An Automated Approach for Annual Layer Counting in Ice Cores

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Introduction:

A novel method for automated annual layer counting in seasonally resolved paleoclimatic records has been developed. It relies on algorithms from the Bayesian statistical framework of Hidden Markov Models (HMMs), which originally was developed for use in speech recognition software. A schematic illustration of the principles behind the method is found in figure 3, and an example of the output from the algorithm is shown in figure 4. The strength of the layer detection algorithm lies in the way it is able to imitate the manual procedures for annual layer counting, while being based on objective yet flexible criteria for annual layer identification.

The method has the following major advantages compared to other automated approaches:

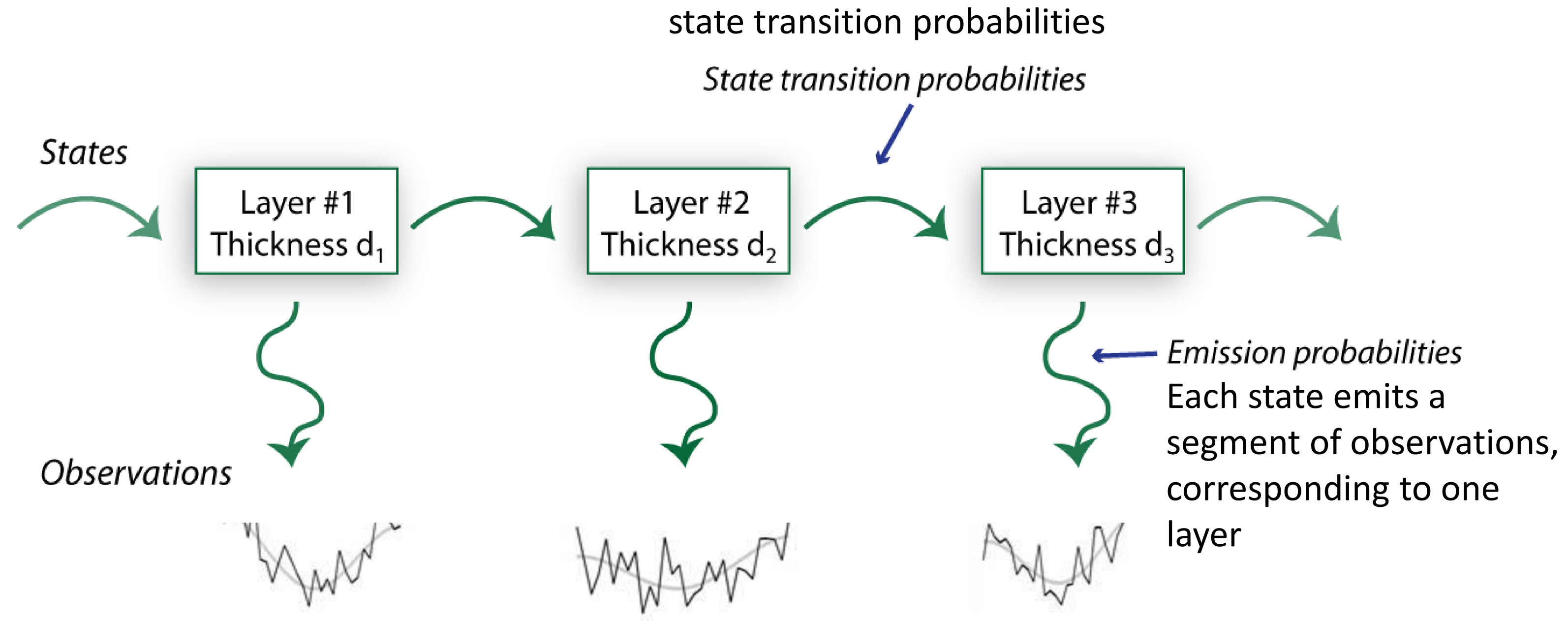
- The most likely positions of multiple layer boundaries in an entire section of data are determined simultaneously.
- An uncertainty estimate on the resulting annual layer count is provided, thereby ensuring objective treatment of ambiguous layers in data.
- Model parameters used as input for the algorithm can be optimally selected according to the appearance of layers in the data.
- Multiple data series can be incorporated and used simultaneously.

In this study, the automated layer counting algorithm has been applied to sections of the visual stratigraphy record from the NGRIP ice core, Greenland, as obtained using a line-scanner (figure 1). A layer is described by a generalized template (figure 2). The results are shown in figure 5 and table 1.

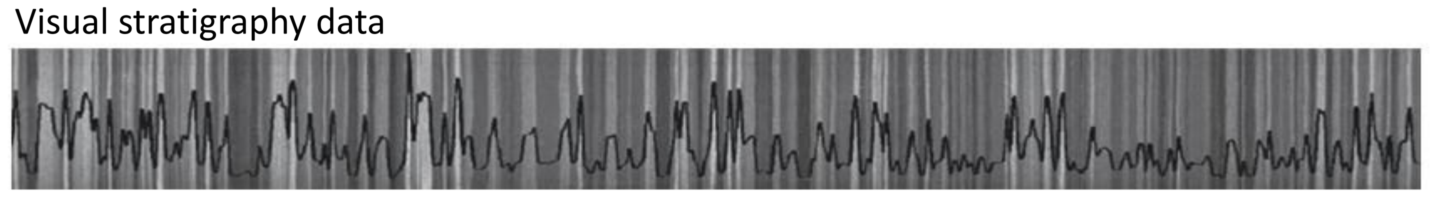
Figure 3: A Hidden Markov Model (HMM) for annual layer detection

The succession of layers ("states") can be viewed as a degenerated Markov chain. The states are "hidden", as they are not directly observed, but they are constrained by observations.

The thickness of an annual layer has a prescribed probability distribution, which is reflected in the state transition probabilities

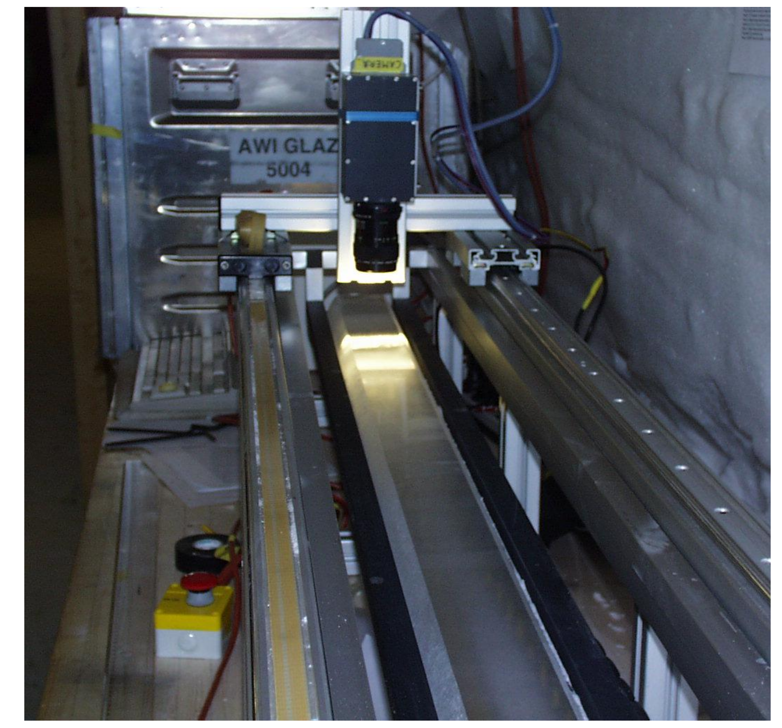


Visual stratigraphy data



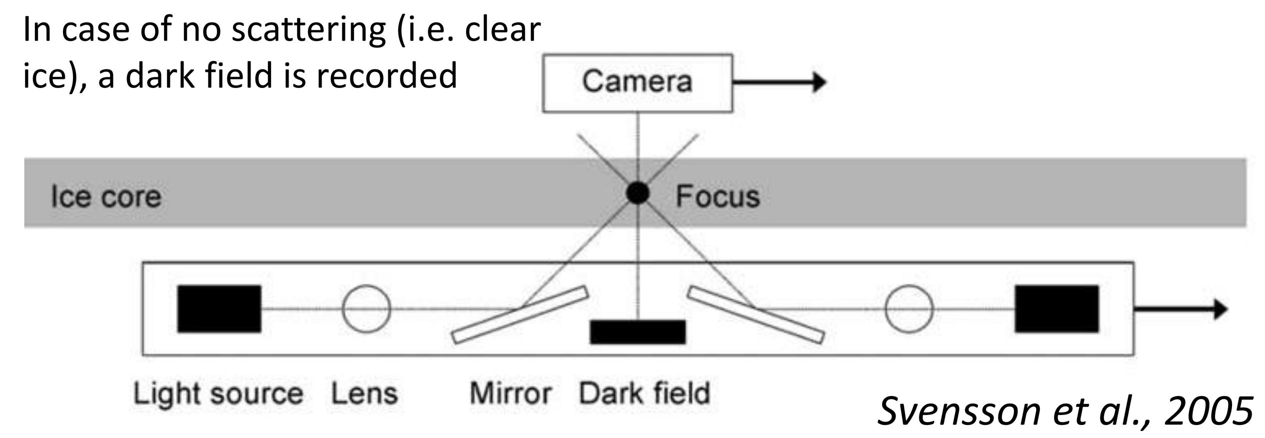
Based on the entire sequence of observations, the algorithms of HMMs can be used to infer the corresponding most likely state sequence along with its uncertainty. This is the depth-age relationship.

Figure 1: The line-scanner



The line-scanner provides high-resolution images of the visual stratigraphy of an ice core. A camera detects the amount of light that is scattered by the ice. The scattering is caused by impurities, mainly dust particles.

The camera is mounted on a trolley

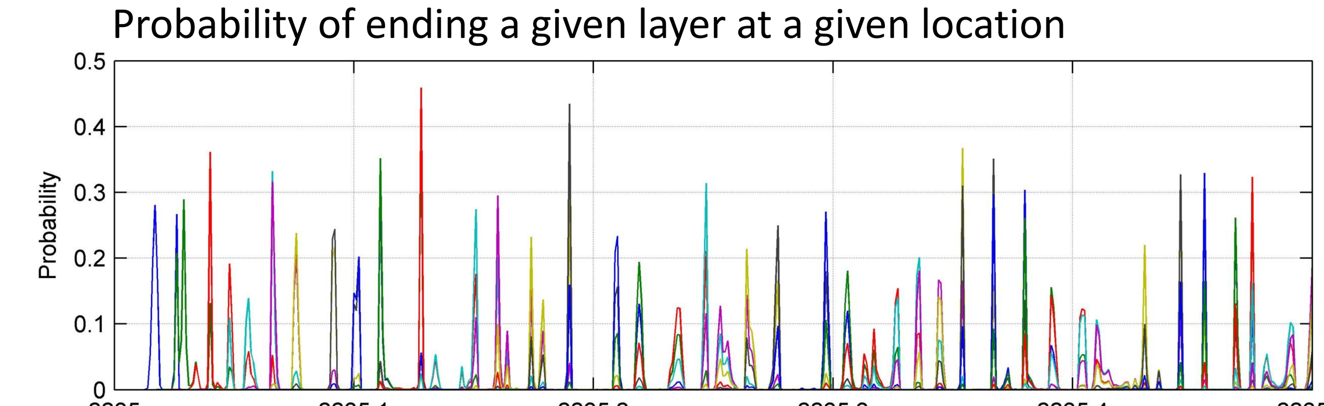


Svensson et al., 2005

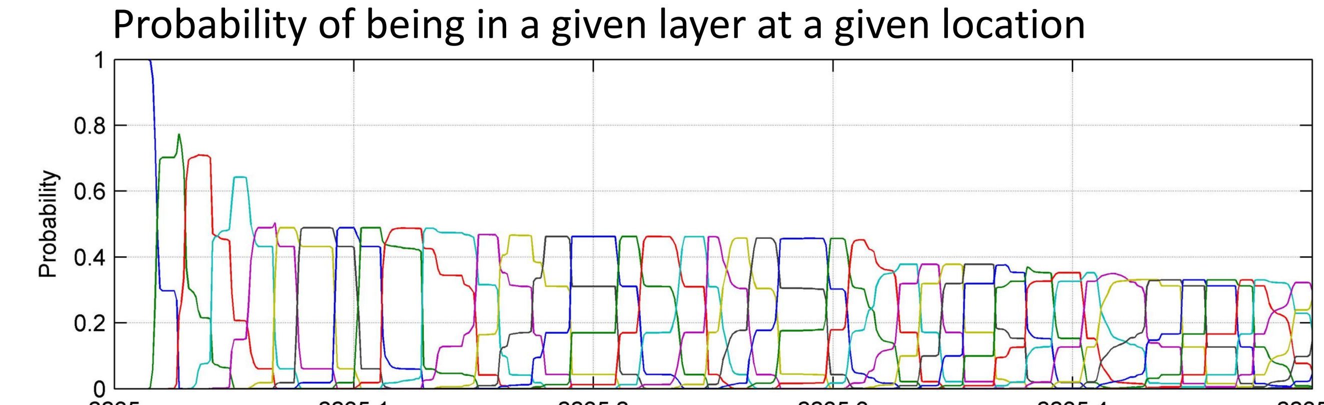
Figure 4: Output from layer detection algorithm

Each color corresponds to a particular layer.

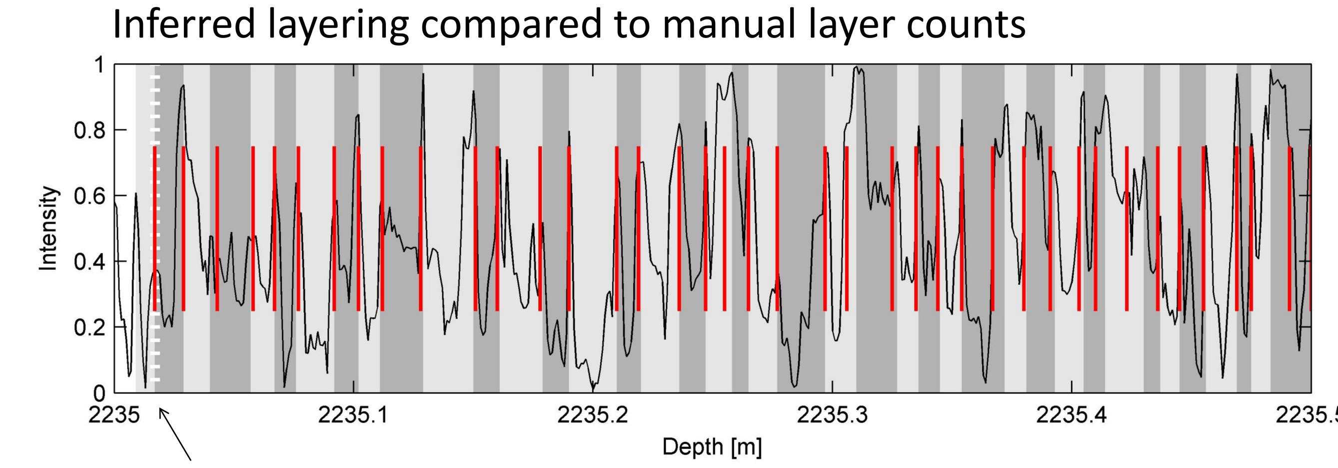
Probability of ending a given layer at a given location



Probability of being in a given layer at a given location



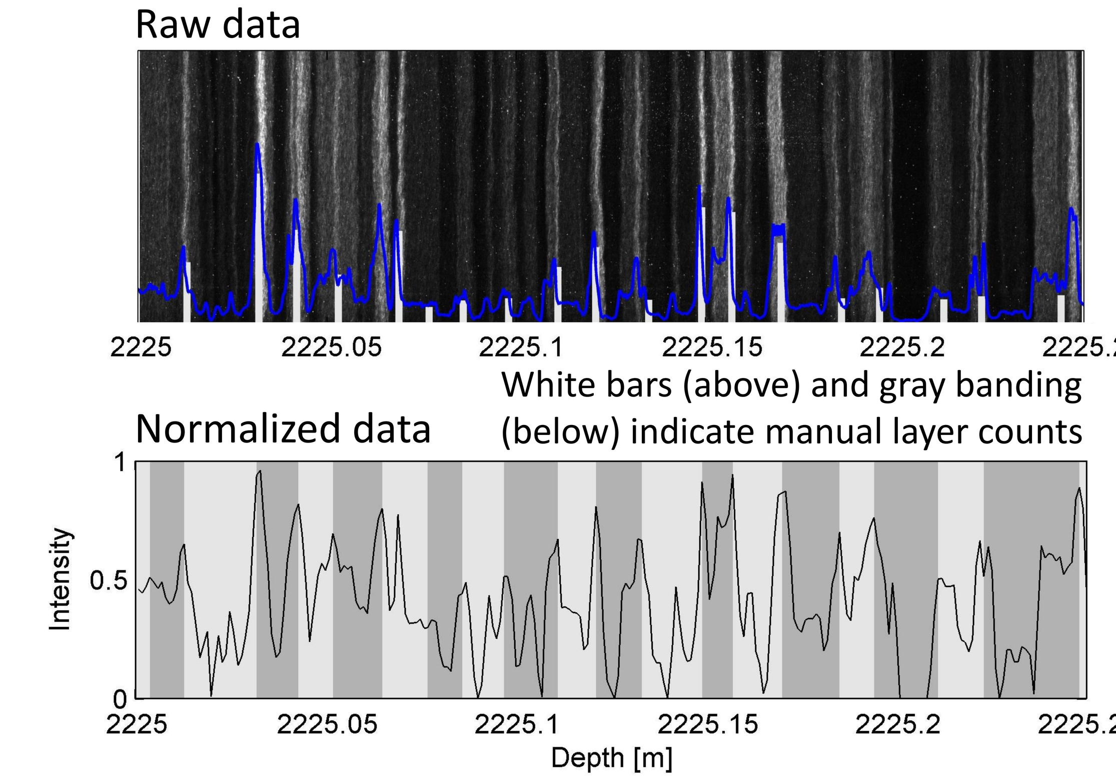
Inferred layering compared to manual layer counts



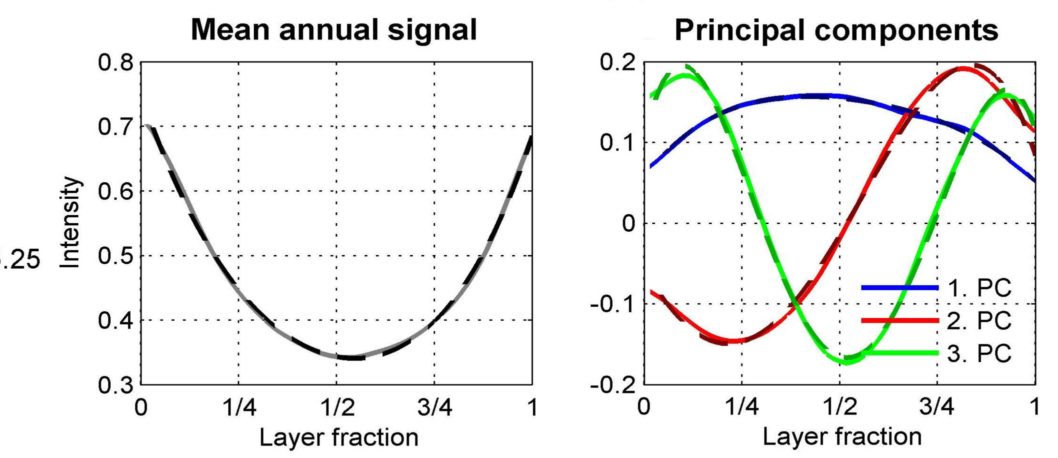
"Uncertain layer" Gray banding indicates manual layer counts

Figure 2: Characterizing an annual layer in the data

Raw data



Annual layer template is based on principal components

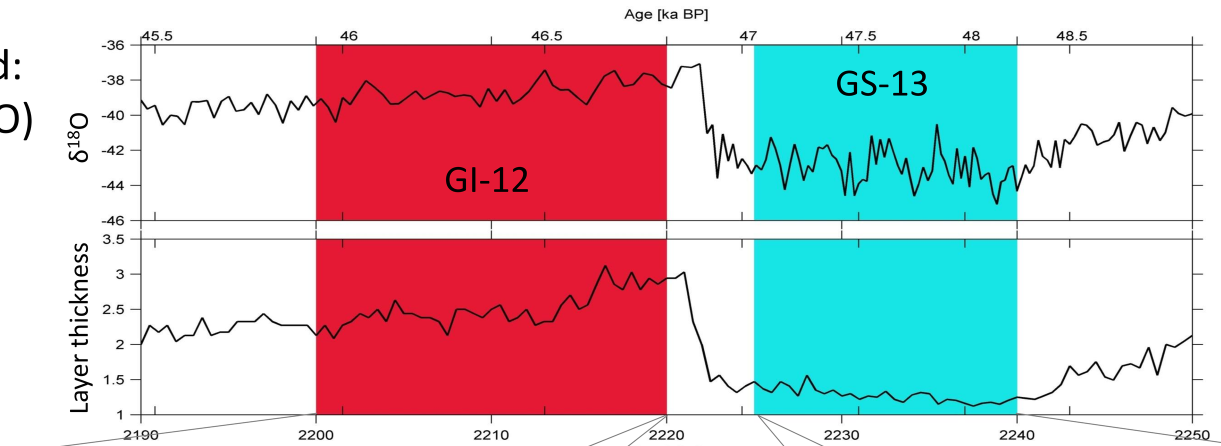


The likelihood that a given data segment is a layer (the "emission probability") is assessed by Bayesian linear regression to the set of principal components.

Figure 5: Inferred annual layers and corresponding layer thicknesses

The algorithm was tested for a data section, where annual layers previously have been manually counted as part of the Greenland Ice Core Chronology 2005 (GICC05). The manual counting was based on a multi-parameter approach, with the visual stratigraphy being one of the components employed.

Section investigated: Climate record ($\delta^{18}O$) and manually obtained annual layer thicknesses



Allowed amount of inter-annual variability in layer shape was estimated from an initial analysis of the uppermost 25% of each section

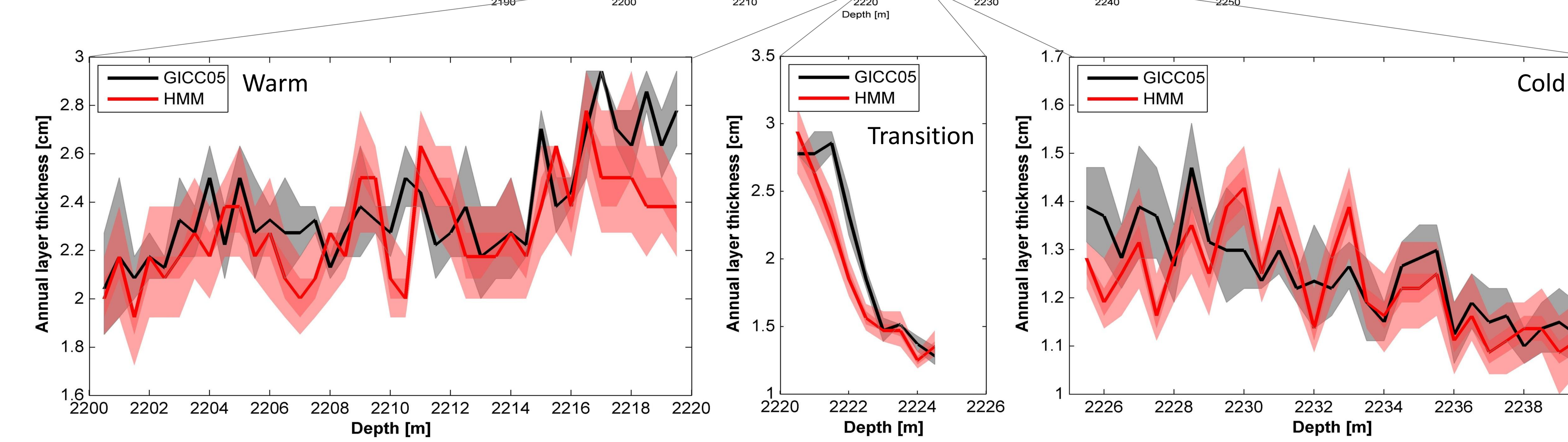


Table 1: Comparison to manual layer counts

Bracketed numbers are estimated 2σ-uncertainties

Epoch	Automated	Manual	Disparity (%)
Warm	(860) 872 (884)	(789) 835.5 (882)	4.3%
Cold	(1212) 1226 (1240)	(1142) 1204 (1266)	1.8%
Transition	(295) 301 (308)	(266) 278 (290)	8.3%

Conclusions and outlook:

The layer detection algorithm is able to identify the annual layering during both cold and warm climate regimes. It shows most skill during cold periods, where the annual layer signal is the most apparent.

The algorithm must next be tested on longer data sections. Using this objective method, it may then be possible to extend the Greenland Ice Core Chronology further back in time.

References: Andersen et al. (2006), *Quaternary Science Reviews* ***25*** *(23-24)*, 3246-3257. Rabiner (1989), *Proceedings of the IEEE* ***77***, 257-286.
Svensson et al. (2005), *J. Geophys. Res* ***110***, D02108.1-11. Yu (2010), *Artificial Intelligence* ***174***, 215-243, DOI 10.1016.

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