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Alpine ice cores as climate proxies

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The ice core people's credo:

Atmospheric signals are most detailed and faithfully recorded in cold glacier archives (→ transiently frozen atmospheric water cycle)

Synopsis of the Alpine ice core archive

The major challenges in actual climate change research are the univocal detection of a possible current climate change due to human activities and to forecast the anthropogenic influence on the climate system. Evidently, the significance of any finding on current or future anthropogenic influence on climate has to be assessed against the background of natural climate variability operating on various spatial and temporal scales. Thus, in tackling the above tasks, historical climate information compiled from instrumental data sets and extended by various climate proxy data archives is urgently needed on the global and particularly on the regional scale. ALP-IMP significantly benefits from the unique situation of the Alps as related to the most dense network of long term instrumental observations in combination with the availability of cold glaciers suitable for climate related ice core studies.

Long term records of water isotopes ($\delta^{18}O$, δD) from cold polar glacier fields have been shown to provide the most faithful atmospheric paleothermometer, which can be relatively well calibrated in terms of local temperature change, at least for the Holocene period. Moreover, concurrent measurements of $\delta^{18}O$ and δD, providing the secondary quantity deuterium-excess may give insight into the water vapour source region of the stored precipitation. However, isotope signals in Greenland are strongly subdued during the recent Holocene and can thus hardly be distinguished from glacio-meteorological noise. Their weak isotope-temperature response to historical climate excursions (e.g. Little Ice Age, Medieval Optimum) makes them less useful therefore to infer the small scale climate variability at European level.

On the other hand, isotope records from cold mountain glaciers are found to show relatively strong long term variations exceeding by far the range explainable by local temperature changes. However, first isotope ice core studies at Alpine sites were hampered by interpretation deficits regarding dating precision, the influence of glacier flow effects and most notably their spatio-seasonal representativeness. These problems originate from the location of Alpine cold glaciers solely in the high elevation summit regions where the mean annual air temperature (MAAT) is low enough. As a consequence, Alpine drill sites have several peculiarities as:

- Due to their exposed location on small scale glaciers in the summit regions, they are subject to strong wind erosion mainly of dry winter snow. Consequently, the finally conserved fraction of annual precipitation may reflect a strongly seasonally weighted atmospheric signal. In this context, the seasonally variable vertical mixing intensity is connected to the spatial representativity of Alpine ice core records.
- Moreover, the seasonal amplitude of stable isotopes in Alpine precipitation is large compared to the respective long term trends. As a result, long term trends of stable water isotopes derived from alpine ice cores are very sensitive to changes in the conserved fraction of annual precipitation. Specifically, the conserved fraction of annual precipitation generally undergoes systematic spatial changes upstream the drill site and due to the glacier movement temporal trends from alpine ice cores are superimposed by the spatial variations along the surface.
- Cold alpine glaciers in the summit regions exhibit a strongly non-linear age-depth relation and complex ice flow pattern. Thus the dating uncertainties impose serious constraints in comparing such isotope records with other climate archives such as instrumental series or tree rings.

In view of these problems, significant "atmospheric" isotope signals from Alpine ice cores may only be derived, as for the Holocene situation at vast polar glacier fields, via a dedicated multi-core approach. In the case of the small scale Alpine drill sites exclusively situated well above 4000m asl this stands for combining several cores from the same drilling area on the one hand as well as from different drilling sites systematically differing in its glacio-meteorological feature on the other hand.

Although the existence of a link between water isotopes and climatic parameters is global in essence as directly resulting from physical laws, regional characteristics have to be taken into account (largely driven by the characteristics of regional climate itself). For Europe, such parameters as the continentality of the site, the origin of the precipitation, and the leading weather regimes are probably essential in linking water isotope signals to climate variability, thus challenging the model based component of ALP-IMP.

Important Climate Proxies from Ice Cores

proxy parameter	paleo-information	relevance at Alpine sites
directly linked to climate		
stable isotopes of water ($\delta^{18}O$, δD)	temperature change	high
accumulation rate	precipitation rate	none
melt layer frequency	surface energy balance (insolation at dry periods)	unclear
indirectly linked to climate		
greenhouse gases (CO_2, CH_4, N_2O)	radiative forcing	marginal
atmospheric dust load	radiative forcing	unclear
cosmogenic isotopes (^{10}Be,...)	solar forcing	marginal

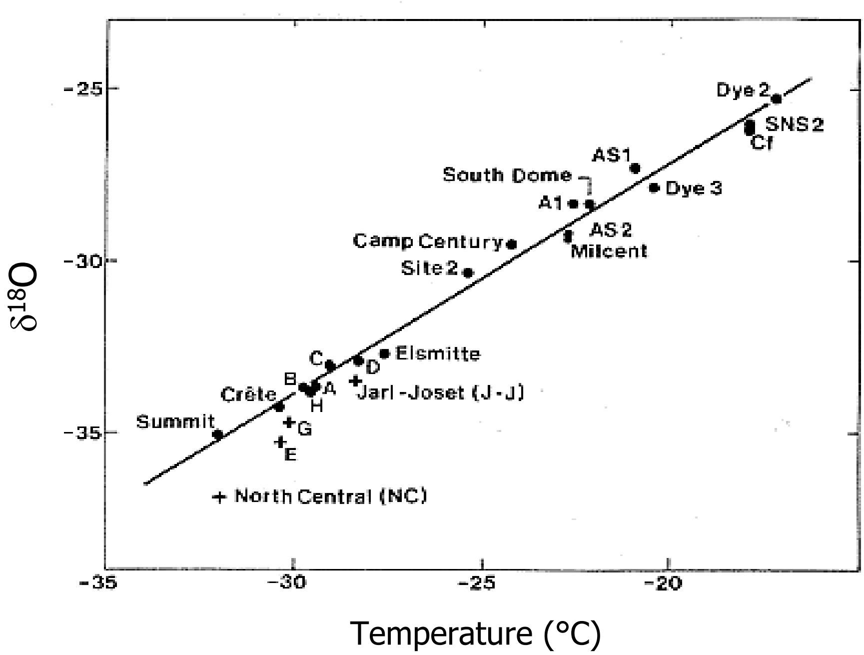
⇒for Alpine cores emphasis on isotope - thermometry

Isotope thermometry basics

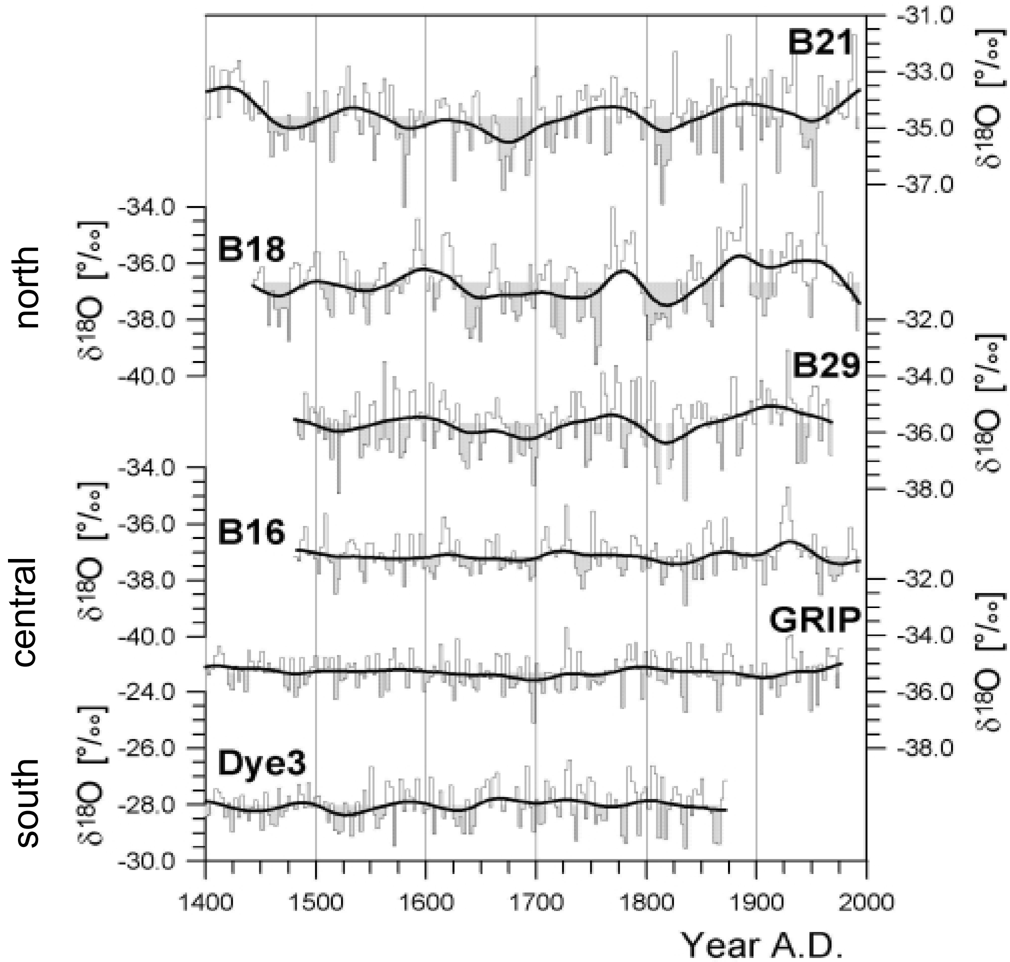
- stable isotope ratio ($^{18}O/^{16}O$) and (D/H) in precipitation mainly reflects local condensation temperature

  ⇒ gradual rain out of advecting, moist air masses during cooling associated with decreasing isotope ratio

- latitudinal, continental, seasonal and altitude effect
- isotope properties are secondarily linked to air mass circulation
- calibration of recent isotope temperature at Central Greenland sites consistent with simple theory and mid-latitude precipitation data (IAEA)



Recent isotope records from Greenland



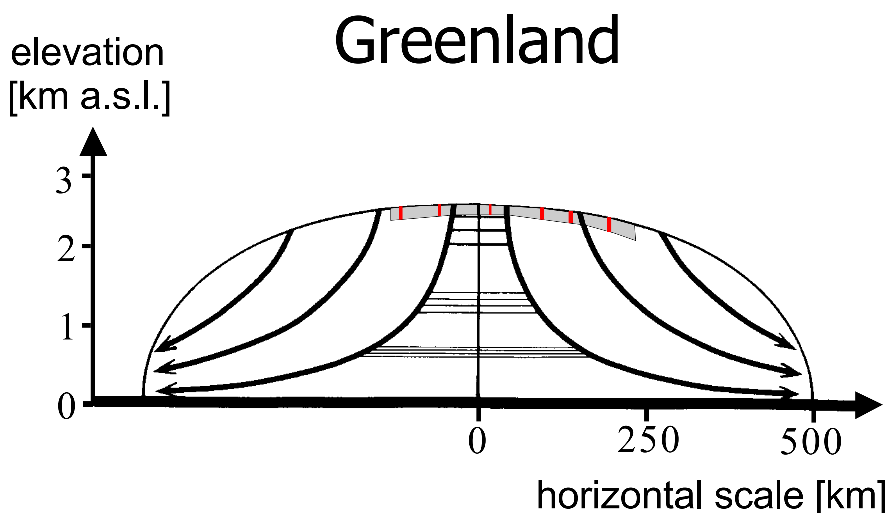
(Fischer et al., 1998)

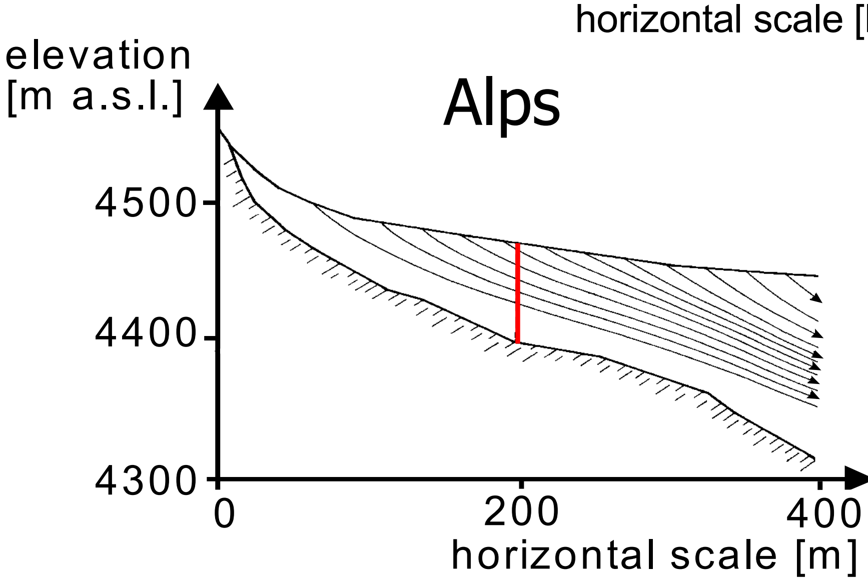
- poor inter-site coherence due to meteorological noise
- significant climate signals only seen from stacked North Greenland records

⇒ *remnant climate flickering during Little Ice Age*

Glaciological constraints at Alpine drill sites

Compared to Greenland at Alpine sites the horizontal and vertical scales are lower by a factor of 1000 and 30, respectively



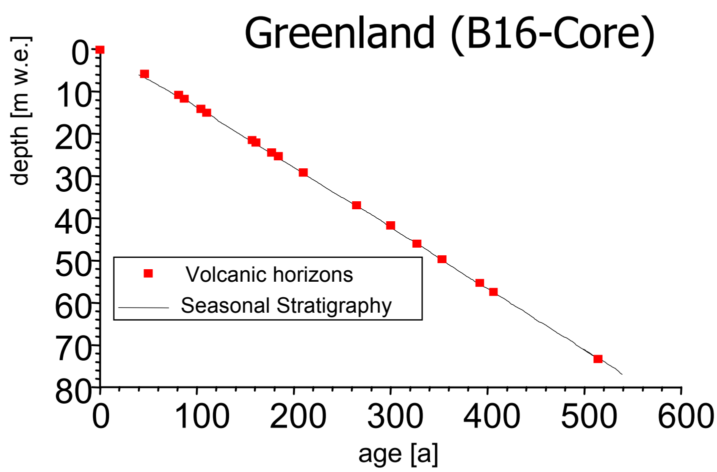


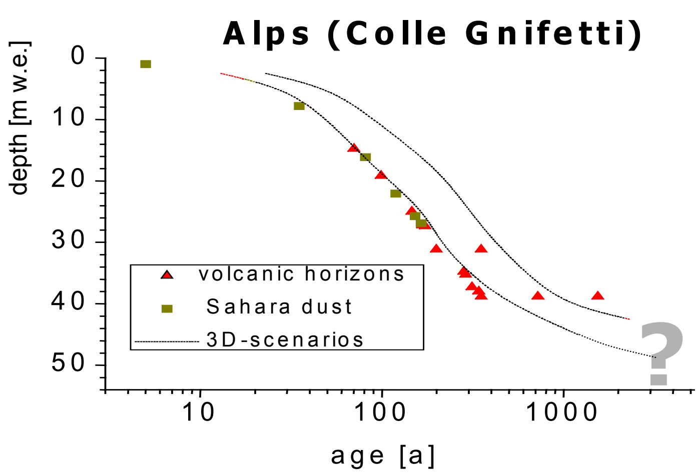
⇒ strong horizontal gradients at Alpine sites

⇒ no closed system at Alpine sites with respect to precipitation input

Glaciological constraints at Alpine drill sites

Ice core chronologies





Depth-age relationship

- virtually linear

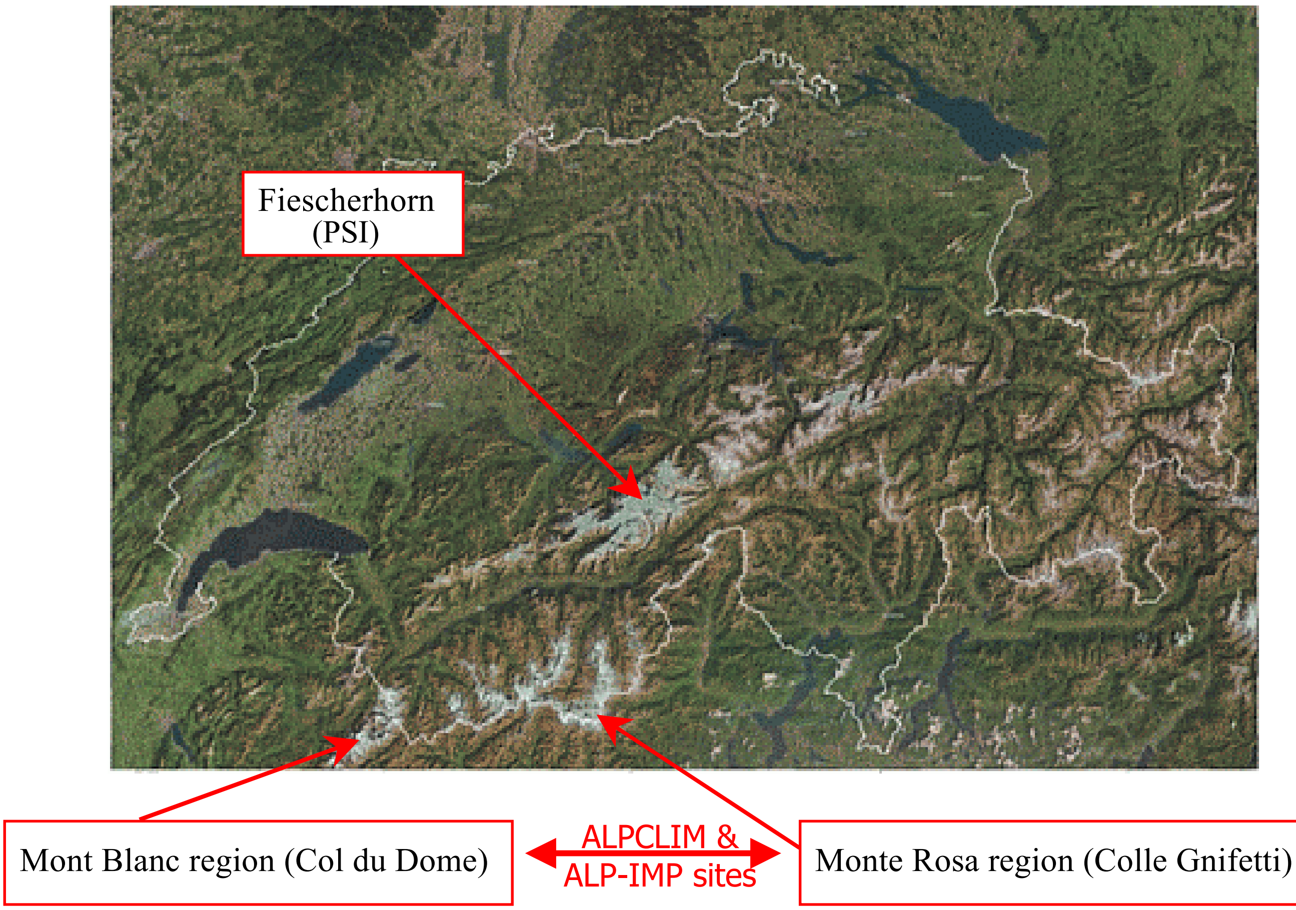
- strongly non-linear
  ⇒ rapid thinning

Chronology

- precise within a couple of years

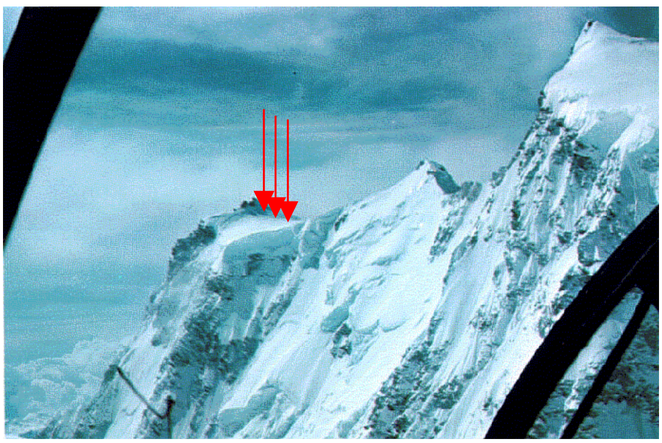
- uncertain within 10-50 years
- essentially unknown beyond ≈ 1000 A.D.

Important Alpine drill sites



ALPCLIM drill sites

Monte Rosa (Colle Gnifetti)



Altitude

- 4500 – 4550 m a.s.l.

Snow accumulation

- low 20 – 50 cm w.e. per year

⇒ key site for centennial records

Mont Blanc (Col du Dome)

Altitude

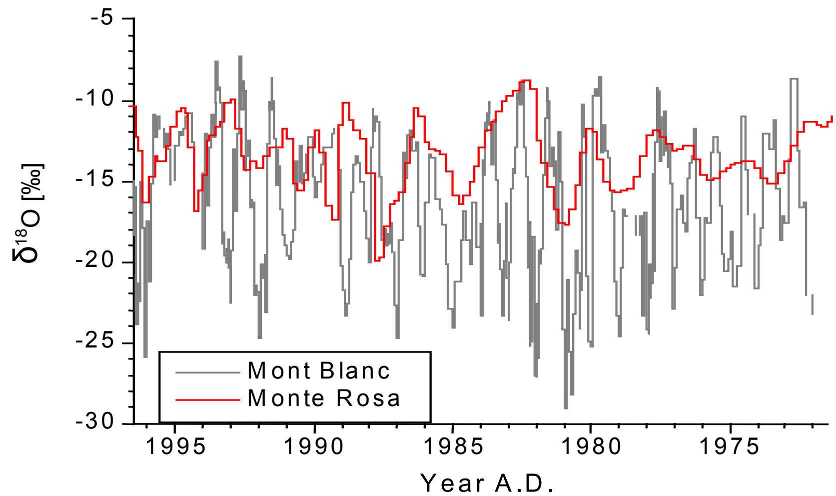
- 4150 – 4250 m a.s.l.

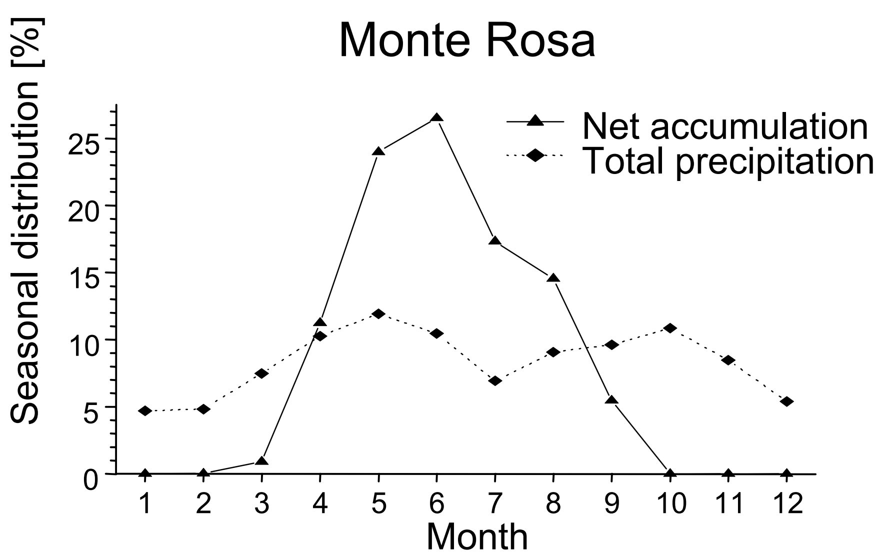
Snow accumulation

- high 200 – 300 cm w.e. per year

⇒ key site for decadal,
seasonally resolved records

Seasonal representativeness

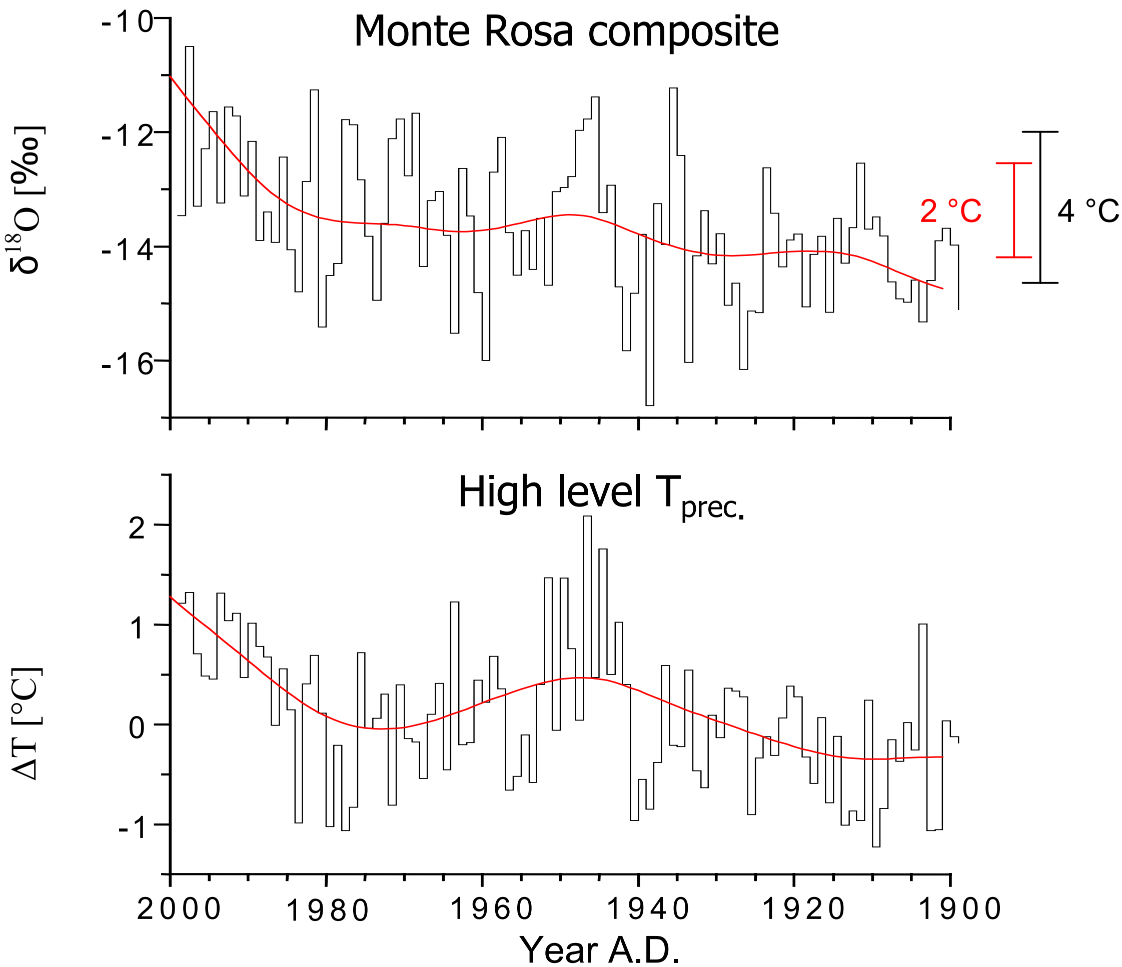




- complete seasonal cycle only preserved in recent high accumulation cores
- low accumulation sites reflect "growing seasons" signal

⇒ *link between long term isotope and tree ring records*

Isotope versus air temperature changes



- annual data comparison not realistic
- good correlation among decadal trends
- isotope sensitivity more than two times higher as expected from standard calibration factor

Summary of isotope record findings derived from the ALPCLIM predecessor project

In view of immediate climate evidence, ice core records of stable water isotopes are shown to provide a uniform pattern over the ALPCLIM area if decadal (and longer) time scales are concerned. In accordance with well established temperature records a significant recent warming trend is seen at all drill sites which appears as well from investigation of the thermal regime at the cold firn areas.

Here, borehole temperature profiles consistently point to recent warming which model based inversion to temporal temperature changes are qualitatively in agreement with the instrumental and isotopic observations. It could be demonstrated that in the Alps the reconstruction of surface temperature changes based on such inversion models will be confined to the centennial time scale. Prospects of the englacial temperature in the ALPCLIM area into the future yield relatively robust results which suggest a dramatic shrinking of the cold firn areas which will have destroyed a large part of the glacier archives by AD 2100. In a retrospective attempt, a general upwards shift of the zero-degree air temperature altitude was depicted from instrumental time series since the late 19th century already in the order of 250m.

Based on specifically compiled 20th century temperature series (i.e. adjusted to the seasonal ice core coverage and to precipitation weighted subsets) it was found that the isotope response to multi-decadal temperature changes are more than three times the commonly applied value. Consequently, isotope temperature trends react extremely sensitive on non-temperature interference (as systematic glacier flow effects). At Colle Gnifetti upstream effects may typically lead to a "non-climatic" trend in the order of 1°C per 100 years which has to be accounted for.

The isotope temperature records are nevertheless demonstrated to be coherent with the instrumental temperature record established at highly homogenised quality for the Greater Alpine Region (ALPCLIM GAR time series) over the last 240 years. This central finding added mutual confidence in the reliability of the net long term trends seen in both climate retrospectives. In particulate it confirms the broad temperature minimum emerging over the second half of the 19th century and, respectively, the enhanced temperature levels in the oldest part of the unique GAR temperature series (around AD 1790-1830).

A further extension of isotope records over up to 1000 years remained inclusive, however, since strong excursions and apparent long term trends may still be influenced through dating errors and inadequate corrections from glacier flow effects, respectively, but also by possible long term changes of the isotope/temperature relationship. Three upstream corrected cores revealed broadly consistent records, surprisingly showing a slightly colder (≈ 0.5°C) isotope-temperature level than present during the so called "Medieval Warming", whereas the "Little Ice Age" does not stand out as a distinctly cold excursion. Over the last 240 years, the isotope temperature however corresponds much better to the instrumental records than what is available from tree ring derived temperature proxy.

It was demonstrated that ice flow induced artefacts would impose the major challenge in deploying millennia scale isotope records, especially if the drill site was not in steady state during this period. Adding specifically selected ice cores from a dome position (i.e. Dome de Gouter, Mont Blanc) and from the relevant catchment area of the Colle Gnifetti (Monte Rosa) cores would improve the situation, however. Moreover, modelling based (REMO) cross linking with other Alpine archives (tree ring series and glacier mass) trying to disentangle temperature and circulation induced isotope changes is envisaged in ALP-IMP to assess the Alpine multi-centennial isotope records more clearly.

The deuterium excess, a secondary quantity of the otherwise redundant $\delta^{18}O$ and δD records revealed a clear decrease from the early 19th century to about 1950, suggesting a long term change in the circulation pattern related to precipitation over the Alps. This finding is in line with the historical ALPCLIM precipitation climatology (established back to the early 19th century) exhibiting a centennial scale "sea saw" feature seen in the dominance of north-west versus south-east shaped precipitation regime. This link would expect Alpine deuterium excess records to provide a potential paleo-circulation proxy which may be successfully deployed along with dedicated modelling studies (i.e. regional circulation model backed up by a water isotope module). Since the seasonal amplitude of the deuterium excess remains generally weak, alteration of such records by glacier upstream effects are much less significant (different to isotope values itself).