Linking pollen deposition, snow accumulation and isotopic composition on the Alto dell'Ortles glacier (South Tyrol, Italy) for sub-seasonal dating of a firn temperate core

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20 **Abstract.** Dating of ice cores from temperate non-polar glaciers is challenging and often problematic. Yet, a proper timescale is essential for a correct interpretation of the proxies measured in the cores. Here, we introduce a new method developed to obtain a sub-seasonal timescale relying on statistically measured similarities between pollen spectra obtained from core samples, and daily airborne pollen monitoring samples collected in the same area. This approach was developed on a 10 m core retrieved from the temperate firn portion of Alto dell'Ortles glacier (Eastern Italian Alps), for which a five-year
25 annual/seasonal timescale already exists. The aim was to considerably improve this timescale, reaching the highest possible temporal resolution, and testing the efficiency and limits of pollen as a chronological tool. A test of the new timescale was performed by comparing our results to the output (date of layer formation) of the mass balance model EISModel, during the period encompassed by the timescale. The correspondence of the results supports the new sub-seasonal timescale based on pollen analysis. This comparison also allows to draw important conclusions on the post depositional effects of meltwater
30 percolation on the pollen content of the firn core, as well as on the climatic interpretation of the pollen signal. Finally, we provide an example of useful application of the timescale related to the direct comparison of measured meteorological parameters and the stable isotopes composition of the core.

Keywords: cryopalynology, ice core, chronology, paleoclimatology

35 **1.   Introduction**

Ice core dating is crucial for the interpretation of the paleo-climatic and paleo-environmental proxies contained in glacial archives. When combined with the detection of absolute temporal horizons, annual layer counting is the most accurate technique to date ice cores (Thompson et al., 2013). However, low snow accumulation and/or post-deposition effects (e.g.

meltwater percolation) hamper the detection of annual layers, especially in temperate glaciers where annual signals are most often smoothed (Eichler et al., 2001). In addition, no proxies had so far a level of temporal precision that allows studying past seasonal changes in detail, while a sub-seasonal temporal resolution would be desirable to reconstruct these changes in detail. Several studies conducted on glaciers worldwide have proven that pollen (Nakazawa et al., 2011, 2005, 2004; Santibañez et

5   al., 2008; Uetake et al., 2006) and stable isotopes (Gabrielli et al., 2008; Haeberli et al., 1983; Thompson, 1980; Dansgaard, 1964; Vareschi, 1934) are valuable proxies to detect seasonality in ice cores. However, annual layer counting from oxygen and hydrogen isotopes ratios is a far more common chronological tool than the palynological approach, the potential of which remains largely unexplored. The reason for the scares use of cryopalynology has functional and conceptual basis. The main issue is that pollen analyses requires a minimum ice sample size of up to 1 L (e.g., Burogois, 2000), which is problematic to

10   obtain because sample volume from ice cores is very limited, especially when working at high resolution. Yet, studies from the Altai (Nakazawa et al., 2011, 2005 and 2004) and the European Alps (Festi et al., 2015; Bortenschlager, 1970a and b; Vareschi et al., 1934) suggest that this is still a limit for clean samples obtained from polar ice caps, whereas in low and middle latitude glaciers, the minimum sample size can be reduced to 10-30 mL (Festi et al., 2015; Nakazawa et al., 2011 and 2005), thanks to the proximity of the source vegetation and the consequent much greater pollen deposition. An additional limit is that

15   pollen analyses are time-consuming and work-intensive, because they imply manual identification and quantification of pollen grains. In order to overcome this latter issue Nakazawa et al., (2011, 2005 and 2004) adopted a simplified approach, focusing on three main taxa (Pinaceae, Betulaceae and *Artemisia*) that are representative of the three corresponding flowering seasons (spring, early summer, late summer). By doing so, they were able to detect seasonal changes in ice cores from the Altai (Nakazawa et al., 2012, 2006 and 2005). Finally, there is little knowledge about the effects of percolating water on the

20   palynological signal and only two studies directly addressed this issue, obtaining contrasting results (Ewing et al., 2014; Nakazawa and Suzuki, 2008).

In Festi et al. (2015) we developed an efficient method to detect seasonality employing a 10 m shallow core extracted in 2009 from the Alto dell'Ortles glacier (South Tyrol, Italy) (Fig. 1) and we improved the existing timescale based on the isotopic composition of the core (Gabrielli et al., 2010). In Festi et al. (2015) we conducted accurate taxonomical identification and

25   implemented a statistical approach consisting in performing a principal component analysis (PCA) on pollen concentration values, and extracting the three principal components (PC) indicative of the three flowering seasons. As each PC summarizes the seasonal information of the pollen assemblage, score values of PC indicate seasonal/annual patterns and enable the identification of seasonal and annual firn layers (Fig.2 a). In Festi et al. (2015) we also discussed that the main pollen input on the glacier likely comes from the near valleys, as the pollen spectra from the ice samples and from valley floor at Solda's

30   monitoring station (Fig. 1) are very similar.

The present study uses the palynological data discussed in Festi et al. (2015) to develop a new refined and innovative pollen-based method to date ice core samples at a sub-seasonal resolution. The aim was to improve the chronology enhancing resolution, dating efficiency, coherence of seasonal patterns. Combined with mass balance modelling the new high resolution results also provide new insights into the processes controlling the formation and preservation of the palynological signal in

35   firn and ice. Finally, we give an example on the potential application of the new pollen based timescale by applying it to the isotopic composition of the core, hereby performing a direct comparison between meteorological parameters (i.e. temperature) and isotopes measured in the core, allowing to gain a new insight on the processes of formation of the isotopic signal.

2.   Study site

40   The Alto dell'Ortles is the highest glacier of South Tyrol (Italy) in the Eastern European Alps (46° 30' 32'' N, 10° 32' 41'' E) (Fig. 1), ranging in altitude between 3018 and 3905 m a.s.l. and covering an area of 1.07 km². The maximum glacier thickness is about 75 m (Gabrielli et al., 2012) and encompasses the last ~ 7 kyr (Gabrielli et al., 2016). In its upper part the glacier is

polythermal, with temperate firn and cold ice underneath (Gabrielli et al., 2012). The local climate is dry and continental, characterized by a mean annual precipitation of 800-950 mm y^{-1} at the valley floor in Solda (Adler, 2015). This study focuses on the uppermost 10 meters of firn accumulated on the glacier from spring 2005 to June 2009, that have been retrieved using a lightweight hand auger at 3830 m a.s.l.. Our previous research (Festi et al., 2015; Gabrielli et al., 2010), proved that the

5   seasonal/annual signature of pollen and stable isotopes is well preserved in these shallow firn layers. Figure 2(a) shows the formerly published timescale (Festi et al., 2015), which is based on the palynological analyses of 103 continuous ~10 cm samples along the core.

In this study, we also use air temperature data recorded by a standalone data logger placed on the Mt. Ortles at 3835 m a.s.l., as well as meteorological (air temperature and precipitation) and airborne pollen data collected at the meteorological station

10   of Solda (Festi et al., 2015). The station is located 4.5 km northeast of the Mt. Ortles at an altitude of 1850 m a.s.l. (Fig. 1).

3.   Methods

This section describes i) the novel pollen-based method "from depth-to-day" developed to obtain a high resolution timescale for the 2009 Mt. Ortles shallow firn core, and ii) the approach used to obtain a core layer dating by using a mass balance model

15   (EISModel), which serves as a comparison for the newly developed palynological timescale.

3.1.   High resolution pollen-based timescale: the depth-to-day method

Details on the composition of the Mt. Ortles and Solda's pollen assemblages are reported in Festi et al. (2015). Here, we use these data to develop an enhanced resolved chronology at sub-seasonal timescale. The extensive pollen analyses carried out on the 103 samples obtained from the 10 m core provide a high diversity of 64 pollen types, including the main pollen types

20   characterizing the forest vegetation in the region (e.g., *Pinus* sp., *Picea*, *Fagus*, *Corylus*, *Betula*, *Fraxinus*, *Quercus*), as well as herbs (e.g. Poaceae, Chenopodiaceae, Asteraceae, Cannabaceae). The Ortles pollen assemblages proved to be representative for the regional vegetation, and to be comparable with airborne assemblages recorded at the Solda aerobiological station during the years 2008 to 2010. Solda's airborne pollen data provided crucial daily information about the timing of local flowering of different plant taxa and of the daily changes in airborne pollen concentration for the years 2008 to 2010. Every plant in the

25   region releases pollen during a certain period of the calendar year, and this is repeated on an annual cycle. However, the onset of flowering may differ by several days (1 to 7 depending on the species; Festi et al., 2015) from year to year, due to different weather conditions.

Solda's airborne pollen samples are characterized by their specific pollen content on a specific day of the year (DOY), while each of the 10 cm sequential Mt. Ortles samples is characterized by its pollen assemblage at a specific depth in the firn core.

30   The three-year palynological dataset of the Solda's aerobiological station has been considered as a representative calibration data-set to define the flowering DOY for in the entire period covered by the 10 m Ortles firn core (2005 to 2009). For every 10 cm sequential Mt. Ortles sample, the three Solda's airborne samples with the highest similarity (one per each year of the three years Solda dataset) were selected, using the Jaccard similarity index (Jaccard, 1901). This index was chosen because it is asymmetrical and hence avoids the double zero problem, i.e. it excludes similarity in case of absence of a pollen type from

35   pairs of compared samples. The Jaccard similarity index was calculated with the SPSS software obtaining a matrix of similarity indices. Indices typically presented values scaled from zero to one: the higher the value, the greater the similarity between two samples. The lower boundary for the Jaccard index was set at 0.5 to ensure high similarity and avoid possible mismatches. Three potential DOYs were obtained for every Mt. Ortles sample. For each sample, the average DOY and uncertainty (one sigma) have been calculated (Table 1, Fig. 2 (b)). Mt. Ortles samples having pollen concentrations reflecting "winter" season

(<0.5 grains ml^{-1},) were excluded from the analyses, as Solda's airborne station observes only pollen distributions during the vegetation period (March - October).

In summary, by coupling the Mt. Ortles firn samples with the most statistically similar assemblage of the Solda's airborne samples, we establish a link between pollen deposition at a specific sample depth on Alto dell'Ortles and a specific DOY. This "space-for-time" substitution (depth-to-day) by pollen is the key concept of the new dating technique developed. This method is based on the assumption that there is no time lag between the flowering in Solda and the pollen deposition on the glacier, thanks to the efficient uplift of pollen grains by thermic wind (Barry and Chorley, 2009). Depth values were converted to water equivalent values to enable comparison with EISModel results, using a polynomial function fitted to the 2009 firn core density sampled at 10 cm depth intervals.

3.2. EISModel

Here we briefly describe the essential parts of the mass balance model used in this study (Carturan et al., 2012a). The cumulated mass balance from 2005 to 2009 at the coring site was calculated using EISModel (Carturan et al., 2012a; Cazorzi and Dalla Fontana, 1996). Before being included in the model, the raw meteorological data recorded on Mt. Ortles and at Solda, were checked and validated against other meteorological weather stations located in the proximity of Mt. Ortles (Madriccio at 2825 m and Cima Beltovo at 3328 m). The precipitation data recorded at Solda were corrected for gauge undercatch errors, using the procedure described in Carturan et al. (2012b).

The mass balance model simulates accumulation and melt processes at hourly time steps. Snow accumulation was calculated from the precipitation data recorded at Solda, extrapolated to the elevation of the study site using a Precipitation Linear Increase Factor *PLIF* (% km^{-1}), to account for the increase of precipitation with altitude. Combining Solda's precipitation with measurements of snow water equivalent performed in the area of Madriccio weather station at the end of winter 2013 and 2014, at an altitude of 2700-2800 m (Carturan L., unpublished data), has enabled the calculation of an average *PLIF* of 50% km^{-1}, which was assumed to be valid also for the period 2005-2009. Effects from preferential snow deposition, sumblimation and erosion by wind were not taken into account in extrapolating precipitations at the core site, assuming they compensate each other. In absence of direct observations, this is a reasonable assumption and its possible effects are discussed further on in the paper. Internal accumulation due to refreezing of percolating water was not calculated because it is negligible in temperate-firn layers (March and Trabant, 1997; Cogley at al., 2011; Zemp et al., 2013)

Ablation was calculated by means of an enhanced temperature-index approach, using the clear-sky shortwave radiation computed from a Digital Elevation Model (LiDAR survey of 2005, provided by the Province of Bolzano) as a distributed morpho-energetic index (Carturan et al., 2012a). The melt rate MLT_t (mm h^{-1}) was calculated for each hour (t) as follows:

$$MLT_t = RTMF \cdot CSR_t(1 - \alpha_t) \cdot T_t \tag{1}$$

where T_t (°C) is the air temperature, CSR_t (W m^{-2}) is the clear sky shortwave radiation and α_t is the surface albedo (calculated in function of T_t, Carturan et al., 2012a). *RTMF* is a calibration coefficient called Radiation-Temperature Melt Factor (mm h^{-1}°C^{-1}W^{-1} m^2). The T_t at the study site was calculated from the air temperature measured at Solda, applying a monthly-variable lapse rate ranging from -4.6°C km^{-1} in November to -6.8°C km^{-1} in July (mean value = -5.9°C km^{-1}), as calculated between Solda and the air temperature logger placed at the core site at 3835 m on Alto dell'Ortles in the period from October 2011 to May 2014. The RTMF value was obtained by using mass balance measurements (snow depth soundings and density measurements in snow pits) carried out at the core site on June 12 and August 31, 2009.

For each snow layer deposited (i.e. the water equivalent that accumulates at the surface of the snowpack during an hourly time step), the model provides its time and date of formation as well as the air temperature during its deposition.

4. Results

4.1. Pollen based timescale

Results of depth-to-day match of firn and Solda's samples are shown in Table 1 and Fig. 2(b). Dates cluster in 5 groups representing 5 vegetation periods, in agreement with the principal component method (Fig. 2(a); Festi et al., 2015), but often

5 providing a better coherence of seasonal and chronological patterns. Dates are distributed in chronological order within each year, with only minor inversions generally included within the error bars of adjacent samples.

The deepest samples of the Mt. Ortles firn core (Fig. 2) represent the flowering (warm) seasons of 2005. The salient feature of this year is its low thickness (12 cm w.e.; 30 cm depth), as it is represented by only three samples (0, 7 and 12 cm w.e.). The bottommost sample (0 cm w.e.) has been pollen-dated to April 25±17 days, and shows high values of the spring component.

10 The sample at 7 cm w.e. is characterized by a simultaneous peak of early summer, spring and late summer components and dates May 16 ± 8 days. The last sample of 2005 is at 12 cm w.e. and is characterized by early and late summer component positive values, corresponding to June 23±23 days. For the warm season 2005 the new method is clearly more efficient in providing a clear and detailed seasonal timescale in comparison to the component method (Festi el al., 2015), where the overlapping of component makes interpretation problematic. Winter 2005/2006 is assumed to be represented by a thick firn

15 layer (60 cm w.e.; 100 cm), basically free of pollen (mean concentration of 0.09 pollen mL^{-1}).

The year 2006 is also represented by a layer with a low thickness (34 cm w.e.; 63 cm depth), corresponding to eight samples, five of which could be assigned to a DOY (Fig. 2(b)). The sample at 72 cm w.e. corresponds to March 11±10 days, accordingly to the small peak in spring component. The overlaying sample at 78 cm w.e. was dated to June 1±15 days. In contrast, the sample at 80 cm w.e. shows the overlapping of all components and is assigned to May 18±7 days. Sample 85 cm w.e.

20 corresponds to May 15±6 and is characterized by the superimposition of spring and late summer components, while the last dated sample of 2006 is at 106 cm w.e., and corresponds to June 14 ± 8 days. Also in the case of 2006 the new method is more efficient in detecting subseasonal and seasonal variations in the pollen spectra. The 2006/2007 nearly pollen-free winter layer is assumed to be composed by 87 cm of firn (44 cm w.e.), with a mean concentration of 0.1 pollen mL^{-1}.

The year 2007 shows a clear chronological order in the dates , starting with the sample at 150 cm w.e., which dates to May

25 15±9 days and is characterized by the spring component. Samples from 160 to 175 cm w.e. refer to May 18±14, 18±7, 26±0 and 21±19, respectively. These samples together represent a peak in spring and early summer components. Samples from 192 to 211 cm w.e. reflect two early summer peaks: the first is dated between June 12±9 and June 9±3, and the second between July 11±2 and July 19±10. The sample at 211 cm w.e. represents the end of the early summer peak and dates July 30±0. August 30±13 is the end date of the flowering year 2007, in agreement with the peak in the late summer component at 226 cm w.e..

30 Also in 2007 the succession of dates provides a more straightforward timescale than the components do. Winter 2007/2008 is assumed to be represented by a 70 cm thick firn layer (33 cm w.e.) with very low pollen content (0.2 pollen mL^{-1}).

The year 2008 shows a very clear seasonal configuration with both methods. According to the samples at 259 and 263 cm w.e., the peak in spring component is dated from May 15±8 to May 19±7. This major peak is followed by a lower peak in early summer and spring components, dated between May 28±8 and May 30±7. A major increase in the early summer component

35 follows, from 296 to 305 cm w.e., which is dated between June 5±7 and 25±30. Finally, two peaks in the late summer component, dated between June 21±27 and August 13±7, indicate the end of the flowering season. Winter 2008/2009 is assumed to correspond to a 225 cm thick firn layer (91 cm w.e.) with very low pollen concentration (0.3 pollen mL^{-1}).

The sample at 415 cm w.e. represents the onset of the flowering season of 2009 and is dated at April 14±14. The spring component peak ends on May 15±12, with the sample at 427 cm w.e. This is followed by the overlapping peaks in spring and

40 early summer components encompassing the timespan between April 27±14 (at 434 cm w.e.) and June 18±16 in the uppermost samples. We note that the surface date is in good agreement with the fact that the core was retrieved on the 12th of June 2009.

In summary, the day-to-depth method significantly improved the timescale by Festi et al. (2015), proving a clear and intuitive representation of the chronological succession. Furthermore, we observe a substantial difference in the pollen dispersal, not only between winter and flowering seasons, but also among different years. Winters are always represented by thick firn layers containing nearly no pollen, while flowering seasons correspond to thinner or thicker layers with high pollen concentration.

5 Flowering seasons cluster in two groups: 2005 and 2006 vs. 2007, 2008 and 2009, according to their thickness and distribution of pollen content. In particular, while the 2007 and 2008 flowering seasons correspond to very thick firn layers (respectively 76 and 65 cm w.e.), along which pollen is distributed with a clear seasonal pattern, the 2005 and 2006 flowering seasons are clearly different as they both show: i) a significantly lower thickness; ii) a thin lower layer with a distinct spring pollen content, and iii) a thin upper layer containing mixed spring/summer pollen.

10 ### 4.2. EISModel ouput

The cumulated mass balance simulated by the model shows high variability of accumulation and melt rates during the period from 2005 to 2009 (Fig. 3). In particular, there is a strong difference between the first two years (2005 and 2006), during which snow accumulation mostly occurred in late summer after weeks with high ablation, and the last three years (from 2007 to 2009), characterized by higher accumulation rates and a much lower summer ablation. In 2005, the ablation removed snow

15 layers accumulated between the 9th April and the 31st of July. The same happened in 2006 to the snow layers accumulated between the end of March and the end of July.

Given that the precipitation regime in the Mt. Ortles area is characterized by a winter minimum and a summer maximum (Schwarb, 2000), corresponding maxima and minima in the snow accumulation rate are expected at the study site, in absence of significant ablation. This behaviour was indeed modelled in the hydrological years 2006 - 2007 and 2007 - 2008. In 2008 -

20 2009 the modelled accumulation rate was high also during winter, as a result of abundant winter precipitation in the Italian Alps.

5. Discussion

5.1. Comparison of the pollen and modelled timescales

25 Application of the "depth-to-day" pollen concept and mass balance modelling provides two independent dating of the snow and firn layers of the 10 m firn core drilled in June 2009. The dates obtained by "depth-to-day" pollen dating are in general agreement with the previously developed principal component method (Festi et al., 2015), but the new method clearly provides a higher resolution and offers a more efficient timescale . The dates obtained show a detailed chronological distribution of the firn samples over 5 years, from April 2005 to June 2009. Few inversions are present (i.e., samples at 78 cm w.e. in 2006; 175

30 cm w.e. in 2007; 324 cm w.e. in 2008; 434, 448 and 452 cm in 2009), but the estimated dates are generally within the uncertainty of adjacent samples. These kinds of overlapping and minor inversions may depend on the limited time period (three years) covered by the available data from the aerobiological station of Solda. A longer training period for our palynological method would probably enable a better dating accuracy. Another factor could be the redistribution of surface snow layers caused by the wind. Nevertheless, layer dating obtained with EISModel and pollen dating are in very good

35 agreement (Pearson correlation coefficient r=0.99; $p<0.01$) as shown in Fig. 3. The chronological development of snow accumulation as modelled by EISModel matches very well with the absolute dates provided by the pollen-based timescale (Fig. 3). This can be partially due to the compensating effects of a small overestimation of the modelled ablation during summer and the higher accumulation during winter (Fig. 4). The most likely cause of such behaviour is the simplified modelling of snow accumulation, which does not account for redistribution processes. Nevertheless,the two methods provide converging

evidence that two distinct types of warm seasons occurred during the investigated period, i.e. the summers with high ablation in 2005 and 2006, and the summers with high accumulation in 2007 and 2008 (Fig. 3 and 4).

5.2.   Melt water effect on the pollen signal

Combination of the pollen dating and mass balance modelling methods also enables a better comprehension of the depositional and post-depositional processes affecting the formation and preservation of the palynological signal in snow and firn. In particular, it is possible to infer that during periods with high summer ablation, as during the warm seasons 2005 and 2006, pollen grains are not transported by percolation to lower layers, but concentrate into surface layers similarly to dust and debris (Gabrielli et al., 2014). This is demonstrated by i) the well-preserved spring pollen signature in 2005 and 2006, despite the strong ablation during the following summer seasons; ii) the preservation of the low pollen concentration in the winter layer of 2005/06, despite the fact that ablation reached 30 cm w.e.in the following summer. Indeed, pollen concentration in this layer remains below 0.5 pollens mL^{-1}. This value is similar to winter pollen concentration values of the hydrological years characterized by lower summer ablation (i.e. 2007 and 2008), and it is in agreement with the low winter pollen accumulation reported from the western Alps (Haeberli et al., 1983). Our results also agree with observations by Nakazawa and Suzuki (2008) in an on-site study on a snowpack on the Norikura Highlands (1590 m asl) in Japan. Nakazawa and Suzuki (2008) proved that during melt phases pollen concentrates on the surface of the snow cover and is not transported downward by meltwater. These outcomes support the idea that pollen grains are too big (5-200 µm) to be displaced by percolation within the firn (Nakazawa et al., 2004). In contrast, Ewing et al. (2014) obtained different results in a laboratory experiment, simulating post-depositional processes with different glacier snowpack conditions using Styrofoam coolers (60 x 30 x 30 cm) filled with natural winter snow accumulation. In this study, they observed a major vertical displacement of pollen grains concluding that meltwater highly affects pollen distribution. These divergent conclusions point to the fact that more specific studies on this phenomenon are needed, as it is likely influenced by laboratory design conditions, the natural interplay of local micro-climatic conditions, physical characteristics of snow and firn, and pollen grain size and shape. For example, on the Alto dell'Ortles, fresh winter snow usually accumulates in windy conditions and has a density of 300 kg m^{-3} (Gabrielli et al., 2010). In contrast, snow deposited at other sites with low wind conditions can have a lower density (50-70 kg m^{-3}) and the resulting firn may have higher porosity, which would facilitate the vertical dislocation of pollen grains. Unfortunately, Ewing et al. (2014) and Nakazawa and Suzuki (2008) do not provide quantitative measurements of the snow density, therefore preventing a fully meaningful comparison.

For the Alto dell'Ortles glacier, a major displacement of pollen grains by meltwater percolation can be ruled out during the studied time period. The few pollen grains retrieved in the cold season layers are likely associated to the occasional input of redeposited regional pollen grains or long-distance transport of pollen brought by windy events, which could carry pollen from the near Mediterranean region, where the flowering season is longer. A local input of redeposited pollen during winter is unlikely at the study site, because during the cold season the local atmospheric boundary layer generally lies below 2000 m a.s.l., trapping pollen and pollutants in the lowermost layers of the troposphere (Gabrieli et al., 2011).

The combined use of the pollen and EISModel timescale further corroborates the finding by Festi et al. (2015), which improved the dating of the 2009 shallow core obtained from chemistry-based seasonality (Gabrielli et al., 2010) that is more likely to be affected by meltwater percolation. Therefore, an approach that combines at least two of these methods turns out to be a more reliable approach for dating firn cores from temperate glaciers in the Alps. This may be valid also for cores retrieved from other ice bodies located in an environmental setting similar to the European Alps, where the vegetation is close to the glaciers and leads to abundant pollen deposition.

5.3.   The potential of pollen for qualitative climatic reconstruction

Based on the comparison between pollen content of sequential firn samples and cumulative mass balance modelling, we argue that pollen has a good potential not only for dating, but also for inferring the impact of past climatic conditions in firn and ice cores at seasonal resolution. Based on the pollen content in the Mt. Ortles strata, three main types of pollen assemblages can be identified and correlated with the corresponding annual climatic conditions: i) thin layers with high pollen concentration and mixed seasonal components, which are the result of intense summer ablation, thus pointing to warm and dry summer periods; ii) thick layers with significant pollen concentration and well-distinguished seasonal components, which indicate snow deposition during spring/summer periods characterized by abundant precipitation and lower temperatures; iii) thick layers with no (or nearly none) pollen, representing snow deposition during winter periods. Undoubtedly, this is only the first step towards a qualitative climatic interpretation of the pollen signal and further investigations are required in order to detect as many combinations of pollen assemblage types-ice layers as possible, and further correlate them with the corresponding conditions of formation. In fact, there are several other possible combinations, e.g. thin layers with high pollen concentration formed during dry (but not particularly hot) summer periods, or thick layers with high pollen content but inconsistent or mixed sequence of seasonal components, deriving from relatively low winter accumulation and possible blending of two or more years. However, our results suggest that, combining the classical stable isotope method with palynological analyses does not only enhance the accuracy of the ice core dating, but also offers the potential to provide additional qualitative paleo-climatic information at sub-seasonal resolution. Clearly, the feasibility of this approach in deeper ice cores depends on the amount of ice available for pollen analyses, the resolution achievable during sampling and the condition of no delay between pollen production and deposition.

5.4.   Application of the pollen based timescale

The application of the new detailed sub-seasonal timescale to other climatic proxies contained in ice cores (e.g. stable isotopes, major ions, dust, etc.) enables a direct comparison with meteorological variables and opens novel possibilities for a better understanding of processes related to the deposition and preservation of specific proxies. An example of a possible application is provided in Fig. 5(a), where the timescale has been applied to the δD values obtained from the same shallow firn core retrieved on Alto dell'Ortles. For this purpose, a complete timescale was calculated for the core, in order to date all the snow and firn samples and to plot their isotopic composition as a function of time. For samples belonging to the flowering seasons, absolute dates obtained with the depth-to-day pollen method were used (Table 1 and Fig. 2) and inversions were also included in the timescale. For the cold season layers, in absence of direct measurements of snow accumulation, a simple linear regression of depth vs. time was calculated. By applying this timescale to the δD values, a direct comparison between isotopes and mean daily temperature data as recorded in Solda became possible. This is supposed to be meaningful as there is a very high correlation (r = 0.95) between daily air temperature measured at Solda and on the Mt. Ortles shallow core drilling site, during the period from 2011-2014. Figure 5 shows a good correlation (Pearson; r = 0.642; *p* < 0.001) between the mean daily temperature and the measured isotopic composition, which is however not-stationary as it is affected by the smoothing of δD in the deepest firn layers (Gabrielli et al., 2010) because of meltwater percolation from the upper layers and partial melting of the snow accumulated during the 2005 and 2006 warm seasons. In contrast, the years 2007 and 2008 show a distinct δD summer peak, likely linked to the above-mentioned higher accumulation and lower ablation during those summers.

In conclusion, this is an example that clearly highlights the utility of combining different approaches for investigating the involved physical processes and for interpreting the proxy data contained in paleo-climatic archives.

6.   Conclusions

In this study, we have proposed a sub-seasonal timescale for the 10 m Mt. Ortles 2009 firn core. When compared to our previous work (Festi et al., 2015), the new approach demonstrates a higher potential of pollen for dating and analysing ice cores. The method can be applied to all types of glaciers, regardless of their thermic state, provided the proximity of the pollen

source, the existence of flowering seasons (typical of mid-latitudes) or a clear contrast between a flowering and non-flowering season (typical of the tropics and equator due to the alternation of dry and humid season), and the support of modern pollen monitoring data. We also show that a three- years training set of pollen monitoring is sufficient to provide meaningful comparison with glacier samples. This consideration becomes particularly relevant when working in glaciated regions that are

5   not covered by the pollen allergy network, which is the main source of pollen data, e.g. World Allergy Organisation-WAO (worldallergy.org), European Aeroallergen Network-EAN (ean.pollenifo.eu), etc. In this case, a three years monitoring can be included in the cryopalynological study and can take place also after the coring. In alternative, data from the closest stations in the region can be used and a correction for the delay between pollen production and deposition can be applied to the dating model. The method is particularly relevant at the moment because of the increasing interest in ice cores from non-polar areas,

10   as testified by recent launch of the "Protecting ice memory" project, which aims at creating the first archive of glacial ice for future generations. In fact, our approach can be applied to date deeper ice cores, if sampling resolution is sufficiently high. In such cores our method can make a significant contribution to the chronological model also by detecting the transition from annual to non-annual layering in the deeper ice.

The combined use of a mass balance model and pollen-based dating methodology brings compelling evidence that on the Alto

15   dell'Ortles glacier pollen grains are resilient to downward transport by percolating meltwater, also in the case of strong melting as in 2005 and 2006. The independent dating of firn layers by mass balance modelling and pollen match well, and highlight detectable intra-seasonal and inter-annual differences of high altitude snow accumulation rates on Mt. Ortles. More specifically, we found evidence of peculiar types of pollen distribution in firn layers, that may be related to well defined weather types (e.g. warm-dry, warm-humid or cold-humid weather). These results reveal the good potential of pollen for

20   inferring past climatic conditions at a sub-seasonal resolution in ice core records. Finally, we show that a sub-seasonal timescale is valuable because it can be used to investigate the relationship between climatic proxies contained in ice cores and measured meteorological variables for sites where this relationship has not been studied on site. Future studies could focus on joined fieldwork observations of meteorological variables (temperature, snow, wind, etc.) with measurements of snow accumulation/ablation, pollen accumulation, signature of isotopes and other chemical species as well as on monitoring of post

25   depositional effects (snow redistribution, water percolation, sublimation) on the proxies in order to directly test the assumptions made in the present study. This type of approach opens the possibility of gaining new insights into the physical processes involved in the formation and preservation of the signal stored in this paleo-climatic archive.

Author contributions

30   D. Festi, W. Kofler and K. Oeggl performed palynological analyses on the Ortles samples and developed the pollen based timescale. E. Bucher performed the pollen analyses at the aerobiological station of Solda. L. Carturan, F. Cazorzi and F. de Blasi processed the raw meteorological data and mass balance measurements, and carried out the mass balance simulations using EISModel. P. Gabrielli planned the logistic of the field campaign, drilled the firn core and coordinated the processing of the samples. D. Festi, L. Carturan, P. Gabrielli and K. Oeggl prepared the manuscript with contributions from all co-authors.

35

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References

Adler, S. : Das Klima von Tirol-Südtirol-Belluno: 1981-2010; Vergangenheit-Gegenwart-Zukunft. Zentralanstalt für Meteorologie und Geodynamik; Südtirol Abteilung Brand- und Zivilschutz, Bozen, 102, 2015.

10 Barry, R. G., and Chorley, R. J.: Atmosphere, weather and climate. Routledge, London and New York, 9th edition, 2009.

Bortenschlager, S.: Neue Pollenanalytische Untersuchungen von Gletschereis und Gletschernahen Mooren in den Ostalpen. Zeitschrift für Gletscherkunde und Glaziologie, 6 (1-2), 107-118, 1970 (a).

Bortenschlager, S.: Probleme und Ergebnisse der Untersuchung von Pollenspektren im Hochgebirge (Kesselwandferner, Ötztaler Alpen, 3240 m). Mitteilungen der Ostalpin-Dinarischen Sektion der Internationalen Vereinigung für
15 Vegetationskunde, 10(2), 5–9, 1970 (b).

Bourgeois, J.C.: Seasonal and inter-annual pollen variability in snow layers of arctic ice caps. Rev. Paleobot. Palyno., 108(1), 17–36, doi:10.1016/S0034-6667(99)00031-7, 2000.

Carturan, L., Cazorzi, F., and Dalla Fontana, G.: Distributed mass-balance modelling on two neighboring glaciers in Ortles-Cevedale, Italy, from 2004 to 2009, J. Glaciol., 58, 467-486, 2012 (a).

20 Carturan, L., Dalla Fontana, G., and Borga, M.: Estimation of winter precipitation in a high-altitude catchment of the Eastern Italian Alps: validation by means of glacier mass balance observations, Geogr. Fis. Din. Quat., 35, 37-48, 2012 (b).

Cazorzi, F. and Dalla Fontana, G.: Snowmelt modeling by combining air temperature and a distributed radiation index, J. Hydrol., 181, 169–187, 1996.

Cogley, J.G., Hock, R., Rasmussen, L.A., Arendt, A., Bauder, A., Braithwaite, R.J., Jansson, P., Kaser, G., Möller, M.,
25 Nicholson, L., Zemp, M.: Glossary of Glacier Mass Balance and Related Terms, IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, Paris, UNESCO-IHP, 114 pp., 2011.Dansgaard, W.: Stable isotopes in precipitation. Tellus, 16(4), 436–468, doi: 10.1111/j.2153-3490.1964.tb00181.x, 1964.

Eichler, A., Schwikowski, M., and Gäggeler, H. W.: Meltwater-induced relocation of chemical species in Alpine firn, Tellus B, 53B, 192-203, 2001.

30 Ewing, M.E., Reese C.A., and Nolan, M.S.: The potential effects of percolating snowmelt on palynological records from firn and glacier ice. J. Glaciol., 60, 661-669, http://dx.doi.org/10.3189/2014JoG13J158, 2014.

Festi, D., Kofler, W., Bucher, E., Carturan, L., Mair, V., Gabrielli, P., Oeggl, K.: A novel pollen-based method to detect seasonality in ice cores: a case study from the Ortles glacier, South Tyrol, Italy. Journal of Glaciology, 61 (229), 815-824, http://dx.doi.org/10.3189/2015JoG14J236, 2015.

Gabrieli, J., Carturan, L., Gabrielli, P., Kehrwald, N., Turetta, C., Cozzi, G., Spolaor, A., Dinale, R., Staffler, H., Seppi, R., dalla Fontana, G., Thompson, L., and Barbante, C.: Impact of Po Valley emissions on the highest glacier of the Eastern European Alps, Atmos. Chem. Phys., 11, 8087-8102, doi:10.5194/acp-11-8087-2011, 2011.

Gabrielli, P., Barbante, C., Bertagna, G., Bertó, M., Binder, D., Carton, A., Carturan, L., Cazorzi, F., Cozzi, G., Dalla Fontana, G., Davis, M., De Blasi, F., Dinale, R., Dragà, G., Dreossi, G., Festi, D., Frezzotti, M., Gabrieli, J., Galos, S., Ginot, P., Heidenwolf, P., Jenk, T. M., Kehrwald, N., Kenny, D., Magand, O., Mair, V., Mikhalenko, V., Lin, P. N., Oeggl, K., Piffer, G., Rinaldi, M., Schotterer, U., Schwikowski, M., Seppi, R., Spolaor, A., Stenni, B., Tonidandel, D., Uglietti, C., Zagorodnov, V., Zanoner, T., and Zennaro, P.: Age of the Mt. Ortles ice cores, the Tyrolean Iceman and glaciation of the highest summit of South Tyrol since the Northern Hemisphere Climatic Optimum, The Cryosphere, 10, 2779-2797, doi:10.5194/tc-10-2779-2016, 2016.

Gabrielli, P., Hardy, D. R., Kehrwald, N., Davis, M., Cozzi, G., Turetta, C., Barbante, C., and Thompson, L. G.: Deglaciated areas of Kilimanjaro as a source of volcanic trace elements deposited on the ice cap during the late Holocene, Quat. Sci. Rev., 93, 1-10, 2014.

Gabrielli, P., Barbante, C., Carturan, L., Cozzi, G., Dalla Fontana, G., Dinale, R., Draga, G., Gabrieli, J., Kehrwald, N., Mair, V., Mikhalenko, V.N., Piffer, G., Rinaldi, M., Seppi, R., Spolaor, A., Thompson, L.G. and Tonidandel, D.: Discovery of cold ice in a new drilling site in the Eastern European Alps. Geogr. Fis. Dinam. Quat., 101–105, doi:10.4461/GFDQ.2012.35.10, 2012.

Gabrielli, P., Carturan, L., Gabrieli, J., Dinale, R., Krainer, K., Hausmann, H., Davis, M., Zagorodnov, V., Seppi, R. and Barbante, C. Atmospheric warming threatens the untapped glacial archive of Ortles mountain, South Tyrol. J. Glaciol., 56(199), 843–853, http://dx.doi.org/10.3189/002214310794457263, 2010.

Gabrielli, P., Barbante, C., Plane, J.M.C., Boutron, C.F., Jaffrezo, J.L., Mather, T.A., Stenni, B., Gaspari, V., Cozzi, G., Ferrari, C., Cescon, P.: Siderophile metal fallout to Greenland from the 1991 winter eruption of Hekla (Iceland) and during the global atmospheric perturbation of Pinatubo. Chem. Geol. 255, 78 – 86, doi:10.1016/j.chemgeo.2008.06.012, 2008

Haeberli, W., Schotterer, U., Wagenbach, D., Haberli-Schwitter, H. and Bortenschlager, S.: Accumulation characteristics on a cold, high -Alpine firn saddle from a snow-pit study on Colle Gnifetti, Monte Rosa, Swiss Alps. J. Glaciol., 29 (102), 260–271, 1983.

Jaccard, P. : Étude comparative de la distribution florale dans une portion des Alpes et des Jura. Bulletin de la Société Vaudoise des Sciences Naturelles 37: 547–579, 1901.

March, R.S., Trabant, D.C.: Mass balance, meteorological, ice motion, surface altitude, and runoff data at Gulkana Glacier, Alaska, 1993 balance year. USGS Water-Resources Investigations Report, 96–4299, 30 pp. 1997

Nakazawa, F.: Application of pollen analysis to dating of ice cores from lower-latitude glaciers. J. Geophys. Res., 109 (F4), F04001, doi:10.1029/2004JF000125, 2004.

Nakazawa, F., Fujita, K., Takeuchi, N., Fujiki, T., Uetake, J., Aizen, V. and Nakawo, M.: Dating of seasonal snow/firn accumulation layers using pollen analysis. J. Glaciol., 51 (174), 483–490, doi: 10.3189/172756505781829179, 2005.

Nakazawa, F., Konya, K., Kadota, T., Ohata, T.: Reconstruction of the depositional environment upstream of Potanin Glacier,

Mongolian Altai, from pollen analysis. Environ. Res. Lett. 7, 2012 035402, doi: 10.1088/1748-9326/7/3/035402, 2012.

Nakazawa,F., Miyake, T., Fujita, K., Takeuchi, N., Uetake, J., Fujiki, T., Aizen, V. and Nakawo, M.: Establishing the Timing of Chemical Deposition Events on Belukha Glacier, Altai Mountains, Russia, Using Pollen Analysis. Arctic, Antarctic, and Alpine Research, 43 (1), 66–72, doi: 10.1657/1938-4246-43.1.66, 2011.

5 Nakazawa, F. and Suzuki, K.: The alteration in the pollen concentration peak in a melting snow cover. Bull. Glaciol. Res. 25, 1–7, 2008.

Santibañez, P., Kohshima, S., Scheihing, R., Jaramillo, J., Shiraiwa, T., Matoba, S., Kanda, D., Labarca, P., Casassa, G.: Glacier mass balance interpreted from biological analysis of firn cores in the Chilean lake district. J. Glaciol, 54(186), 452-462, doi: http://dx.doi.org/10.3189/002214308785837101, 2008.

10 Schwarb, M.: The alpine precipitation climate. Evaluation of a high-resolution analysis scheme using comprehensive rain-gauge data, Doctoral dissertation, Diss., Naturwissenschaften ETH Zürich, Nr. 13911, 2000.

Thompson, L.G.: Glaciological investigations of the tropical Quelccaya ice cap, Peru. J. Glaciol. 25(91), 69-84, http://dx.doi.org/10.3198/1974JoG25-91-69-84, 1980.

Thompson, L.G.: Glaciological investigations of the tropical Quelccaya ice cap, Peru. J. Glaciol. 25(91), 69-
15 84, http://dx.doi.org/10.3198/1974JoG25-91-69-84, 1980.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Zagorodnov, V.S., Howat, I.M., Mikhalenko, V.N., Lin P.-N. Annually resolved ice core records of tropical climate variability over the past ~1800 years. Science, 340(6135), 945-9502013, doi:10.1126/science.1234210, 2013.

Uetake, J., Kohshima, S., Nakazawa, F., Suzuki, K., Kohno, M., Kameda, T., Arkhipov, S. and Fujii, Y.: Biological ice-core
20 analysis of Sofiyskiy glacier in the Russian Altai. Ann. of Glaciol., 43(1), 70–78, doi: 10.3189/172756406781811925, 2006.

Vareschi, V.: Pollenanalysen aus Gletschereis. Ber. Geobot. Inst. Rübel, 81–99, 1934.

Zemp, M., Thibert. E., Huss, M., Stumm, D., Rolstad Denby, C., Nuth, C., Nussbaumer, S.U., Moholdt, G., Mercer, A., Mayer, C., Joerg, P.C., Jansson, P., Hynek, B., Fischer, A., Escher-Vetter, H., Elvehøy, H., Andreassen. L.M.: Reanalysing glacier mass balance measurement series. The Cryosphere, 7, 1227-1245, doi:10.5194/tc-7-1227-2013, 2013.

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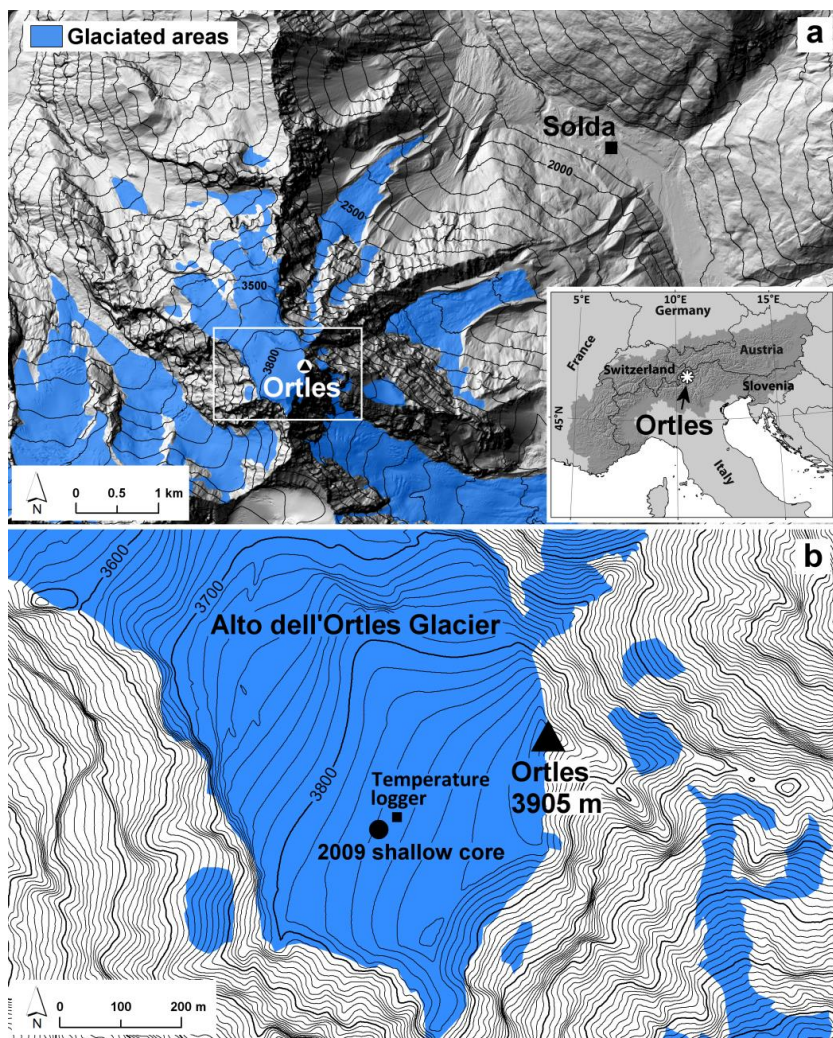
Figure 1 Geographical setting of Mt. Ortles and of the meteorological station of Solda. b) Close up of the Alto dell'Ortles Glacier, where the 2009 shallow firn core was retrieved (figure adapted from Festi et al., 2015).
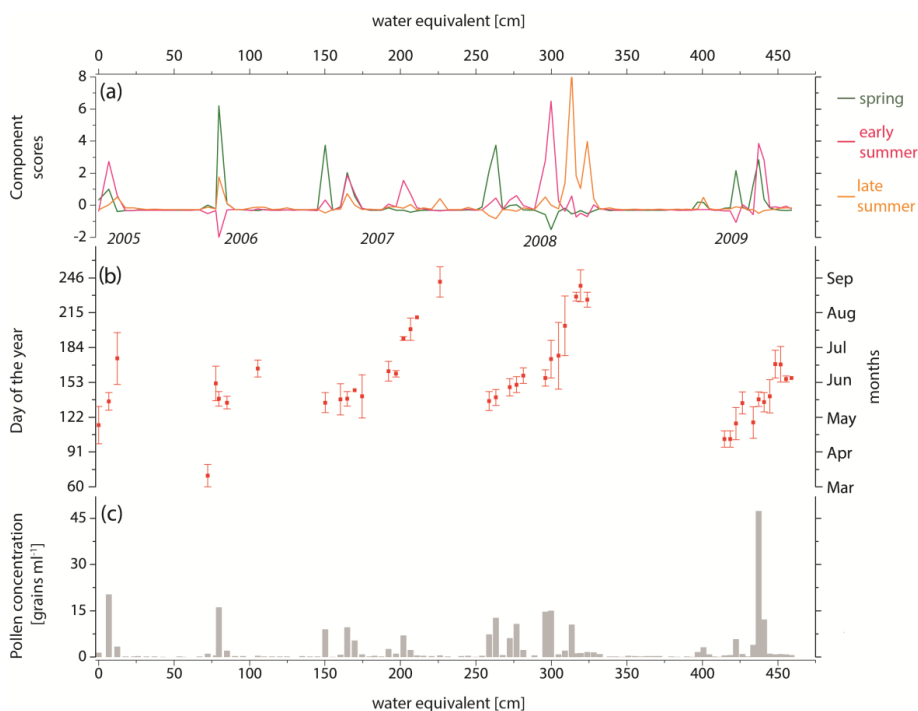
Figure 2 (a) Mt. Ortles firn core 2009 timescale (Festi et al., 2015) based on Principal Component Analyses. As every principal component (PC) condenses the seasonal information of the pollen spectrum, scores values should to be interpreted as follows: a sample (w.e. depth) presenting high component scores values for a specific PC is characterized by a pollen content reflecting predominantly the season corresponding to that particular PC. (b) Mean date (day of the year ± 1 sigma) obtained by using the new method developed in this paper. (c) Pollen concentration in the Mt. Ortles 2009 firn core.
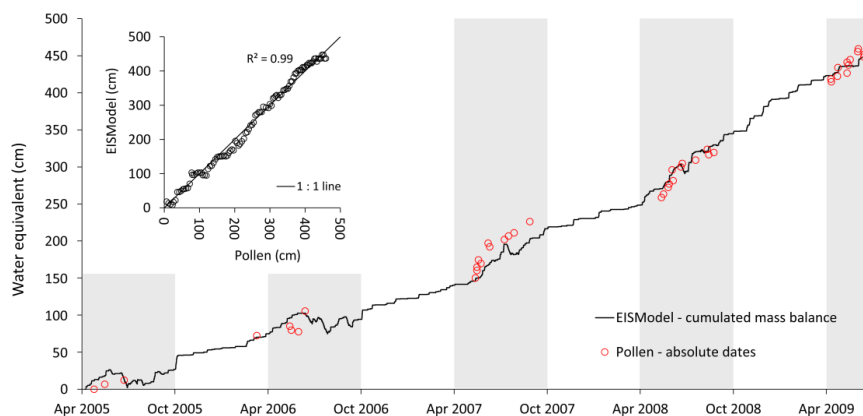
Figure 3 Comparison between cumulated mass balance modelled by EISModel and obtained by pollen dating. Alternating grey/white bars have a six months duration and roughly indicate the warm/cold season.
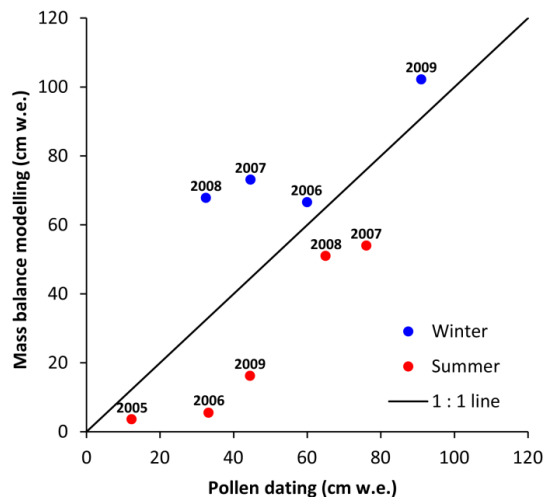
Figure 4 Comparison of the winter and summer mass balance as obtained by pollen dating and modelling (EISModel).
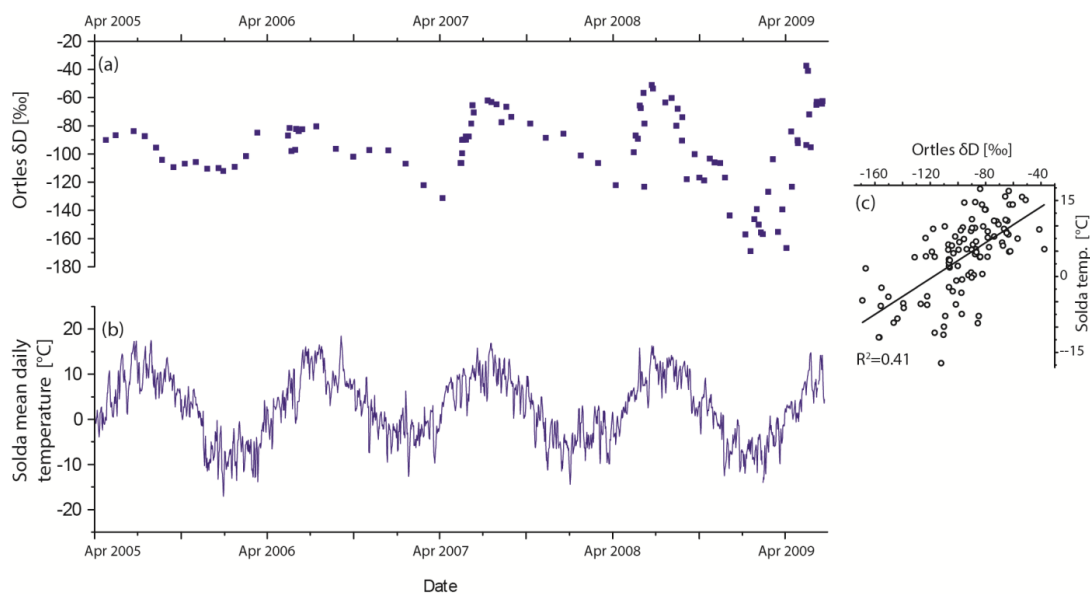
Figure 5 Isotopic variations in the Mt. Ortles 2009 core plotted with the new timescale (this work) (a) compared with the air temperature measured at Solda during the same period (b); Correlation diagram of Ortles isotopic composition (δD) and Solda's mean daily temperature.

Table 1. Results of the depth to date matching obtained by similarity analyses between Mt. Ortles snow samples and pollen monitoring data from Solda from the years 2008 to 2010. DOY= day of the year

Depth (cm)	Water Equivalent (cm)	2008 (DOY)	2009 (DOY)	2010 (DOY)	Mean (DOY)	Date (dd.mm.yy)	SD (±days)
10	459	157	157	-	157.0	06.06.2009	0
20	456	159	155	154	156.0	05.06.2009	3
30	452	163	157	187	169.0	18.06.2009	16
40	448	166	159	183	169.3	17.06.2009	12
50	445	-	130	151	140.5	21.05.2009	15
60	441	132	129	145	135.3	15.05.2009	9
70	437	132	137	145	138.0	18.05.2009	7
79.5	434	132	104	116	117.3	27.04.2009	14
99	427	129	129	146	134.7	15.05.2009	12
110.5	422	132	104	113	116.3	26.04.2009	12
120.5	418	111	99	98	102.7	13.04.2009	10
130.5	415	111	99	98	102.7	14.04.2009	14
355.5	324	219	231	230	226.7	13.08.2008	7
365.5	319	229	-	249	239.0	26.08.2008	14
372.5	316	225	233	230	229.3	16.08.2008	4
389.5	309	178	231	201	203.3	21.07.2008	27
399.5	305	211	157	162	176.7	25.06.2008	30
410.5	300	193	166	162	173.7	22.06.2008	17
419.5	296	149	159	163	157.0	05.06.2008	7
452.5	281	152	159	166	159.0	07.06.2008	7
462.5	277	149	159	145	151.0	30.05.2008	7
472.5	272	147	142	157	148.7	28.05.2008	8
492.5	263	132	141	146	139.7	19.05.2008	7
502.5	259	132	131	146	136.3	15.05.2008	8
572.5	226	233	252	-	242.5	30.08.2007	13
604.5	211	212	-	-	211.0	30.07.2007	0
613.5	207	211	191	199	200.3	19.07.2007	10
623.5	202	194	191	191	192.0	11.07.2007	2
633.5	197	164	159	159	160.7	09.06.2007	3
643.5	192	173	157	159	163.0	12.06.2007	9
679.5	175	-	127	154	140.5	21.05.2007	19
689.5	170	-	-	146	146.0	26.05.2007	0
699.5	165	132	138	145	138.3	18.05.2007	7
708.5	160	129	131	154	138.0	18.05.2007	14
728.5	150	132	128	145	135.0	15.05.2007	9
815.5	106	167	157	172	165	14.06.2006	8
854.5	85	134	141	130	135.0	15.05.2006	6
864.5	80	132	138	145	138.3	18.05.2006	7
868.5	78	148	139	169	152.0	01.06.2006	15
878.5	72	-	77	63	70.0	11.03.2006	10
988.5	12	201	162	160	174.3	23.06.2005	23
998.5	7	132	131	145	136.0	16.05.2005	8
1010.5	0	134	104	107	115.0	25.04.2005	17