Reviewer 1/ Felix Riede:

The manuscript "Climate and society impacts in Scandinavia following the 536/540 CE volcanic double event" makes a major contribution to our understanding of and recent debate about the climatic perturbations and societal impacts in the 6th century CE. The manuscript is lengthy and ambitious in its attempt to integrate new climate modelling work with terrestrial proxies and archaeological evidence for abandonment and resilience. In a novel and important analytical step, the author team explicitly links the results of their climate models (e.g. temperature and precipitation surfaces) to on-the-ground consequences by linking them to agricultural production via a growing degree model. This conversion allows them to make a very strong case for regional differences in impact (i.e. the magnitude of change away from the optimal conditions) as well as prior vulnerability (i.e. the dependence on sensitive crops or lack of economic buffering) across different regions.

Dear Felix Riede,

Thank you for your thorough comments. We have added our replies below each comment in bold and blue text. We have also added your written comments from the attached PDF below the general comments. At times, it was a bit challenging to decipher your handwriting and what the comment was exactly, but we have tried our best to reply to all of them.

1. While the paper is already ambitious in its scope, I wonder why - when zooming out - the situation in Norway is only compared to Sweden, especially as the title suggests a pan-Scandinavian perspective. There is ample literature on the societal changes that occurred in Denmark at this time and the climate model data are also interesting in this regard (i.e. any impacts are more likely to be indirect rather than climatically-forced). Some relevant literature is also missing - and here I refer particularly to my own core area of expertise (= archaeology).

Thank you for your comment. We agree with this and have added additional sources for Denmark and Finland to the discussion as well.

2. I would urge the author therefore not to focus all too much on impacts (= resilience or its lack) but to really highlight how vulnerable ths communities already were prior to any disturbance (please see the attached pdf for further information).

Thank you for your comment. These are interesting and valuable perspectives that would be suitable for future inquiries, but are unfortunately beyond the scope of the present study. The main target of our paper is to demonstrate how variations in the climate, landscapes and farming response may have contributed to different regional patterns in human consequences during and after the 536/540 CE volcanic double event in Scandinavia. Vulnerability is an integral part of our approach, in particular concerning crop cultivation, but also one that could clearly be explored further with relation to our case-studies. We have therefore rewritten parts of the discussion in order to put more emphasis on this subject (cf. our reply to your comment No. 28). However, vulnerability is also a highly complex concept, manifesting itself in various ways in every aspect of society, and addressing community or household levels of vulnerability to the 536/540 CE event would not only require us to incorporate a larger body of archaeological and paleo-botanical (and perhaps faunal) evidence, but also redesign the whole study. We feel that this would be too ambitious at the moment, but could be a valuable follow-up from our present study. A more complex picture of the 6th century is about to emerge (in this article explored by combining multidisciplinary datasets and demonstrating regional diversity), that opens up for many new perspectives and research designs in the future. The concept of vulnerability will probably prove valuable in this respect, especially as a tool for analyzing climate change versus human change along multiple social scales.

3. In places, the paper would benefit tremendously from a tightening of terminology and language; also a thorough double-checking of technical terms and their spelling for consistency would be good. I have added a number of specific and mostly technical comments in the attached file.

Thank you for your comment. We have gone through the text and rewritten the manuscript where necessary, taking your and reviewer 2's comments into account.

Comments from the manuscript attachment:

4. Line 7. Museum of Cultural History is with capital letters.

Thanks, we corrected this.

5. Are there multiple corresponding authors?

Yes, it is possible to have multiple corresponding authors at CP. We would like to stay with this because of the different disciplines that are covered in the paper.

6. Denmark is not included in the proxies or discussion, why?

Thank you for your comment. We agree we should have included Danish sites as well, since we promise Scandinavia in the title of the paper. We have therefore added sources from Denmark and Finland to the discussion and synthesis sections of the manuscript. For example Nielsen 2005; 2006, Hansen 2016, and Odgaard & Nielsen, 2009 for Denmark, and Oinonen et al., 2020 for Finland.

7. Abstract should be one block of text, and is very long and detailed.

Thank you for your comment. We have shortened the abstract.

'In the Northern Hemisphere, the mid-6th century was one of the coldest periods of the last 2000 years, as indicated by both proxy records and Earth System Model (ESM) simulations. This cold period was initiated by volcanic eruptions in 536 CE and 540 CE. Evidence from historical sources, archaeological findings, and proxy records suggests that the extent and severity of this volcanic induced cooling was spatially heterogeneous. In addition, the effect on society resulted in adaptation and resilience at some locations, whereas social crisis has been indicated at others. Here, we study the effect of the volcanic double event in 536 CE and 540 CE on the climate and society in Scandinavia with a special focus on Southern Norway. Using an ensemble of Max Planck Institute ESM transient simulations for 521-680 CE, the temperature, precipitation and atmospheric circulation patterns are studied. The simulated cooling magnitude is then used as input for the growing degree day (GDD) model set-up for Southern Norway. This GDD model indicates the possible effects on agriculture for three different study areas in Southern Norway, representative of typical meteorological and landscape conditions. Pollen from bogs and archaeological records inside the study area are then analyzed at high resolution (1-3 cm sample intervals) to give insights into the validity of the GDD model set-up with regard to the volcanic climate impact on the regional scale, and to link the different types of data sets. Finally, we discuss the likely climate and

societal impacts of the 536/540 CE volcanic double event by synthesizing the new and available data sets for the whole Scandinavia.

Introduction

8. Line 45. Two times ‘Large’ in.

Thanks, we changed the sentence to avoid repetition.

‘Large volcanic eruptions are the main driver of natural climate variability in the pre-industrial era of the last millenium (Hegerl et al., 2006).’

9. Line 49-50. Add Baillie to references.

Thanks, we have added Baillie (1994) to the references.

10. Line 51. Cite original sources!

Thanks for your comment. We have added Stothers and Rampino (1983) to the references for the dust veil and Büntgen et al. (2016) and Di Cosmo et al. (2018) for the 547 CE eruption.

11. Line 58. More recent?

We have changed the sentence to:

‘Climate model studies indicate a multidecadal cooling rather than a centennial one for the NH, likely impacting society in Scandinavia …’

12. Line 64 (and forward) I’d capitalize periods.

Thanks, we capitalized all periods throughout the manuscript.

13. Line 70. Change ‘in’ to ‘during’.

Thanks, corrected.

14. Line 81. Degroot 2021 is Degroot et al. 2021.

Thanks, corrected.

15. Line 104. What is meant by ‘the likely volcanic climate and society response over Scandinavia’?

Thank you for your comment. We mean here that we try to fit the evidence from pollen and archaeological data to the model simulations, to find a 'most likely' response pattern for Scandinavia. There is still a range of uncertainty, as the pollen and archaeology data are from local sites, which we try to connect to spatial patterns. Thus, we would leave it like it is.

Methods

16. Line 136. Explain 'historical'

Thanks, we have taken out the repetition and elaborated on the meaning of 'historical' here.

'... we used an extension of the past2k run (#2) over the historical period (1850-2014 CE).'

17. Line 166. GDD is already mentioned before.

Thanks, we have taken out the abbreviation, as it was already introduced before.

18. Line 174. Change 'had' to 'needed'.

Thanks, corrected.

19. Line 205. Strike 'written in the mid-6th century'.

Thanks, corrected.

20. Line 216. Strike 'In history'.

Thanks, corrected.

21. Section of 2.3.1 is not clear.

Thank you for the comment, we have rewritten section 2.3.1.

'... Likewise, we have omitted dates from cooking pits, as they represent a temporally restricted cultural phenomenon in Norwegian archaeology (Gundersen, Rødsrud, & Post-Melbye, 2020). They are mostly associated with the Early Iron Age (500 BCE-550 CE) and frequently used for dating purposes, thus creating an overrepresentation of Early Iron Age dates in the overall record.

To model the C14 dates, we have used the Summed Probability Distributions (SPD) analysis within the rcarbon package (Crema and Bevan 2020) in the R statistical programming language (R Core Team, 2019). Dates were calibrated using the Intcal20 calibration curve (Reimer et al., 2020). All dates are presented as calibrated dates BCE/CE.

Well-researched areas and well-dated sites can potentially cause the SPDs to be biased and might generate misleading peaks in the SPD. To mitigate this effect we have implemented artificial bins in rcarbon. We have structured the dates into bins at the site level, with a cut-off value at 50 years, prior to the SPD analysis. The method and data are further described by Loftsgarden and Solheim (in press).'

Results

22. Line 434. Explain 'wrt'.

Thanks, it means 'with respect to'. We have now written this out throughout the manuscript.

23. Line 473. Change 'former' to 'the'.

Thanks, corrected.

24. Line 490. Strike 'highly'.

Thanks, corrected.

25. Section 3.3. So how much farming was there at all?

Around the mid 6 century, farming was well established at all three sites, however of different sizes and with different characteristics. We have added information to Section 2.3, Discussion 4.4, and to the new Table 4 (see your comment No. 38).

Discussion

26. The first paragraph in section 4.1 about the growing season is poorly explained.

Thank you for your comment. We have rewritten this section.

'The modeled mean temperature response for both the short-term and the long-term after the 536/540 CE volcanic double event over Scandinavia is a significant cooling (Fig. 3a). In addition, we simulate a mean growing season 2m air temperature below 5 °C over parts of Scandinavia, which also includes Fron. This could have implications for agriculture, as it is likely that the accumulated temperature sum fails to reach the GDD requirements. For precipitation, the ensemble mean indicates a drying over entire Scandinavia during the 536-560 CE mean as well as for the two years after the eruptions (Fig. 3b), which could also have impacted the crop production. The drying is not surprising, as in general volcanic induced cooling leads to reduced precipitation/evaporation, as colder air can hold less humidity. This is in line with the findings of Büntgen et al. (2011), who studied the climate variability of the past 2500 years in Europe. They found a reduction in summer temperature due to volcanic eruptions to coincide with a drying in the sixth century.'

27. Last paragraph of section 4.1. Cite Bondeson and Bondesson (2014).

Thanks for your comment. Ergot is discussed more in detail below, including the study of Bondeson and Bondesson. However, we have added a citation to Alm and Elvevåg (2013), which thoroughly outlines the main characteristics of ergot and ergotism.

‘Another indicator of rising water levels is the fungus claviceps purpurea, commonly known as ergot, which thrives in cool areas with poor drainage and damp conditions (Alm and Elvevåg, 2013).’

28. Second paragraph of section 4.2. Citations needed! Halstead and O’Shea (1989).

Thanks for your comment. The section builds on the conclusions in Foss’ (1926) experimental studies with pre-modern cereals. Our main argument is that long periods with poor harvest potentially deplete the amount of available sowing grains in a farming community, thus making it increasingly difficult to uphold widespread cereal cultivation. The volume of Halstad and O’Shea (1989) provides interesting case studies on the topic, and adds some important nuances to our argumentation. We have reached the same main conclusion, but rewritten parts of the section.

‘According to Foss (1926), failing to meet the required temperature sum is by no means directly synonymous with crop failure, but would result in smaller yields and a higher frequency of unripened grains unsuitable for sowing. Traditional farmers are likely to have secured themselves by long-term storage, but would only be able to sustain themselves in this way for a limited amount of time. Surplus exchange between neighbouring households and communities may therefore have been an important measure against unforeseen events, thus stimulating the development of specialized craft and stratified societies (Halstead, 1989; O’Shea and Halstead, 1989). However, multiple years with low temperatures and poor harvests, potentially impacting societies on large spatial scales, would nonetheless gradually cause a lack of available sowing grains, thus making it difficult to maintain production. A prolonged volcanic cooling could therefore make necessary changes in subsistence strategies including a shift towards more robust species selection, husbandry practices, and wildlife reliance. Whether this was actually the case must be substantiated by paleo-botanical and archaeological records.’

29. Line 644. Highlighted ‘on the other hand’.

See comment 30.

30. Line 646-650. Not clear to me.

Thanks for your comment. Here we tried to argue that even though the GDD model is a simplified parametrization that might not take all aspects into account, we would have also had biases using daily climate model output (which in this case was not available). We have clarified the sentence.

‘However, the GDD model is a simplified model, and these factors are not included. Here we focus on the temperature, precipitation, altitude, latitude, and growing season length. Still, for this study the GDD model is the appropriate tool to use. If we would have had the daily data output from the climate model, our modelled present-day temperature and GDD estimates would be influenced by the climate model biases and the limited spatial resolution. Therefore, carrying out a scenario with a prescribed volcanic cooling, and using this with the GDD model as we have done here, is more appropriate.’

31. Line 672. Write out 5-9.

Thanks, corrected.

32. Line 672. Change ‘contain’ to ‘have’.

Thanks, corrected.

33. Line 705. Connect the paragraphs.

Thanks, we have added a connection between the paragraphs.

34. Line 724. Explain ‘wide stretching’.

Thanks. We mean extensive/continuous here, as opposed to the topographically restricted farmlands in Fron and around Høgsfjorden. We have reformulated this in the manuscript.

35. Paragraph 2 under ‘Sarpsborg area’. So the evidence here does not fit the model result?

Thank you for your comment. The argument made here is that the decline in burial data, as well as farming indicators, predates the 6th century, which is indicative of other causes than the 6th century cold event. As such, the evidence does not contradict the model results. On the contrary, the low but nonetheless continuous and stable presence of anthropochores and apophytes throughout the 6th century may suggest little direct impact from volcanic cooling on local farming, as opposed to Høgsfjorden and Fron, where farming indicators dropped significantly within the same period. This is explained here in the original manuscript:

‘There is nonetheless a suspicious lack of Migration Period (400-550 CE) and Merovingian Period (550-800 CE) burials at the Bjørnstad site, which might be indicative of some kind of societal disruption, but with unclear temporal relation to 6th century circumstances.’

36. Line 781. Change ‘is’ to ‘they are’.

Thanks, corrected.

37. Line 784-786. Is that softening necessary?

Thanks, we have reformulated this sentence in the manuscript.

‘Particularly important in this respect is the site of Hove-Sørbø, which was contemporaneous with Forsand, but able to maintain settlement and farming during and after the 6th century. Westling et al. (2022) argue that differences in soil qualities and subsistence strategies were decisive for the profoundly different outcomes at the two sites, thus demonstrating the importance of incorporating both human and environmental factors when assessing social vulnerability to changing climates.’

38. Line 800-805. Table? Or ranking?

Thanks for your suggestion. We have added a table summing up the conclusions for each of our study areas at the end of the synthesis section:

Area	Landscape	GDD model after volcanic cooling	Pollen	Farm abandonment
Fron	Mountainous	Crops fail	Decline in grain species	Clear evidence
Høgsfjorden	Fjord	Some crops fail	Decline in some grain species	Clear evidence, end of Forsand complex (Løken, 2020)
Sarpsborg	Clay-rich terminal moraines	Only wheat might fail	No change in grain species	No clear evidence

39. Line 826-829. Plus hard frost?

Thanks for your comment, we have added a reference to the frost rings in the text.

'In addition, frost rings have been found in northern Scandinavia after the 536 CE eruption (Helama et al., 2019), indicating freezing conditions during the growing season. '

40. Line 849. Change 'we aim to' to ???.

Thanks, we have changed '... we aim …' to '... we investigate the role of the 536/540 CE volcanic double event …'

41. Line 864. Change 'though' to 'although'.

Thanks, corrected

42. Line 871-874. Include Højlund-Nielsen? 'At risk' model?

Thank you for your comment. We are not entirely sure what you are referring to here. However, we have added several new references to the discussion, including Nielsen (2005, 2006) and Odgaard and Nielsen (2009).

Code and data availability

43. Add repo for data.

Thank you for your comment. We have added the repository/DOI for the climate and GDD model data, as well as the pollen data. The archaeological C14 data will be published in Loftsgarden and Solheim (2022, in press), and is available on request until then.

References

Alm, T., & Elvevåg, B. 2013. Ergotism in Norway. Part 1: The symptoms and their interpretation from the late Iron Age to the seventeenth century. History of Psychiatry, 24(1), 15-33. doi:10.1177/0957154X11433960

Baillie, M.G., 1994. Dendrochronology raises questions about the nature of the AD 536 dust-veil event. The Holocene, 4(2), pp.212-217.

Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J.O., Herzig, F., Heussner, K.U., Wanner, H. and Luterbacher, J., 2011. 2500 years of European climate variability and human susceptibility. science, 331(6017), pp.578-582.

Büntgen, U., Myglan, V.S., Ljungqvist, F.C., McCormick, M., Di Cosmo, N., Sigl, M., Jungclaus, J., Wagner, S., Krusic, P.J., Esper, J. and Kaplan, J.O., 2016. Cooling and societal change during the Late Antique Little Ice Age from 536 to around 660 AD. Nature geoscience, 9(3), pp.231-236.

Crema, E.R., Bevan, A. 2020. Inference from large sets of radiocarbon dates: software and methods. Radiocarbon 63(1): 23–39. https://doi.org/10.1017/RDC.2020.95

Di Cosmo, N., Oppenheimer, C., & Büntgen, U. (2017). Interplay of environmental and socio-political factors in the downfall of the Eastern Türk Empire in 630 CE. Climatic change, 145(3), 383-395.

Foss, H. (1926). Beretning fra Statens forsøksstasjon for fjellbygdene 1925. Ottende arbeidsår. Forsøk med rug og hvete i fjellbygdene. Oslo: Grøndahl & Søns Boktrykkeri.

Gundersen, I. M., Rødsrud, C. L., & Post-Melbye, J. R. 2020: Kokegroper som massemateriale. Regional variasjon i en kulturhistorisk brytningstid. In C. Rødsrud Løchsen & A. Mjærum (Eds.),

Halstead, P. 1989. The economy has a normal surplus: economic stability and social change among early farming communities of Thessaly, Greece. In J. O'Shea & P. Halstead (Eds.), Bad Year Economics: Cultural Responses to Risk and Uncertainty (pp. 68-80). Cambridge: Cambridge University Press.

Hegerl, G.C., Crowley, T.J., Hyde, W.T. and Frame, D.J., 2006. Climate sensitivity constrained by temperature reconstructions over the past seven centuries. Nature, 440(7087), pp.1029-1032.

Helama, S., Saranpää, P., Pearson, C.L., Arppe, L., Holopainen, J., Mäkinen, H., Mielikäinen, K., Nöjd, P., Sutinen, R., Taavitsainen, J.P. and Timonen, M., 2019. Frost rings in 1627 BC and AD 536 in subfossil pinewood from Finnish Lapland. Quaternary Science Reviews, 204, pp.208-215.

Loftsgarden, K. and S. Solheim. In press. Uncovering population dynamics in Southeastearn Norway from 1300 BC to AD 800 using summed radiocarbon probability distributions. In: Ystgaard, I. and M. Ødegaard (Eds.), Complexity and dynamics: Settlement and landscape from the Iron Age and Medieval period in the Nordic Countries. Sidestone Press

Løken, T. 2020. Bronze Age and Early Iron Age house and settlement development at Forsandmoen, south-western Norway. Stavanger: Museum of Archaeology, University of Stavanger.

Nielsen, K. H. 2005. "... the sun was darkened by day and the moon by night ... there was distress among men ..." - on social and political development in the 5th- to 7th-century southern Scandinavia. In H.-J. Häßler (Ed.), Neue Forschungsergebnisse zur nordwesteuropäischen Frühgeschichte unter besonderer Berücksichtigung der altsächsischen Kultur im heutigen Niedersachsen (pp. 247-285). Oldenburg: Isensee Verlag.

Nielsen, K. H. 2006. Abundant Gold and Bad Harvests: Changes in Southern Scandinavian Society during the 5th to 7th Centuries. In M. Bertasius (Ed.), Transformatio mundi. The transition from the late migration period to the early Viking age in the east Baltic (pp. 41-50). Kaunas: Kaunas University of Technology, Department of Philosophy and Cultural Science.

Odgaard, B., & Nielsen, A. B. 2009. Udvikling i arealdækning i perioden 0-1850. Pollen og landskabshistorie. In B. Odgaard & J. R. Rømer (Eds.), Danske landbrukslandskaper gennem 2000 år. Fra digevoldinger til støtteordninger (pp. 41-58). Århus: Aarhus Universitetsforlag.

Oinonen, M., Alenius, T., Arppe, L., Bocherens, H., Etu-Sihvola, H., Helama, S., Huhtamaa, H., Lahtinen, M., Mannermaa, K., Onkamo, P. and Palo, J., 2020. Buried in water, burdened by nature—Resilience carried the Iron Age people through Fimbulvinter. PloS one, 15(4), p.e0231787.

O'Shea, J. & Halstead, P. 1989. Conclusion: bad year economics. In J. O'Shea & P. Halstead (Eds.), Bad Year Economics: Cultural Responses to Risk and Uncertainty (pp. 123-126). Cambridge: Cambridge University Press.

Reimer, P.J., Austin, W.E., Bard, E., Bayliss, A., Blackwell, P.G., Ramsey, C.B., Butzin, M., Cheng, H., Edwards, R.L., Friedrich, M. and Grootes, P.M., 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon, 62(4), pp.725-757.

Stothers, R. B., & Rampino, M. R. (1983). Volcanic eruptions in the Mediterranean before AD 630 from written and archaeological sources. Journal of Geophysical Research: Solid Earth, 88(B8), 6357-6371.

Westling, S., Fredh, E. D., Lagerås, P., & Oma, K. A. 2022. Agricultural Resilience during the 6th Century Crisis: Exploring Strategies and Adaptations Using Plant-Macrofossil Data from Hove-Sørbø and Forsandmoen in Southwestern Norway. Norwegian Archaeological Review, 1-26. doi:10.1080/00293652.2022.2071331