## Responses to Short Comment by David Pyle

**Comment #1:** For me the leading questions (which come out of this paper) are:
- was the LST eruption the source of a sulphur 'spike' in Greenland ice cores; and how could we test this assertion?

**Response #1:** This could be tested by searching for, and fingerprinting, ash in the ice containing the sulphur spike. We also mention using triple sulphur isotopes to detect stratospheric aerosols as future work. Although this would not pinpoint the LSE as the cause, it would suggest that it was a large eruption where aerosols reached the stratosphere, reducing the likelihood of a localised Icelandic eruption being the origin of the sulphur spike. We now state this as critical future work.

**Comment #2:** What was the total volatile yield from the LST eruption; and what new measurements are needed to improve on this assessment. (And did the halogen release have any impact?)

**Response #2:** The magma that fed the LSE was undoubtedly sulphur-rich (see Textor et al., 2003; and Table 5 in Scaillet et al. 2003), and would have injected significant amounts of $H_2S$ and/or $SO_2$ into the atmosphere, enabling it to have an effect on climate comparable to eruptions that are substantially larger in total erupted volume. Estimating volatile yields from ancient eruptions is difficult and complex (see the review in Scaillet et al., 2003), but we have updated this section (Section 2.0, Background) to include work that builds on the work of Schmincke et al., (1999) that was previously cited. A full petrological study of sulphur in the magma, using updated methodology (for example, that of Vidal et al., (2016)) is beyond the scope of this paper, but we hope that our work will stimulate others to undertake this important study. We have now included the most recent estimates of total sulphur produced by the eruption, as reported in the suggested manuscripts.

**Comment #3:** What cascade of physical processes could lead to the observed pattern of response seen for the onset of the YD; and is a volcanic eruption a sufficient driver, on its own.

**Response #3:** The mechanisms that lead from the initial hemispheric cooling from the LSE sulphate cloud (itself uncontroversial) through to the YD as experienced across western Europe, is described in Section 3.3. Crucially, the LSE occurred during a period of intermediate ice cover, when we infer that the climate was particularly sensitive to short-term cooling events. Thus, we consider that the sulphur-rich LSE was capable of acting as the catalyst for longer term cooling and climatic reorganisation characteristic of the YD. We have also included a much more detailed discussion regarding the positive feedback, and outlining in detail the substantial amount of recent research that has similarly concluded that volcanic eruptions can have long-term consequences for climate.

### Detailed points

Line 44 – there is also a documented enrichment in noble metals (e.g. platinum), at this stratigraphic level both in North America and Europe (Moore et al., Scientific Reports 7 Article Number: 44031, 2017; and papers by A Andronikov).

**Response:** We have now included references to the paper by Moore et al. and Andronikov.

Line 50 – 'new support' yes, but not much new evidence.

**Response:** We explain how short-term, volcanogenic sulphate-induced hemispheric cooling could have acted as the trigger for the longer-term cooling and climatic changes associated with the YD. In the last few comprehensive reviews of the Younger Dryas event (e.g., Carlson 2010; Fiedel 2011) there was no mention of the LSE or any volcanic eruption as a trigger. We therefore feel that we use existing evidence to arrive at a very novel and provocative conclusion.

Line 50 – ages: some explanation is needed
about the framing of time in the paper, as the model ages are derived from multiple approaches.

**Response:** We have now clarified the origin of the dates, as well as added dating uncertainties where needed.

Lines 53- 56: the emphasis here isn't quite right. The evidence for a 200-year time break between LST and the onset of 'YD' conditions in continental Europe remains firm. What has changed – since Lane et al., 2015, is the recognition that the onset of YD is time-transgressive. So – by inference – LST overlaps with GS-1 and the onset of YD as recorded in ice chemistry in Greenland.

**Response:** We believe that it is correct as we have it written. The YD is a term that has its origins in central European climate studies that detected the change in atmospheric circulation. So whereas GS-1 cooling did lead to the manifestation of the YD in central Europe, GS-1 cooling was not the YD itself.

Line 57 – does the 'GICC05modelext chronology' need a word or two of explanation
**Response:** We have now clarified this at the first occurrence in the text.

LST Impacts
Line 74: see also the extensive work by Felix Riede on the impacts of the LST:
Book, 2017 - Splendid Isolation : The eruption of the Laacher See volcano and southern Scandinavian Late Glacial hunter-gatherers. / Riede, Felix. Aarhus : Aarhus Universitetsforlag, 2017. 214 p.
2016 - Changes in mid- and far-field human landscape use following the Laacher See eruption (c. 13,000 years BP). / Riede, Felix. In: Quaternary International, Vol. 394, 02.2016, p. 37-50.
2012 - Bayesian radiocarbon models for the cultural transition during the Allerod in southern Scandinavia, Riede, Felix; Edinborough, Kevan, JOURNAL OF ARCHAEOLOGICAL SCIENCE 39, 744-756
2008 - The Laacher See-eruption (12,920 BP) and material culture change at the end of the Allerod in northern Europe, Riede, Felix, JOURNAL OF ARCHAEOLOGICAL SCIENCE 35, 591-599

**Response:** We thank Professor Pyle for bringing these studies to our attention and we now reference Riede (2008) and Riede (2016) in the appropriate section.

Volcanic Emissions
Lines 78 - 85 – this section needs some critical revision and updating. Harms and Schmincke (2000) estimated, using mass balance, an SO2 yield of 20 Tg. Harms et al. (2004) did some experiments on LST magmas and determined the P, T , H2O conditions under which the magma was stored; you could revisit the calculations of Harms & Schmincke to re-estimate the S and water budgets of the system – taking account of the work that Bruno Scaillet and colleagues have done on other systems. The '150 Mt' value should be cited as Schmincke et al (1999, Quaternary International, 61, 61-72) – it is, as the authors say 'highly speculative' and based on using the 'Pinatubo multiplier'; this can certainly be improved upon, rather than being taken as a starting point for the argument. Similar calculations have been attempted by Textor et al., 2003, (Geol Soc London Spec Pub, 'Volcanic Degassing', 213, 307-328); who also estimated the total halogen yield. Discussion on volcanic emissions Recent papers may also add a little to the discussion here: for example - - Colose, C.M., A.N. LeGrande, and M. Vuille, 2016: Hemispherically asymmetric volcanic forcing of tropical hydroclimate during the last millennium. Earth Syst. Dyn., 7, 681-696, doi:10.5194/esd-7-681-2016. - LeGrande, A.N., K. Tsigaridis, and S.E. Bauer, 2016: Role of atmospheric chemistry in the climate impacts of stratospheric volcanic injections. Nature Geosci., 9, no. 9, 652-655, doi:10.1038/ngeo2771.

**Response:** These are very good points and we have extensively updated this section. We now include the improved sulphur yield estimates of Textor et al., (2003), and note that these are still significantly greater than those emitted by the climatically-important Pinatubo eruption. A detailed petrological investigation of S contents in LS tephra would be a very interesting, substantial study, and we hope our research will encourage other researchers to look into this.

Line 178 – 'five years' may be an overestimate: in Graf and Timmreck's model, sulphate aerosol had an e-folding time of 11 months; and the detectable signal of volcanic stratospheric sulphate aerosol is usually considered to be less than three years.

**Response:** The text has been modified throughout.

Lines
180 – 195 – there's not really any new evidence here?

**Response:** Here we are drawing links between different a wide range of studies to establish a plausible mechanism to trigger long-term cooling following a short-term volcanic forcing of climate. We have added substantially more discussion to make this point clearer.

Line 208 – the magnitude of the eruption is not relevant, it's the magnitude of the gas release that is the key point. The LST magma is an unusual composition, so surely this is the starting point for why it may have had an exceptional impact?

**Response:** This is a very useful comment, and although we did appreciate that this was the case before, the manuscript did focus too much on magnitude and not enough on sulphur yield and the unusual composition of the magma. We have added a statement on the importance of the sulphur content of the erupting magma, as well as emphasising the sulphur yield rather than the magnitude throughout.

Lines 274 – 284: there still is no way of linking a sulphate peak in an ice core to a particular eruption, in the absence of any tephra so this remains speculative. It remains possible that sulphur mass-independent isotopic fractionation signals may help to identify plumes that entered the stratosphere (e.g. Martin et al., 2014, Volcanic sulfate aerosol formation in the troposphere, JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES Volume: 119 Issue: 22 Pages: 12660-12673), but this still won't help with source identification.

**Response:** This is an important point and we now discuss this in more depth, with the following text added to the conclusions:

*"Similarly, volcanic sulphate 'triple' isotope ratios of sulphur and oxygen provide information regarding the residence time of volcanic plumes in the stratosphere. The majority of atmospheric processes encourage mass dependent fractionation; however rare mass-independent fractionation processes produce isotope ratios that do not behave according to predictions based on mass dependent processes (Martin et al., 2014). Historical volcanic eruptions where sulphate aerosols reached the stratosphere have been successfully identified in ice cores (Baroni et al., 2008; Savarino et al., 2003), indicating that the technique is effective at distinguishing large explosive eruptions from smaller local ones. This technique could also determine if the sulphate in the potential LSE sulphate spike reached the stratosphere. Although this would not necessarily confirm the LSE as the source, it would strongly suggest that the sulphate was sourced from a climatologically important eruption rather than a smaller Icelandic one."*