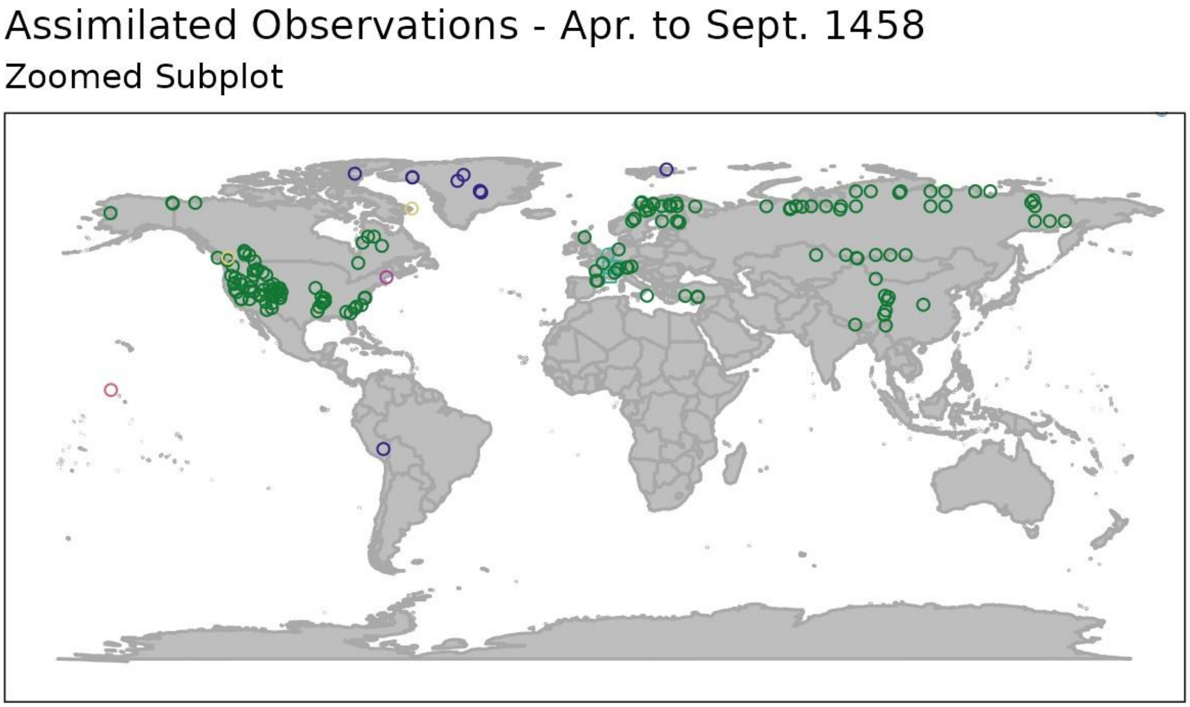


Figure 1: Composite JJA temperature anomaly for 1458 and 1459 (upper panel) and 1453 and 1454 (lower panel) based on >170 proxy records relative to the time period 1422-1452. (Valler et al., 2024)



Assimilated Observations - Apr. to Sept. 1458

Zoomed Subplot

Figure 2: Proxy records used for the climate field reconstruction in Figure 1 before data assimilation (Valler et al., 2024)

References:

Abbott, P. M., Plunkett, G., Corona, C., Chellman, N. J., McConnell, J. R., Pilcher, J. R., Stoffel, M., and Sigl, M.: Cryptotephra from the Icelandic Veiðivötn 1477 CE eruption in a Greenland ice core: confirming the dating of volcanic events in the 1450s CE and assessing the eruption's climatic impact, Clim. Past, 17, 565-585, 2021.

Ballard, C., Bedford, S., Cronin, S. J., and Stern, S.: Evidence at source for the mid-fifteenth century eruption of Kuwae, Vanuatu, Journal of Applied Volcanology, 12, 12, 2023.

Büntgen, U., Arseneault, D., Boucher, É., Churakova, O. V., Gennaretti, F., Crivellaro, A., Hughes, M. K., Kirdyanov, A. V., Klippel, L., Krusic, P. J., Linderholm, H. W., Ljungqvist, F. C., Ludescher, J., McCormick, M., Myglan, V. S., Nicolussi, K., et al.: Prominent role of volcanism in Common Era climate variability and human history, Dendrochronologia, 64, 125757, 2020.

Burke, A., Innes, H. M., Crick, L., Anchukaitis, K., Byrne, M., Hutchison, W., McConnell, J. R., Moore, K., Rae, J., Sigl, M., and Wilson, R.: High sensitivity of summer temperatures to stratospheric sulfur loading from volcanoes in the Northern Hemisphere, P Natl Acad Sci USA, 2023.

Gao, C. C., Robock, A., Self, S., Witter, J. B., Steffenson, J. P., Clausen, H. B., Siggaard-Andersen, M. L., Johnsen, S., Mayewski, P. A., and Ammann, C.: The 1452 or 1453 AD Kuwae eruption signal derived from multiple ice core records: Greatest volcanic sulfate event of the past 700 years, J Geophys Res-Atmos, 111, 2006.

Guillet, S., Corona, C., Oppenheimer, C., Lavigne, F., Khodri, M., Ludlow, F., Sigl, M., Toohey, M., Atkins, P. S., Yang, Z., Muranaka, T., Horikawa, N., and Stoffel, M.: Lunar eclipses illuminate timing and climate impact of medieval volcanism, Nature, 616, 90-95, 2023.

Marshall, L., Schmidt, A., Toohey, M., Carslaw, K. S., Mann, G. W., Sigl, M., Khodri, M., Timmreck, C., Zanchettin, D., Ball, W., Bekki, S., Brooke, J. S. A., Dhomse, S., Johnson, C., Lamarque, J. F., LeGrande, A., Mills, M. J., Niemeier, U., Poulain, V., Robock, A., Rozanov, E., Stenke, A., Sukhodolov, T., Tilmes, S., Tsigaridis, K., and Tummon, F.: Multi-model comparison of the volcanic sulfate deposition from the 1815 eruption of Mt. Tambora, Atmos. Chem. Phys. 2018.

Marshall, L., Schmidt, A., Toohey, M., Carslaw, K. S., Mann, G. W., Sigl, M., Khodri, M., Timmreck, C., Zanchettin, D., Ball, W. T., Bekki, S., Brooke, J. S. A., Dhomse, S., Johnson, C., Lamarque, J. F., LeGrande, A. N., Mills, M. J., Niemeier, U., Pope, J. O., Poulain, V., Robock, A., et al.: Multi-model comparison of the volcanic sulfate deposition from the 1815 eruption of Mt. Tambora, Atmos. Chem. Phys., 18, 2307-2328, 2018.

Nardin, R., Severi, M., Amore, A., Becagli, S., Burgay, F., Caiazzo, L., Ciardini, V., Dreossi, G., Frezzotti, M., Hong, S. B., Khan, I., Narcisi, B. M., Proposito, M., Scarchilli, C., Selmo, E., Spolaor, A., Stenni, B., and Traversi, R.: Dating of the GV7 East Antarctic ice core by high-resolution chemical records and focus on the accumulation rate variability in the last millennium, Clim Past, 17, 2073-2089, 2021.

Newhall, C., Self, S., and Robock, A.: Anticipating future Volcanic Explosivity Index (VEI) 7 eruptions and their chilling impacts, Geosphere, 14, 572-603, 2018.

Plummer, C. T., Curran, M. A. J., van Ommen, T. D., Rasmussen, S. O., Moy, A. D., Vance, T. R., Clausen, H. B., Vinther, B. M., and Mayewski, P. A.: An independently dated 2000-yr volcanic record from Law Dome, East Antarctica, including a new perspective on the dating of the 1450s CE eruption of Kuwae, Vanuatu, Clim Past, 8, 1929-1940, 2012.

Plunkett, G., Sigl, M., McConnell, J. R., Pilcher, J. R., and Chellman, N. J.: The significance of volcanic ash in Greenland ice cores during the Common Era, Quaternary Sci Rev, 301, 107936, 2023.

Sigl, M., McConnell, J. R., Layman, L., Maselli, O., McGwire, K., Pasteris, D., Dahl-Jensen, D., Steffensen, J. P., Vinther, B., Edwards, R., Mulvaney, R., and Kipfstuhl, S.: A new bipolar ice core record of volcanism from WAIS Divide and NEEM and implications for climate forcing of the last 2000 years, J Geophys Res-Atmos, 118, 1151-1169, 2013.

Sigl, M., McConnell, J. R., Toohey, M., Curran, M., Das, S. B., Edwards, R., Isaksson, E., Kawamura, K., Kipfstuhl, S., Kruger, K., Layman, L., Maselli, O. J., Motizuki, Y., Motoyama, H., Pasteris, D. R., and Severi, M.: Insights from Antarctica on volcanic forcing during the Common Era, Nat Clim Change, 4, 693-697, 2014.

Sigl, M., Winstrup, M., McConnell, J. R., Welten, K. C., Plunkett, G., Ludlow, F., Büntgen, U., Caffee, M., Chellman, N., Dahl-Jensen, D., Fischer, H., Kipfstuhl, S., Kostick, C., et al..: Timing and climate forcing of volcanic eruptions for the past 2,500 years, Nature, 523, 543-549, 2015.

Sigl, M. & Toohey M.: Volcanic stratospheric sulfur injections from 500 BCE to 1900 CE, eVolv2k_version4, PANGAEA, submitted.

Stoffel, M., Corona, C., Ludlow, F., Sigl, M., Huhtamaa, H., Garnier, E., Helama, S., Guillet, S., Crampsie, A., Kleemann, K., Camenisch, C., McConnell, J., and Gao, C.: Climatic, weather, and socio-economic conditions corresponding to the mid-17th-century eruption cluster, Clim. Past, 18, 1083-1108, 2022.

Toohey, M. and Sigl, M.: Volcanic stratospheric sulfur injections and aerosol optical depth from 500 BCE to 1900 CE, Earth System Science Data, 9, 809-831, 2017.

Valler, V., Franke, J., Brugnara, Y., Samakinwa, E., Hand, R., Lundstad, E., Burgdorf, A.-M., Lipfert, L., Friedman, A. R., and Brönnimann, S.: ModE-RA: a global monthly paleo-reanalysis of the modern era 1421 to 2008, Sci Data, 11, 36, 2024.

Wainman, L., Marshall, L. R., and Schmidt, A.: Utilising a multi-proxy to model comparison to constrain the season and regionally heterogeneous impacts of the Mt Samalas 1257 eruption, Clim. Past, 20, 951-968, 2024.