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# *Interactive comment on* "Novel approach for ice core based temperature reconstructions – a synthetic data study for Holocene $\delta^{15}$N data" *by* Michael Döring and Markus Leuenberger

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The submitted paper by Döring and Leuenberger presents an new fitting approach to model $\delta^{15}$N time series as measured in air extracted from ice cores, together with the corresponding temperature history. This fitting approach is combined with an existing firn model (Schwander et al., 1997) run in a forward mode. First, a synthetic dataset mimicking Holocene $\delta^{15}$N and temperature is constructed. Then, the three steps of the fitting method are described. At each step of the procedure the accuracy compared to the synthetic dataset, used as reference value, is estimated. The final distribution of all distances to the synthetic dataset is used to estimate a 95% confidence interval (or 2



$\sigma$ uncertainty estimate). It is worth mentioning that this method can also be adapted to invert other parameters such as $\delta^{40}$Ar or $\delta^{15}N_{excess}$.

In my view this paper presents clear and outstanding improvements compared to existing methods. Temperature reconstructions obtained with such a method applied to new or existing $\delta^{15}$N datasets will be very valuable in the future for the scientific community.

Four specific advantages of the new approach are discussed hereafter and compared to existing published work in this field:

1. The fitting approach requires as input measured $\delta^{15}$N data only (as well as time scale and accumulation rate, as any firn model). The reconstructed temperature is therefore entirely independent from any other temperature proxy records (in particular, water stable isotopes), allowing future unbiased intercomparison in between different reconstructions in the future;
2. An uncertainty of the fitting approach itself is provided (excluding uncertainty due to $\delta^{15}$N measurement, firn physics and firn dynamics modeling). Again this will allow for future valuable intercomparison of temperature proxies;
3. The method is entirely automated, i.e. it is completely user-independent and allows to save significant working hours;
4. The fitting approach, uncertainty estimation and automation are described in an entirely transparent and reproducible manner.

## 1 Independence of the produced temperature history from any other temperature proxy records

Döring and Leuenberger present a temperature reconstruction method requiring $\delta^{15}$N data only as input. The fitting approach is based on a randomly generated first guess (i.e., a constant temperature) combined with randomly generated noise to progressively improve the initial guess. The only section requiring water isotope variations as input, scaled with a linear relationship, is the spin-off section of the dataset, and should therefore have only an insignificant influence on the final obtained temperature history. Therefore this method requires no prior input temperature signal nor any other assumption on the expected shape of the temperature signal. The obtained temperature history is consequently fully independent from other proxy records. Hence, this approach permits for the first time a future intercomparison of results in an unbiased manner. This is a clear improvement compared to existing work.

Many previous work relied indeed on other proxy records to generate a first guess temperature scenario, also because the fitting approach was (partly) manual and it would have been a huge effort to start from a flat temperature scenario. In many studies, water stable isotope variations measured in the same ice core were used as first input, with a linear function as scaling factor. This is likely one of the best option, as both proxies are sensitive to local, surface of the ice sheet temperature variations, with second order effects for water isotopes (such as seasonality of precipitation, temperature gradient in between surface and cloud condensation temperature, source temperature variations). This approach has been applied to fitting $\delta^{15}$N data only (e.g., Lang et al., 1999; Huber et al., 2006; Kindler et al., 2014; Guillevic et al., 2013; Buizert et al., 2014) or combined with $\delta^{40}$Ar data (e.g., Landais et al., 2004a; Capron et al., 2010), leading to the second order parameter $\delta^{15}N_{excess}$.

To model abrupt events, a step function as probable shape for the temperature increase/decrease has also been used instead of a linear function to water isotopes (e.g., Severinghaus et al., 1998; Severinghaus and Brook, 1999; Rosen et al., 2014), which is also an approximation, however valid for large and sharp temperature increase/decrease. Indeed changing the steepness of the increase has a non negligible effect on the $\delta^{15}$N and temperature reconstruction, a sharper increase leading to a smaller estimated amplitude for the temperature increase (e.g., Landais et al.



(2004b), Fig.3, Rosen et al. (2014), Fig. 3). Another alternative to using water isotopes, without supposing any prior shape for the temperature increase, was developed by Kobashi et al. (2008a). They used both nitrogen and argon isotope data to calculate a first firn $\Delta$T, combined with the Goujon firn model (Goujon et al., 2003) to reconstruct lock-in-depth temperature, leading finally to a surface temperature reconstruction. Orsi et al. (2014) also developed a new fitting approach using $\delta^{15}$N and $\delta^{40}$Ar, using a linearized firn model. However both approaches work only when argon isotope data are measured in addition to nitrogen, with a sufficient precision. This requires dedicated ice samples and a highly precise measurement procedure (e.g., Severinghaus et al., 2003). Such argon data are (still) not available for most of the NGRIP or NEEM ice core for example (Huber et al., 2006; Kindler et al., 2014; Guillevic et al., 2013; Rosen et al., 2014), making the approach from Döring and Leuenberger highly relevant.

Using the approach presented in Döring and Leuenberger, it would be valuable (in a future work) to try to reproduce previous results on the relationship between $\delta^{15}$N-based temperature reconstruction and water isotopes, that used water isotope variations as first guess for the temperature scenario (e.g., Landais et al., 2004a; Kindler et al., 2014; Guillevic et al., 2013; Buizert et al., 2014).

To clearly show the usefulness of this new approach, it could be helpful for the reader to highlight in the method section of this manuscript the independence of this approach from other temperature proxies, in particular from water isotope records.

## 2 Uncertainty estimate of the fitting approach

A soundly estimated uncertainty with a 95% confidence interval is provided. This is made possible by first generating a synthetic temperature scenario mimicking Holocene temperature variations, compatible with the precise, high resolution GIPS2 $\delta^{15}$N dataset published in Kobashi et al. (2008b). The constructed synthetic dataset is used as 'true value' and the difference in between the fitting approach result and this true value is quantified for each time point of the generation. The aggregation of all distances produces a distribution of distances around the 'true value'; the limits corresponding to 95% of the distances are used as 2 $\sigma$ uncertainty estimate. To my knowledge, this is the first time the accuracy of a fitting approach for $\delta^{15}$N is tested in this way by first creating an arbitrary 'true value'. It seems an excellent method to test and quantify the uncertainty introduced by the fitting approach itself, independently of any other uncertainty (introduced by $\delta^{15}$N data resolution and precision, firn processes, accumulation rate, time scale, etc, which are not considered in this paper).

In the literature, uncertainty estimate are usually reported for the entire reconstruction as a whole, including all considered types of uncertainty. Moreover until now the uncertainty of the reconstructed temperature was usually estimated using a sensitivity study of the reconstructed temperature to various changes in input values (e.g., Landais et al., 2004b; Huber et al., 2006; Guillevic, 2013). The Monte Carlo simulation used in Buizert et al. (2014) (n.b. also modeling – part of – the GISP2 $\delta^{15}$N dataset published in Kobashi et al. (2008b), among other records) was already a highly valuable alternative method for uncertainty estimation. However, until this study from Döring and Leuenberger, using a synthetic dataset as reference value to estimate fitting approach accuracy, no uncertainty was really possible to estimate for the fitting approach itself.

In a future study applied to the glacial period (as hinted by Döring and Leuenberger), it would be valuable to test the fitting accuracy for the reconstructed delta age as well, by comparison to a synthetic delta-age obtained at the same time as synthetic $\delta^{15}$N. This is likely not highly relevant for the Holocene period where $\Delta$age remains relatively constant and small, but should be an interesting aspect to test for the glacial.



## 3 Automation

The automation presented in Döring et al. is actually certainly a prerequisite for the generation of thousands of temperature scenarii progressively modified to match $\delta^{15}$N data. Moreover, this automated fitting method is applied over a relatively long time period of $\tilde{1}0$ kyr, and as stated by the authors could be applied to the entire last glacial period (120 kyr). The automation supersedes the manual or semi-automated fitting process, and therefore decouples the result from the potential influence of the user. This automated method is working for the reconstruction of a thousand year long temperature record where few clear and sharp temperature variations exist (except perhaps the 8.2 kyr event). So I expect that this method should work as well for the glacial, where extremely abrupt events occurred, giving a better constrain to the reconstructed temperature scenario. The authors demonstrate moreover that the successive steps of the approach, starting first by matching low frequency $\delta^{15}$N variance (expected to be caused mostly by firn thickness changes), then high frequency variations (caused by surface temperature oscillations), and finally fine tuning the timing of each temperature oscillation, is a robust method well suited to match firn dynamics history.

To my knowledge, Buizert et al. (2014) also used an automated approach applied to long dataseries, to reconstruct the temperature history of the last deglaciation, as well as gas age histories (Buizert et al., 2015; Rasmussen et al., 2013; Seierstad et al., 2014). However as stated on Sect. 1, the Buizert automated method requires input water isotope data and user-chosen points where the linear fit in between water isotopes and temperature is allowed to change.

The approach presented in Döring and Leuenberger, combining automation and independence from any other temperature proxy records, run over a long time period, can therefore be considered as a remarkable improvement.

## 4 Transparency

The approach developed in Döring and Leuenberger is described in full details together with the required input data, the different steps of the procedure and the parameters needed to be chosen/defined at the beginning of the procedure. Also the target of the modeling procedure is clearly stated, i.e. the synthetic $\delta^{15}$N dataset, as well as the testing criterion to estimate if a newly generated $\delta^{15}$N scenario better fits the synthetic target. I find excellent that effort is given to making the fitting approach completely transparent for the reader. This has not always been the case, likely because (i) at the very beginning fitting approaches were manual and therefore difficult to precisely describe, (ii) the uncertainty of the fitting approach was likely very small compared to $\delta^{15}$N analytical uncertainty, (iii) finding appropriate physical description of firn densification processes and dynamics was the most challenging scientific goal and (iv) only small datasets, covering limited time slices (usually one to two Dansgaard-Oeschger events), were considered.

I would actually recommend to add a schematic figure sketching each step of the procedure, to provide a method overview for the reader. This would help to follow the text description.

### Final comment

In short, I consider the method presented in Döring and Leuenberger an outstanding contribution to the field of $\delta^{15}$N modeling.



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