

1 **Variation of accumulation rates over the last eight centuries**
2 **on the East Antarctic Plateau derived from volcanic signals in**
3 **ice cores**

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4 **Abstract.** Volcanic signatures in ice-core records provide an excellent means
5 to date the cores and obtain information about accumulation rates. From sev-
6 eral ice cores it is thus possible to extract a spatio-temporal accumulation pat-
7 tern. We show records of electrical conductivity and sulfur from 13 firn cores
8 from the Norwegian-USA scientific traverse during the International Polar Year
9 2007–2009 (IPY) through East Antarctica. Major volcanic eruptions are iden-
10 tified and used to assess century-scale accumulation changes. The largest changes
11 seem to occur in the most recent decades with accumulation over the period 1963–
12 2007/08 being up to 25 % different from the long-term record. There is no clear
13 overall trend, some sites show an increase in accumulation over the period 1963
14 to present while others show a decrease. Almost all of the sites above 3200 m
15 above sea level (asl) suggest a decrease. These sites also show a significantly
16 lower accumulation value than large-scale assessments both for the period 1963
17 to present and for the long-term mean at the respective drill sites. The spatial
18 accumulation distribution is influenced mainly by elevation and distance to the
19 ocean (continentality), as expected. Ground-penetrating radar data around the
20 drill sites show a spatial variability within 10–20 % over several tens of kilo-
21 meters, indicating that our drill sites are well representative for the area around
22 them. Our results are important for large-scale assessments of Antarctic mass
23 balance and model validation.

1. Introduction

24 The mass balance of the Antarctic ice sheet is a crucial parameter in climate research [*Alley*
25 *et al.*, 2005; *Vaughan*, 2005] and is constantly under debate [*Vaughan et al.*, 1999; *Giovinetto*
26 *and Zwally*, 2000; *Arthern et al.*, 2006; *van de Berg et al.*, 2006; *Horwath and Dietrich*, 2009]
27 and a conclusive outcome is not yet reached, despite new and promising results and satellite
28 techniques. For example, *Davis et al.* [2005] report growth of the Antarctic ice sheet over the
29 time period 1992–2003. Recently, a study by *Velicogna* [2009] found a net mass loss over the
30 time period 2002–2009 with an accelerating trend, based on data from the Gravity Recovery
31 and Climate Experiment (GRACE) satellite mission. Yet interannual variations are large as are
32 the uncertainties and there is no conclusive trend for individual drainage basins [*Horwath and*
33 *Dietrich*, 2009]. *Rignot et al.* [2008] use radar interferometry and a climate model to assess
34 recent Antarctic mass changes and obtain also a total mass loss with increases during the most
35 recent decade. In addition to gravity missions, altimetry data give information about mass
36 changes, derived from elevation changes. However, analyses of repeat altimetry measurements
37 and accumulation pattern showed that observed elevation changes are largely determined by
38 accumulation variability [*Davis et al.*, 2005], especially near the coast [*Helsen et al.*, 2008],
39 while little is known about the impact on a continent-wide scale. Especially the East Antarctic
40 interior is to a large degree uncovered by ground-based measurements and in situ data are scarce.
41 *Turner et al.* [2009] review recent results of Antarctic mass balance and find that East Antarctica
42 seems to be mostly quiescent with local exceptions. The results reported by *Turner et al.* [2009]
43 range from zero to slightly positive values for the mass balance of East Antarctica, but again the
44 error bars are large and errors can be as high as the variability itself. Moreover, *Turner et al.*

45 [2009] conclude that studies on Antarctic mass balance employing glaciological field data, e.g.
46 *Vaughan et al.* [1999], give the most reliable results. *Genthon and Krinner* [2001] explain that
47 especially the regions devoid of field observations introduce large errors in modeled assessments
48 of a continent-wide accumulation pattern. Thus, it is important to obtain ground-truth for large-
49 scale estimates of Antarctic mass changes.

50 The Norwegian-USA scientific IPY 2007–2009 traverse through East Antarctica aims to con-
51 tribute a set of field data comprising among others firn-core records and ground-penetrating
52 radar (GPR) data and thus help understanding the status of the East Antarctic ice sheet and
53 its changes on scales of a few decades to more than one millennium. The traverse went from
54 Norwegian Troll Station to South Pole in the austral summer 2007/08 and back on a different
55 route via the Recovery Lakes area in 2008/09 (see Figure 1). We will refer to the route taken
56 in 2007/08 as the first leg and the route from 2008/09 as the second leg in this paper. Together
57 the two consecutive traverse legs covered large parts of the interior of Dronning Maud Land.
58 Along the route shallow (20–30 m) and intermediate-depth (80–90 m) firn cores were drilled
59 of which we present 13 records in total (9 shallow and 4 intermediate-depth). All the drill sites
60 were linked by GPR data [*Müller et al.*, 2010].

61 Firn and ice cores are a valuable climate archive, allowing scientists to research climate vari-
62 ations as far back as 800000 years [*Lambert et al.*, 2008]. For the purpose of determining
63 accumulation rates, mostly chemical species are used, often in conjunction with oxygen isotope
64 data and electrical conductivity. Since all of these records tend to show an annual variation, they
65 allow for identification of summer or winter peaks (depending on the species considered) and
66 hence annual dating. However, in very low accumulation areas like the East Antarctic interior,
67 an annual signal might not be preserved. Hence, identification of time markers is crucial in these

68 areas for accumulation determination. Here, we focus on chemistry data (sulfur and sodium)
69 and electrical conductivity to date the 13 firn cores by identifying known volcanic eruptions.
70 This enables the calculation of accumulation rates and variability for the time periods between
71 major eruptions.

2. Data and Methods

72 The firn cores NUS07-3, -4, -6, and -8 (Figure 1) from the first leg were analysed in the cold
73 laboratory at Norwegian Polar Institute in Tromsø using the dielectric profiling (DEP) technique
74 [Moore *et al.*, 1991; Wilhelms *et al.*, 1998]. From the measured capacitance and conductance we
75 derived dielectric permittivity and electrical conductivity. The records have been presented and
76 discussed in *Anschütz et al.* [2009] where we also give some more details about the measuring
77 technique. The firn cores NUS07-1, -2, -5 and -7 were analysed for chemical composition
78 (Figures 2 and 3) at the Desert Research Institute (DRI) in Reno, USA, using a sophisticated
79 combination of continuous-flow analysis and mass spectrometry [McConnell *et al.*, 2002]. The
80 record of NUS07-1 has also been shown by *Anschütz et al.* [2009] where sulfur, sodium and
81 electrolytical conductivity (i.e., the conductivity of the meltwater) are discussed for this core.
82 Note that this core is named "site I" in *Anschütz et al.* [2009] due to a nomenclature of drill sites
83 used during the expedition. The name has since been changed to "NUS07-1" for the sake of
84 consistency and we therefore also refer to this core as NUS07-1 here.

85 From the second leg the firn cores NUS08-2, -3, -4, and -6 were analysed using DEP (Figure
86 4) and cores NUS08-4 and -5 for chemistry (Figure 5). From the large amount of species
87 measured by the device at DRI we use sulfur and sodium here. The sodium records were used
88 to calculate non-sea-salt (nss) sulfur (see e.g. *Traufetter et al.* [2004]) which differs less than
89 10 % from the total sulfur at these inland sites. In the following we will refer to the nss-sulfur

90 data as the "sulfur records" only. The DEP and sulfur records allow for detection of volcanic
91 peaks as shown by several studies on Antarctic and Greenland ices cores [*Hofstede et al.*, 2004;
92 *Traufetter et al.*, 2004; *Langway et al.*, 1995; *Cole-Dai et al.*, 2000]. We follow the criterion
93 outlined by *Cole-Dai et al.* [1997] and other authors for identification of a volcanic peak: First,
94 the large peaks likely stemming from volcanic input were removed from the records. Second,
95 the mean (background value) and standard deviation were calculated. For a peak to qualify as a
96 volcanic eruption it has to fulfill two criteria: (1) the value has to be at or above two times the
97 standard deviation and (2) has to stay at that level for at least two consecutive samples, in order
98 to exclude outliers in the measurement. As the electrical conductivity increases with depth, we
99 followed the method outlined by *Karlöf et al.* [2000] and other authors and normalized the DEP
100 data by first detrending the conductivity records and then dividing by the standard deviation.
101 Again, a peak has to be at or above two times the standard deviation for at least two samples.

102 In order to derive accumulation rates from the dated horizons, information about density is
103 needed. We measured the bulk density in the field and fitted a third order polynomial to these
104 values [*Ren et al.*, 2010] to obtain a smooth density distribution. Often the Looyenga-based
105 density is used for accumulation calculation where DEP data are measured [*Anschütz et al.*,
106 2009; *Hofstede et al.*, 2004]. However, we do not have DEP data available for the chemistry
107 cores, therefore the bulk density was used here. A comparison between Looyenga-based density
108 and bulk density for the DEP cores yields an average difference of 3–4 %, comparable to the
109 values reported by *Hofstede et al.* [2004].

110 Error estimation follows the discussion by *Anschütz et al.* [2009] and *Müller et al.* [2010]:
111 We assume an age uncertainty of three years between volcanic horizons (discussed below in
112 more detail) [*Traufetter et al.*, 2004; *Hofstede et al.*, 2004], a depth error of two centimeters

113 and a relative density error of 3.5 % of the respective density values [Hofstede *et al.*, 2004].
114 From error propagation we derive an overall mean error of the calculated accumulation rates of
115 4.8 % for the time periods considered here. Errors are given as absolute values for the respective
116 results in Table 3. The relative errors for the period 1815–2007/08 are comparable with results
117 by Frezzotti *et al.* [2005, 2007].

118 A reflection horizon at the corresponding depth of the Tambora layer (1815) was identified in
119 the GPR data based on the dating of the firn cores. In order to evaluate the areal representativity
120 of the firn core data, the layer was followed between two firn cores (Figure 6). Uncertainties in
121 the GPR derived layer depth and conversion to accumulation rates originate from uncertainty in
122 firn core dating, lateral density variability between the firn cores, digitization of the GPR data,
123 and accuracy in layer picking. We estimate the combined effect of these error sources to be up
124 to 8 % [Müller *et al.*, 2010].

3. Results

125 The records of electrical conductivity and sulfur were used to identify volcanic horizons by
126 comparison with well-dated records [Hofstede *et al.*, 2004; Traufetter *et al.*, 2004]. Yet not all
127 peaks could be assigned to known volcanic eruptions. Here, we focus on some prominent peaks,
128 roughly one per century, in order to detect longer-term (century-scale) accumulation changes.
129 The volcanoes and depths of the respective DEP or sulfur peaks in the different cores are given
130 in Tables 1 and 2.

131 The DEP-signal responds to both enhanced acidity due to large volcanic eruptions and en-
132 hanced sea-salt input [Moore *et al.*, 1991]. In order to distinguish between conductivity peaks
133 from volcanic events and peaks from enhanced sea-salt content, we also looked at the sodium
134 data for the deep chemistry core NUS07-2 from the first leg and compared sodium peaks with

135 peaks in electrolytical conductivity. A direct comparison between electrical conductivity and
136 sodium is not possible since we do not have DEP data for this core, therefore we use the elec-
137 trolytical conductivity here. Figure 2 shows that some peaks in the electrolytical conductivity
138 record indeed seem to coincide with enhanced sodium. However, the peaks discussed here are
139 not linked to enhanced sea salts, at least not for this core. Furthermore Figure 2 shows that
140 peaks in sulfur and electrolytical conductivity coincide very well, strengthening also the dating
141 of the DEP records by comparison with the sulfur records.

142 The most prominent peaks served as time markers, like the double peak Tambora (Indonesia)
143 1815/Unknown 1809 that has been observed widely in Antarctic ice cores [*Legrand and Delmas,*
144 *1987; Langway et al., 1995; Karlöf et al., 2000; Cole-Dai et al., 2000; Hofstede et al., 2004,*
145 *among others*]. Thus, we used this double peak as an absolute time marker to date the other
146 peaks in respect to the Tambora peak. Generally, a time lag of about one year between eruption
147 and deposition is assumed by most studies, however, deposition dates are usually less certain
148 than eruption dates, therefore all volcanic dates mentioned in this paper are eruption dates.
149 *Traufetter et al. [2004]* report an uncertainty in deposition dates between ± 1 year and ± 5 years
150 back to AD 1200. As has been already mentioned in the error discussion, we thus assume
151 an average age uncertainty of ± 3 years here, in accordance with *Anschütz et al. [2009]* and
152 *Hofstede et al. [2004]*.

153 One of the more recent peaks that is observed well in Antarctic ice cores corresponds to the
154 eruption of Agung (Lesser Sunda Islands, Indonesia, 1963) [*Delmas et al., 1985*]. Although
155 the signal is not very large in most of our cores, we use this as the most recent time marker.
156 The eruption of Pinatubo (1991), which would provide an even more recent time marker, is
157 not unambiguously detected in our firn-core records. Krakatau (Indonesia) erupted in 1883 and

158 has been detected in several ice cores around the continent [Traufetter *et al.*, 2004; Hofstede
159 *et al.*, 2004; Karlöf *et al.*, 2000]. The unknown peak from 1695 is reported by several authors,
160 with slightly different dates, varying from 1693–1697 [Ren *et al.*, 2010; Hofstede *et al.*, 2004;
161 Cole-Dai *et al.*, 2000; Budner and Cole-Dai, 2003]. Here, we use 1695 as the eruption date in
162 accordance with Hofstede *et al.* [2004] and Anschütz *et al.* [2009]. The subantarctic volcano
163 of Deception Island erupted in 1641 [Aristarain and Delmas, 1998], however, some authors
164 ascribe a signal at that time to the eruption of Awu (Sangihe Islands, Indonesia) [Stenni *et al.*,
165 2002; Karlöf *et al.*, 2000] or Mount Parker (Philippines) [Cole-Dai *et al.*, 2000; Traufetter *et al.*,
166 2004]. Most likely, the signal is an overlap of several eruptions. Since Deception Island is the
167 closest one to the Antarctic continent, we attribute the 1641 peak to this volcano. Another
168 unknown eruption occurred in 1622 [Hofstede *et al.*, 2004], and in 1600 Huaynaputina (Peru)
169 erupted, being also visible in several ice cores [Cole-Dai *et al.*, 2000; Karlöf *et al.*, 2000; Budner
170 and Cole-Dai, 2003]. Here, we use the Huaynaputina peak where it is detectable and Deception
171 Island or Unknown 1622 for cores that do not quite reach back to 1600. Before 1600 dating
172 is less certain due to the sparsity of historic documentation of volcanic eruptions [Traufetter
173 *et al.*, 2004]. However, some prominent peaks have been dated in deeper ice cores and allow
174 us to assume reliable dating for several of our observed peaks as well. The eruption of Kuwae
175 (Vanuatu, southwest Pacific) in 1453 is easily identified in ice cores from both hemispheres
176 [Langway *et al.*, 1995; Oerter *et al.*, 2000; Karlöf *et al.*, 2000; Ren *et al.*, 2010] and in some
177 studies it provided the largest peak in the entire record [Gao *et al.*, 2006; Palmer *et al.*, 2001].
178 The eruption of El Chichon (Mexico) in 1342 is seen less often than the one of Kuwae, but some
179 authors report prominent peaks for this eruption as well [Budner and Cole-Dai, 2003; Karlöf

180 *et al.*, 2000; *Hofstede et al.*, 2004; *Cole-Dai et al.*, 2000]. Here, it is not as large as the Kuwae
181 signal, but visible in all of the deeper cores.

182 The "1200-sequence" of several peaks in the late 13th century is another obvious time marker.
183 This sequence has been detected in deeper cores from the Antarctic plateau [*Hofstede et al.*,
184 2004; *Ren et al.*, 2010; *Cole-Dai et al.*, 2000; *Karlöf et al.*, 2000] as well as some Greenland
185 cores [*Langway et al.*, 1995]. We picked the oldest and - in most cores - the largest one of
186 these four peaks for our discussion. It is believed to have occurred in 1259 where some authors
187 attribute it to El Chichon in Mexico and some prefer to call it an unknown volcano. Since there
188 has not been a conclusive attribution to El Chichon, we stay with the term "Unknown" here.

4. Discussion

4.1. Temporal variability

189 In light of sea-level change it is important to assess the mass budget of the Antarctic ice
190 sheet and determine accumulation rates and possible spatial and temporal changes. *Anschütz*
191 *et al.* [2009] discuss temporal accumulation variability for some of the sites from the first leg
192 (NUS07-3, -4, -6 and -8). They find a decreased accumulation averaged over the time period
193 1815–2007 in relation to the value for 1641–1815. They also give a comprehensive discussion
194 of temporal variability in other cores from East Antarctica. Here, we present new results from
195 the chemistry cores of the first leg (NUS07-2, -5 and -7, Figures 2 and 3) and the DEP (Figure 4)
196 and sulfur records (Figure 5) of most of the cores from the second leg (NUS08-2, -3, -4, -5 and
197 -6). We identified the eruption of Agung (1963) in all of the cores but NUS07-6 which enables
198 us to address the question of recent accumulation changes. Arguably the Agung eruption is
199 not always very clear in the DEP profiles as they are generally more noisy than the sulfur data.
200 However, intercomparison of the records allows for a reliable identification also in most of the

201 DEP cores. Where identification is somewhat questionable due to noisy data or small peaks,
202 a question mark is depicted in the respective figures. In the chemistry cores from the first
203 leg the Agung peak is much smaller than the very prominent earlier peaks like Tambora and
204 Kuwae. Thus, due to the scaling of the full record the Agung peak does not depict very well
205 and therefore we show in addition a figure of the top meters of these records where Agung is
206 visible (Figure 3). The accumulation rates averaged over the time periods between the respective
207 volcanic horizons are depicted in Figures 7 and 8.

208 All the data from the first leg exhibit a slight decrease in accumulation since 1963, with the
209 exception of the northernmost site NUS07-1 (Figure 7). NUS07-3 shows a very slight increase
210 over the period 1963–2007 in comparison with 1883–1963, however, this increase is within the
211 range of uncertainty. For the majority of the sites (NUS07-2, -4, -5, -7 and -8) the accumulation
212 between 1963–2007 is the lowest in comparison to the other time periods considered in the
213 respective record. NUS07-6 (depicted in *Anschütz et al.* [2009]) does not show the eruption
214 of Agung due to lower core quality in the top meters, therefore only the period 1883–2007
215 is considered, which again reveals the lowest accumulation in the entire record from this site
216 (Figure 7). These results show that virtually all of the highest elevation sites (above 3200 m)
217 reveal a decreasing trend of accumulation over the last decades. This is in accordance with
218 the findings of *Isaksson et al.* [1999] who report accumulation values from firn cores along a
219 traverse line from the grounded coastal area up to the Amundsenisen plateau in Dronning Maud
220 Land. They find that accumulation has been decreasing over the time period 1965–1996 for
221 sites above 3250 m and mostly increasing below. Hence, they conclude that an accumulation
222 increase as reported for instance by *Mosley-Thompson et al.* [1999]; *Hofstede et al.* [2004];
223 *Oerter et al.* [2000] is not necessarily valid for the whole plateau area of Dronning Maud Land.

224 In the 17th century accumulation at the three sites NUS07-3, -4 and -6 seems to be consid-
225 erably higher than during the 20th century, whereas sites NUS07-2, -5 and -7 exhibit no such
226 changes (Figure 7). This shows that temporal accumulation changes are site-dependent and
227 can vary significantly between sites spaced several hundreds of kilometers apart. The largest
228 changes in the long-term records from sites NUS07-2, -5 and -7 occur largely in the most recent
229 decades, as the accumulation rates over the period 1963–2007 are mostly lower than during
230 the other time periods considered here. This contrasts with results from some other studies on
231 the East Antarctic plateau that found a recent increase in accumulation, for instance *Mosley-*
232 *Thompson et al.* [1999]; *Frezzotti et al.* [2005]; *Stenni et al.* [2002]; *Hofstede et al.* [2004].
233 However, distances between individual study sites are large and observational time periods be-
234 tween the studies differ, rendering it difficult to compare changes in more detail.

235 The sites from the second leg are all located more westerly and at lower elevations compared
236 to the ones from the first leg and the temporal accumulation pattern is quite different. Sites
237 NUS08-2 and -4 show a decrease and sites NUS08-3, -5 and -6 an increase over 1963–2008. At
238 sites NUS08-3 and -6 the recent accumulation (1963–2008) is in fact the highest in the entire
239 record for the time periods considered here (Figure 8). Sites NUS08-4 and -5 are only spaced
240 55 km apart, yet the temporal accumulation pattern is rather different for the recent decades.
241 NUS08-5 shows a slow, but continuous decrease of accumulation since 1600 with the exception
242 of the most recent period (1963–2008). NUS08-4 shows a similar decrease since 1622, but here
243 the decrease continues also over 1963–2008.

244 The changes between the periods 1883–1963 and 1963–2007/08 vary between +26 % at site
245 NUS08-3 to -22 % at site NUS07-2. When compared with the long-term record for the respec-
246 tive core, the changes range from +17 % to -25 % (Table 3 and Figures 7 and 8). Even though

247 the Agung peak is not as certain in some of our DEP cores as for example the Tambora peak,
248 the overall picture as discussed above remains valid, where accumulation seems to have mostly
249 decreased for the sites of the first leg and mostly increased for the second leg.

250 *Ren et al.* [2004] report accumulation values from snow pits along a traverse line from Zhong-
251 shan Station to Dome A. They find that higher-elevation sites (above 3400 m) show a decrease
252 in accumulation for the recent decades whereas sites below that elevation show an increase.
253 This fits well with our findings from both traverse legs.

254 In summary, there is no consistent trend over the area of the two traverse legs and different
255 sites show a different temporal pattern. Yet for some of the sites the most recent changes seem to
256 be the largest. This might implicate that recent changes are in fact occurring over different parts
257 of the East Antarctic plateau, even though the direction of changes (decreasing or increasing)
258 does not exhibit the same trend for all sites.

259 As for the earlier time periods, there is no evidence of the Little Ice Age in our deeper cores:
260 the accumulation averaged over the period 1453–1815, i.e., between the eruptions of Kuwae
261 and Tambora, results as $32.6 \text{ kg m}^{-2} \text{ a}^{-1}$ at site NUS07-2, $25.7 \text{ kg m}^{-2} \text{ a}^{-1}$ at site NUS07-
262 5, $29.2 \text{ kg m}^{-2} \text{ a}^{-1}$ at site NUS07-7 and for the second leg $35.5 \text{ kg m}^{-2} \text{ a}^{-1}$ at NUS08-
263 5. All these values differ only insignificantly from the long-term accumulation rates and the
264 values over the period 1815 to present at the respective sites (Table 3). *Li et al.* [2009] report
265 sharply reduced accumulation rates for the period 1450–1850 from a drill site to the east of our
266 investigation area in Princess Elizabeth Land (core DT263 at $76^{\circ}32.5'S$, $77^{\circ}01.5'E$ and 2800 m
267 asl). A comparison with their results stresses that a different temporal accumulation pattern over
268 different parts of the East Antarctic plateau persisted also for earlier time periods and evidence
269 of the Little Ice Age is not necessarily found in all cores around the continent.

4.2. Spatial variability

270 The South-Pole Queen Maud Land Traverses (SPQMLT) went through large parts of Dron-
271 ning Maud Land in the 1960s [*Picciotto et al.*, 1971] and some of their sampling sites are rela-
272 tively close to our drill sites (see Figure 1). They determined accumulation rates from snow-pit
273 stratigraphy and at selected sites additionally from measurements of radioactivity, discovering
274 fallout from nuclear tests in the 1950s and 1960s. *Anschütz et al.* [2009] compare accumu-
275 lation values from the first leg with SPQMLT data and find that accumulation in this area is
276 lower than reported by SPQMLT. For sites close to the area visited during the second leg of the
277 traverse, *Picciotto et al.* [1971] report an accumulation value of $38 \text{ kg m}^{-2} \text{ a}^{-1}$ for their site
278 SPQMLT-2-12 which is 31 km from our site NUS08-5 and 33 km from NUS08-4. The value of
279 $37.6 \text{ kg m}^{-2} \text{ a}^{-1}$ at site NUS08-5 thus is in good agreement, whereas NUS08-4 shows a slightly
280 lower value of $36.1 \text{ kg m}^{-2} \text{ a}^{-1}$. For their site SPQMLT-2-16, 22 km from our site NUS08-6,
281 *Picciotto et al.* [1971] obtain $35 \text{ kg m}^{-2} \text{ a}^{-1}$. Here, our results are higher with $49.2 \text{ kg m}^{-2} \text{ a}^{-1}$,
282 yet this is one of the sites where a recent accumulation increase occurs. The 200-year mean of
283 $39.2 \text{ kg m}^{-2} \text{ a}^{-1}$ is in better agreement with the results of *Picciotto et al.* [1971]. However,
284 one should bear in mind that comparison is limited due to large spatial distances and different
285 time periods. Moreover, *Magand et al.* [2007] demonstrate that older data sets, like some of the
286 SPQMLT data, are often biased and tend to overestimate accumulation on the polar plateau.

287 In general, the spatial representativity of point measurements such as firn-core records can be
288 assessed by GPR data. For the first leg, *Anschütz et al.* [2009] show 5.3 GHz-GPR data around
289 the sites NUS07-4 and -6 and find a general variability of about 10–20 % over several tens
290 of kilometers for the Tambora layer. *Müller et al.* [2010] follow GPR layers over an 860 km

291 long profile of the first leg and find a mean accumulation of $23.7 \text{ kg m}^{-2} \text{ a}^{-1}$ over the period
292 1815–2007 with a standard deviation of $4.7 \text{ kg m}^{-2} \text{ a}^{-1}$ or 20 % over the entire GPR profile.

293 Figure 6 shows a radargram between NUS08-5 and -6 with the Tambora layer highlighted.
294 The system used is an ultrawideband FMCW-radar with a center frequency of 1.75 GHz and
295 a bandwidth of 2.5 GHz. System parameters and processing steps are discussed in detail by
296 *Müller et al.* [submitted]. The layering over some parts of this stretch is very smooth. Yet espe-
297 cially in the northern part (towards NUS08-6) the amplitude of layer variation is larger (Figure
298 6). The average accumulation over the time period 1815–2008 over this 170 km long stretch is
299 $36.8 \text{ kg m}^{-2} \text{ a}^{-1}$ with a standard deviation of $3.6 \text{ kg m}^{-2} \text{ a}^{-1}$ or 10 %. This is on the lower edge
300 of the values reported by *Anschütz et al.* [2009] and *Müller et al.* [2010] for parts of the first leg.
301 Our results of spatial variability of GPR layers are in good agreement with the findings from
302 *Richardson and Holmlund* [1999]. Even though the core sites are thus representative for the
303 area around them, comparison between individual sites is still limited by large spatial distances
304 and spatial variability between them. However, a general pattern is obvious, as accumulation
305 decreases with increasing elevation and distance to the coast (continentality). This has been
306 reported in various studies [*Vaughan et al.*, 1999; *van de Berg et al.*, 2006; *Müller et al.*, 2010;
307 *Isaksson et al.*, 1999] and is confirmed by our results as well.

308 Table 3 shows accumulation values for the most recent decades, averaged over the period
309 1963 to present, based on the detection of the eruption of Agung. For comparison, we also
310 give the 200-year mean values, based on the eruption of Tambora in 1815 and the respective
311 long-term mean for the individual cores. As explained above, the Tambora eruption was used
312 as an absolute time marker, and the 200-year mean should give a sufficiently long time interval
313 to obtain a stable accumulation result where possible decadal variations are smoothed out. Ac-

314 cumulation is mostly higher for sites on the second leg than on the first. This is clearly related
315 to elevation differences (Table 3). The accumulation over parts of the Recovery Lakes area
316 (NUS08-4 and -5) is in the range of the higher values of the first leg. In general, accumulation
317 is very low on the high East Antarctic plateau, for parts of the first leg even lower than expected
318 [*Anschütz et al.*, 2009] which fits the results from some other studies as well, e.g. *Genthon et al.*
319 [2009].

320 Several large-scale assessments have been carried out in order to derive a spatial pattern of
321 accumulation for the entire Antarctic ice sheet, e.g. by *Vaughan et al.* [1999]; *Giovinetto and*
322 *Zwally* [2000]; *Arthern et al.* [2006]; *Monaghan et al.* [2006]; *van de Berg et al.* [2006]. Even
323 though a detailed comparison is limited due to the resolution of these studies (typically around
324 50–100 km or more), it is interesting to compare values for the area around our drill sites based
325 on the large-scale assessments. *Anschütz et al.* [2009] discuss accumulation at sites NUS07-3,
326 -4, -6 and -8 for the period 1815–2007 in comparison to the results by *Monaghan et al.* [2006]
327 and *Arthern et al.* [2006]. They find lower in-situ values than these two studies. *Müller et al.*
328 [2010] derive accumulation averaged over the time period 1815–2007 along an 860 km GPR
329 profile for the first leg and likewise find lower values compared to the studies by *Monaghan et*
330 *al.* [2006], *Arthern et al.* [2006] and *van de Berg et al.* [2006]. They conclude that this might
331 support the suggestion that accumulation has been increasing for much of the East Antarctic
332 plateau over the last 50 years, as the studies by *Arthern et al.* [2006] and *Monaghan et al.*
333 [2006] represent largely this time period. This finding is not supported by our firn-core data
334 from the first leg, highlighting again the complexity of the temporal accumulation behavior and
335 the difficulties to draw conclusions for a large area from single drill sites.

336 Furthermore it is important to be aware that the values reported by *Anschütz et al.* [2009] and
337 *Müller et al.* [2010] are point measurements and twodimensional profiles, respectively, and are
338 averaged over a 200-year period, whereas the other studies give areal averages and look at more
339 recent time periods of a few decades.

340 In Table 3 we compare our accumulation values over the period 1963 to present with the
341 results by *Arthern et al.* [2006]. It is evident that the drill sites of the first leg show a much
342 lower accumulation (up to 50% lower) compared to the study by *Arthern et al.* [2006], whereas
343 the results from the second leg mostly fit well, with deviations between 2–12 %. The differences
344 might be due to scarcity of in-situ observations available for the compilation by *Arthern et al.*
345 [2006] as well as the reasons mentioned above, namely different time periods and resolution of
346 this large-scale assessment. *Monaghan et al.* [2006] and *van de Berg et al.* [2006] both report
347 values of 20–50 kg m⁻² a⁻¹ for our area of investigation with the exception of the area around
348 South Pole where accumulation reaches 50–100 kg m⁻² a⁻¹ in both compilations. Thus, our
349 in-situ values are largely on the lower edge or even below their assessments, especially for the
350 sites of the first leg.

351 Our results show that some parts of the plateau with elevations above 3200 m exhibit less
352 accumulation than obtained by large-scale assessments which has important implications for
353 the determination of the overall mass balance of the Antarctic ice sheet.

5. Conclusions

354 In total 13 shallow and intermediate-depth firn cores from the East Antarctic plateau have
355 been analysed for electrical conductivity and sulfur to establish a volcanic chronology and as-
356 sess accumulation rates. The spatial accumulation distribution is influenced by elevation and
357 continentality, fitting the expected pattern well. Spatial variability derived from GPR data is in

358 the range of 10–20 % over several tens of kilometers which is in accordance with other studies
359 from the interior of East Antarctica [*Richardson and Holmlund*, 1999; *Frezzotti et al.*, 2005].
360 The accumulation results for the high elevation sites above 3200 m are lower than values by the
361 large-scale assessment of *Arthern et al.* [2006], yet the sites at lower elevations are in reasonably
362 good agreement.

363 The temporal pattern does not show an overall clear trend, however, most of the sites of the
364 first leg, i.e., the more easterly and higher elevation sites, reveal a decrease in accumulation
365 over the period 1963–2007. For the second leg (the more westerly sites at comparatively lower
366 elevations), there are some sites that show an increase over this time period in accordance with
367 other results from East Antarctica [*Mosley-Thompson et al.*, 1999; *Hofstede et al.*, 2004; *Frez-*
368 *zotti et al.*, 2005]. The largest changes seem to have occurred in the most recent decades, with
369 the longer-time pattern being mostly rather stable. Recent changes deviate from the long-term
370 mean of the respective core by up to 25 %. No clear indication of the Little Ice Age could be
371 found in our data.

372 Our study shows that temporal variability differs strongly between different sites, rendering
373 difficulties to obtain a conclusive outcome for Antarctic mass changes based on individual ice-
374 core studies. Hence, our results can serve, together with similar studies, as a valuable input for
375 large-scale models and obtaining ground truth for satellite-based estimates of the mass balance
376 of East Antarctica.

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Table 1. Snow depths of volcanic peaks in the cores from the first leg. All depth units are in meters and the date refers to the year of eruption as this is more certain than the year of deposition (see text).

volcano	year	NUS07-1	NUS07-2	NUS07-3	NUS07-4	NUS07-5	NUS07-6	NUS07-7	NUS07-8
Agung	1963	6.44	3.49	3.00	2.37	2.72	-	3.39	3.22
Krakatau	1883	14.44	10.48	7.62	6.93	7.66	5.63	9.1	9.22
Tambora	1815	20.70	15.24	10.98	10.33	11.62	8.98	13.42	13.57
Unknown	1695	-	22.96	16.98	16.03	18.12	13.76	20.37	-
Deception Island	1641	-	26.02	20.34	16.92	20.10	17.03	23.21	-
Unknown	1622	-	27.27	22.49	20.39	-	20.32	-	-
Huaynaputina	1600	-	28.96	25.33	-	22.77	-	25.29	-
Kuwae	1453	-	36.19	-	-	29.36	-	32.55	-
El Chichon	1342	-	42.29	-	-	34.72	-	36.39	-
Unknown	1259	-	46.75	-	-	38.44	-	42.01	-

Table 2. Snow depths of volcanic peaks in the cores from the second leg. All depth units are in meters and the date refers to the year of eruption.

volcano	year	NUS08-2	NUS08-3	NUS08-4	NUS08-5	NUS08-6
Agung	1963	7.19	5.51	4.92	4.76	7.33
Krakatau	1883	18.10	12.17	11.70	11.39	14.31
Tambora	1815	26.91	17.84	16.83	16.32	18.02
Unknown	1695	-	25.85	25.19	24.25	-
Deception Island	1641	-	29.27	28.43	27.61	-
Unknown	1622	-	-	29.71	28.86	-
Huaynaputina	1600	-	-	-	29.94	-
Kuwae	1453	-	-	-	38.05	-
El Chichon	1342	-	-	-	43.98	-
Unknown	1259	-	-	-	48.40	-

Table 3. Accumulation over the most recent decades, 200-year mean and long-term mean in the NUS-cores, compared with the results by *Arthern et al.* [2006]. The 200-year values for sites NUS07-1, -3, -4 and -6 have been taken from *Anschütz et al.* [2009].

core name	lat.	long.	elevation m a.s.l.	acc. 1963–2007/08 $\text{kg m}^{-2} \text{a}^{-1}$	acc. 1815–2007/08 $\text{kg m}^{-2} \text{a}^{-1}$	long-term acc. $\text{kg m}^{-2} \text{a}^{-1}$	acc. from <i>Arthern et al.</i> [2006] $\text{kg m}^{-2} \text{a}^{-1}$
NUS07-1	73°43' S	07°59' E	3174	55.9±3.9	52.0±2.0	-	58
NUS07-2	76°04' S	22°28' E	3582	28.0±2.0	33.0±0.7	33.3±1.2 ¹	42
NUS07-3	77°00' S	26°03' E	3589	23.7±1.7	22.0±0.5	27.8±1.0 ²	40
NUS07-4	78°13' S	32°51' E	3595	17.5±1.2	19.0±0.5	20.9±0.8 ³	36
NUS07-5	78°39' S	35°38' E	3619	20.1±1.4	24.0±0.5	26.0±0.9 ¹	37
NUS07-6	80°47' S	44°51' E	3672	-	16.0±0.4	21.1±0.7 ²	32
NUS07-7	82°04' S	54°53' E	3725	26.1±1.9	29.4±0.6	29.5±1.0 ¹	30
NUS07-8	84°11' S	53°32' E	3452	30.0±2.1	32.0±1.2	-	40
NUS08-2	87°51' S	01°48' W	2583	63.4±4.2	67.4±2.6	-	65
NUS08-3	84°08' S	21°54' E	2625	45.3±3.1	40.1±1.0	38.8±1.4 ⁴	43
NUS08-4	82°49' S	18°54' E	2552	36.1±2.1	36.7±0.9	37.2±1.3 ³	34
NUS08-5	82°38' S	17°52' E	2544	37.6±2.3	35.0±0.8	35.5±0.8 ¹	34
NUS08-6	81°42' S	08°34' E	2447	49.2±3.4	39.2±1.5	-	41

¹1259–2007/08

²1600–2007/08

³1622–2007/08

⁴1641–2007/08

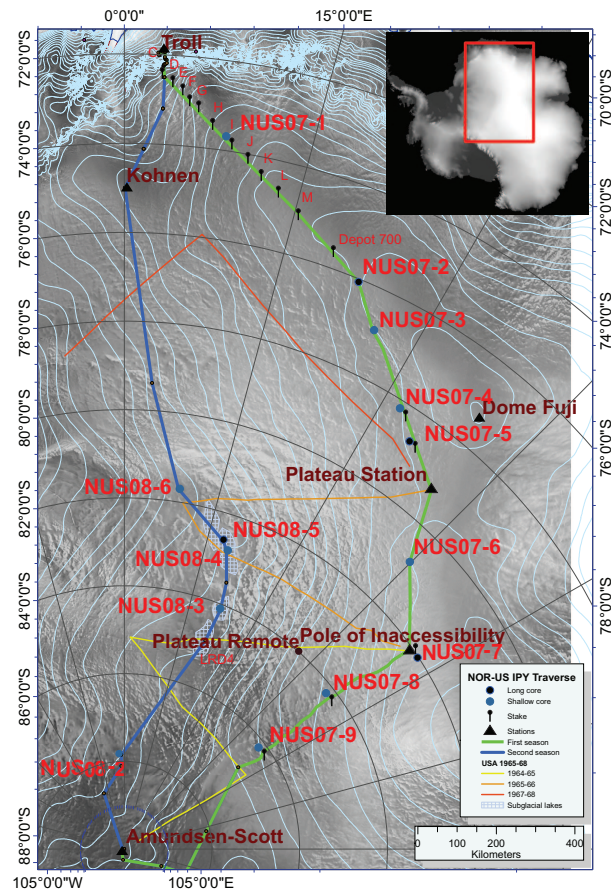


Figure 1. Map of the traverse route 2007/2008 (green line) and 2008/2009 (blue line) with drill sites from both legs indicated (NUS07-X and NUS08-X). The South Pole Queen Maud Land Traverse routes [Picciotto *et al.*, 1971] are indicated by the yellow-orange lines and relevant stations in the area of investigation are shown as well. Other dots indicate science stops along the traverse routes not relevant for this paper but shown for the sake of completeness. Elevation contour lines are in 100 m intervals. The map was compiled by K. Langley and S. Tronstad (Norwegian Polar Institute).

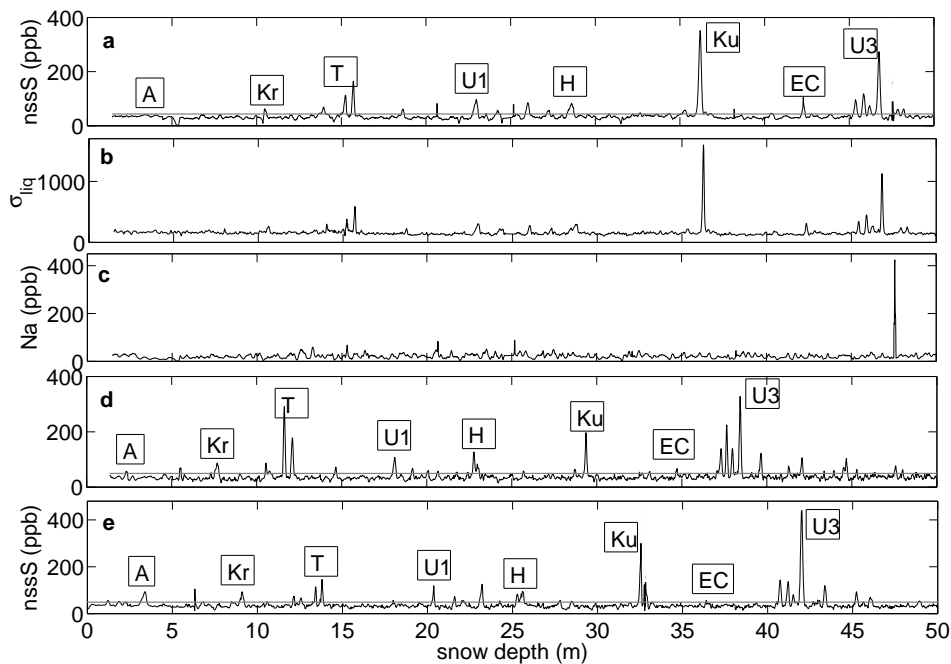


Figure 2. Records of chemistry data for the cores NUS07-2 (a: nss-sulfur, b: electrolytical conductivity, c: sodium), NUS07-5 (d: nss-sulfur) and NUS07-7 (e: nss-sulfur). The two-fold standard deviation is indicated by the grey line in the sulfur records. A: Agung 1963, Kr: Krakatau 1883, T: Tambora 1815, U1: Unknown 1695, H: Huaynaputina 1600, Ku: Kuwae 1453, EC: El Chichon 1342, U3: Unknown 1259. Note that only the top 50 m are shown here as they fully cover the time period we are concerned with here.

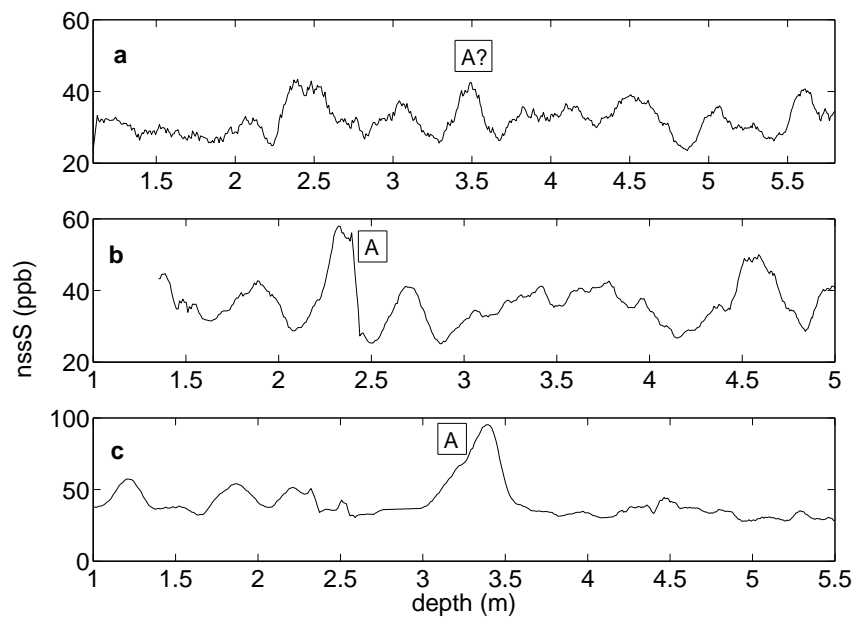


Figure 3. The Agung eruption in the deep cores from the first leg. a) NUS07-2, b) NUS07-5, c) NUS07-7. Since the peak in NUS07-2 is just at the two-fold standard deviation (see Figure 2) and also less clear than in the other cores, it is displayed with a question mark here.

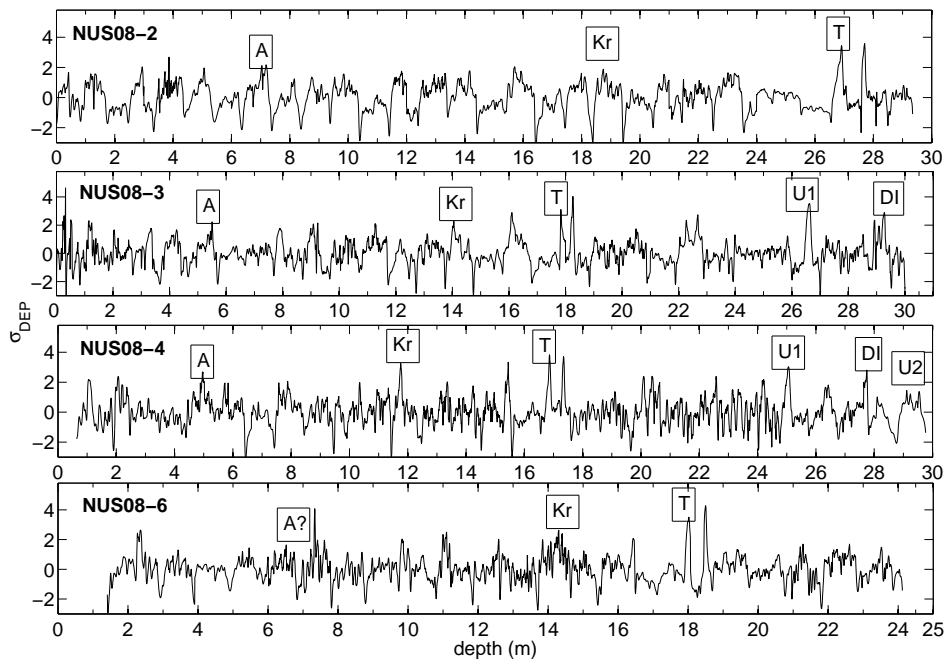


Figure 4. Normalized DEP-based conductivity for the cores NUS08-2, -3, -4 and -6 from the second leg. The volcanoes discussed in the text are indicated. DI: Deception Island 1641, U2: Unknown 1622; other abbreviations see Figure 2. The negative spikes in parts of the records are due to varying core quality and slightly differing diameter and are not eliminated here completely as full elimination would induce data gaps.

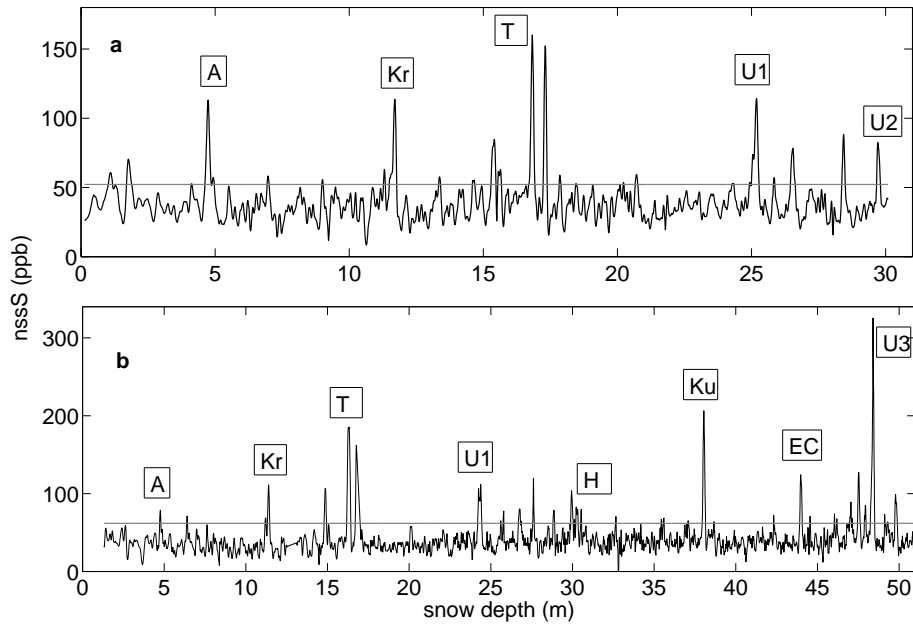


Figure 5. Sulfur data for the cores NUS08-4 (a) and NUS08-5 (b) from the second leg. The two-fold standard deviation is indicated by the grey line. Same abbreviations as in Figure 2. Note that only the top 50 m of NUS08-5 are displayed here, covering the period back to about 1250 AD that we are concerned with in this paper.

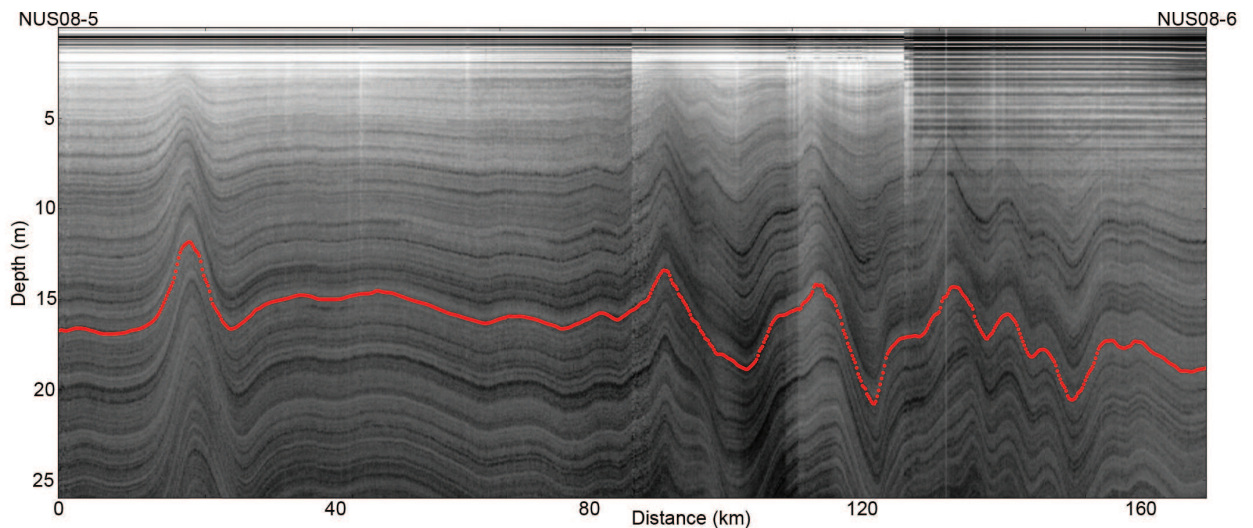


Figure 6. Radargram of the stretch between NUS08-5 and -6. The TAMBORA layer is highlighted by the red dashed line.

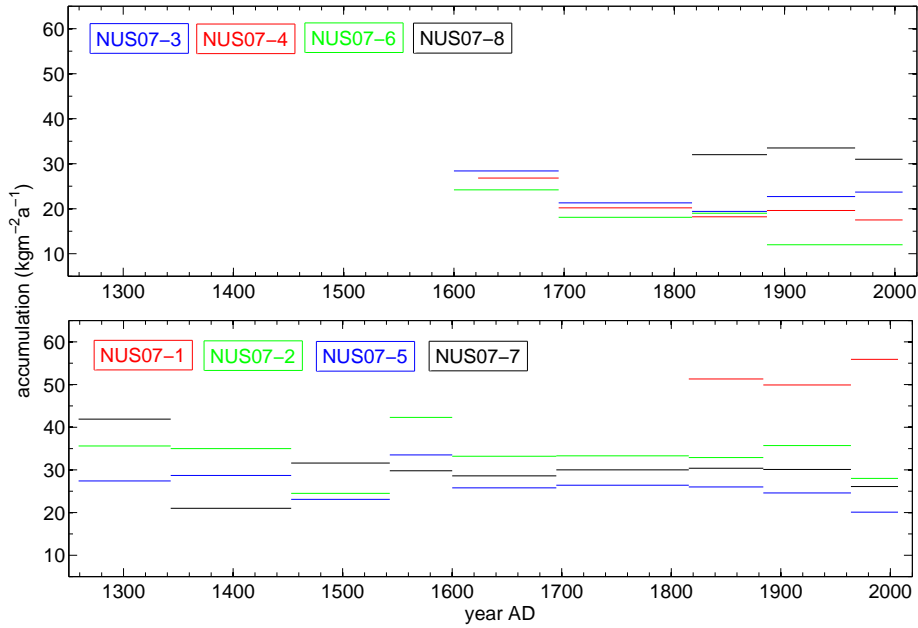


Figure 7. Temporal variability of accumulation rate in the cores from the first leg. Top: DEP cores; bottom: chemistry cores.

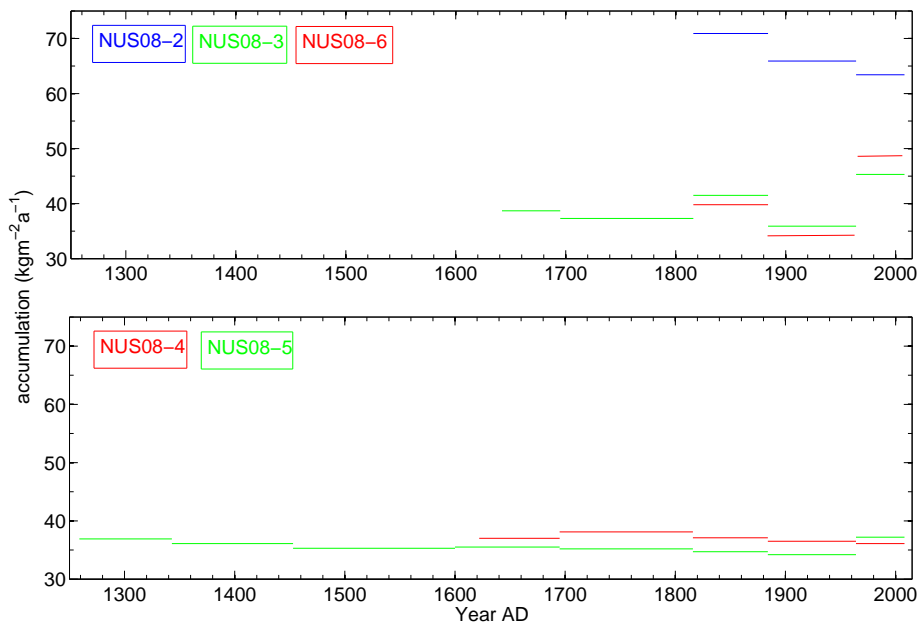


Figure 8. Temporal variability of accumulation rate in the cores from the second leg. Top: DEP cores; bottom: chemistry cores.