Clim. Past, 8, 509–517, 2012
www.clim-past.net/8/509/2012/
doi:10.5194/cp-8-509-2012

Climate of the Past

Volcanic synchronisation of the EPICA-DC and TALDICE ice cores for the last 42 kyr BP

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Received: 14 October 2011 – Published in Clim. Past Discuss.: 28 October 2011
Revised: 3 February 2012 – Accepted: 14 February 2012 – Published: 14 March 2012

Abstract. The age scale synchronisation between the Talos Dome and the EPICA Dome C ice cores was carried on through the identification of several common volcanic signatures. This paper describes the rigorous method, using the signature of volcanic sulphate, which was employed for the last 42 kyr of the record. Using this tight stratigraphic link, we transferred the EDC age scale to the Talos Dome ice core, producing a new age scale for the last 12 kyr. We estimated the discrepancies between the modelled TALDICE-1 age scale and the new scale during the studied period, by evaluating the ratio *R* of the apparent duration of temporal intervals between pairs of isochrones. Except for a very few cases, *R* ranges between 0.8 and 1.2, corresponding to an uncertainty of up to 20 % in the estimate of the time duration in at least one of the two ice cores. At this stage our approach does not allow us to unequivocally identify which of the models is affected by errors, but, taking into account only the historically known volcanic events, we found that discrepancies up to 200 yr appear in the last two millennia in the TALDICE-1 model, while our new age scale shows a much better agreement with the volcanic absolute horizons. Thus, we propose for the Talos Dome ice core a new age scale (covering the whole Holocene) obtained by a direct transfer, via our stratigraphic link, from the EDC modelled age scale by Lemieux-Dudon et al. (2010).

1 Introduction

A wealth of different information about palaeoclimate and paleoenvironment can be extracted from polar ice cores, and the achievement of this knowledge on past climates represents a critical step to understand future climate changes. The full potential of data achieved using polar ice cores can be exploited only with a reliable depth-to-age relation. Especially when studying the abrupt climatic transitions of the past, an accurate dating is of great importance, because the relative timing of climate changes around the globe gives indications about forcing and feedback mechanisms (Bond et al., 1993; Blunier et al., 1998, EPICA community members, 2006). Great efforts have therefore been put into developing time scales for ice cores, using either identification and counting of annual layers or modelling the depth-age relationship (Hammer et al., 1978; Andersen et al., 2006; Vinther et al., 2006; Parrenin et al., 2007a).

Past climatic events are recorded in several different paleoarchives (tree rings, speleothems, lacustrine cores, marine cores and ice cores) and a consistent dating of paleo-archives (i.e. a dating that allow us to compare the timing and the duration of events recorded in the different archives) is a prerequisite for the construction and interpretation of different climatic scenarios. Due to the complexity of this issue, in this paper we focus on two deep ice cores and on the consistency of their dating.

Published by Copernicus Publications on behalf of the European Geosciences Union.

The dating of a single ice core is carried out by several time consuming steps (e.g. measurements, modelling and synthesis) and for this reason, one strategy consists of obtaining a reference chronology for a given ice core, which is then wiggle matched to several other cores (Ruth et al., 2007; Rasmussen et al., 2008) using common paleo-events such as tephra layers (Basile et al., 2001; Narcisi et al., 2005, 2006) or volcanic sulphate spikes (Traufetter et al., 2004; Udisti et al., 2004; Severi et al., 2007; Rasmussen et al., 2008). This inter-core match has also the advantage of providing a consistent dating for multiple drilling sites, reducing the uncertainty in paleoclimatic reconstructions. In the last few years, some reference chronologies have become available for Greenland and Antarctic ice cores: the GICC05 chronology built in the framework of the Greenland Ice Core Chronology 2005 initiative, the EDC3 chronology built for the EPICA Dome C core (hereafter EDC) and TALDICE-1 modelled for the new Talos Dome ice core (Buiron et al., 2011). GICC05 is a layer counted age scale, unified for the DYE-3, GRIP and NGRIP cores (Andersen et al., 2006; Rasmussen et al., 2006; Svensson et al., 2006, 2008), which currently covers the last 60 thousand years before the year 2000 AD (kyr b2k). Conversely, EDC3 is an age scale partly built with an inverse 1-D flow model (Parrenin et al., 2007b), but local corrections were subsequently applied to correct the modelled chronology, in order to solve discrepancies with a number of stratigraphic markers such as: time markers of the orbital tuning, known volcanic eruptions, ^{10}Be and ^{14}C features etc. (see Parrenin et al., 2007a for details). Several Antarctic ice core chronologies have further been matched to EDC3. In particular, EDC3 was transferred on the EPICA Dronning Maud Land core (hereafter EDML) using common volcanic signatures (Severi et al., 2007), and this work led to the EDML1 ice chronology (Ruth et al., 2007). Aside from absolute dating, searching for common events in different cores is of high value since the difficulty of dating an ice archive is strongly related to many characteristics of the drilling locations (e.g. dome location, different accumulation rates, influence of upstream ice flow contribution). The availability of common signatures found in different cores is a useful tool that can greatly help in the construction of the new Antarctic Ice Core Chronology (AICC2012) currently in progress.

Volcanic products (mainly ash, dust, tephra particles and SO_2, rapidly oxidised to H_2SO_4) are emitted into the high stratosphere and into the troposphere during volcanic eruptions, deposited on the Earth's surface via wet and/or dry deposition and preserved in ice or sediment stratigraphies as tephra layers and/or sulphate (and as a consequence acidity and conductivity) spikes. The total volcanic deposition can greatly differ in different locations depending on geographic location, atmospheric transport pathways and the ratio between wet and dry deposition contributions (Gao et al., 2006; Wolff et al., 2005). Different methods can be used to identify volcanic signatures recorded in the ice with different degrees of specificity. Either the electrical conductivity measurement of solid ice (ECM) or the dielectric profiling (DEP) have often been used to point out volcanic signatures in ice cores, mainly because of their great advantage of being non-destructive techniques (Clausen et al., 1997; Wolff et al., 1999). Liquid conductivity as well can be used when acidity is the main contributor to the ionic load. Although more time consuming to obtain, and generally at lower depth resolution, sulphate concentrations are specific indicator for volcanic deposition on ice sheets. Sulphate stratigraphies were successfully used in the past to reconstruct paleo-volcanic time series since they are not affected by post-depositional variations (Traversi et al., 2004), except for very slow effects of diffusion (Barnes et al., 2003) or some glaciological artefact occurring exclusively in the deepest part of ice records (Traversi et al., 2009).

In this paper, we describe the synchronisation between the EDC and the Talos Dome ice cores for the last 42 kyr. More than 130 common signatures were identified and used to evaluate the consistency of the first official timescale for the Talos Dome ice core (TALDICE-1) built by Buiron et al. (2011). During the construction of the TALDICE-1 agescale, the well dated eruptions were not taken into account, so that it was possible to use them to check the reliability of the modelled time-scale and this is one of the main goal of this work. Moreover, using the historically known eruption of the last two millennia, a new age scale was produced for the last thousands years, refining the official time-scale over this period.

2 Ice coring and processing

Talos Dome (72°48′ S, 159°06′ E; 2316 m a.s.l.; 290 and 250 km from the Pacific and Ross Sea coasts, respectively) is a coastal dome in northern Victoria Land on the edge of the East Antarctic ice sheet (see map on Fig. 1). The annual mean air temperature is −41 °C and the annual snow accumulation rate is about 80 mm w.e. (http://www.taldice.org). The radio echo-sounding results showed that the bedrock of the Talos Dome summit (TDS 159°04′21″ E, 72°47′14″ S, 2318.5 m) is at about 440 m in elevation, and that it is covered by about 1880 m of ice. The dome summit is located above a bedrock slope. A relatively flat bedrock was identified at 5–6 km from summit along the SE ice divide (ID1), where the bedrock is about 770 m in elevation and covered by about 1600 of ice. At ID1, internal layering is continuous and horizontal with divergent flow, while at the dome summit internal layers follow the slope of bedrock topography (Urbini et al., 2006), as a consequence the ID1 site (159°11′ E, 72°49′ S, 2315 m) was chosen as the drilling site for the TALDICE project. The deep drilling at Talos Dome started during the 2004–2005 summer campaign and successfully reached a depth of 1620 m during the 2007–2008

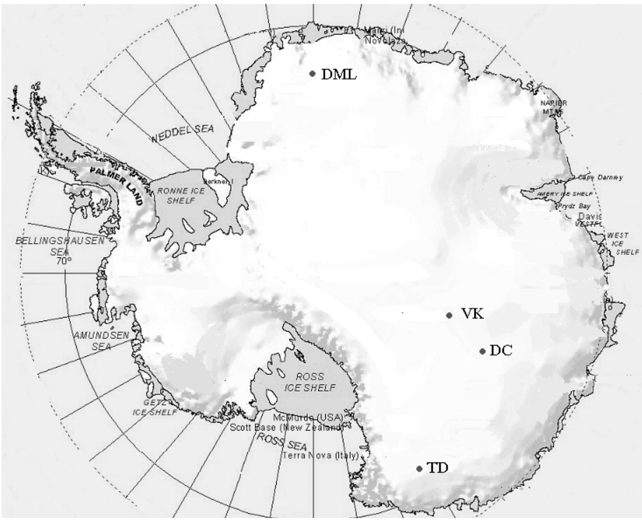

Fig. 1. Map showing the drilling site of Talos Dome (TD) together with other ice core drilling sites
(DC: Dome C, VK: Vostok; DML: Dronning Maud Land).

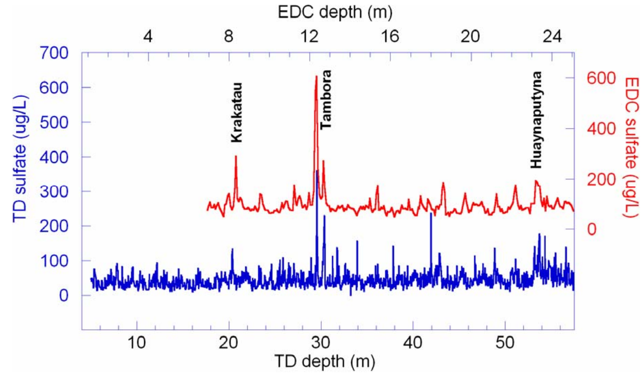

Fig. 2. Sulphate profiles of the top parts of the EDC and Talos Dome ice cores spanning the last four centuries of volcanic history recorded in Antarctic ice. Three known and well-dated volcanic events are pointed out: Krakatau (1884 AD), Tambora (1815 AD) and Huaynaputyna (1600 AD).

season. The first 5 m of Talos Dome ice core were not sampled but the search for volcanic signatures in this part of the core was previously carried out by Severi et al. (2009) pointing out the Pinatubo eruption (1991 AD) in a 6 m deep snow pit dug one year before the beginning of the TALDICE drilling.

Drilling operations in Dome C began in 1996/1997 and reached a depth of 788 m (where the drill got stuck) in the 1998–1999 season retrieving a core named EDC96 spanning about 45 kyr. The first 100 m of EDC96 were not suitable for chemical measurements and analysis was performed on a firn core named FIRETRACC, drilled a few hundreds of meters away. A new core was drilled from the surface (EDC99) and reached a depth of 3260 m in January 2005, covering a period of more than 800 kyr (EPICA community members, 2004; Jouzel et al., 2007; Wolff et al., 2010).

Both EDC and TALDICE ice cores have been processed and analysed by FIC (Fast Ion Chromatography) (Traversi et al., 2002), over the complete depth range, but sulphate data for TALDICE are at the moment available only for the first 1100 m (corresponding to about 42 kyr BP), while older ice is still undergoing post-analysis processing. The upper part of the Talos Dome ice core (down to 73 m) was not suitable for FIC measurement because of the firn porosity. This part of the record was decontaminated by hand using a microtome blade and analysed using classical ion chromatographic methods with a mean depth resolution of 3.5 cm (Morganti et al., 2007).

3 Volcanic matching

The volcanic synchronisation started from about 5.0 m depth of the Talos dome ice core, comparing this record to the EDC96. The search for common volcanic horizons in the uppermost 5 m of the Talos Dome ice core was carried on using data from the 2003–2004 snow pit analysed by Severi et al. (2009). The matching procedure is based on a first identification of major spikes followed by the recognition of common minor eruptions. Thus, common volcanic signals were not identified by chemical signature but by pattern matching of peculiar features of volcanic peaks. Figure 2 shows the very first common volcanic signatures found spanning back to 430 yr BP. In this section of the two records, we can find three historically known events: the eruption of Krakatau (1883 AD), the double peak due to the eruption of Tambora (1815 AD) and an unknown volcano that erupted 5–6 yr earlier; the last common signal highlighted in Fig. 2 can be ascribed to the eruption of Huaynaputina (1600 AD). Such historically known volcanic signatures have often been used as temporal absolute horizons in dating polar ice cores drilled both in Antarctica and in Greenland (Langway et al., 1995; Udisti et al., 2000; Parrenin et al., 2007a; Severi et al., 2007).

Figure 3 shows the sulphate profiles in the time range spanning from 550 to 980 yr BP. In this section of the two ice cores, many sulphate peaks easily detectable in both cores are recorded. The first common signature was ascribed to the eruption of the submarine volcano Kuwae (1452 AD), which is reported to be one of the largest sulphate deposition events of the past 700 yr (Gao et al., 2006). This volcanic horizon is very important in the synchronisation of time series, because it is a bipolar signature found in several Antarctic and Greenland ice cores. In the same figure other volcanic spikes are visible; among these signatures, the highest one is the 1259 AD eruption. This large sulphate signal is found in

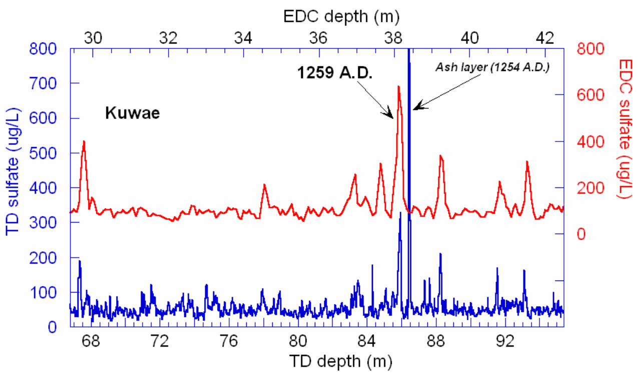

Fig. 3. Sulphate profiles of the EDC and Talos Dome ice cores covering the period between 1450 AD and 1130 AD. The historically known eruption of Kuwae (1453 AD) and the 1259 AD eruption of an unknown volcano are highlighted by arrows in the plot. An ash layer was found in the TD ice core together with a sharp high sulphate peak (1254 AD according to Narcisi et al., 2001).

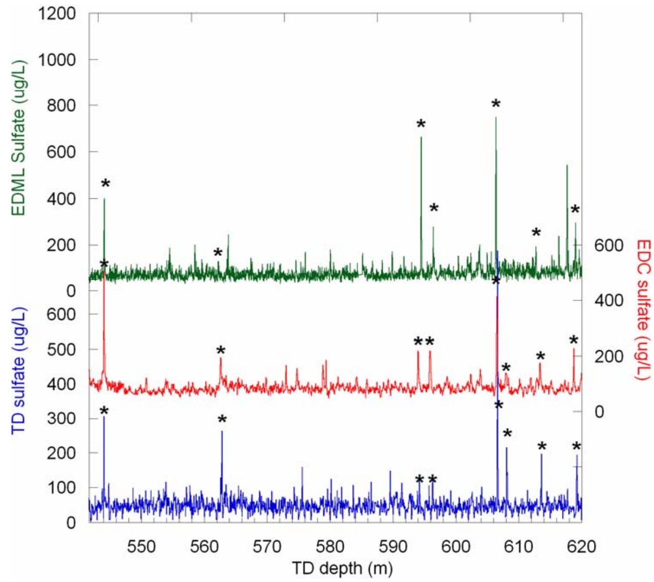

Fig. 4. Synchronisation of the Talos Dome, EDML and EDC cores in the time period between 8.5 and 10.4 kyr BP. The three records show a low background "noise" and several common volcanic spikes are clearly visible. Events marked with * have been used to build the stratigraphic link between the EDC and the TD ice cores.

most of the Greenland and Antarctica ice cores and is an important interhemispheric reference horizon for ice core dating. In this case, the eruption site is unknown but is probably close to the equator (Langway et al., 1988); a Mexican eruption site (El Chichón) was suggested by Palais et al. (1992). Figure 3 shows also a strong and sharp sulphate signal in the Talos Dome profile without a corresponding peak in the EDC core. A possible explanation for this signature is a local source in the Talos Dome area; in fact, at the same depth, a visible ash layer was found, confirming the short distance between the Talos Dome drilling site and the volcanic source. This ash layer was also found in a previous ice core drilled in this area and Narcisi et al. (2001) dated the eruption 1254 ± 2 AD and made the hypothesis of the Pleiades or Mount Rittmann (both in the Melbourne volcanic province) as its source.

Figure 4 shows the synchronisation of the two cores in the time period between 8.5 and 10.4 kyr BP (corresponding to the depth interval 541.7–620.0 m of the Talos Dome ice core and 269.0–322.0 m of the EDC96). In the same plot, the FIC sulphate profile of the EDML record is also shown, as an example of the great effectiveness of sulphate volcanic signatures to synchronise records achieved in several sites. In the three records the background "noise" is relatively low and a large number of volcanic spikes can be easily detected at the three sites, pointing out the wide range deposition of volcanic aerosols over the whole Antarctic ice sheet.

Figure 5 shows the volcanic comparison during the transition from LGM to the Holocene, a period characterized by strong climatic changes (as shown in the δ^{18}O profile), with fast changes in the accumulation rate (Stenni et al., 2011). Only a few common signals (marked with *) between EDC96 and Talos Dome ice cores can be unambiguously detected between 11.5 and 13.2 kyr, especially in the EDC96 record, which shows a very stable background concentration

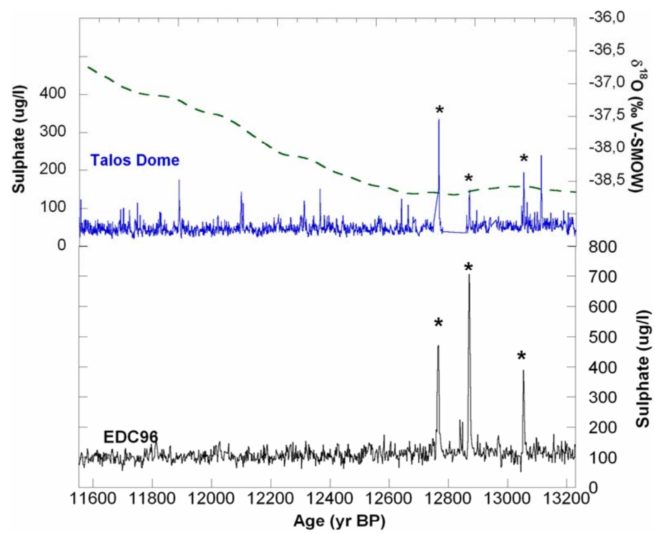

Fig. 5. Synchronised sulphate profiles of the EPICA-DC and Talos Dome records during the transition from LGM to the Holocene. Few common volcanic signals are detected. Three major eruptions (marked with *) are shown at the start of the transition and they represent a useful horizon for the synchronisation in this section. The TD δ^{18}O smoothed profile (green dashed line) is also shown in order to highlight the significant climatic change in this part of the comparison (from 11.5 to 13.2 kyr BP).

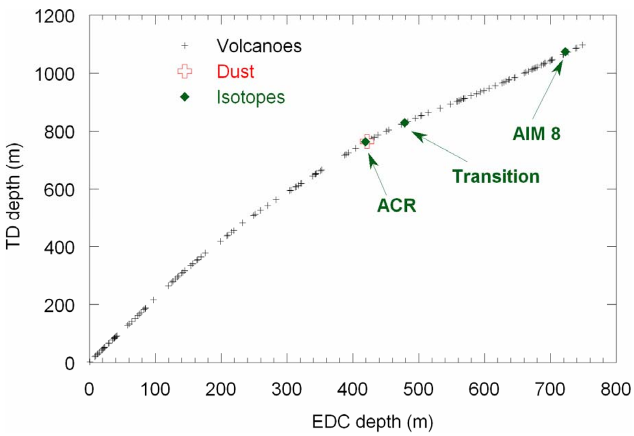

Fig. 6. Depth-to-depth relationship of the common volcanic events detected in the two ice cores and pairs of synchronous events identified using other parameters (isotopes and dust).

of sulphate with only three volcanic spikes superimposed to this background. This sequence of three volcanic eruptions has been found also in the Vostok (Udisti et al., 2004) and EDML (Severi et al., 2007) ice cores and proved to be a very useful marker to synchronise different records during this time interval, which is a crucial one due to the large climatic changes occurring all over the Earth. Following this method, other 59 tie points were found between 13.2 and 42 kyr BP.

4 Depth-to-depth relationship

A total of 132 common volcanic events (see Supplement) was found in the 42 kyr dataset analysed in this work. The depth-to-depth relationship between pairs of isochrones is plotted in Fig. 6. In order to verify the consistency of sulphate profile by the mean of different records (dust and stable isotopes), a few pairs of non-volcanic synchronous events are also plotted in the same depth-to-depth graph and they show a good consistency with the curve obtained with volcanoes. The non-volcanic events reported in Fig. 6 consist of: a clearly identified common feature in the dust profiles (Stenni et al., 2011) and three features of the isotopic profiles (onset of Antarctic Cold Reversal, onset of Antarctic Isotope Maximum 8 (EPICA community members, 2006) and an onset of the transition from LGM to Holocene (Stenni et al., 2011). The dust concentration record from TALDICE (Delmonte et al., 2010) shows a clear decrease from high LGM to low Holocene values, similar to records from other ice cores on the East Antarctic Plateau (Delmonte et al., 2002). At Talos Dome, the dust concentration decrease is very sharp and its minimum is found at around 765 m depth. The same feature can be observed in the EDC ice core, where the end of this dust decrease is located around 421 m depth (Stenni et al., 2011). While volcanic deposition of sulphate are surely synchronous, it is not self-evident that these four additional events must be synchronous at the two drilling sites, but they are reported here to support the consistency of our volcanic match.

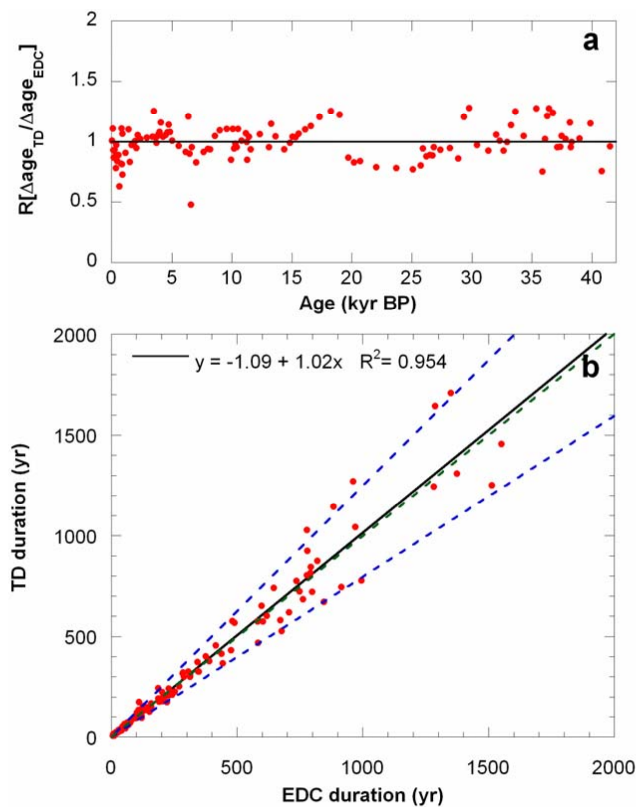

Fig. 7. The top panel **(a)** shows the ratio Age diff.$_{EDC}$/Age diff.$_{TALDICE}$ (R) between couples of volcanic events dated using EDC dating by Lemieux-Dudon et al. (2010) and the TALDICE-1 model by Buiron et al. (2011). The bottom panel **(b)** shows the durations between two consecutive synchronisation markers in TD compared to durations in EDC. The bold black line is the linear regression line; the bold dashed green line is the 1:1 curve. Dashed blue lines represent the 1:0.8 and 0.8:1 lines.

5 Consistency of the TALDICE and EDC dating models

The modelling of the age-scales at the two sites led to the construction of two independent chronologies, which have been compared in this paper. A new dating method based on inverse techniques had been recently developed (Lemieux-Dudon et al., 2009) and was applied to both ice cores (Lemieux-Dudon et al., 2010; Buiron et al., 2011). This method requires background scenarios for the accumulation rate, the thinning function, the close-off-depth and the difference of depth for a given age between the trapped gas and the ice matrix. These preliminary scenarios are provided by simulations (ice flow and snow densification modelling) and are improved with absolute age markers. The reliability of this

Table 1. List of the historically known volcanic events occurred in the last two millennia and recorded in the TD ice core. The corresponding depths and years of the deposition are listed. For both age scales (TALDICE-1 and the new one proposed in this work) the calculated deposition year and age offset are reported in the table.

TD depth (m)	Volcano	Year of deposition (AD)	TALDICE-1 Buiron et al. (2011)		EDC age tranfer from Lemieux-Dudon et al. (2010) (this work)	
			Age (yr AD)	Age offset	Age (yr AD)	Age offset
2.75	Pinatubo	1992 [a]	1992	0	1995	3
20.37	Krakatau	1885 [c]	1889	4	1892	7
29.56	Tambora	1816 [a,b,c]	1813	−3	1817	1
30.37	Unknown 1809	1810 [b,c]	1806	−4	1811	1
42.86	Serua	1695 [c]	1684	−11	1697	2
48.82	Awu; Decept. Is.	1643 [c]	1622	−21	1642	−1
53.20	Huaynaputina	1603 [c]	1573	−30	1599	−4
67.36	Kuwae	1453 [b,c]	1396	−57	1450	−3
85.94	El Chichón	1259 [a,c]	1135	−124	1257	−2
144.88	Rabaul; Krakatau	536 [d,e]	361	−175	559	23
172.33	Taupo	186 [b,d]	−12	−198	191	5

[a] Castellano et al., 2005; [b] Traufetter et al., 2004; [c] Stenni et al., 2002; [d] Cole-Dai et al., 2000; [e] Vinther et al., 2006.

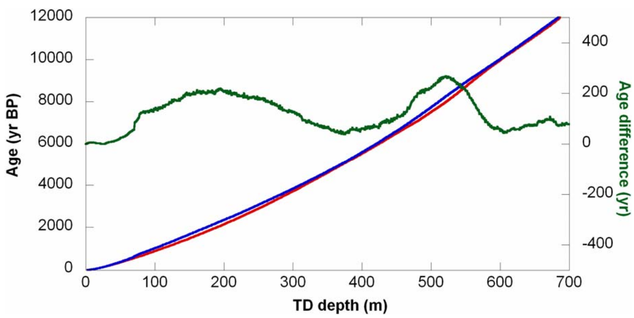

Fig. 8. Age-to-depth plot for the TD ice core. The blue curve represents the TALDICE-1 modelled age scale and the red curve represents the new age-to-depth relation built in this work. Green curve represents the age offset between the two age-scales.

method has already been illustrated by improving the consistency between EPICA Dome C (EDC), EPICA Dronning Maud Land (EDML), and NorthGRIP age scales (Lemieux-Dudon et al., 2010) over the last 50 kyr.

The volcanic match between EDC and TALDICE records carried out in this work represents a good tool to test the consistency of the two dating models. Indeed, this consistency can be estimated by calculating the ratio R (Age diff.$_{\text{EDC}}$/Age diff.$_{\text{TALDICE}}$) (Parrenin et al., 2007a) of the time duration of the intervals between two consecutive volcanic markers in the modelled EDC (Lemieux-Dudon et al., 2010) and TALDICE-1 age scales. If R equals 1.0 in a certain time period, that means the duration between two isochrones is the same in the EDC and TALDICE ice cores for the modelled age scales. In periods when R is greater than 1.0 the duration estimate is larger at Dome C than at TALDICE and vice-versa. The deviations pointed out by our volcanic matching cannot be unequivocally ascribed to any of the parameters involved in the modelling (i.e. accumulation rate and thinning ratio at the two sites), but we can just state that these deviations arise from a combination of the errors in the evaluation of these parameters. One key contribution to the uncertainty might be the accumulation rates estimated using the stable isotope data (Stenni et al., 2010), which are used as input in glaciological models, as well as elevation changes taking place during the deglaciation and the beginning of the Holocene in the Talos Dome area (Stenni et al., 2011). The top panel of Fig. 7 shows the deviations of R from the theoretical value of 1.0 during the last 42 kyr; the mean value of R in the whole period is 0.999 with a standard deviation of 0.16. The bottom panel of Fig. 7 compares the durations of the time intervals between pairs of consecutive eruptions in TALDICE and EDC cores. The slope of the linear regression (black solid line) is 1.02 and the regression coefficient (R^2) is 0.954; this means that the Dome C and Talos Dome age scales are consistent, generally within 20 % for each duration between two consecutive time markers. It should be noted that differences depicted on this figure may either reflect a real difference in the age scales, or an error in the volcanic synchronisation process, even though the latter seems to be unlikely.

6 Improving the dating of the Holocene

During the construction of the TALDICE-1 age scale, Buiron et al. (2011) did not include in their model any temporal horizon such as known volcanic eruptions for the last thousands years; thus the accuracy of the dating in this time period is questionable. The volcanic signatures identified in this work have been used to evaluate the goodness of the modelled chronology in the last 2 kyr. Table 1 shows a list of historically known volcanic events detected in both TD and EDC ice cores. Among these volcanic signatures, all the eruptions younger than 1259 AD are historically known and their uncertainties are included within few years. The volcanic peak corresponding to the date 536 AD was chosen following the results of the dating effort carried out by Vinther et al. (2006) via annual layers counting of three Greenlandic ice cores (Larsen et al., 2008), even if slightly different ages have been proposed by Traufetter et al. (2004) and by Baillie (2008). The oldest volcanic signal used to check the dating is the Taupo (New Zealand) eruption dated 186 AD according to Cole-Dai et al. (2000) and Traufetter et al. (2004). For every eruption we report in Table 1: (a) the dating obtained calculating the age using the TALDICE-1 age scale and (b) the dating of the same event in the EDC core using the model by Lemieux-Dudon et al. (2010). The years of deposition of volcanic eruptions used in Table 1 have been taken from several works (Stenni et al., 2002; Castellano et al., 2005; Traufetter et al., 2004; Ruth et al., 2007). Age offset up to 200 yr appear in the TALDICE-1 age scale and, although these differences are included within the uncertainty of the modelled age, the need for a refined age scale for the more recent part of the TALDICE ice core is evident. In this paper we propose a new dating for the whole Holocene obtained by a direct age transfer from the Lemieux-Dudon et al. (2010) dating via the stratigraphic link established between Talos Dome and EDC. This new age scale shows a much better agreement with the volcanic horizons, giving a maximum age offset of 23 yr for the 536 AD eruption (see Table 1). In Fig. 8, our new dating is plotted together with the official TALDICE-1 in order to highlight the age offset all along the Holocene. As shown in Fig. 8, the age offset between our age scale and the TALDICE-1 increases up to 200 yr from the surface to about 200 m depth (corresponding to ca. 2.3 kyr BP); between 200 m and 400 m, the age offset decreases and reaches values of about 50 yr. The maximum offset during the Holocene is 315 yr in the depth range between 520 and 535 m, corresponding to about 8.0–8.5 kyr BP.

7 Conclusions

More than 130 volcanic isochrones have been detected in the EDC and TALDICE ice cores during the last 42 kyr. These common signatures have been used in this paper to highlight some inconsistencies in the modelling of past accumulation rates and thinning functions at the two drilling sites. Indeed, the ratio Age $\text{diff.}_{\text{EDC}}$/Age $\text{diff.}_{\text{TALDICE}}$ (R) between pairs of consecutive common eruptions has been used as a tool to point out that the two chronologies are generally consistent within 20 %. In particular, our volcanic matching has pointed out age offset up to 200 yr with the official TALDICE-1 age scale (Buiron et al., 2011) during the last 2 kyr, and for this reason a direct age transfer from EDC age model (Lemieux-Dudon et al., 2010) to TALDICE ice core using our stratigraphic link was accomplished for the last 12 kyr. Thus, a new age scale covering the whole Holocene is proposed (see Supplement) for the Talos Dome ice core in order to allow a reliable comparison at sub-millennial or centennial scale of environmental and climatic markers recorded in the EDC and Talos Dome ice cores.

Supplementary material related to this article is available online at: http://www.clim-past.net/8/509/2012/cp-8-509-2012-supplement.zip.

Acknowledgements. We thank the logistic and drilling TALDICE team. The Talos Dome Ice Core Project (TALDICE), a joint European programme led by Italy, is funded by national contributions from Italy, France, Germany, Switzerland and the United Kingdom. The main logistical support was provided by Programma Nazionale di Ricerche in Antartide (PNRA) at Talos Dome.

This work is also a contribution to the ESF HOLOCLIP project. The HOLOCLIP Project, a joint research project of ESF PolarCLIMATE programme, is funded by national contributions from Italy, France, Germany, Spain, Netherlands, Belgium and the United Kingdom. In Italy HOLOCLIP is funded by PNRA This is TALDICE publication no. 16, and HOLOCLIP publication no. 5.

Edited by: F. Parrenin

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