Response to the comments from Thomas Aubry, Lauren Marshall and Anja Schmidt:

‘This manuscript by Jiamei Lin and co-authors represents the first effort to constrain stratospheric volcanic SO2 emissions for the 60-9 ka period using a bipolar array of ice cores, and these emissions are then used to estimate the corresponding volcanic forcing. This will without doubt be a very useful contribution for the community working on volcano-climate interactions.’

We are grateful for the positive comments and suggestions from Thomas Aubry, Lauren Marshall and Anja Schmidt. Below, we provide our responses in blue color.

‘We would like to draw the attention of the authors to potential improvements for estimating volcanic forcing from emissions.

First, to estimate a global-mean Stratospheric Aerosol Optical Depth (SAOD), the authors use a linear scaling between SAOD and the aerosol loading. However, it is well known that for large eruptions this relationship is not linear (e.g. Crowley and Unterman, 2013). As highlighted by the authors, the scaling used in their work is calibrated against the 1991 Mt. Pinatubo eruption and the reference used does not employ the latest estimates of SO2 mass and SAOD for this eruption. For example, the post-Pinatubo peak global mean SAOD in Crowley and Unterman (2013) (ca. 0.14-0.15) is 16% larger than in the GloSSAC dataset (0.12-0.13, Kovilakam et al. 2020). We suggest that the authors consider either using the EVA model (Toohey et al., 2016) or the EVA_H model (Aubry et al., 2020) to obtain SAOD. EVA is calibrated using more up-to-date data for Pinatubo and is also a reference model for the community as it has been used to derive the volcanic forcing for CMIP6’s Paleoclimate Model Intercomparison Project (PMIP4). EVA_H is an extension to EVA that was calibrated using the full 1979-2015 period with state-of-the-art observational datasets. Additionally, in EVA_H the predicted global mean SAOD depends on the eruption latitude, which is not the case in EVA.

We thank the authors for pointing out potential limitations of our method for eruptions with excessive sulfate loadings and recommend the easy volcanic aerosol (EVA) model (Toohey et al., 2016) and the EVA_H model (Aubry et al., 2019) to derive SAOD from the stratospheric sulfate aerosol loading. We now apply those scaling factors in addition to the approach of the submitted version of the manuscript (see below).

Second, to convert global-mean SAOD to global-mean radiative forcing, the authors use the scaling factor of Hansen et al. (2005). This scaling factor was constrained using climate model simulations for the 1991 Mt. Pinatubo eruption without full consideration of rapid adjustments. Several recent studies have suggested that consideration of rapid adjustments leads to a reduction in the scaling factor (e.g., Gregory et al., 2016; Larson & Portmann, 2016; Schmidt et al., 2018; Marshall et al., 2020). Revised scaling factors for a wide range of eruptions are available in Marshall et al. (2020). Collectively, these studies suggest a reduced conversion factor compared to Hansen et al. (2005) and IPCC AR5.

To obtain the global radiative forcing, we now also adopt the revised scaling factor from Marshall et al., (2020).

We acknowledge that using more recent methods will result in differences in reconstructed forcings that are likely small relative to uncertainties in ice-core derived estimates of the SO2 mass. We nonetheless think that it remains important to acknowledge and use the latest tools developed by the community to provide volcanic forcing estimates. At the minimum, the authors should discuss differences that may emerge from using different scaling factors.

Thank you for recommending the newer approaches to reconstruct the volcanic forcing. We have added to following text to section 4.3: ‘To estimate the volcanic radiative forcing from eruptions occurring in the last glacial and early Holocene we need to constrain the sulfate stratospheric aerosol loading (we applied the method of Gao et al. (2007)), to convert the stratospheric aerosol loading into the global mean stratospheric aerosol optical depth (SAOD) (we applied the methods of Crowley and Unterman. (2013) and that of Aubry et al. (2020)), and to convert global mean SAOD to the global mean radiative forcing (we applied the methods of Hansen et al. (2005) and that of Marshall et al. (2020)). The global stratospheric sulfate aerosol loading requires a separation of NH high-latitude eruptions from other eruptions, as the two eruption groups are scaled differently (Gao et al., 2007). We defined NH high latitude eruption as eruptions that occurred at a latitude above 40° N. To identify the NH high latitude eruptions, we applied a Support Vector Machine learning classifier model (SVM – see methods section), that is trained by the bipolar sulfate deposition of volcanic eruptions for which the eruption site is known. We applied 17 Holocene and 4 glacial volcanic eruptions of known origin (Table S6) to predict that 50 out of 85 bipolar eruptions of unknown origin are likely to have occurred in the NH high latitudes (Fig. 1 and Fig. 6). We then reconstruct the volcanic radiative forcing using three different approaches:

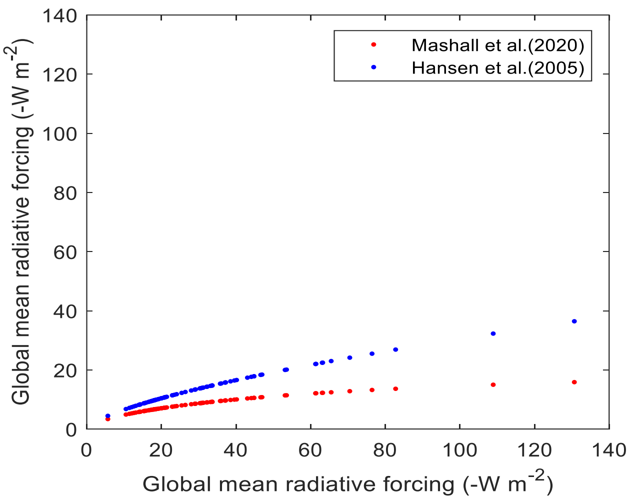
1) The global mean SAOD is obtained using the method of Crowley and Unterman. (2013) and the radiative forcing calculation applies the scaling factor of Hansen et al. (2005). Here the volcanic radiative forcing is calibrated against Pinatubo 1991 AD (at 15°N), and the approach is similar as Sigl et al. (2015).

2) The global mean SAOD is obtained using the scaling factor of Aubry et al. (2020) and the radiative forcing calculation applies the scaling factor of Hansen et al. (2005). This approach is similar as the one used in the IPCC AR5.

3) The global mean SAOD is obtained using the scaling factor of Aubry et al. (2020) and the radiative forcing calculation applies the scaling factor of Marshall et al. (2020), which considers rapid aerosol adjustment for large volcanic eruptions.

All of the reconstructed volcanic radiative forcings are calibrated and evaluated based on modern volcanic eruptions, and they are therefore potentially biased when applied to the eruptions occurring in the very different glacial climate. Table S5 and Fig. S11 present the reconstructed volcanic radiative forcing of individual volcanic events using three approaches. The reconstructed volcanic forcing obtained by method 2) and 3) is significantly weaker than that obtained by method 1) by a factor of 1.3 and 2.8, respectively, when integrated over all events. In the following, we adopt method 3) to present the reconstructed volcanic forcing values.'.

The figure below shows the comparison of the above three volcanic forcing reconstructions. The reconstructed volcanic forcing by the recent methods (Y axis values in red and blue dots) is relatively weaker than that reconstructed by the same method as Sigl et al. (2015) (X axis values in red and blue dots). The total volcanic forcing value for all the bipolar volcanoes reconstructed by the second and the third methods are respectively 1.3 times and 2.8 times weaker than that using the same method of Sigl et al. (2015).



The same method as Sigl et al. (2015)

Thanks again for a very interesting manuscript.

Thank you very much for your comments that have led to an improved manuscript.