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The Cryosphere Discussions

Impact of subsurface crevassing on the depth-age relationship of high-alpine ice cores extracted at Col du Dôme between 1994 and 2012

Susanne Preunkert[1], Pascal Bohleber[2,3,4] Michel Legrand[1,5], Hubertus Fischer[6], Adrien Gilbert[1], Tobias Erhardt[6,7], Roland Purtschert[6], Lars Zipf[2,8], Astrid Waldner[2], Joseph R. McConnell[9]

[1]Université Grenoble Alpes, CNRS, Institut des Géosciences de l'Environnement (IGE), Grenoble, France
[2]Institute of Environmental Physics, Heidelberg University, Heidelberg, Germany
[3]Institute for Interdisciplinary Mountain Research, Austrian Academy of Sciences, Innsbruck, Austria
[4]Ca' Foscari University of Venice, Department of Environmental Sciences, Informatics and Statistics, Scientific Campus, via Torino 155, 30172 Mestre (VE), Italy
[5]Laboratoire Interuniversitaire des Systèmes Atmosphériques, Université de Paris and Univ Paris Est Creteil, CNRS, LISA, F-75013, France
[6]Climate and Environmental Physics, Physics Institute, and Oeschger Centre for Climate Change Research, University of Bern, Switzerland
[7]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
[8]Laboratoire de Glaciologie, Université Libre de Bruxelles, Brussels, Belgium
[9]Division of Hydrologic Sciences, Desert Research Institute, Reno, Nevada, USA

Correspondence to: Susanne Preunkert (suzanne.preunkert@univ-grenoble-alpes.fr)

Abstract.

Three seasonally-resolved ice-core records covering the 20th century were extracted in 1994, 2004 and 2012 at a nearly identical location at the Col du Dôme (4250 m above sea level, m asl, Mont Blanc, French Alps) drill site. Here we complete and combine chemical records of major ions and radiometric measurements of ^{3}H and ^{210}Pb obtained on these three cores together with a 3D ice flow model of the Col du Dôme glacier, to investigate in detail the origin of the discontinuities observed in the depth-age relation of the ice cores drilled in 2004 and 2012. Taking advantage of the granitic bedrock at Col du Dôme, which makes the ^{210}Pb ice-core records sensitive to the presence of upstream crevasses, and the fact that the depth-age disturbances are observed at depths for which absolute time markers were available, we draw an overall picture of a dynamic crevasse formation which can explain the non-disturbed depth-age relation of the ice core drilled in 1994 as well as the perturbations observed in those drilled in 2004 and 2012. Since crevasses are common at high alpine glacier sites, our study points out the mandatory need of rigorous investigations of the depth-age scale before using high alpine sites to interpret atmospheric changes.

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1. Introduction

Close proximity to European source regions makes ice cores from high-elevation Alpine glaciers an important target to reconstruct past anthropogenic perturbations of the atmospheric chemistry. In the French Alps, the Col du Dôme (CDD) glacier close to the Mont Blanc summit has been studied extensively over the last 25 years for its glaciological properties and suitability for glacio-chemical studies (e.g. Vincent et al., 1997, Preunkert et al., 2000). The glacier has been shown to be entirely cold although it has experienced a significant warming in response to climate change since the eighties (Vincent et al., 2007; Gilbert and Vincent, 2013; Vincent et al., 2020). Ice cores extracted at CDD have been used to reconstruct various aspects of atmospheric changes during the 20th century over western Europe. This includes major inorganic species (NH_4^+, NO_3^-, and SO_4^{2-}, Fagerli et al., 2007, Preunkert et al., 2003, and Preunkert et al., 2001a), halogens (HCl and HF, Legrand et al., 2002, Preunkert et al., 2001b; total I and Br, Legrand et al., 2018 and Legrand et al., 2021), black carbon (Moseid et al., 2022), dissolved organic carbon (DOC, Legrand et al., 2013), organic molecules (Legrand et al., 2003 and 2007, Guillermet et al., 2013), and trace elements such as Pb and Cd (Legrand et al., 2020), V and Mo (Arienzo et al., 2021), and Tl (Legrand et al., 2022). Underpinning these efforts are three ice cores drilled to bedrock in a distance of only a few meters at most in 1994 (C10, Vincent et al., 1997, Preunkert et al., 2000), 2004 (CDK, Legrand et al., 2013) and 2012 (CDM, Legrand et al., 2018, this study).

Whereas the C10 ice core drilled in 1994 indicated a depth age relationship that was consistent between the derived annual layer counting and several time markers (Preunkert et al., 2000), it was shown that the 2004 CDK core did not include ~ 16 years between ~ 1970 and ~ 1954 (Legrand et al., 2013) as confirmed by the absence of the well-known ^3H maximum in 1963 caused by atmospheric nuclear tests. Although its precise cause remained unclear, it was suggested that the missing 1954-1970 period in the record was related to a crevasse that has disturbed the continuity of the CDK record. The presence of one or more crevasses in the upstream vicinity of the drill site was also suspected to cause strongly elevated concentrations of ^{210}Pb observed in the C10 core (Vincent et al., 1997). This was concluded, since the bedrock at the CDD consists of granite that emits ^{222}Rn (half-life of 3.8 days), which is able to diffuse in snow and firn, but much less in ice (see also Pourchet et al., 2000), and subsequently decays to produce ^{210}Pb (half-life of 22.3 years).

Concerning CDM, in addition to the ^{210}Pb profile (Zipf, 2013), only the upper core sections (down to 81 m depth, i.e. 1979) were already investigated (Legrand et al., 2018). Additional investigations are made here using NO_3^-, NH_4^+ and ^3H analysis, to extend the depth age relationship of the CDM core back to 1950. This homogeneous set of chemical and radiochemical data gained on the C10, CDK and CDM ice cores, permits to investigate the consistency of the depth-age relation back to 1950 between these ice cores drilled in 1994, 2004, and 2012. In addition, a first attempt to provide a qualitative glaciological explanation for the observed discontinuity in the depth-age relation and the link with the presence of unexpectedly high ^{210}Pb levels will be made. This is important for understanding the extent to which existing and further CDD ice cores drilled at this location on the CDD saddle are suitable to reconstruct past atmospheric chemistry changes.

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2. Site and Analysis

The CDD site is located on a small cold glacier saddle downslope of the Dôme du Gouter (4300 m asl) (Fig. 1). On this slope, the C10, CDK, and CDM cores were drilled down to ~125 m (Table 1), i.e., close to bedrock. Detailed glaciological descriptions of this site can be found in Vincent et al. (1997, 2020), whereas, based specifically on data from the C10 ice core, Preunkert et al. (2000) characterized this site in terms of its usefulness to reconstruct past atmospheric changes since the beginning of the 20th century. Ice flow, firn compaction and thermal regime have been modeled in three dimensions by Gilbert et al. (2014), allowing particle back-tracking and flow-based estimation of the depth-age relationship for the drilling site.

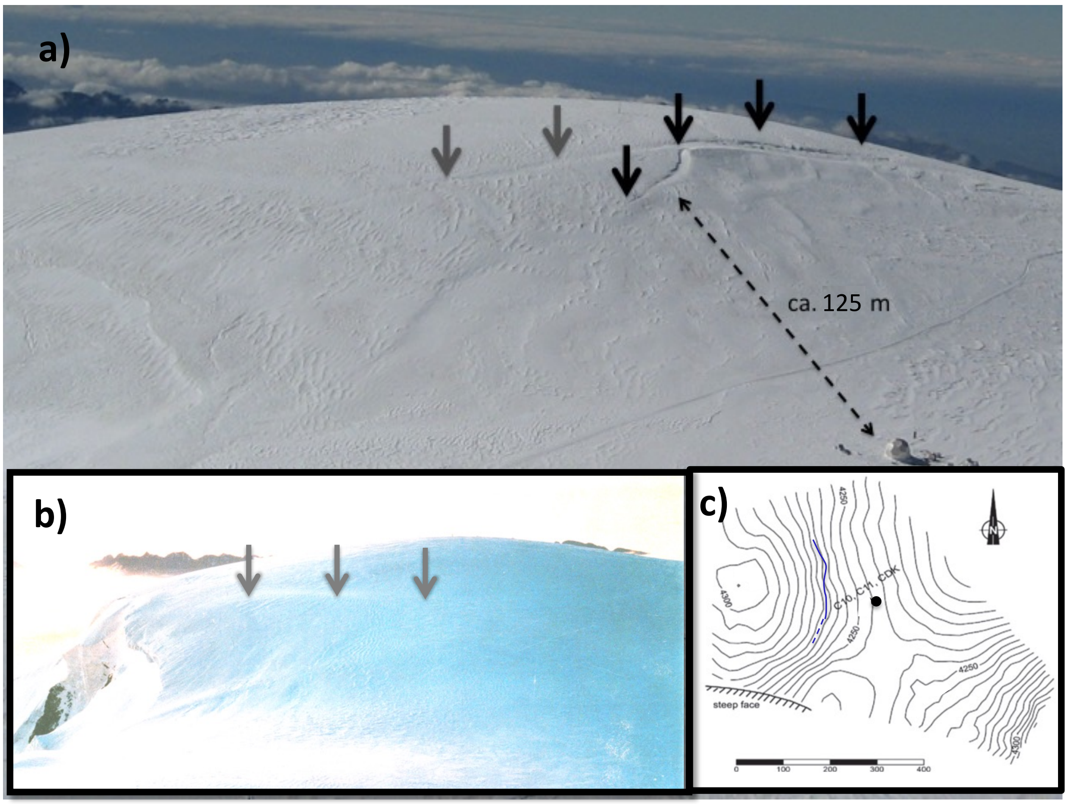

Figure 1: View of the South-East flank of the Dome de Gouter (CDG) and Col du Dome saddle including the drill site of 1994, 2004, and 2012 situated downslope of Dome du Gouter. (a) Picture taken in summer 2012: A large crevasse extends across the upstream catchment area (indicated with black arrows) of the drilling site. At that time the crevasse was found distinctly visible but mainly snow-covered. A potential second crevasse is indicated by grey arrows. (b) Picture taken in summer 1999: Evidence of a crevasse limited to the southwestern side of the Dome du Gouter. (c) Topographic map of the Col du Dome and Dome de Gouter (adapted from Wagenbach et al. 2012). The crevasse highlighted in (a) and (b) is reported (blue line) on the base of an aerial photo from Institut national de l'information géographique et forestière (IGNF) taken at 30th June 2004. Contour lines are spaced at 5 m interval.

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Table 1 summarizes the main characteristics of the three ice cores and basic findings related to radiometric analyses. ^{3}H analyses in CDK (Legrand et al., 2013) and CDM ice were performed at the Institute for Environmental Physics, Heidelberg University (IUP), by low-level gas counting with a detection limit typically around 1.5 TU (tritium units). ^{210}Pb samples of CDK (Waldner, 2011) and CDM ice (Zipf, 2013) were analyzed by α-spectrometry for its decay product ^{210}Po at IUP (see Stanzick, 2001, and Elsässer et al., 2011 for working analytical conditions) whereas ^{210}Pb in C10 ice was analyzed at the Laboratoire de Glaciologie et Géophysique de l'Environnement, now Institut des Géosciences de l'Environnement (IGE) (Vincent et al. 1997).

Table 1: Basic glaciological and radiometric parameters of the CDD ice.

Core name	C10	CDK	CDM
Drilling year	1994	2004	2012
Ice core length [m]	126	124	122.5
Surface (uppermost 15years) accumulation [m (mwe)]	6 (2.6)	3.8 (2.5)	3.5 (2.3)
Accumulation over uppermost 30 years [m (mwe)]	2.9 (2.1)	2.7 (2.0)	2.6 (1.85)
Firn-ice transition [m (years)]	56 (13)	54 (14)	52 (14)
Depth of the ^{3}H maximum [m]	87.67	-	93.3 (87.3)
Top and bottom depth of the ^{210}Pb anomaly [m]	83–108	85–~108	81-~102

^{3}H analyses (using liquid scintillation counting) in CDM ice were also performed at the division for Climate and Environmental Physics (CEP) of the Physics Institute, University of Bern, using ice core samples at higher depth resolution than used at IUP. Continuous flow analyses of CDM ice, including nitrate (NO_3^-) and ammonium (NH_4^+), were made at Desert Research Institute in Reno (DRI) from 45 to 86 m (see Legrand et al. (2018) and references therein). Additional NO_3^- and NH_4^+ data that are useful to derive dating by annual layer counting at CDD (Preunkert et al., 2000) were obtained in CDM ice with CFA measurements conducted at CEP along the whole ice core. Working conditions of the CFA analyses at CEP are detailed in Kaufmann et al. (2008), Gfeller et al. (2014) and Erhardt et al (2022).

Since the CDM ice core has a 3 inch diameter, the ice cross section available for the CFA analyses at CEP was only a section of 2.5 x 3.0 cm instead of the usual standard size of 3.2 x 3.2 cm used at CEP, which may have led to a higher risk of contamination of the inner sample melt water stream and a reduced analyte spectrum. Despite the undersized core section available at CEP, the nitrate profile obtained at DRI and IUP are in very good agreement (Fig. 2). After having discarded high peak NO_3^- values (14% of data), which could be easily attributed to contamination, mean NO_3^- values from 45.3-86.0 m were

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263 ppb (CEP) and 255 ppb (DRI). The agreement is somewhat weaker for NH_4^+. After having discarded 30% of NH_4^+ data, considered as not free of contamination, mean NH_4^+ values of 101 ppb (CEP) and 95 ppb (DRI) are in good agreement with the corresponding DRI measurements. Therefore, and since in general ammonium is far more sensitive to contamination than nitrate (Legrand et al., 1984), we minimize the use of ammonium in this study.

3. Data and Methods

3.1 Ice Core Dating

The net annual accumulation in the upper layers of the site covering the last 15 years is on average 2.5 m water equivalent (mwe) (Table 1), a typical order of magnitude encountered at high alpine glacier sites (Vincent et al., 2020; Bohleber, 2019). The surface mass balance observed in the upstream area of the drilling site (i.e., upwind in the southeastern Dôme du Gouter flank, Fig.1) decreases by one order of magnitude and reaches only ~0.2 mwe yr^{-1} at the summit of the Dôme de Gouter (Vincent et al., 1997, 2020), where the glacier thickness is only ~40 - 45 m. In addition to the annual layer thinning caused by the glacier flow, this upstream net accumulation decrease, which is accompanied by a decrease of the winter to summer net snow accumulation rate, also impacts the annual layer thickness at the drill site. As a consequence, annual layer thicknesses of only 0.7 and 0.2 mwe are observed at 100 m and 118 m depth (Preunkert et al., 2000) and the winter to summer layer thickness ratio decreases from 1 at the surface to 0.5 at 100m depth.

Based on a well-marked seasonality in the chemical stratigraphy for all cores, annual layer counting was used as the main dating tool over the time period of interest in this study, supplemented by Saharan dust events such as the one of 1977 (Preunkert et al., 2000 for C10; Legrand et al., 2013 for CDK, Legrand et al., 2018 and this study for CDM) and radiometric analyses aimed to detect the fallout from atmospheric thermonuclear bomb tests via ^{3}H (Legrand et al., 2013 for CDK and this study for CDM) and ^{137}Cs (Vincent et al., 1997) for C10, as already done for other Alpine ice cores records (e.g. Schotterer et al., 1998). The ^{210}Pb depth profiles (Vincent et al., 1997 for C10; Waldner, 2011 for CDK and Zipf, 2013 for CDM) were also obtained in the three ice cores, but because of the presence of strong anomalies discussed in section 3.2, these data are not useful as dating tools.

3.1.1 The C10 core

The dating of the C10 ice core back to 1925 obtained from annual layer counting of the ammonium record was initially established by Preunkert et al. (2000). More recently, the availability of additional measurements such as lead, cadmium and thallium allowed the dating to be extended back to 1890 without changing the original dating back to 1935 (Legrand et al., 2018).

The agreement between results of the annual layer counting and several time markers shows that the depth age relation is continuous and increases monotonically with depth (Fig. 2). The dating of the C10 core was found to be in excellent agreement

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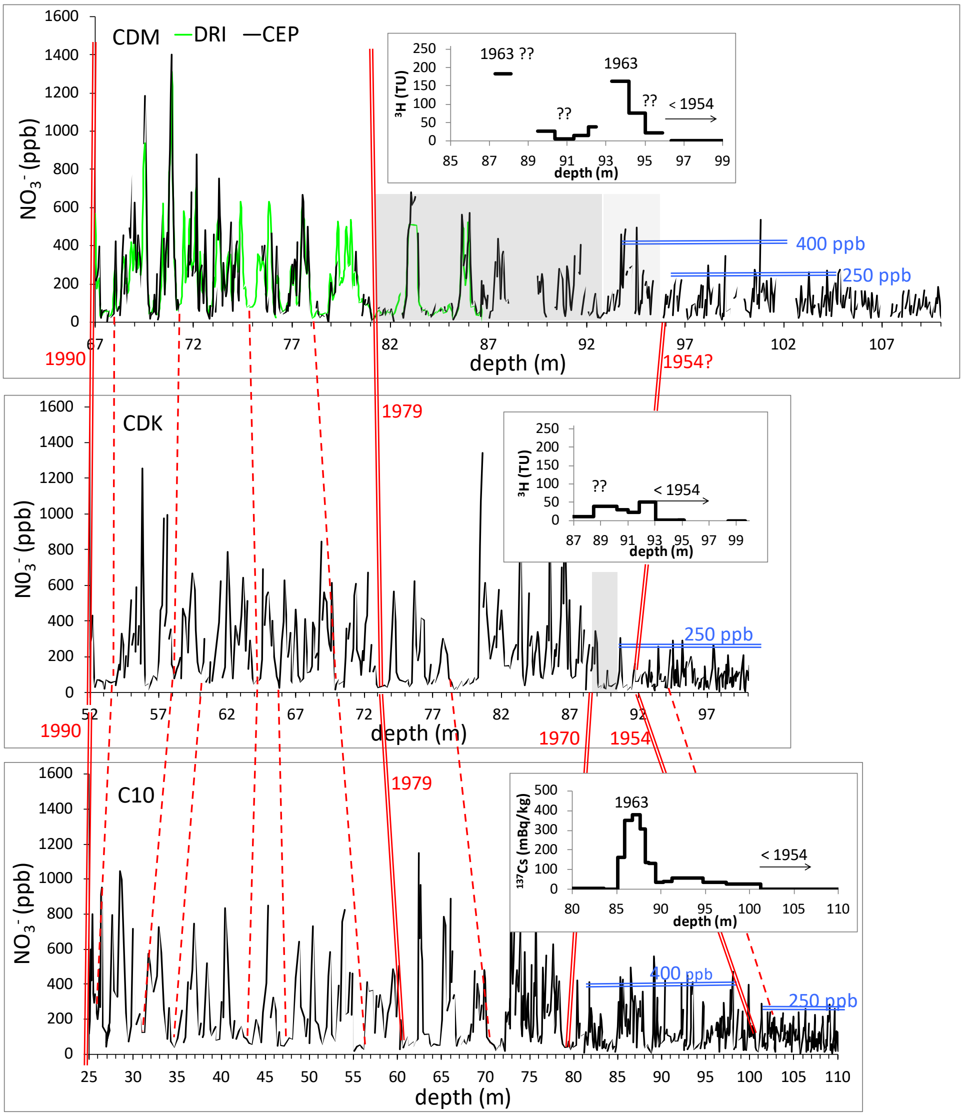

140 **Figure 2. Comparison of nitrate depth stratigraphies of CDM (this study), CDK (Legrand et al., 2013) and C10 (Preunkert et al., 2003) ice. In addition, for each core the bomb test horizons are also reported (this study for CDM, Legrand et al., 2013 for CDK and Vincent et al., 1997 for C10). Red lines mark common years in the different cores. Grey zones mark depth layers which do not fit in the continuous depth stratigraphies in CDM and CDK.**

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with several outstanding atmospheric changes or events that occurred during the 20th century such as the well-marked increase of fluoride after 1930 resulting from the rapid growth of the aluminum industry (Preunkert et al., 2001b), the large increase of sulfate after World War II (Preunkert et al., 2001a), and hydrochloric acid (HCl) peaks during the hot summers 1947-1949 caused by large forest fires (Legrand et al., 2002). Several of these events are recorded within the depth interval where increased ^{210}Pb values were observed (Vincent et al. 1997, and also Fig. 2 and section 3.2). Thus, we can assume that the depth age relation of the C10 core was not significantly disturbed (i.e. by more than the dating uncertainty estimated to be ± 5yr, at a depth of 90 m (Preunkert et al., 2000)) by the phenomenon (i.e. potential upstream crevasses) which caused the anomaly of the ^{210}Pb record.

3.1.2 The CDK core

As done in the C10 core, the dating of the CDK ice core was mainly achieved by annual layer counting largely using the ammonium stratigraphy. However, the seasonality of ammonium as well as those of other major ions like nitrate and sulfate disappears at 89.5 m and then recovers at 92 m (Legrand et al., 2013). Since the CDK ^{3}H profile lacks the main bomb maximum and ^{210}Pb anomalies were detected in this depth zone, Legrand et al., 2013 concluded that net depositions of a few years around 1963 are missing due to the existence of upstream crevasses, but suggested neither a reasonable glaciological mechanism for this effect nor an explanation for whatever reason it appeared in CDK and not in C10. The comparison of ammonium, nitrate, and sulfate mean summer CDK concentrations with those in C10 layers deposited above 89 m and between 92.0 and 106 m depth, suggests, however, a reliable CDK record of the 2004-1970 and 1954-1925 years (see Legrand et al., 2013 and Fig. 2 and 3).

3.1.3 The CDM core

Ionic species were analyzed as discrete samples using ion chromatography along the upper 35 m of the CDM core at IGE. From 45 m to 86 m depth, sections were measured with CFA at DRI (Legrand et al., 2018). These previous data were complemented by CFA measurements (NO_3^- and NH_4^+) at CEP. Figure 2 shows sequences of the CDM depth-profile for nitrate and comparison with those from CDK and C10. Down to 81 m depth, the nitrate CDM stratigraphy matches very well those of C10 and CDK, where the layer is dated at 1979 based on annual layer counting. Below 81 m depth, the CDM depth profile differs from those of the two other cores. The possibility that the three NO_3^- peaks between 81 and 88 m depth in the CDM core (Fig. 2) correspond to those seen between 73.2 and 78 m depth in CDK, would imply an annual layer thickness being 1.75 larger in the CDM than the CDK core. This conflicts with the expected decrease of annual layer thickness of layers having the same age in CDM compared to CDK drilled 8 years before. For instance, between 1992 and 1979 the annual layer thickness in CDM is approximately half that in CDK, as expected since the corresponding ice layers are deeper in the CDM core than in the CDK one (hence likely more thinned by glacier flow and having been deposited upstream further away from the drill site). In addition, the preceding assumption suggests that the three nitrate peaks between 81 and 88 m depth in CDM would be dated to 1978, 1977, and 1976, conflicting with the ^{3}H level found in this core (see Fig. 2). Therefore, it is assumed that a

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discontinuity occurs between 81 and at least 88 m depth in the CDM stratigraphy. Interestingly, whereas a winter to summer layer thickness ratio of ~0.55 is expected at ~80–100 m depth at this drill site, as seen in the C10 core (see section 3 and Preunkert et al., 2000), a very high winter to summer layer contribution (>2) is observed in CDM core between 81 and 88 m depth. Such an unexpected high winter to summer contribution was also observed in CDK between 89.5 and 92 m depth, i.e. where the NH_4^+ seasonal cycle vanished.

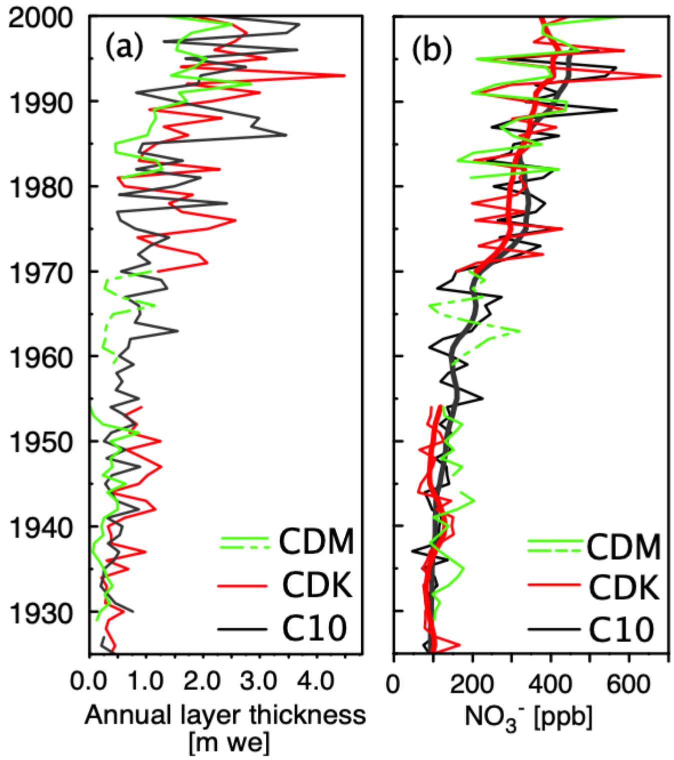

Figure 3: (a) Annual layer thickness of C10 (Preunkert et al. 2000) and CDK (Legrand et al., 2013) compared to CDM. For CDM, the annual layer thickness is estimated via the ammonium stratigraphy back to 1980 and via the nitrate (and ammonium) stratigraphy further back in time (section 3.1.3). (b) comparison of nitrate summer half-year means of C10 (Preunkert et al., 2003), and CDK (Legrand et al., 2013) with CDM. The thick solid lines marked for C10 and CDK refer to the smoothed profile (single spectrum analysis, see Legrand et al., 2013). CDM layers for which the dating is uncertain since the NH_4^+ and NO_3^- stratigraphies and trends do not match with what is expected (section 3.1.3), are marked with dashed lines.

Figure 2 reports the ^3H profile measured on CDM ice core samples at CEP. Ages were assigned according to the expected ^3H concentrations based on comparison with values obtained in a high-resolution ice core from Fiescherhorn, Switzerland

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(Schotterer et al. 1998). Strikingly, we find not one but two distinct peaks of 183.1 ± 9.7 TU and 162.7 ± 8.8 TU (one tritium unit, TU, being equals to 0.12 Bq L^{-1}) less than 6 m apart, starting at 87.29 to 88.2 m and 93.29 to 94.1 m depth, respectively. Notably, both maxima are close to the ^3H peak value normally reached in 1963. Note that an analytical or sample handling error can be excluded, since this anomaly has been confirmed by independent measurements made on different aliquots. Measurements on drilling chips of the ice core from 87–88 m depth made at IUP indeed revealed 212 TU instead of 183.1 TU measured at CEP. Based on the undisturbed depth-age scale of C10 drilled 18 years before CDM, the 1963 maximum would be expected at about 105 m depth in CDM (49 years before the 2012 drilling year). The ^3H profile of CDM, however, indicates low values below 96.3 m depth suggesting the ice to be older than 1954. Referring to the disturbed depth age relation in CDK, drilled 8 years before CDM, a 49-year-old ice layer should be located at 92 m depth, i.e., close to the second ^3H peak observed from 93.29 to 94.1 m depth in CDM. We therefore assume at this stage that the ^3H peak observed between 93.29 and 94.1 m depth in CDM ice corresponds to 1963.

Following what is expected from the Fiescherhorn depositional record, a mean TU value around the 1963 peak should be 10-40 TU in the 1958-1975 years. This is consistent with the observed value in CDM ice around the second ^3H peak (89.5 to 96 m depth) except the value of 6.4 TU observed at 90.3-91.3 m depth. Since the ^3H profile is only available at coarse resolution (75 cm long samples), it is not possible to be more accurate in dating the bomb test period (1954 to ~1976). Further attempts to determine whether the ice layers around the ^3H peak (i.e. from 88-96 m depth) are well preserved were not conclusive. First, assuming that the profile is continuous between 93.3 and 96.3 m (i.e., 1954 as indicated by ^3H data) depth would imply an annual layer thickness of 0.28 mwe over the 1963-1954 years, which is similar to what is seen in the C10 core (0.4 mwe). Second, due to decreasing anthropogenic emissions back in time, we consistently observed a decreasing trend in NH_4^+ and NO_3^- concentrations with age in the C10 ice (mean summer value in 1964–1968: NH_4^+: 110 ppb; NO_3^-: 178 ppb; in 1963–1954: NH_4^+: 95 ppb; NO_3^- 140 ppb). This feature, however, is not detected when comparing summer NH_4^+ and NO_3^- means in CDM ice above and below the 1963 peak at 93.3 m. Over the 88 to 93.3 m depth interval in CDM ice, we observed mean summer NH_4^+ and NO_3^- concentrations of 90 ppb and 175 ppb, respectively; lower than those between 93.3 and 96.3 m depth (NH_4^+: 116 ppb; NO_3^-: 193ppb; see also Fig. 3 for NO_3^-). To illustrate this mismatch, the result of annual layer counting around 1963 is also reported (dashed lines) in Fig. 3. Third, annual layer counting based on the CDM nitrate or ammonium profiles suggest only 4 years instead of 9 years for the 93.3-96.3 m depth interval (i.e., from 1963 to 1954).

If the first ^3H peak is considered as the true 1963 maximum, this would mean that a hiatus of 16 years exists in the CDM record between 1979 at 81 m depth and 1963 in 87.3 m depth. The depth layers between 88 and ~93.3 m depth would then correspond to years prior to 1963. This assumption is again in contradiction with the mean summer levels of NH_4^+ and NO_3^- observed in C10 for this period (see discussions above). Another stratigraphic perturbation is therefore required to produce the second ^3H maximum at 93.3 m.

In conclusion, our results suggest a continuous depth age relation from the surface back to 1980 and for years older than ~1954 (96 m), and imply an entire disturbance encompassing at least 25 years in this core. To confirm the assumption of the recovery of an undisturbed depth age relation prior to 1954 done on the basis of the NO_3^- profile and the observations made in C10 and

CDK ice, further investigations of additional absolute time markers (as done in C10 ice, see section 3.1) are needed before using the lower part of the CDM core as an archive of past atmospheric changes.

3.2 The ^{210}Pb depth profiles

Figure 4 reports the ^{210}Pb depth profiles of C10, CDK and CDM. Three common features can be identified in each of the records. First, in the upper core sections down to 80 m, the ^{210}Pb activities are of the order of magnitude of those expected from atmospheric deposition at high Alpine sites (Gaeggeler et al., 2022). The fact that the expected decrease by a factor of two of ^{210}Pb activities over the 22 years (half life of ^{210}Pb) is not clearly observed at the drill site is not surprising since the ^{210}Pb deposition at the glacier surface is not constant in time and space. Based on atmospheric ^{210}Pb measurements achieved at high-elevated Alpine sites (see Hammer et al. (2007) for Sonnblick at 3106 m asl, Austria and Gaeggeler et al. (1995) for Jungfraujoch station at 3450 m asl, Switzerland), it was shown that the intensity of vertical upward transport of ^{210}Pb-rich continental boundary layer air masses strongly impact levels at high elevation sites. As a consequence, a strong seasonal cycle with ^{210}Pb concentrations three to four times higher in summer than in winter is observed at high altitude Alpine sites. Together with the systematic decrease of winter to summer layer thickness ratio with increasing core depth at the drill site (see section 3 and Preunkert et al., 2000), this pronounced ^{210}Pb seasonality counteracts the expected ^{210}Pb decrease from radioactive decay. Second, a well-marked anomaly characterized by ^{210}Pb enhancements including ^{210}Pb peaks up to 10 times more ^{210}Pb than what is expected from atmospheric deposition, is observed in the three cores. The anomaly extends from ~83 to 108 m depth (i.e., ~26 to 54 years) in C10, ~85 to 108 m (i.e., ~32 to 70 years) in CDK, and ~81 to 102 m (i.e., ~33 to more than 58 years) in CDM ice. Third, below the anomaly, a further decrease in ^{210}Pb is observed. However, it is worth noting that, especially in the case of the CDM and CDK cores, there is a remaining non-zero level of ^{210}Pb activity even in the bottommost core sections (in the case of C10, levels are below the formal limit of detection). Since the age of the bottom core sections at CDD exceeds however several half-lives of ^{210}Pb, as for example indicated by radiocarbon dating for CDK (Preunkert et al., 2019), a zero ^{210}Pb activity is expected as a result of atmospheric deposition with no additional ^{210}Pb inputs from the granitic bedrock emissions.

As outlined before, the ^{210}Pb perturbations found at the drill site were attributed to the granite bedrock at CDD in combination with the presence of crevasses in the vicinity of the drill site. Pourchet et al. (2000) conducted measurements of ^{222}Rn in snow above a crevasse at the Mont Blanc summit, revealing peak values as high as an unexpected 145,000 Bq m^{-3}, and free atmospheric background values of a few tens of Bq m^{-3} at this elevation. Based on calculations, the authors suggested the existence of convective Rn transport and diffusion from the underlying fractured granitic bedrock.

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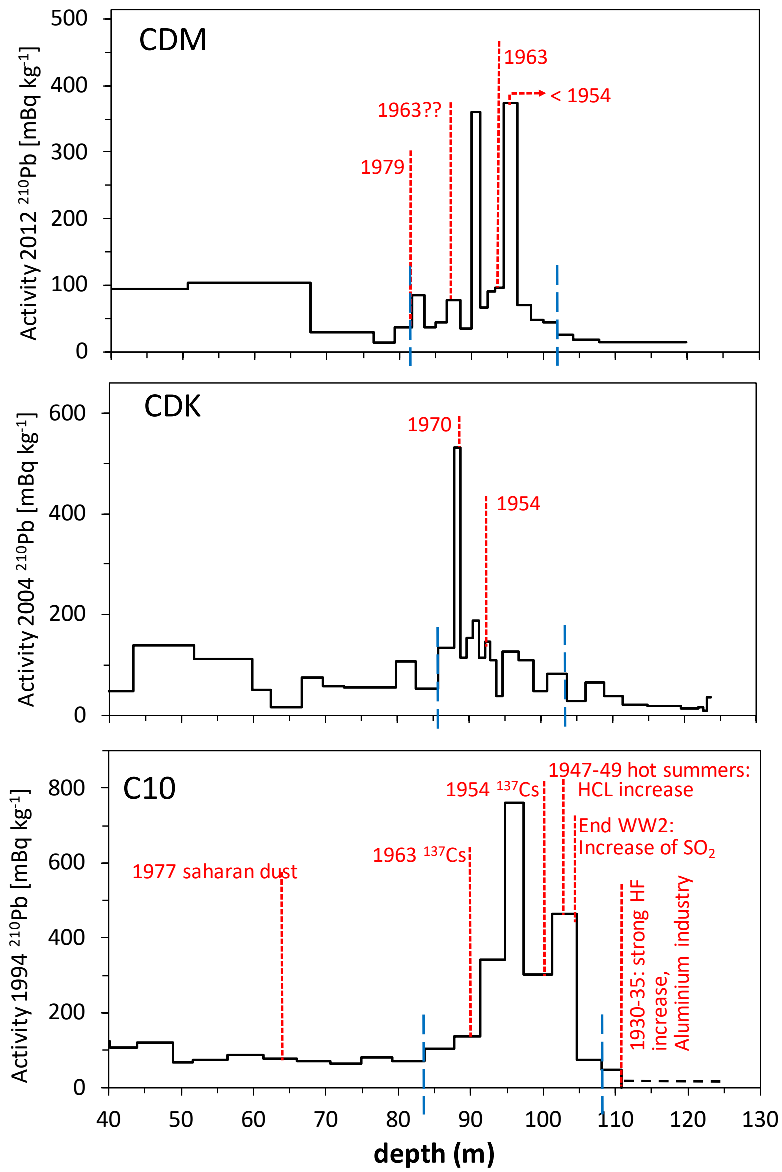

260 **Figure 4: ^{210}Pb profiles of the three CDD ice cores. The decay-corrected ^{210}Pb activity is shown using the drilling year of the respective ice cores as reference. Blue dashed vertical lines indicate the approximate boundaries of the anomaly. Where available, absolute time markers detected over the ^{210}Pb perturbed depth zones are also reported. Data are from Zipf, 2013 (CDM), Waldner, 2011 (CDK) and Vincent et al., 1997 (C10).**

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4. Discussion of upstream crevasse impact on ice core records

Since the ^{210}Pb anomalies are located at similar depths in C10, CDK and CDM cores (section 3.2), and start in the three cores ~30 years before the drilling year, we assume that the ^{210}Pb perturbations originate from the same area upstream where one or more crevasses reache bedrock. Further, since the ^{210}Pb anomalies are restricted to a specific depth zone in the cores, we assume that the ^{222}Rn diffusion in the surrounding firn layers is sealed at the top and bottom, by the presence of a snow-bridge containing horizontal summer ice layers as have been observe to occur regularly at the site (Preunkert et al., 2000), and the firn-ice transition of the glacier, respectively (see thick green flow lines in Fig. 5b).

The impact of the upstream crevasse on the depth-age relation of the ice cores changed, however, between the C10 core drilled in 1994 and the CDM and CDK cores drilled after 2000. Whereas for C10 an excellent agreement between annual layer counting and independent absolute time markers was found over the depth interval influenced by the crevasse, i.e. in which increased ^{210}Pb values were observed (Fig. 4), this is not the case for the CDK and CDM ice cores. In the latter two cores, the ^{210}Pb anomaly comprises the layers for which the depth-age relation was found to be disturbed (Fig. 2 and 4). Furthermore, the CDK and CDM ^{210}Pb anomaly inventories (Fig. 4) are 4 times lower than in C10, whereas we would have expected similar ^{210}Pb anomaly inventories if the open bedrock surface and the surrounding ice layer stratigraphy of the crevasse had remained unchanged. The spatial variability of the ^{210}Pb anomaly inventory at the CDD site can be estimated by examining the ^{210}Pb inventory of a 140 m long ice core extracted 30 m away from C10 in 1994 (Vincent et al., 1997), and which revealed a ^{210}Pb anomaly inventory of 80% that of C10. Hence, this difference is small compared to the difference seen between C10, CDK, and CDM. Thus, the two preceding points suggest that the upstream glacier flow of the drill site in the area of the crevasse has changed with time.

Figure 5a shows the glacier thickness changes between 1993 and 2017 overlayed with the modelled flow line reporting the calculated arrival depth at the drill site of C10, CDK, and CDM (Gilbert et al., 2014), and Fig. 5b represents a vertical cut along the modelled flow line of Fig. 5a overlayed by a sketch of the upstream crevasse. Tracing back the arrival depths of the ^{210}Pb disturbance at the drill site, model calculations made by Vincent et al. (1997) (not shown) and Gilbert et al. (2014) (Fig. 5a and b) suggest both that the origin of the ^{210}Pb anomaly should lie ~100-150 m upstream to the drill site, which is in good agreement with visual observations of the crevasse obtained via aerial and ground-based photos (see Fig. 5b and 1). A bedrock reaching crevasse which is situated near or in this upstream region would lead to a continuous enrichment of ^{222}Rn and ^{210}Pb within the volume of the crevasse itself, and by diffusion of ^{222}Rn in firn situated in its vicinity. As mentioned above, the ^{222}Rn diffusion would be sealed at the top and the bottom, by the presence of a snow-bridge containing impermeable ice layers and the firn-ice transition of the glacier at the bottom, respectively. This would imply that the firn ice transition lies at a depth of ~50 m (i.e. ~20 years) in the surrounding area of the crevasse (see Fig. 5b), whereas the firn air transition is located at ~25 m depth at the summit of Dome de Gouter (i.e., ~100 years, Rehfeld, 2009) and ~50-55 m depth at the C10, CDK and CDM drill site (i.e., ~13-14 years). After having been enriched in ^{210}Pb, the firn/ice layers would continue to flow downslope and

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thereafter arrive at the drill site as indicated by the bold green flow lines drawn in Fig. 5b. A rough estimation for this downstream travelling time between the crevasse and the drill site can be done following the flow lines of the ice flow model of Gilbert et al. 2014 (see Fig. 5b). Doing so, 30-year-old ice found at depth of ~80 m depth at the CDD drill site would have passed nearby or crossed the crevasse ~25 years before.

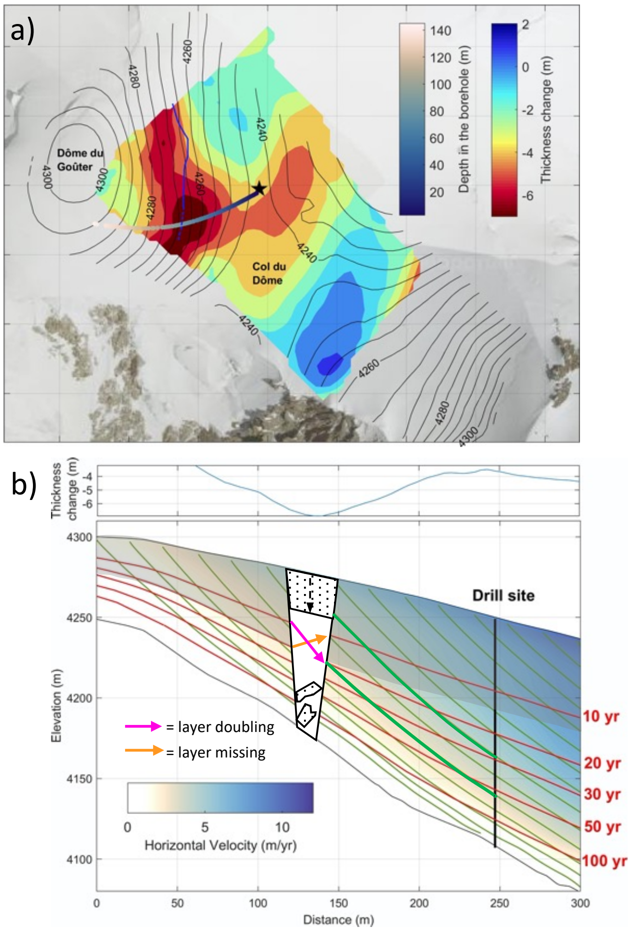

Figure 5: (a) Thickness changes between 1993 and 2017. The contour lines of surface topography correspond to the surface of 1993 (adapted from Vincent et al., 2020) overlayed with modelled flow line (color scale on top) which reports the calculated arrival depth at the drill site of C10, CDK, and CDM marked with a black star (Gilbert et al., 2014). The crevasse is reported (blue line) on the base of an aerial photo from IGNF taken at 30th June 2004 (see Fig.1) (b) Schematic representation of the origin of the ^{210}Pb anomalies found at the drill site following the ice flow model of Gilbert et al., 2014, extracted along the flow path reaching the drill site. Isochrones are marked in red, flowlines in green (see also section 4). The grey shaded zone indicates firn, the dotted zone indicates the snow bridge of the crevasse. The formation of missing or doubling ice layers is indicated by the orange and pink arrows.

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Recent visual observations made on the CDD glacier attest to the presence of crevasse(s) upstream the CDD drill sites (Fig. 1). Comparing photos taken in 2012 (Fig. 1a) and in 1999 (Fig.1b), an enlargement and horizontal propagation of the crevasse in the east can be observed from 1999 to 2012. Whereas in 2012, the crevasse is clearly visible as a snow-covered depression on the surface slope, the crevasse appeared limited to the southwestern flank of the drill site catchment area in 1999. Although speculative, if we assume such a crevasse did exist already earlier but was limited in its horizontal extension and did not intersect the catchment area of the drill site in the 1970s, i.e. before the strong and fast recent increase in CDD near-surface temperature started around 1980 (Vincent et al., 2020), this would explain the occurrence of the ^{210}Pb anomaly observed in C10 together with an undisturbed depth age relation in this ice core. Later in time, maybe in relation with the above-mentioned surface temperature increase (2.5°C between 1980-1998, Vincent et al., 2020), and since ice viscosity strongly depends on ice temperature (Cuffey and Paterson, 2010) this situation might however had changed. Assuming that the crevasse would have enlarged and also propagated horizontally to cross the flow line of the drill site, the appearances of winter snow enriched layers and discontinuities (i.e. lacking and/or doubling of ice layers) in the depth-age relations of CDK and CDM, drilled 10 and 18 years later than C10, could be explained. The presence of unexpectedly large winter snow layers observed in CDK and CDM (section 3.1.3) could originate in snow and firn layers coming from the snow bridge or directly from snow deposits. The lack of or doubling of ice layers could be explained by a shift in the isochrones occurring from the ice layer transition through the crevasse (or crevasse system), which opens and closes constantly during its lifecycle (Colgan et al., 2016).

For the ice layer transition through the crevasse, two scenarios could be imaginable. Due to the bedrock and glacier surface inclination, ice of the upper border of the crevasse (left side of the crevasse in Fig. 5b) would be mapped in offset to the lower border of the crevasse (right side of the crevasse in Fig. 5b) in the sense that an upper side isochrone arrives at a deeper depth compared to this isochrone on the lower side of the crevasse (see pink arrow in Fig. 5b), which would result in a layer doubling at the drill site as it is seen in CDM. On the other hand, if the bottom of the crevasse is filled up with snow from the previously existing snow bridge and/or from wind-blown surface snow, it might happen that isochrones of the upper border of the crevasse arrive at shallower depths compared to the respective isochrones on the lower border of the crevasse (see orange arrow in Fig. 5b), that would result in missing layers at the drill site as seen in CDK.

Note that the concurrent occurrence of both phenomena (i.e. opening of the crevasse to the atmosphere and shift in isochrones) would be consistent with the ^{210}Pb anomaly inventory decrease observed in CDK and CDM compared to C10. An open crevasse alone would have led to a minimized production of ^{210}Pb in the firn and to ^{210}Pb anomaly inventories of at least 70 and 55% in CDK and CDM compared to C10, because of radioactive decay of ^{210}Pb over 10 and 18 years, respectively. However as reported above, the ^{210}Pb anomaly inventories of CDK and CDM amount to only ~25% of the C10 one, strongly suggesting that in addition to the aperture of the crevasse the isochrones are disturbed, leading to a lack of ice layers with high ^{210}Pb activities, and thus to disturbed depth-age relations in both cores.

Interestingly, though recent long-term glaciological observations of the CDD site are only available since 1994 and show only minor changes in glacier dynamics (Vincent et al., 2020), a glacier thickness reduction of ~6-7m, being the maximal value of the whole saddle area, was observed from 1994 to 2017 in the area of the upstream crevasse of the C10, CDK, CDM drill site

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(Fig. 5a). This could be a sign for a partly collapsing crevasse, that could lead to further stratigraphic problems (compared to CDM and CDK) at the drill site in the future.

5. Summary and conclusion

Combining existing and new chemical depth profiles, bomb test time markers and the ^{210}Pb depth profiles of three ice cores extracted at the same drill CDD site in 1994, 2004 and 2012, allowed us for the first time to highlight changes over time of the depth-age characteristics at an alpine drill site. Due to the granitic bedrock prevailing at the site, the imprint of a crevasse located upstream of the drill site is visible in all three ice cores, through a distinct anomaly in their ^{210}Pb profiles extending over just a few meters in depth and with ^{210}Pb concentrations elevated by up to a factor of 10. Whereas the depth-age relation of the C10 ice core drilled in 1994 does not appear to be disturbed by the upstream crevasse, this is not the case for the CDK and CDM ice cores drilled after 1994 (in 2004 and 2012). For CDK and CDM, the depth-age relationships were found to be disturbed in ice layers deposited ~30 year before drilling and over a period of 16 years in CDK and at least 25 years in CDM, very likely due to an extension of the crevasse over time. This finding is consistent with long-term glaciological observations that show significant glacier thickness changes in the surrounding area of the upstream crevasse.

Although at this stage we can provide only a qualitative explanation for the recently observed stratigraphic discontinuities, our work points towards the need for careful examinations of the depth-age relationship, when using ice cores from this CDD drill site, to reconstruct past atmospheric conditions. More generally, since crevasses are often present on non-polar glaciers, such disturbances in the depth-age relation, as observed at CDD, could also appear at other non-polar ice core drill sites and stay undetected, particularly when the bedrock is not granitic, no or few absolute time markers are available, and/or only one core is collected from the site. To identify such depth-age problems, in addition to the commonly used annual layer counting, an extended use of absolute time markers including bomb horizons through ^{3}H, ^{137}Cs, or ^{239}Pu (Arienzo et al., 2016), ^{39}Ar (Feng et al., 2019), large Saharan dust events or volcanoes (e.g. Plunkett et al., 2022) are mandatory. Furthermore, at other non-polar sites where the net snow accumulation is far lower than at CDD (i.e., with ice as old as several thousands of years located well above the bedrock), additional tools like ^{14}C measurements (Jenk et al., 2006 and 2009; Hoffmann et al., 2018) should be applied.

Data availability

Ice core data are available as supplementary data, and will be made available at NCEI (National Centers for Environmental Information) data base (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data).

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Author contribution

SP, PB and ML performed research and wrote the original manuscript. HF, TE, RP, LZ, AW, JRM analyzed ice samples and data, and commented the original manuscript. AG did model calculations and commented the original manuscript.

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References

Arienzo, M. M., Legrand, M., Preunkert, S., Stohl, A., Chellman, N., Eckhardt, S., Gleason, K.E. and McConnell J.R.:
390 Alpine ice-core evidence of a large increase in vanadium and molybdenum pollution in Western Europe during the 20th century. Journal of Geophysical Research: Atmospheres, 126, e2020JD033211. https://doi.org/10.1029/2020JD033211, 2021.

Arienzo, M.M., J.R. McConnell, N. Chellman, A. Criscitiello, M. Curran, D. Fritzsche, et al. S. Kipfstuhl, R. Mulvaney, M.
395 Nolan, T. Opel, M. Sigl, & J.P. Steffensen (2016). A method for continuous ^{239}Pu determinations in Arctic & Antarctic ice cores, *Environ Sci Technol,* doi: 10.1021/acs.est.6b01108.

Bohleber, P.: Alpine Ice Cores as Climate and Environmental Archives, https://doi.org/10.1093/acrefore/9780190228620.013.743, 2019.

400

Colgan, W., Rajaram, H., Abdalati, W., McCutchan, C., Mottram, R., Moussavi, M., and Grigsby, S.: Glacier Crevasses: Observations, Models and Mass Balance Implications. Rev. Geophys., 54, 119-161, https://doi.org/10.1002/2015RG000504, 2016.

405 Cuffey, K. M., and Paterson, W. S. B.: The physics of glaciers. Academic Press, 2010.

Elsässer, C., Wagenbach, D., Weller, R., Auer, M., Wallner, A., and Christl, M.: Continuous 25-yr aerosol records at coastal Antarctica Part 2: variability of the radionuclides ^{7}Be, ^{10}Be and ^{210}Pb, Tellus B, 63(5), 920-934, https://doi.org/10.1111/j.1600-0889.2011.00543.x, 2011.

410

Erhardt, T., Bigler, M., Federer, U., Gfeller, G., Leuenberger, D., Stowasser, O. et al., High-resolution aerosol concentration data from the Greenland NorthGRIP and NEEM deep ice cores. Earth System Science Data, 14(3), 1215-1231, https://doi.org/10.5194/essd-14-1215-2022, 2022.

415 Fagerli, H., Legrand, M., Preunkert, S., Vestreng, V., Simpson, D., and Cerqueira, M.: Modeling historical long-term trends of sulfate, ammonium, and elemental carbon over Europe: A comparison with ice core records in the Alps, J. Geophys. Res., 112, D23S13, https://doi.org/10.1029/2006JD008044, 2007.

Feng Z., Bohleber, P., Ebser S., Ringena L., Schmidt, M., Kersting A., Hopkin P., Hoffmann, H., Fischer A., Aeschbach W.,
420 and Oberthaler M.K.: Dating glacier ice of the last millennium by quantum technology, Proc. Natl. Acad. Sci. U.S.A. 116,

8781–8786, https://doi.org/10.1073/pnas.1816468116, 2019.

Gäggeler HW; Radioactivity in the Atmosphere, Radiochimica Acta 70/71, 345-35, https://doi.org/10.1524/ract.1995.7071.s1.345, 1995.

Gäggeler, H., Tobler, L., Schwikowski, M., and Jenk, T.: Application of the radionuclide 210 Pb in glaciology – an overview, Journal of Glaciology. 66. 1-10, https://doi.org/10.1017/jog.2020.19 , 2020.

Gfeller, G., Fischer, H., Bigler, M., Schüpbach, S., Leuenberger, D., and Mini, O.: Representativeness and seasonality of major ion records derived from NEEM firn cores, The Cryosphere, 8, 1855–1870, https://doi.org/10.5194/tc-8-1855-2014 , 2014.

Gilbert, A. and Vincent, C.: Atmospheric temperature changes over the 20th century at very high elevations in the European Alps from englacial temperatures, Geophysical Research Letters, 40, 2102–2108, https://doi.org/10.1002/grl.50401, 2013.

Gilbert, A., Gagliardini, O., Vincent, C., and Wagnon, P.: A 3-D thermal regime model suitable for cold accumulation zones of polythermal mountain glaciers, Journal of Geophysical Research: Earth Surface, 119(9), 1876-1893, https://doi.org/10.1002/2014JF003199, 2014.

Guilhermet, J., Preunkert, S., Voisin, D., Baduel, C., and Legrand, M.: Major 20th century changes of water-soluble HUmic LIke Substances (HULISWS) aerosol over Europe inferred from Alpine ice cores, J. Geophys. Res. Atmos., 118, https://doi.org/10.1002/jgrd.50201, 2013.

Hammer, S., Wagenbach, D., Preunkert, S., Pio, C., Schlosser, C., and Meinhardt, F.: Lead-210 observations within CARBOSOL: A diagnostic tool for assessing the spatiotemporal variability of related chemical aerosol species?, J. Geophys. Res., 112, D23S03, https://doi.org/10.1029/2006JD008065, 2007.

Hoffmann, H., Preunkert, S., Legrand, M., Leinfelder, D., Bohleber, P., Friedrich, R., and Wagenbach, D.:, A new sample preparation system for micro-14C dating of glacier ice with a first application to a high alpine ice core from Colle Gnifetti (Switzerland), Radiocarbon, 60(02), 517–533, https://doi.org/10.1017/rdc.2017.99, 2018.

Jenk, T., Szidat, S., Schwikowski, M., Gäggeler, H., Brütsch, S., Wacker, L., Synal, H.-A., and Saurer, M.: Radiocarbon analysis in an alpine ice core: Record of anthropogenic and biogenic contributions to carbonaceous aerosols in the past (1650–1940). Atmospheric Chemistry and Physics, 6(12), 5381–5390, https://doi.org/10.5194/acp-6-5381-2006 , 2006.

Jenk, T., Szidat, S., Bolius, D., Sigl, M., Gäggeler, H., Wacker, L, Ruff, M., Barbante, C., Boutron, C.F., Schwikowski, M.: A novel radiocarbon dating technique applied to an ice core from the Alps indicating late Pleistocene ages, Journal of Geophysical Research, 114, D14305. https://doi.org/10.1029/2009JD011860, 2009.

Kaufmann; P.R., Federer, U., Hutterli, M.A., Bigler, M., Schüpbach, S., Ruth, U., Schmitt, J., and Stocker, T.F.: An improved Continuous Flow Analysis (CFA) system for high-resolution field measurements on ice cores, Environ. Sci. Technol., 42, 21, 8044–8050, https://doi.org/10.1021/es8007722, 2008.

Legrand, M., de Angelis, M., and Delmas, R. J.: Ion chromatographic determination of common ions at ultratrace levels in Antarctic snow and ice, Anal. Chim. Acta, 156, 181-192, https://doi.org/10.1016/S0003-2670(00)85549-X, 1984.

Legrand, M., Preunkert, S., Wagenbach, D., and Fischer, H.: Seasonally resolved Alpine and Greenland ice core records of anthropogenic HCl Emissions over the 20th century, J. Geophys. Res., 107, D12, https://doi.org/10.1029/2001JD001165, 2002.

Legrand, M., Preunkert, S., Wagenbach, D., Cachier, H., and Puxbaum, H.: A historical record of formate and acetate from a high elevation Alpine glacier: Implications for their natural versus anthropogenic budgets at the European scale, J. Geophys. Res., 108, D24, 4788, https://doi.org/10.1029/2003JD003594, 2003.

Legrand, M., Preunkert, S., Schock, M., Cerqueira, M., Kasper-Giebl, A., Afonso, J., Pio, C., Gelencsér, A., and Dombrowski-Etchevers, I.: Major 20th century changes of carbonaceous aerosol components (EC, WinOC, DOC, HULIS, carboxylic acids, and cellulose) derived from Alpine ice cores, J. Geophys. Res., 112, D23S11, https://doi.org/10.1029/2006JD008080 , 2007.

Legrand, M., Preunkert, S., May, B., Guilhermet, J., Hoffman, H., and Wagenbach, D.: Major 20th century changes of the content and chemical speciation of organic carbon archived in Alpine ice cores: Implications for the long-term change of organic aerosol over Europe, J. Geophys. Res, 118(9), 3879-3890, https://doi.org/10.1002/jgrd.50202 , 2013.

Legrand, M., McConnell, J. R., Preunkert, S., Arienzo, M., Chellman, N., Gleason, K., Sherwen, T., Evans, M. J., and Carpenter, L. J., Alpine ice evidence of a three-fold increase in atmospheric iodine deposition since 1950 in Europe due to increasing oceanic emissions, Proceedings of the Nat. Academy of Sciences of the USA, https://doi.org/10.1073/pnas.1809867115, 2018.

Legrand, M., McConnell, J. R., Lestel, L., Preunkert, S., Arienzo, M., Chellman, N. J., Stohl, A., Eckhardt, S.: Cadmium pollution from zinc-smelters up to fourfold higher than expected in western Europe in the 1980s as revealed by alpine ice. Geophysical Research Letters, 46, e2020GL087537, https://doi.org/10.1029/2020GL087537, 2020.

https://doi.org/10.5194/tc-2022-259
Preprint. Discussion started: 31 January 2023

Legrand, M., McConnell, J. R., Preunkert, S., Chellman, N. J., and Arienzo, M. M.: Causes of enhanced bromine levels in Alpine ice cores during the 20th century: Implications for bromine in the free European troposphere, J. Geophys. Res, 126, e2020JD034246, https://doi.org/10.1029/2020JD034246, 2021.

Legrand, M., McConnell, J. R., Preunkert, S., Bergametti, G., Chellman, N. J., Desboeufs, K., Plach, A., Stohl, A., Eckhardt, S.: Thallium pollution in Europe over the twentieth century recorded in Alpine ice: Contributions from coal burning and cement production. Geophysical Research Letters, 49, e2022GL098688, https://doi.org/10.1029/2022GL098688, 2022.

Moseid, K. O., Schulz, M., Eichler, A., Schwikowski, M., McConnell, J. R., Olivié, D., Criscitiello, A. S., Kreutz, K.J., and Legrand, M.: Using ice cores to evaluate CMIP6 aerosol concentrations over the historical era. J. Geophys. Res., 127, e2021JD036105, https://doi.org/10.1029/2021JD036105, 2022.

Plunkett, G., Sigl, M., Schwaiger, H., Tomlinson, E., Toohey, M., Mcconnell, J., Pilcher, J., Hasegawa, T., and Siebe, C.: No evidence for tephra in Greenland from the historic eruption of Vesuvius in 79 CE: Implications for geochronology and paleoclimatology, Climate of the Past, https://doi.org/10.5194/cp-2021-63, 2000.

Pourchet, M, Richon, P.,, Sabroux, J.-C.: Lead-210 and radon-222 anomalies in Mont Blanc snow, French Alps. Journal of Environmental Radioactivity. 48. 349–357, https://doi.org/10.1016/S0265-931X(99)00084-3, 2000.

Preunkert, S., Wagenbach, D., Legrand, M., and Vincent, C.: Col du Dôme (Mt Blanc Massif, French Alps) suitability for ice-core studies in relation with past atmospheric chemistry over Europe. Tellus B, 52(3), 993-1012, https://doi.org/10.3402/tellusb.v52i3.17081, 2000.

Preunkert, S., Legrand, M., and Wagenbach, D.: Sulfate Trends in a Col du Dôme (French Alps) Ice Core: A Record of Anthropogenic Sulfate Levels in the European Mid-Troposphere over the 20th Century, J. Geophys. Res., 106, 31991-32004, https://doi.org/10.1029/2001JD000792, 2001a.

Preunkert, S., Legrand, M., and Wagenbach, D.: Causes of enhanced fluoride levels in Alpine ice cores over the last 75 years: Implications for the atmospheric fluoride budget, J. Geophys. Res, 106(D12), 12619-12632, https://doi.org/10.1029/2000JD900755, 2001b.

Preunkert, S., Wagenbach, D., and Legrand, M.: A seasonally resolved Alpine ice core Record of Nitrate: Comparison with Anthropogenic Inventories and estimation of Pre-Industrial Emissions of NO from Europe, J. Geophys. Res., 108, D21, 4681, https://doi.org/10.1029/2003JD003475, 2003.

https://doi.org/10.5194/tc-2022-259
Preprint. Discussion started: 31 January 2023

Preunkert, S., McConnell, J. R., Hoffmann, H., Legrand, M., Wilson, A. I., Eckhardt, S., Stohl, A., Chellman, N., Arienzo, M., and Friedrich, R.: Lead and antimony in basal ice from Col du Dome (French Alps) dated with radiocarbon: A record of pollution during antiquity, Geophys. Res. Lett., 46, 4953-4961, https://doi.org/10.1029/2019GL082641, 2019.

Rehfeld, K.: Investigations into Mont Blanc region summit ice cores at seasonal resolution, Institute of Environmental Physics, Diploma thesis, University of Heidelberg, Germany, 2009.

Schotterer, U., Schwarz, P., and Rajner, V.: From pre-bomb levels to industrial times: A complete tritium record from an alpine ice core and its relevance for environmental studies. In Isotope techniques in the study of environmental change, International Atomic Energy Agency (IAEA), 1998.

Stanzick, A.: Raum-Zeit-Variationen von Be-10, Pb-210 und Cl-36 in der grönländischen Firndecke: Luft-Firn-Transfer und rezente Trends, PhD thesis, Institute of Environmental Physics, University of Heidelberg, Germany, 2001.

Vincent, C., Vallon, M., Pinglot, J. F., Reynaud, L., and Funk, M.:, Snow accumulation and ice flow at Dôme du Goûter (4300 m), Mont Blanc, French Alps, Journal of Glaciology, 43(145), 513-521, https://doi.org/10.3189/S0022143000035127, 1997.

Vincent, C., Le Meur, E., Six, D., Possenti, P., Lefebvre, E., and Funk, M.: Climate warming revealed by englacial temperatures at Col du Dôme (4250 m, Mont Blanc area), Geophys. Res. Lett., 34, L16502, https://doi.org/10.1029/2007GL029933, 2007.

Vincent, C., Gilbert, A., Jourdain, B., Piard, L., Ginot, P., Mikhalenko, V., Possenti, P., Le Meur, E., Laarman, O. and Six, D.: Strong changes in englacial temperatures despite insignificant changes in ice thickness at Dôme du Goûter glacier (Mont Blanc area), The Cryosphere, 14. 925–934, https://doi.org/10.5194/tc-14-925-2020, 2020.

Wagenbach, D., Bohleber, P., and Preunkert, S.: Cold, alpine ice bodies revisited: what may we learn from their impurity and isotope content?, Geografiska Annaler: Series A, Physical Geography, 94(2), 245-263, https://doi.org/10.1111/j.1468-0459.2012.00461.x, 2012.

Waldner, A.: Analyse des 210Pb-Konzentrations-Profils eines Eisbohrkerns des Mont-Blanc-Gebiets hinsichtlich einer ungeklaerten Konzentrations-Anomalie, Bachelor thesis, Institute of Environmental Physics, University of Heidelberg, Germany, 2011.

Zipf, L.: Untersuchung eines Eisbohrkernes des Col du Dôme auf eine in benachbarten Bohrkernen auftretenden 210Pb-Aktivitaetanomalie, Bachelor thesis, Institute of Environmental Physics, University of Heidelberg, Germany, 2013.