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Lunar eclipses as a proxy for investigating the chronology and climate impact of volcanism during the Little Ice Age

BOISSEL Lucas^{1,2}, HUREAU Charlie^{2,3}, GUILLET Sébastien⁴, LAVIGNE Franck², DAHECH Salem¹



¹Université Paris Cité, Paris, France & Pôle de recherche pour l'organisation et la diffusion de l'information géographique (PRODIG), UMR 8566 CNRS/IRD/UPC/AgroParisTech/SU, Paris, France

²Université Paris 1 Panthéon-Sorbonne, Paris, France & Laboratoire de Géographie Physique (LGP), UMR 8591 CNRS/UP1/UEPC, Thiais, France

³Laboratoire des Sciences du Climat et de l'Environnement (LSCE/IPS), UMR 8212 CEA/CNRS/UVSQ, Gif-sur-Yvette, France

⁴Climate Change Impacts and Risks in the Anthropocene (C-CIA), Institute for Environmental Sciences, University of Geneva, Genève, Suisse
Contact: l.boissel@hotmail.com



Introduction

Descriptions of lunar eclipses observations mentioned in historical texts can provide valuable insights for estimating the chronology and impact of volcanism over the past millennium. **Visibility of lunar eclipses is influenced by the quantity of volcanic aerosols present in the upper atmosphere.**

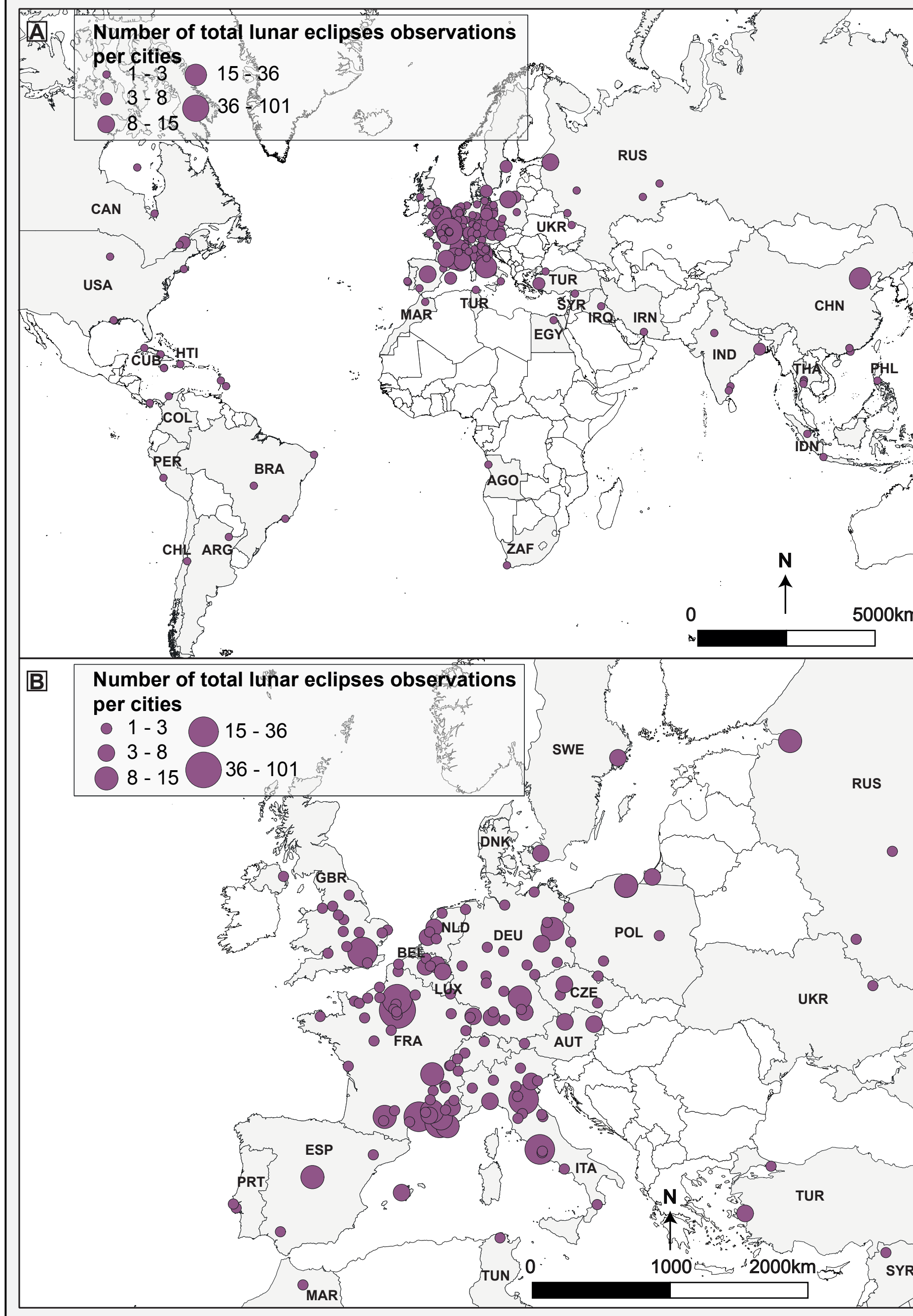
Material and Method

Around 1,000 observation documents were found in several archives and online digitalized collections.

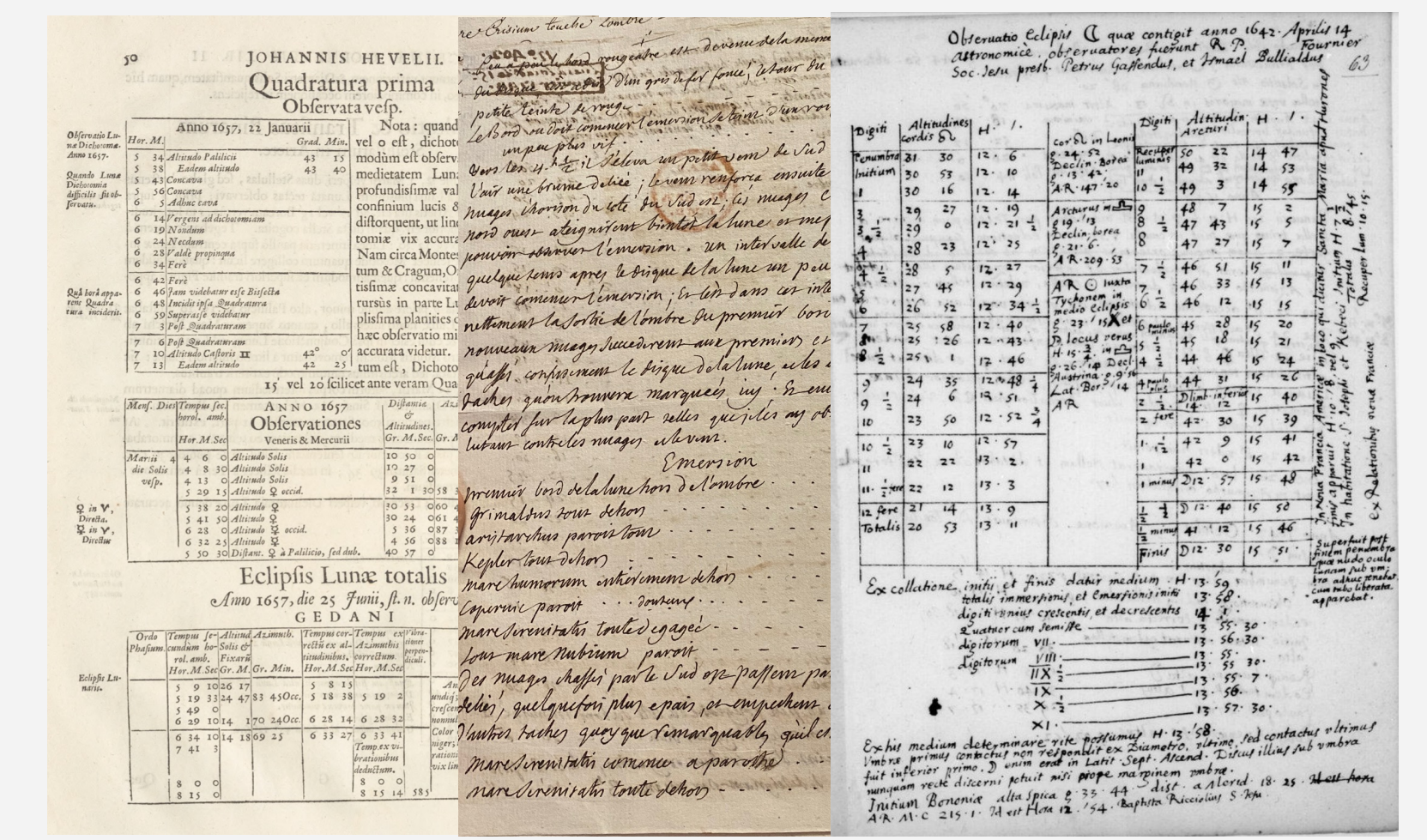
60 total eclipses over the period 1600-1800 were rated according to the Danjon scale, which quantifies naked-eye lunar brightness, ranging from L = 0 (very dark, nearly invisible) to L = 4 (very bright, copper-red or orange eclipse).

Utilizing established conversion methods^{1,2}, we construct a chronology of stratospheric turbidity.

This chronology was subsequently compared with eVolv2k aerosol optical depth (AOD)³, Greenland NEEM-2011-S1 and Antarctica WDC06A ice cores^{4,5}, and tree rings series (tree-ring width (TRW) data ; and maximum latewood density (MXD) data compiled in Guillet *et al.*, 2020⁶.



Example of documents used for setup the chronology

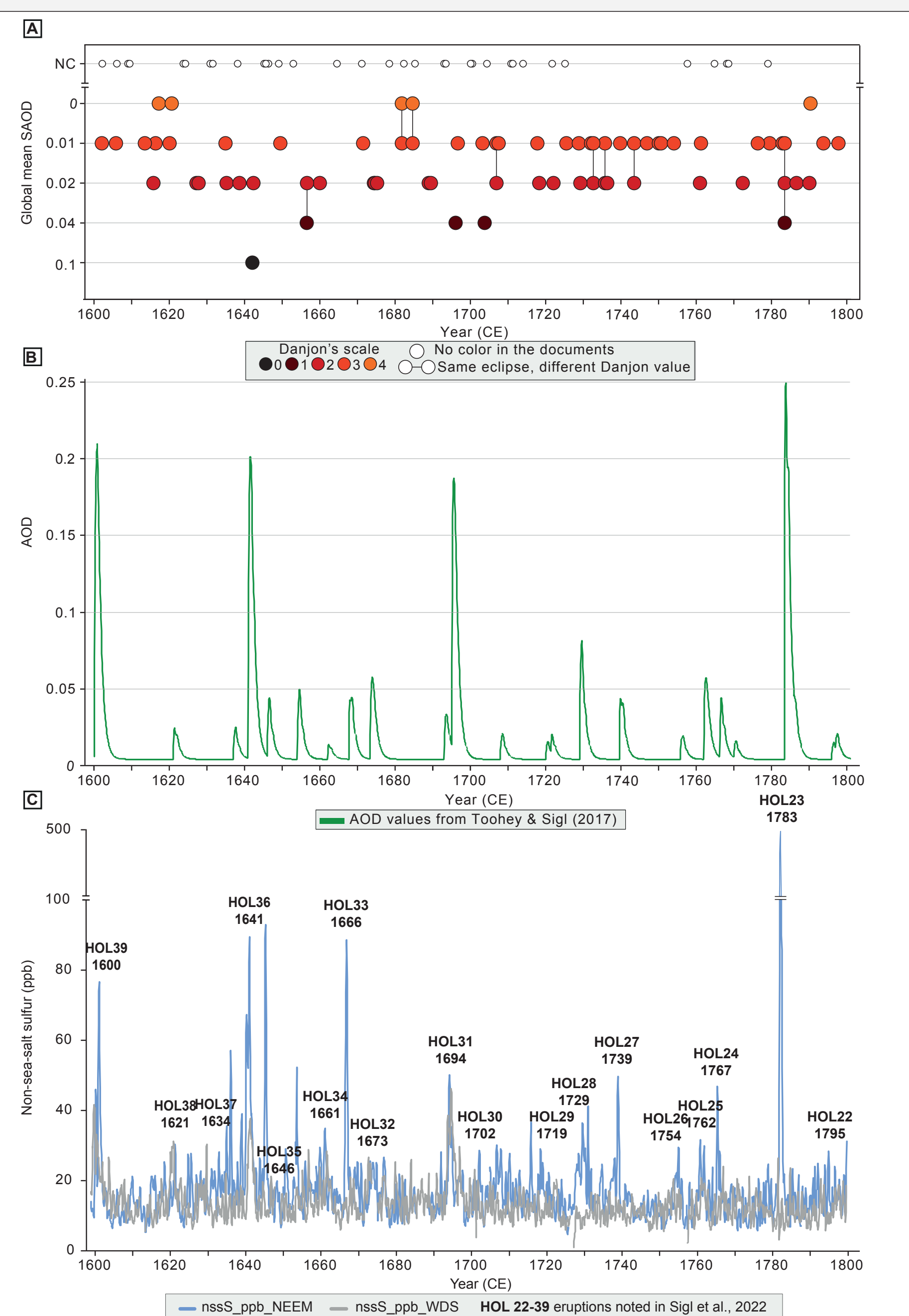


The main document collections used

- | | |
|---|--|
| Manuscripts: | Printed: |
| - Academy of Sciences and Letters of Montpellier | - Astronomy Book from various authors |
| - Archives of the Jesuit Society in Vanves | - Works from European Academy of Science (England, Germany, Italy, Portugal, Russia) |
| - Archives of the Lyon Academy of Sciences, Belles Lettres and Arts | - Works from Jesuit Society |
| - Archives of the Paris Academy of Sciences | - Various correspondences |
| - French National Library | |
| - Paris Observatory Library Archives | |
| - Toulouse Academy of Sciences, Inscriptions and Belles-Lettres | |

Zonality of observation locations in recovered documents.

Results



A: Chronology SAOD (1600-1800) derived from color of total lunar eclipses
B: Aerosol optical depth (AOD) values from Toohy and Sigl (2017)³, estimated from VSSI⁵.

C: Monthly resolved non-sea-salt sulfur concentrations from the Greenland NEEM-2011-S1 (blue line) and Antarctica WDC06A (grey line) ice cores⁴.

Our stratospheric aerosol optical depth (SAOD) chronology is consistent with AOD and ice cores data.

We identified **two very dark lunar eclipses** that are closely related to the AOD and ice cores series : the dark lunar eclipse of April 1642 link with the eruptions of 16417 (22.05 estimated volcanic stratospheric sulfur injection (VSSI))⁵, and the dark eclipse of May 1696 possibly associated with the unknown.s eruption.s of 1694 (18.07 estimated VSSI)⁵.

The unusually dark eclipse of December 1703, however, may reflect local phenomena, as it does not correspond with the estimated magnitude (1.15 estimated VSSI)⁵ of the 1702 eruption.

The nature of the Laki eruption (1783) remains uncertain. Although dark lunar eclipse was observed in Europe in September 1783, these records are insufficient to ascertain whether the eruption reached the stratosphere or remained within the troposphere.

However, a report from Brazil describing a darkened moon during the September 1783 eclipse provides valuable evidence, corroborating the findings of Zambri *et al.* (2019)⁸.

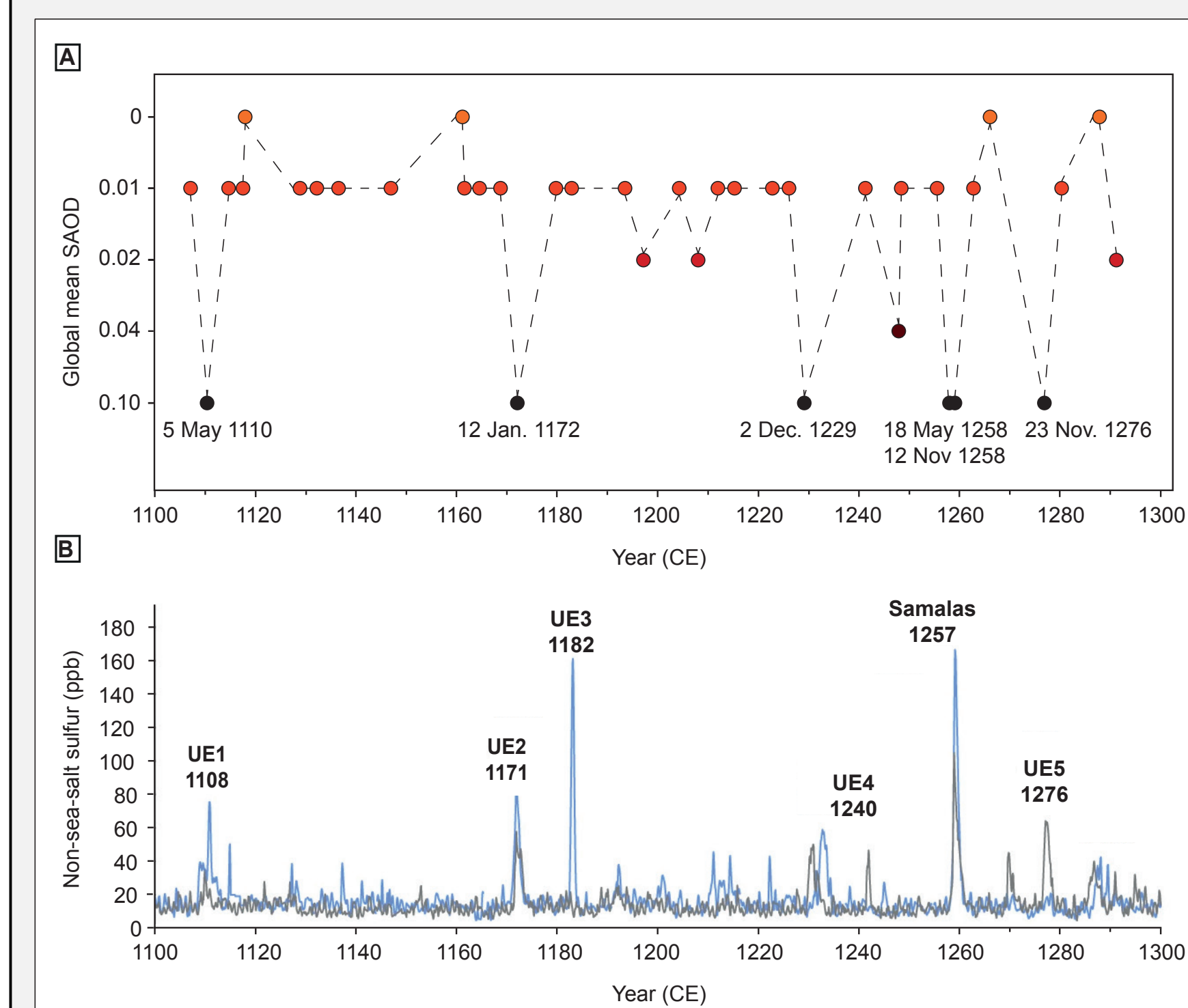
The two dark eclipses linked to volcanic eruptions coincide with particularly cold years in the northern hemisphere. In contrast, the dark eclipse of 1703 is not associated with a cold year.

This suggests that, except during periods of major eruptions, dark eclipses (SAOD > 0.02) are not consistently related to volcanic activity or exceptionally cold years.

This method provides valuable insights into volcanic chronology by providing SAOD estimates at a given time at several geographical positions. However, it has limitation. Total lunar eclipses only occur a maximum of 3 times per year, limiting temporal resolution. In addition, various factors, such as weather conditions, can significantly impact the visibility of the moon. Moreover, historical records often lack detailed descriptions of the moon's color during eclipses.

Discussion

Stothers (2004)² provides the only existing study linking 17th and 18th centuries lunar eclipses to volcanic activity, establishing a chronology beginning in 1671 based on available historical records. While his work offers valuable insights, our chronology extends this research by filling data gaps, incorporating additional sources, and re-evaluating previously analyzed documents for greater accuracy.



A: Chronology SAOD (1100-1300) derived from color of total lunar eclipses
B: Monthly resolved non-sea-salt sulfur concentrations from the Greenland NEEM-2011-S1 (blue line) and Antarctica WDC06A (grey line) ice cores⁴
Adapted from Guillet *et al.*, 2023³. Same legend as the first result figure.

The results of our study align with recent research (1100-1300 CE)⁹ showing that dark lunar eclipses are linked to major volcanic eruptions, causing significant cooling. In the 1700-1800 period, we observed more events with SAOD ≥ 0.02 than in the High Medieval Period. This suggests that while both periods show connections between dark lunar eclipses and volcanic eruptions, interpreting these links depends on the quality and quantity of the historical records.

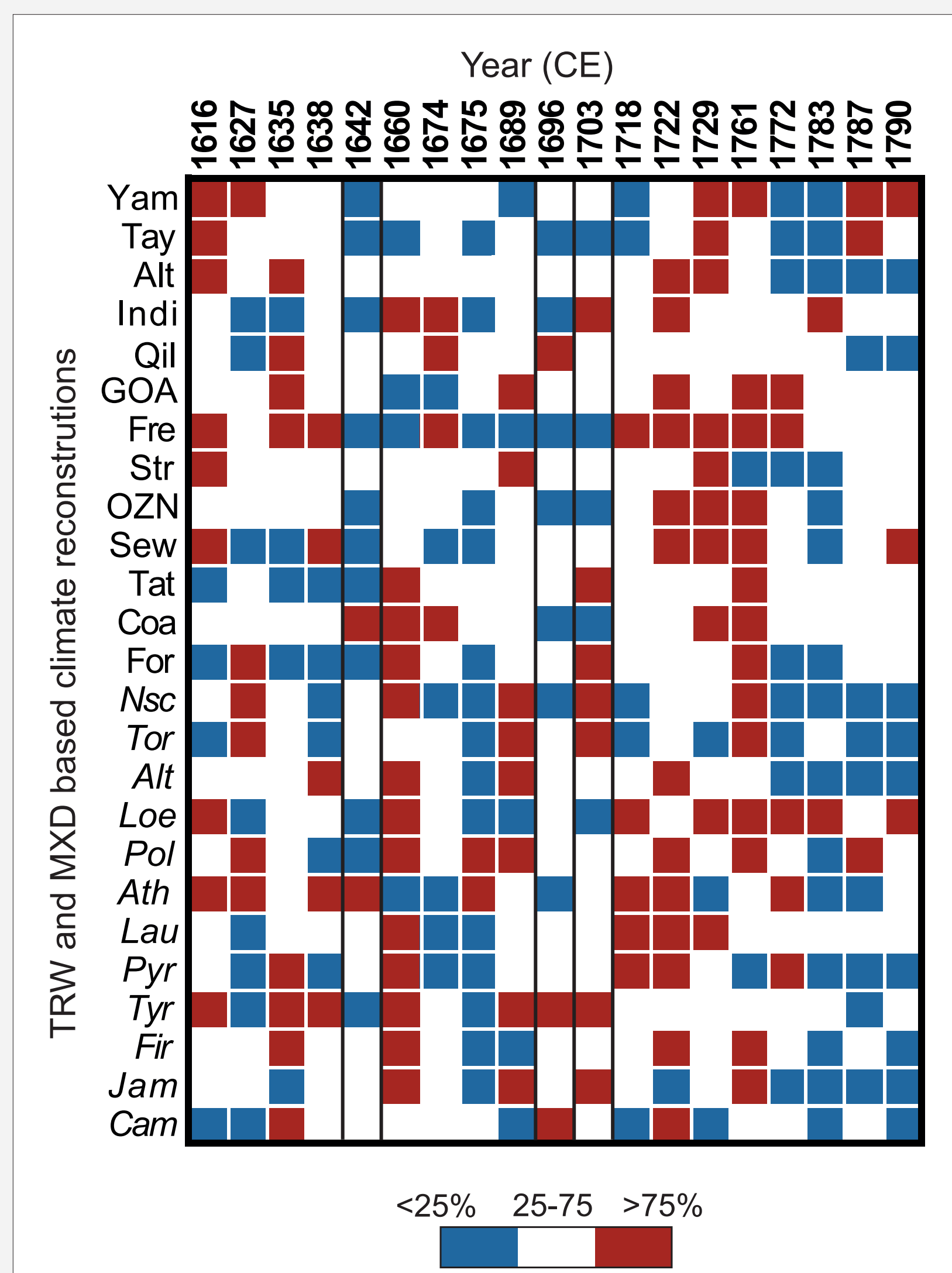
Conclusion and perspectives

These results suggest that lunar eclipses could be a useful proxy for accurately reconstructing the chronology and impact of volcanism during the end of the Little Ice Age. Beyond enhancing the precision of volcanic chronologies and understanding their climatic impacts, this method can offer additional insights. Observations of lunar eclipses allows us to infer the presence and density of stratospheric aerosols from past eruptions, helping to determine whether an eruption reached the troposphere or stratosphere. This approach could also support the calibration of volcanic forcing models, and thus refine our understanding of the timing and intensity of volcanic events.

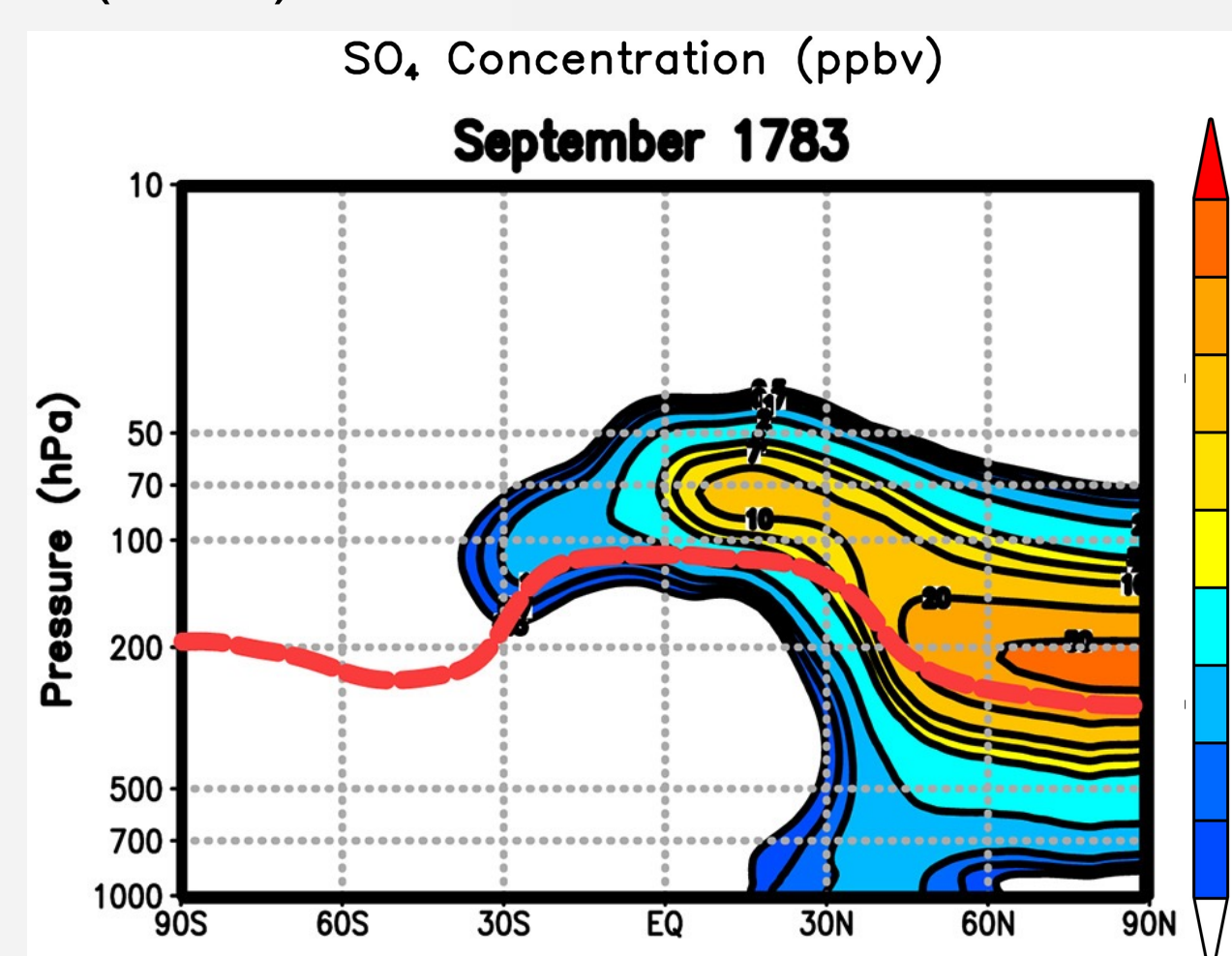
Use data from eclipses observations in multi-proxy studies can lead to a more comprehensive reconstruction of past volcanic activity and its atmospheric effects.

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NH climate conditions according to different tree-rings reconstructions over the years with the darkest eclipses observed (SAOD > 0.02). In blue, values below the 1st quartile indicate very cold years. In red, the 3rd quartile, indicate very warm years. The chronologies noted in italic represent the MXD. Data compiled in Guillet *et al.*, 2020⁶.



Zonal mean sulfate aerosol concentration (ppbv) for the Laki eruption in September 1783. The red line shows the model tropopause from the Laki simulations. Figure adapted from Zambri *et al.*, 2019⁸ (1).