Comment on ice-core chronology, volcanic eruptions and solar proton events in 774 and 993

Thanks for the authors for describing and making available this data from an exceptionally high-resolved ice-core record from East Antarctica. I would here like to add some perspective on chronological questions, which I believe would be helpful to address to raise awareness in the broader research community and potential users of the data.

The DSS layer counted timescale was derived independently without reference to volcanic eruptions or other potential stratigraphic age markers. This approach is thus very useful in quantifying uncertainties of annual-layer counting in ice cores, which cannot be done if external age constraints were used during development of the dating. You provide subjective quantitate estimates of the dating uncertainty based on the number and quality of independent seasonal tracers and consider your age error estimates as "conservative" and rather biased towards undercounting than over-counting.

I wonder what is your basis for these considerations? Can these be underpinned by existing data or analyses? Undercounting would be the exemption for ice-core chronologies based on annual-layer counting. For the Holocene and Common Era (see Table 1), at least three different annual-layer counted chronologies exist: (1) *Meese/Sowers* for GISP2 (Meese 1999), (2) *GICC05* for Dye3, GRIP and NGRIP1 (all in Greenland (Vinther et al., 2006)), and (3) *WDC06A-7* for WDC (Antarctica (Sigl et al., 2013)). All three of these chronologies were subject to over-counting (up to 70-80 years at 11 ka BP as was established with the help of cosmogenic radionuclides (i.e. ^{14}C, ^{10}Be; (Muscheler et al., 2014; Sigl et al., 2016)). Following the discovery of global-scale anomalies in the tree-ring ^{14}C content in trees (Büntgen et al., 2018; Miyake et al., 2012) and subsequent detection of corresponding anomalies (up to +9 standard deviations from natural variability) in ^{10}Be ice-core concentrations (Miyake et al., 2015; Sigl et al., 2015), a dating bias (towards c. 7 years too old at 775 CE) was established in Greenland (2) and Antarctica (3) chronologies. Details about the reasons explaining this bias are presented elsewhere (e.g. Plunkett et al., 2022; Sinnl et al. 2021). Consequently, new annual-layer counted chronologies were constructed constrained by the 775 CE anomaly (see Figure 1). In Greenland this was (4) *NS1-2011* for NEEM(2011-S1), and (5) *DRI_NGRIP2* for NGRIP2 (5) and in Antarctica this was (6) *WD2014* for WDC (replacing WDC06A-7).

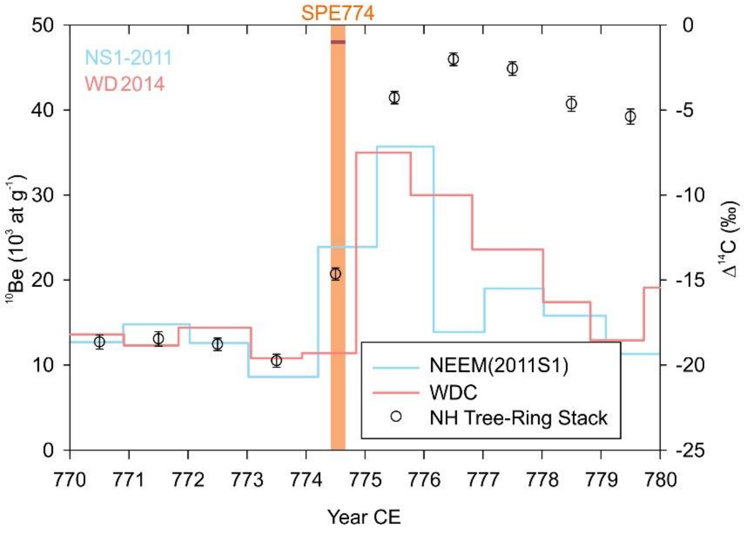

Figure 1: High-resolution ^{10}Be data from NEEM(2011S1) on the NS1-2011 chronology and WDC on the WD2014 chronology (Sigl et al., 2015) relative to Δ^{14}C derived from a Northern Hemisphere (NH) tree-ring stack (Büntgen et al., 2018). Shading indicates the error estimate for the solar proton event in 774 CE.

Table 1: Selection of key annual-layer counted ice-core chronologies.

ID	Chronology	Region	Ice Core(s)	Age Constraints	References
(1)	Meese/Sowers	Greenland	GISP2	unknown	Meese (1999)
(2)	GICC05	Greenland	Dye3, GRIP, NGRIP1	Volcanoes (V)	Vinther et al., (2006)
(3)	WDC06A-7	Antarctica	WDC	V	Sigl et al. (2013)
(4)	NS1-2011	Greenland	NEEM(2011-S1)	V, ^{10}Be anomaly	Sigl et al. (2015)
(5)	DRI_NGRIP2	Greenland	NGRIP2	V, ^{10}Be anomaly	McConnell et al. (2018)
(6)	WD2014	Antarctica	WDC	V, ^{10}Be anomaly	Sigl et al. (2015)
(7)	ANT2k	Antarctica	DSS, WDC, NGRIP1	V	PAGES2k Cons. (2013)
(8)	DSS	Antarctica	DSS	none	Jong et al. (2022)

The revised and constrained chronologies (4,6) have been used to reconstruct volcanic aerosol forcing recommended by PMIP4/CMIP for *past2k* climate simulations (Jungclaus et al., 2017; Toohey and Sigl, 2017). It could further be demonstrated that only by using the volcanic forcing on these chronologies consistent temperature responses could be detected in absolute-dated tree-ring temperature reconstructions throughout the last 2000-2500 years (Büntgen et al., 2020; Sigl et al., 2015).

In parallel to these chronological developments within the ice-core community, multi-proxy reconstructions and data assimilations of regional (including Antarctica) and later global temperature and precipitation have been compiled (PAGES2k Consortium 2013, 2017, Konecky et al., 2020; Steiger et al., 2018; Stenni et al., 2017). Instead of using the independent chronologies for this purpose a common chronology, named *ANT2k* (7) has been produced for Antarctica by averaging the ages of *GICC05*, *WDC06A-7* and DSS (8) for c.40 common volcanic marker events (PAGES 2k Consortium 2013). To my best knowledge (and with the exception of WDC for which the data was later updated to *WD2014*), this common chronology is used for all subsequent composite reconstructions from Antarctica within the PAGES2k Consortium. The previous mentioned revisions made on two out of the three chronologies underpinning ANT2k (largely consistent with an age shift of 5-10 years towards younger ages during the 1st millennium CE) have not yet been implemented in these major paleoclimate databases. This means that volcanic forcing and a large body of paleoclimate evidence remain temporally offset throughout most of the first millennium. Implications of this mismatch are exemplified by studies focusing on the Northern Hemisphere (Büntgen et al., 2020; Plunkett et al., 2022; Sigl et al., 2015) with far-reaching consequences for our limited understanding of amplitudes of past natural climate variability (PAGES 2k Consortium 2019; Neukom et al., 2019) culminating for example in strongly contested (Anchukaitis et al., 2012; Büntgen et al., 2018) claims of missing tree rings and alleged chronological errors in tree-ring reconstructions that accumulate back in time (Mann, 2021; Mann et al., 2012).

I am describing these lengthy details on the history of ice-core chronologies in the last decades not at all to convince the authors to change the chronology or the datasets presented in this paper. A fully independent, year-by-year history of aerosols, snow-accumulation and stable-isotopes is a very valuable asset in the research field, as demonstrated recently (Vance et al., 2022). However, there will also continue to be research applications (e.g. analyzing spatial response to rapid climate changes (Buizert et al., 2018) or estimating mean volcanic sulfate deposition across Antarctica (Sigl et al., 2014)) in which a common chronology over Antarctica will be required. In this case, it would be mandatory to know existing age differences among ice-cores.

Investigating the age differences between DSS and *WD2014* for some outstandingly large common volcanic eruption signals it appears that DSS is consistently older than WD2014 during the 1st millennium CE sometimes slightly outside the stated error bounds which you consider conservative for DSS (Table 2; Figure 2). Owing to the absence of major global-scale volcanic eruption signals between c.680 and 1230 any additional and absolute dated age marker would be very helpful to explore this age offset further. The 774 and 993 CE solar proton events previously identified in Antarctica are in my view ideal to overcome this lack of information, and to objectively evaluate the stated uncertainty bounds for DSS.

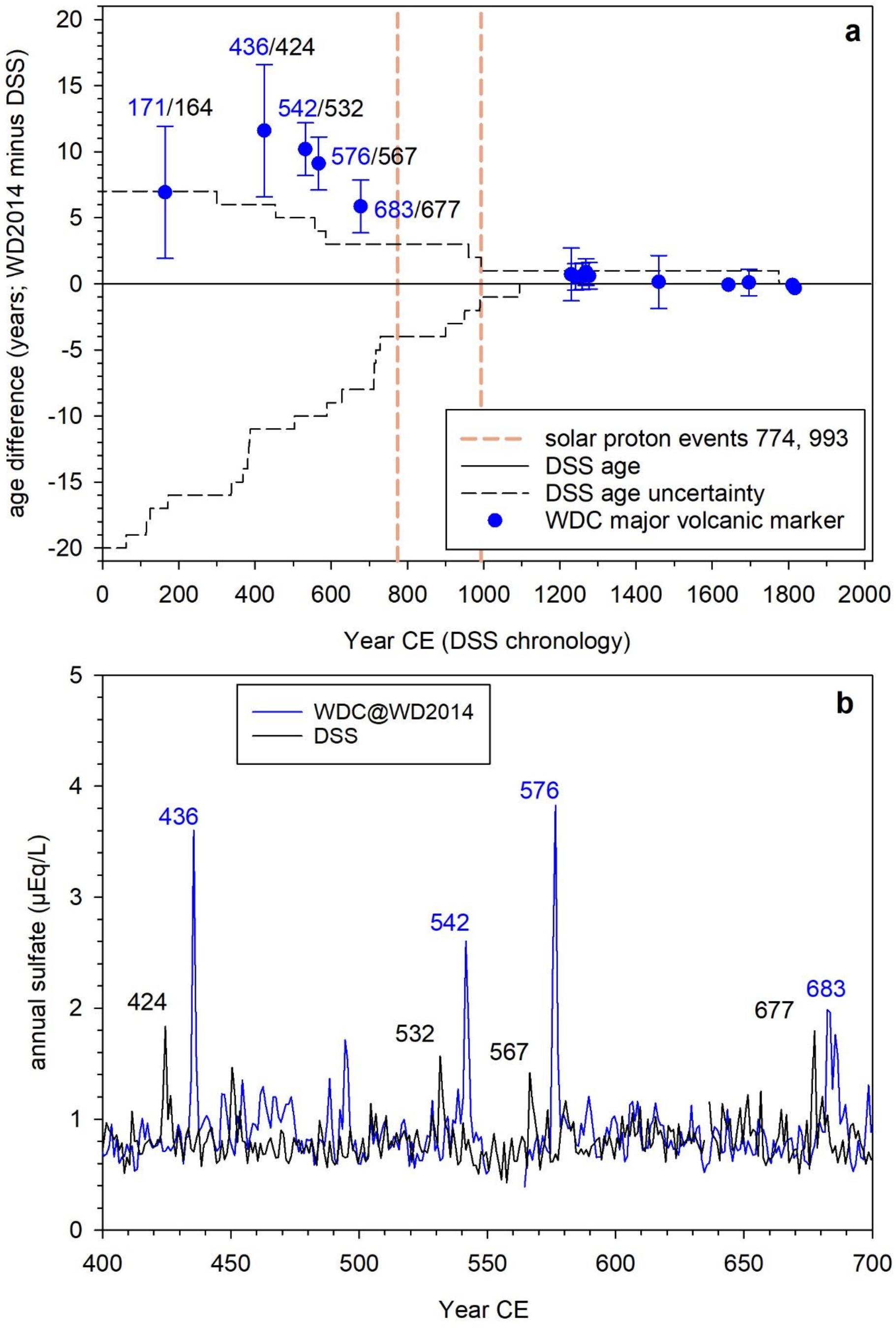

Figure 2: Volcanic matching between WDC and DSS; **a:** age difference between WD2014 and DSS for common major volcanic marker events. Positive values indicate younger ages for WDC during the 1st millennium; **b:** measured or inferred (for WDC sulfur was analyzed) sulfate concentrations between 400-700 CE with the ages of the used matching-points (see Table 2 for details) indicated using the WD2014 timescale (blue) and DSS (black). Note these do not indicate the eruption dates.

Table 2: Volcanic synchronization between annual-layer counted ice-core chronologies DSS and WD2014.

Year WD2014 (CE)	**Year DSS (CE)**	**age difference (WD2014 minus DSS) years**	**WD2014 error (+/-) years**	**DSS Depth (m)**	**WD Depth (m)**
1816.0	1816.3	-0.3	0	133.41	59.03
1810.4	1810.5	-0.1	0	137.04	60.49
1695.9	1695.8	0.1	1	204.04	87.82
1642.5	1642.5	-0.1	0	234.48	100.47
1459.7	1459.6	0.1	2	328.29	142.96
1277.3	1276.7	0.6	1	411.39	184.59
1269.6	1268.7	0.9	1	414.72	186.23
1258.8	1258.3	0.6	1	418.89	188.71
1241.7	1241.2	0.5	1	426.00	192.82
1230.5	1229.8	0.7	2	430.68	195.38
682.9	677.1	5.9	2	625.14	325.87
576.0	566.9	9.1	2	656.21	351.44
541.8	531.6	10.2	2	665.50	359.73
435.7	424.1	11.6	5	694.27	384.63
170.8	163.9	6.9	5	756.64	445.63

To summarize, I suggest the authors should consider:

1) To weaken the language that the DSS layer-counting errors are conservative.
2) To analyze in high-resolution ^{10}Be around 774 and 993 CE for evaluation of the chronology.
3) To include a table as supporting information providing the ice-core depths for the previously identified common age markers in NGRIP1, WDC and DSS allowing age-transfer between ice cores.
4) Provide some information in the main text that DSS is independent but not synchronous with the *WD2014* chronology commonly used for synchronizing ice cores in Antarctica – and a backbone for volcanic forcing reconstructions. For ongoing initiatives such as PAGES CLIVASH2k this information will be helpful, since it can help to avoid the smoothing and amplitude loss inherent in the stacking of proxy records with limited age synchronization (e.g. PAGES 2k Consortium 2019) which remains a major limitation for our understanding of natural climate variations.

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