The introduction to this work contains a motivation on why the research is of relevance, on what basis the general idea is based upon, and how the method is carried out. Along with this, it contains a brief walk through of the content of the entire thesis, and a short description of what software was developed, and where it is available.

0.1 Ice Cores as a Window to the Past

The studies of ice cores have revealed much information and knowledge about the dynamics of the world's past climate, atmosphere and geology through measured proxies such as isotopic [**?**, W. Dansgaard, 1964], [**?**, S. Johnsen et al., 2001] and chemical compositions, conductivity [**?**, Moore et al., 1990], and dust measurements [**?**, F. Lambert et al., 2008]. By disclosing information about our past, the analysis of ice cores leads us to a greater understanding of the behaviors of the Earth system, which opens up for possibilities of modeling and predicting the future that lies ahead of us.

When analyzing ice cores it is most important that a relationship between depth and age is accurately established, as these timescales are of the essence when building empirical models and reconstructing paleoenvironments [**?**, E. Capron, 2013]. Dating of ice cores can be attempted through a variety of methods: visual inspection of annual layers in data, known volcanic events detected in the ice [**?**, B. M. Vinther et al., 2006] or radiocarbon dating [**?**, S. Aciego et al., 2011], to name a few.

A difficulty, that arises when dating ice cores, is the effects of diffusion through the firn column. Both gas and water molecules can diffuse through the firn which presents a number of obstacles for the continued dating. Firstly, the diffusion of gases in firn, through air pockets connected to the atmosphere, makes the age of the gas in the ice younger than the age of the firn at the same depth. Secondly, the diffusion of solid state molecules present in the firn, like water molecules, erases some of the signal, when measuring different properties of the ice. This erasure is commonly described through the average diffusion length of a molecule at a given depth, σ. This work focuses in particular on the densification and diffusion processes affecting water isotopic ratios in the firn.

The diffusion length σ is affected by a variety of parameters: the depth, the annual average accumulation, the ice flow and - especially inter-

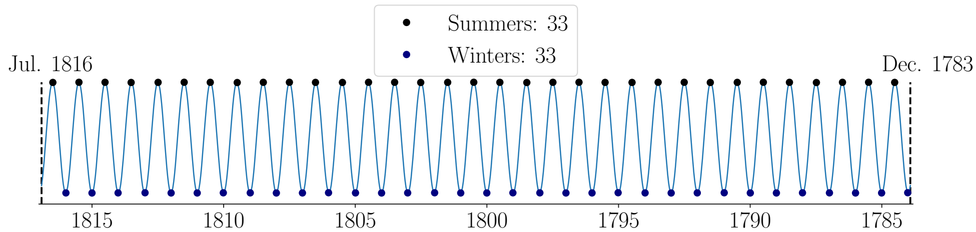

Figure 0.1: Visualization of pattern of summers and winters in the time span between the Laki and Tambora volcanic depositions in Greenland.

esting - the temperature [**?**, C. Holme et al., 2018]. By understanding which parameters influence the behavior of σ, it might be possible to use this signal erasure obstacle to gain more knowledge about paleoconditions: if it is possible to empirically estimate a diffusion length at a given depth, it may be achievable to reconstruct the temperature for this time interval.

The goal of this thesis is to establish a method for estimating the diffusion length for a given depth section. This is achieved through different analyses, and through a hidden gem in the ice cores.

0.2 A Rare Gem of Knowledge

In June 1783 the Icelandic volcano Laki erupted explosively [**?**, J. Steingrímsson, 1998]. The eruption led to an eight-month long emission of volcanic aerosols into the European airspace, bringing climatic and sociological disruptions with it [**?**, R. Stone, 2004], [**?**, T. Thordaldson and S. Self, 2004]. Although a cataclysmic catastrophe for much of Europe, with extreme weather, famine and higher death rates, the violence of the impact on the life of Europeans, led to this eruption being very well documented and recorded across most of Europe. Later, in April of 1815 on the Southern Hemisphere, the eruption of the Indonesian volcano Tambora resulted in a series of events just as, or even more fatal than, the Laki eruption [**?**, C. Oppenheimer, 2003]. Tens of or even hundreds of thousands died either during the eruption or in direct consequences hereof, from starvation or epidemic diseases. Furthermore, the eruption, following a number of decades with heavy volcanic activity [**?**, J. Cole-Dai et al., 2009], left its mark on the climate of the entire Earth system, disrupting global temperatures. In Europe, the following year of 1816 became knwon as *The Year Without a Summer* [**?**], and the apocalyptic climate affected not only the crops and human necessities, but also the artistic and sociological environment of Europe. Writers like Lord Byron (*Darkness* 1816, **??**) and Mary W. Shelley (*Frankenstein* 1815-1818) became inspired by the cold and dark weather [**?**, A. Marshall, 2020], and painter J. M. W. Turner was clearly influenced by the change of colour of the world, to a more yellow, brown and gloomy ambiance of the 1816 European summer, for example in the painting *The Eruption of the Soufriere Mountains in the Island of St Vincent, 30 April 1812*, 1815, see Figure **??** [**?**, C. Zerefos, 2007].

Both volcanic events were not only landmarks in European history, but quite literally also left their marks on the Greenlandic ice sheet, by deposition of volcanic material through precipitation. These layers of snow with extra high content of volcanic material shows to be a rare gem of knowledge, hidden in the ice. When measuring ice cores this can be utilized along with a different property of the data signals available through ice core analysis, namely the seasonality of a given parameter.

Some measured signals in the ice cores contain annual cycles. For example, the water isotopic ratios in the firn are sensitive to temperature [**?**, J. Jouzel, 1997], leading to a clear summer-to-winter cycle. This makes it relatively easy to date shallow ice cores as the cycles can be counted, but as diffusion takes place in the firn column, some of this signal is washed away. Luckily, another method can be utilized to date the ice: detection of known volcanic events through electrical conductivity measurements. This reveals a quite unique gem of knowledge: by knowing the time of a certain volcanic event, either through historical observations or through previous ice core synchronization, and matching this with the depth of the detected event in the ice, it is possible to set some very certain dates on the timescale of the ice.

An example of this type of event dating, which is used in this work, is by examining the volcanic eruptions of Laki and Tambora. Both eruptions are, as described, very well historically documented and are visible and detectable in a great number of ice cores [**?**, H. Clausen, 1988], [**?**, C. Langway, 1988]. The deposition in Greenlandic ice cores has been estimated to be in December 1783 for Laki and in July 1816 for Tambora, yielding 33 summers and winters between the two events, see Figure 0.1 [**?**, J. Cole-Dai et al., 2009], [**?**, L. Wei, 2008]. This does not only make it possible to generally date and synchronize different ice cores, but it also allows for in depth analysis of the diffusion and densification processes in the ice.

0.3 Utilizing the Rare Gem

By considering an isotopic depth series situated between two volcanic events, it is possible to back diffuse this series over the known time span in years - or even months - using the diffusion length as a tuning parameter. This is an optimal way to empirically estimate the diffusion length of a given depth interval which makes it possible to obtain a temperature reconstruction of this interval, as σ is temperature sensitive [**?**].

The goal is thus to reconstruct the lost signal by a back diffusion scheme, tuning σ of the diffusion process, until the known actual number of winters/summers between the events can be counted as peaks and valleys in the depth signal. Then the estimated optimal diffusion length can be used to make a temperature estimate of the given interval. The back diffusion method is built on both empirical models and signal analysis of the measured data. A simplified flowchart of the general idea is illustrated in Figure 0.2.

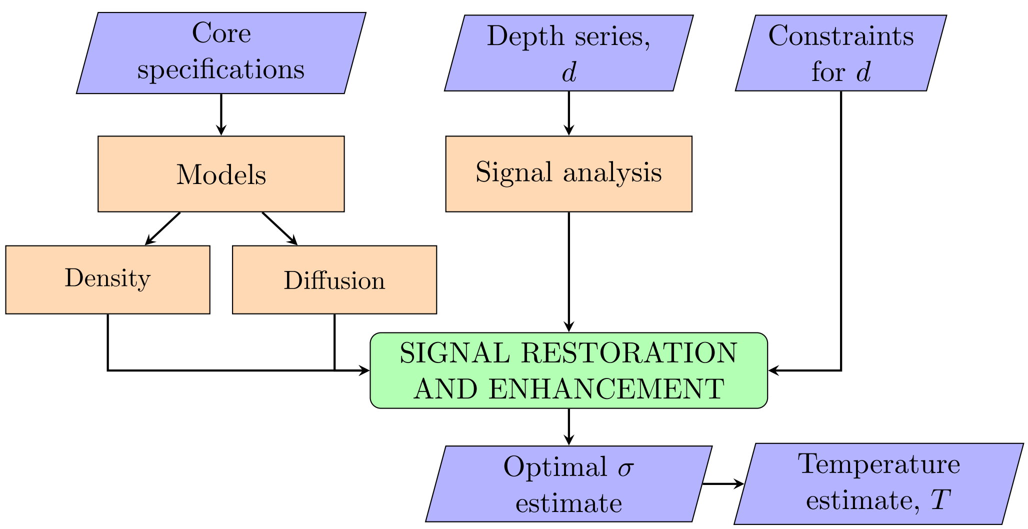

Figure 0.2: Illustration of the general idea, restoring signal by tuning the diffusion length until the expected number of years is detectable in the depth interval.

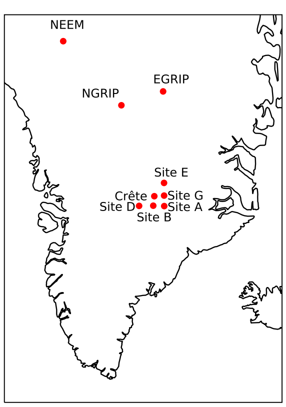

Figure 0.3: Location of Alphabet cores along with some major ice cores, NEEM, EGRIP and NGRIP.

The data under consideration in this thesis is mostly shallow ice cores, namely the Alphabet cores drilled in the vicinity of the 405 m Crête ice core [**?**, H. Clausen and C. Hammer, 1988].

The spatial locations of Crête, the alphabet cores and three other major ice cores, the NEEM [?], NGRIP [?] and EGRIP [?] cores, can be seen in Figure 0.3.

0.4 Reading Guide

In this thesis, Chapter **??** contains an introduction to the theory of diffusion of water isotopes in ice cores along with theoretical and empirical methods for modeling densification and diffusion profiles. Following, still in Chapter **??**, is a brief examination of different experimental methods for detection of deposited volcanic material and which methods have been used for the data under inspection. The chosen data are then presented in Chapter **??**, along with an argumentation of why they were selected. Then a thorough presentation of the data and signal analysis along with important computational methods are presented in Chapter **??**. These different tools are then combined in the method description in Chapter **??**, depicting a walk-through and testing of the final algorithm developed for estimating the diffusion length given the specific number of years. The final method is tested, and further discussed, developed and fine tuned, still in Chapter **??**, and results from the final iteration of the method are presented along with a statistical analysis of variations in the final estimates in Chapter **??**. On the basis of these results, finally, a basic temperature reconstruction of the examined depth intervals for the ice cores is presented. Finally, a walk through of the most important conclusions and an outlook to future research is given in Chapter **??**.

Chapter **??** contains already existing material, as it is a walk through of the theory of ice cores developed throughout the last century. Chapter **??** contains, as mentioned, a description of data, which is per se not new material, as the ice cores in focus were drilled and analyzed in the 1970's and 1980's, but some small corrections were made to the estimates of the locations of the volcanic events. Chapter **??** contains a presentation of the existing computational methods utilized, but also a walk through of how the choices of methods and parameters affect the final method. In Chapter **??** the newly developed back diffusion method is presented along with a discussion of various subjects in the thesis.

0.5 Software

All computational analysis carried out in this work is implemented through `Python v3.8.10`. All code is available on GitHub repository by T. Quistgaard, Master's Thesis, (2021), GitHub repository: https://github.com/TheaQG/AWI_Bcores_Analysis. The main modules implemented are:

- Herron-Langway densification model, Section **??**, in file `HL_AnalyticThea_class.py`.
- Diffusion length profile model, Section **??**, in files `DiffusionProfiles_calculations.py` and `Diffusivity.py`.
- Interpolation methods, Sections **??** and **??**, in file `Interpolation_Class.py`.
- Signal attenuation and annual layer thickness estimation, Section , in file `SignalAttenuation.py`.
- Spectral transforms and analysis, along with general deconvolution/back diffusion method, Sections **??**, **??** and **??**, in file `Decon.py`.
- The final optimization module, along with the constrained peak detection method, Sections **??** and **??**, in file `BackDiffuse_LT.py`.
- Final temperature estimates, Chapter **??**, in files `sigmaSolver.py` and `TemperatureEstimates.py`.

The modules are all described in depth in the corresponding sections referred to, and the connections between modules are illustrated in Figures **??** and **??**. Along with the presented files are a number of files containing code for testing the different modules and for generating the final results.