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# Footprints of climate in groundwater and precipitation

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## Abstract

In the last decades, the  $^{18}\text{O}/^{16}\text{O}$  signature of meteoric water became a key tracer intensively used both in hydrology and in paleoclimatology, based primarily on the correlation of the  $^{18}\text{O}/^{16}\text{O}$  ratio in precipitation with temperature. This correlation with temperature is generally well understood as a result of Rayleigh processes of atmospheric vapour during the formation of precipitation. The resulting isotopic signals in precipitation are also transferred into the groundwater body since the isotopic composition of groundwater is determined by the precipitation infiltrating into the ground. However, the whole variability of the  $^{18}\text{O}/^{16}\text{O}$  ratio especially in temporal data series of precipitation and groundwater can not be explained with temperature alone. Here we show for the first time that certain interactions between different climate induced changes in local parameters prevailing during precipitation events are responsible for the observed deviation. These effects are superimposed by an overall isotopic pattern representing the large scale climate input primarily based on temperature. The intense variability of isotopes due to the particular topography of Austria recorded over a time period of 40 years provides an unique possibility to uncover this hidden information contributed by relative humidity and type of precipitation. Since there is a growing need to predict the variation of climate together with its associated potential hazards like floods and dry periods the results of this work are contributing to a better overall understanding of the complex interaction of climate with the corresponding water cycle.

## 1 Introduction

It is of common understanding that isotopic depletion in atmospheric waters is based conceptually on a Rayleigh distillation process (Dansgaard, 1964; Clark and Fritz, 1997) describing the fractionation that differentiates the heavy and light molecules as to be strongly dependent on temperature. Although simple distillation models fail to consider the entire history of moisture that leads to the final isotopic content of precipi-

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tation it is found that there is indeed some correlation between the isotopic composition of precipitation and the local temperature (Siegenthaler and Oeschger, 1980), but at all timescales examined a large part of the variance in the isotope data remains unexplained. Typically only 20% of this isotope variance can be explained by temperature changes (Noone and Simmonds, 2002) and thus the accurate acquisition of paleotemperature from isotope data has been placed under scrutiny (Edwards and Wolfe, 1996; Jouzel et al., 1997).

Most of the research regarding the relationship between stable isotopes in meteoric waters and climatic parameters is dealing with model approaches based on physical and meteorological processes. These models take into account the complex dependences of the (isotopic) composition of atmospheric vapor upon environmental conditions, such as the transport pathways and the source region conditions. On the other hand due to their wide scale such global circulation models (GCM) are consequently neglecting the influences on the final isotope concentration coming from the location of the precipitation event itself. To cope with that new models have been recently developed mainly based on the local climatic conditions (Liebminger et al., 2006b). Moreover it has been shown that the spatial isotopic variability especially in alpine regions is to a large extent due to meteorological conditions prevailing at the sampling site (Liebminger et al., 2006a).

In general, groundwater values of  $\delta^{18}\text{O}$  (which are the per mille deviation of the isotope ratio of the accepted standard, VSMOW – Vienna standard mean ocean water) are reflecting the volume-weighted mean of annual precipitation (Clark and Fritz, 1997). The amplitude of the isotopic signal in the groundwater becomes more and more attenuated as the mean residence time (MRT) is increasing which therefore decreases the possibility to obtain climatic information from groundwater samples. Temporal changes in the conditions affecting the  $\delta^{18}\text{O}$  of precipitation can therefore only be expected to be seen in groundwater of shorter MRTs.

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## 2 Methods

The precipitation is collected on a daily basis in ombrometers (500 cm<sup>2</sup>) and mixed to monthly samples. Samples for this study were taken between 1961 and 2003. Analyses of oxygen 18 have been made by the isotope laboratories of Austrian Research Centers Seibersdorf (formerly Arsenal research). All together more than 16000 samples were collected during this period. Climate data for this period were provided by Central Institute for Meteorology and Geodynamics, Vienna<sup>1</sup>, Auer et al. (2006)<sup>2</sup> and Schöner (2004).

## 3 Results and discussion

In the following the results of an analysis of a unique dataset of almost 30 years of monthly Vienna drinking water samples are presented together with temporal isotopic precipitation data of the corresponding recharge area located in the Austrian Alps (Wildalpen). Figure 1a clearly shows an continuous increase of  $\delta^{18}\text{O}$  in the 1980s followed by an opposite trend from 1990 to 1996 within the drinking water samples. Since recharge is not a constant process over the whole season, i.e. there is less recharge occurring during seasons of warmer temperatures and stronger plant growth due to enhanced evapotranspiration, it is essential not to use the plain precipitation data from the

<sup>1</sup>CD-ROM: Klimadaten von Österreich 1971–2000, Central Institute for Meteorology and Geodynamics, Vienna ZAMG 2002

<sup>2</sup>Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., Schöner, W., Ungersböck, M., Matulla, C., Briffa, K., Jones, P., Efthymiadis, D., Bruntetti, M., Nanni, T., Maugeri, M., Mercuri, L., Mestre, O., Moisselin, J. M., Begert, M., Müllerwestermeier, G., Kveton, V., Bochnicek, O., Stastny, P., Lapin, M., Szalai, S., Szentimrey, T., Cegnar, T., Dolinar, M., Gajic-Capka, M., Zaninovic, K., Majstorovic, Z., and Nieplov, E.: HISTALP – Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region 1760–2003, Intern. J. Climat., revised version submitted, 2006.

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recharge area for comparison but to calculate an input function including an appropriate recharge factor for this area. Figure 1b shows the input function for the concerned recharge area of the Vienna drinking water calculated according to Maloszewski and Zuber (1996) applying a sinusoidal fit for the recharge factor (McGuire et al., 2002).

5 The temporal pattern found in the drinking water is also observed in the input function data whereas the summer months do not reflect the same trends (Fig. 1d). This observation is leading to the assumption that the colder months are main responsible for the observed pattern in the Vienna drinking water. The corresponding temperature data explains 27% ( $R^2$  for Summer;  $p=0.006$ ) to 32% ( $R^2$  for Winter;  $p=0.003$ ) of the variance in the  $\delta^{18}\text{O}$  pattern whereas the peak in 1989/90 is also present within the winter temperature data (Fig. 1c).

10 The  $\delta^{18}\text{O}$  fluctuations of precipitation correlate to a large extent ( $R^2=34\%$ ;  $p=0.002$ ) with those of the North Atlantic Oscillation (NAO) index, especially for the most extreme values during years 1989/90 and 1996 (Fig. 2a). The NAO has strong impacts on the mean wind speed and direction over the Atlantic and the heat and moisture transport between the North Atlantic region and surrounding continents, especially Europe (Hurrel et al., 2003). Since the NAO is particularly dominant in winter, average values of the December to March period are shown in the time series of Fig. 2. The ratio of snow to total precipitation (S/P) is a hydrologic indicator that like the NAO is sensitive to climate variability and can be used to detect and monitor hydrologic responses to climatic change (Huntington et al., 2004). Changes in S/P ratio over time could influence the magnitude and timing of spring runoff and recession to summer base flow. While the climate information within the NAO index is primarily determined at the source of the precipitation (Atlantic Ocean) the S/P ratio, although also mainly based on temperature changes, is potentially influencing the final composition of the precipitation due to non-equilibrium fractionation taking place at the location of the precipitation event itself. The formation of snow as well as sub cloud evaporation processes are both considered to be kinetic processes shifting the final concentration of stable isotopes in precipitation to opposite directions (Liebminger et al., 2006a). Especially the non-equilibrium fraction-

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ation during sub cloud evaporation processes of the falling rain drops plays a key role in governing higher  $\delta^{18}\text{O}$  values. At inter mountain valley stations where air masses arrive due to surrounding mountains at a high level above the ground and at large basins where convective movement of clouds due to higher temperatures is prevailing relative humidity which is mainly responsible for sub cloud evaporation is therefore of increased importance. On the other hand, at locations in front of orographic barriers enhanced precipitation amounts are occurring which leads to a faster saturation of the ambient air during a precipitation event, thus limiting the effect of evaporation on the falling rain drop. As shown in Fig. 2b the S/P ratio is nearly in anti phase to the  $\delta^{18}\text{O}$  pattern indicating that higher  $\delta^{18}\text{O}$  values are prevailing when there is more rain among the precipitation falling in the winter months ( $R^2=29\%$ ;  $p=0.005$ ). Considering a lower relative humidity at these winter days with rain (Fig. 2c;  $R^2=25\%$ ;  $p=0.010$ )  $\delta^{18}\text{O}$  values are definitely more influenced by sub cloud evaporation than at days with snowfall and higher relative humidity prevailing.

Figure 3a and b prove strong evidence of such local influences on the  $\delta^{18}\text{O}$  variation as there are quite different isotopic trends despite of geographic proximity of the sample locations Innsbruck (valley) and Patscherkofel (mountain) as well as quite similar trends at stations located in regions farther away but within a comparable landscape profile like Weyregg and Kufstein. For both examples the overall year to year  $\delta^{18}\text{O}$  variation remains quite similar overriding an essential part of the information which does not come directly from temperature. In order to reveal this hidden part it is necessary to compare the  $\delta^{18}\text{O}$  data of interest to a different data set with lower or none dependence upon sub cloud evaporation. This is the case for the above mentioned valley/mountain example, because the influence of sub cloud evaporation at the summit of Patscherkofel (2245 m a.s.l.) is negligible. Another possibility is to compare  $\delta^{18}\text{O}$  with  $\delta\text{D}$  since Deuterium will be enriched by a lesser extent during evaporation processes. Figure 3c and d clearly show a decrease of the relative difference between  $\delta^{18}\text{O}$  and  $\delta\text{D}$  over the last decades for sample stations Innsbruck and Kufstein manifested in a steeper slope of  $\delta^{18}\text{O}$  in comparison to  $\delta\text{D}$  clearly indicating that sub cloud evaporation

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has become of increased importance during the last 30 years.

The above described effect is either enhanced or lowered by the amount of precipitation which is occurring during the events. Drizzle or very small rain drops are relatively more affected by sub cloud evaporation as heavy rain during storm events. Therefore smaller precipitation amounts have to be expected at times with higher  $\delta^{18}\text{O}$  values and vice versa which is confirmed by Fig. 4a showing an example of Vienna precipitation records. From the local meteoric water lines (LMWL) drawn for this location for the time periods before 1989 (Fig. 4c) and after 1989 (Fig. 4d) it can be seen that the slope of the later values is significantly lower than that of the earlier values which is always a strong indicator of enhanced evaporation effects (Clark and Fritz, 1997).

## 4 Conclusion

We summarize that the isotopic composition of meteoric water is not only reflecting the influence of temperature but also that of local meteorological parameters which will definitely be of considerable interest for (paleo)climatic applications! Especially we show for the first time that younger groundwater due to special recharge conditions is a potential reservoir of climate information bearing just more than temperature. A general overview over the processes described in this study is given in the supplement (<http://www.hydrol-earth-syst-sci-discuss.net/3/271/hessd-3-271-sp.pdf>). Although especially alpine regions are able to deliver a lot of different and representative sample sites future studies covering larger geographical areas will be necessary in order to get more input on the extent of the obvious and hidden information within the stable isotopes variation in precipitation and groundwater.

*Acknowledgements.* We thank the Umweltbundesamt (Vienna) which is in charge of the majority of the sampling stations. We are further grateful to the people of the "Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Abteilung VII/3 – Wasserhaushalt (Hydrographisches Zentralbüro" for providing the monthly mean temperature data

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(status: 05/2004) and to R. Böhm from the Central Institute for Meteorology and Geodynamics, Vienna for his valuable input on climatology.

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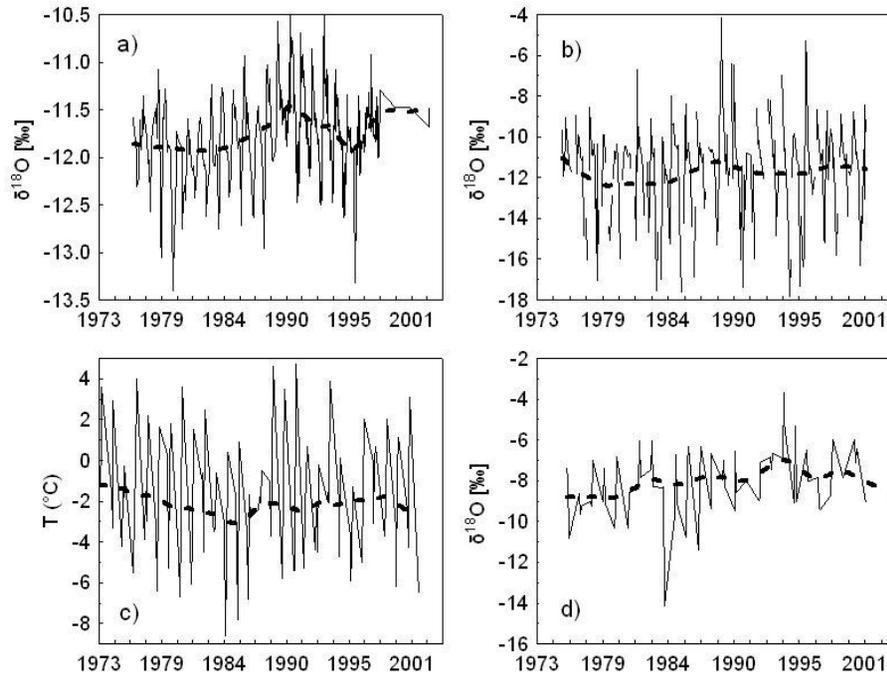
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**Fig. 1.** Time series of Vienna drinking Water and input factors at the recharge area. **(a)** Monthly mean  $\delta^{18}\text{O}$  values of Vienna drinking water **(b)** Input function calculated from monthly mean  $\delta^{18}\text{O}$  values of precipitation sampled at Wildalpen the recharge area for Vienna drinking Water; **(c)** Average air temperature data for winter months December to March measured at Wildalpen; **(d)** Average  $\delta^{18}\text{O}$  values of precipitation for summer months June to August sampled at Wildalpen; For all plots low pass filters are applied (dashed lines).

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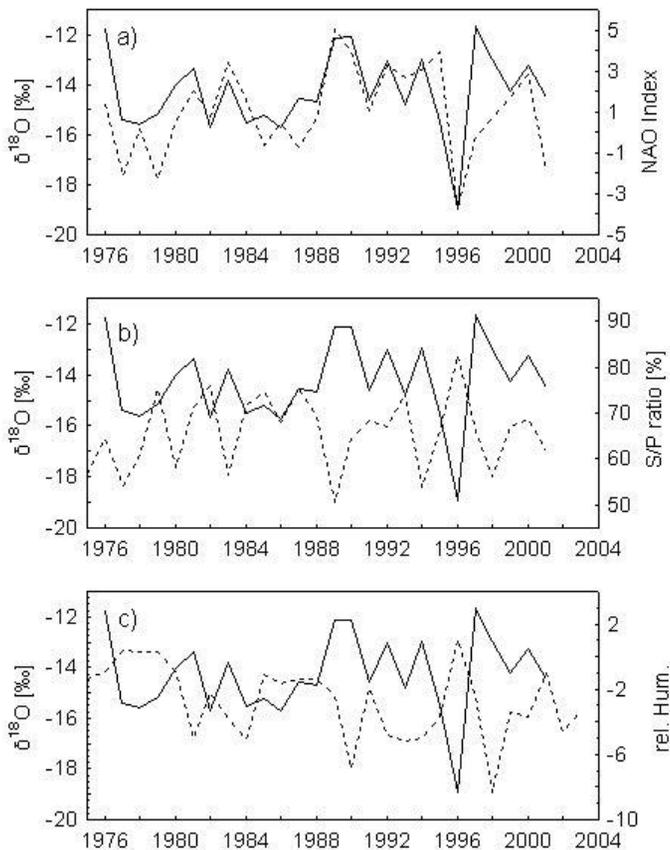
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**Fig. 2.** Comparison time series for  $\delta^{18}\text{O}$  values of precipitation sampled at Wildalpen (full lines) together with climate time series (dashed lines) averaged for winter months December to March **(a)** Comparison with NAO Index; **(b)** Comparison with snow to precipitation ratio (S/P); **(c)** Comparison with relative humidity calculated as a relative deviation from the long term mean (Schöner, 2004).

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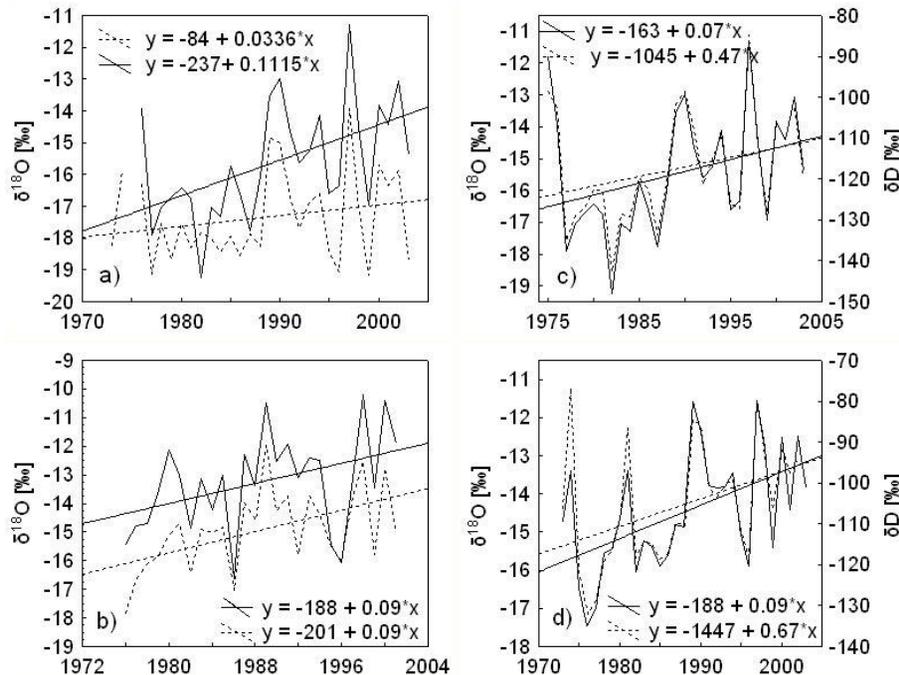
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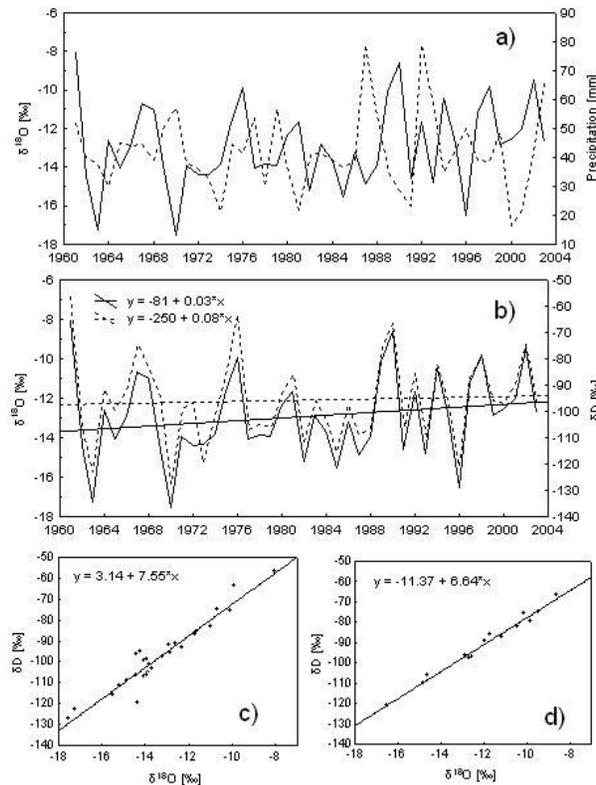


**Fig. 3.** Comparison time series for different locations in  $\delta^{18}\text{O}$  and  $\delta\text{D}$ . **(a)**  $\delta^{18}\text{O}$  values of precipitation sampled at Innsbruck (full line) and Patscherkofel (dashed line). The mountain sample station Patscherkofel at an altitude of 2245 m a.s.l. is located within 10 km of geographic proximity to the city of Innsbruck (577 m a.s.l.) in the deep inner alpine “Inn-valley”. **(b)**  $\delta^{18}\text{O}$  values of precipitation sampled at Weyregg (full line) and Kufstein (dashed line). Both sample stations are located on the northern border of the Alps but at a lateral distance of more than 150 km. **(c)**  $\delta^{18}\text{O}$  (full line) and  $\delta\text{D}$  (dashed line) trends for Innsbruck; **(d)**  $\delta^{18}\text{O}$  (full line) and  $\delta\text{D}$  (dashed line) trends for Kufstein. All time series represent average values for winter season.

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**Fig. 4.** Influences on stable isotopes in Vienna precipitation. **(a)** Comparison time plot for  $\delta^{18}\text{O}$  values of precipitation (full line) and amount of precipitation (dashed line) sampled at Vienna Hohe Warte; **(b)**  $\delta^{18}\text{O}$  (full line) and  $\delta\text{D}$  (dashed line) trends for Vienna; **(c)** Plot of the Vienna local meteoric water line for  $\delta^{18}\text{O}$  and  $\delta\text{D}$  representing the winter months of the years 1961 to 1989; **(d)** Plot of the Vienna local meteoric water line for  $\delta^{18}\text{O}$  and  $\delta\text{D}$  representing the winter months of the years 1989 to 2003.

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