**Comparison of Carbon Dynamics**

**in two Icelandic Glacial Rivers:**

**Vestari-Jökulsá and Virkisá**

Submitted in partial fulfilment of the requirements

for the degree of Master of Science in Physical Geography

Submitted by: **Sophia Kokkas**

Student ID: **2654520**

Supervisor: Prof. Dr. Peter Chifflard

Second Supervisor: Ann-Kathrin Wild

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**Philipps University Marburg**

**Department 19 – Geography**

Abstract

Comparison of Carbon Dynamics in two Icelandic Glacial Rivers: Vestari-Jökulsá and Virkisá

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  + Chifflard (weil mans halt so macht, dass er so nen nettes Forschungprojekt hat) für die große Freiheit und den guten Geschmack an Forschungsprojekten
  + AK und Alicia
  + RG Hot Pot, RG Gletscher (Gruppenfoto)
* ~~Mention~~ **~~funding sources~~** ~~(if applicable).~~
* Appreciate **collaborators and colleagues**.
  + Jonas
  + Maria for the English help
  + AI: getting to utilise working in the future and scraping their incapacities.(See Appendix)
* Express gratitude to **friends and family** (optional but common).
  + Family and friends
    - My brother for paying for chatgpt prime
* Keep it professional and concise.

For the final English, which is a language more complicated as I thought, I want to thank Rita and Maria

I did scientific work and used AI, which, even with the premium (thanks, Konsti, for letting me use your Pro-account), while the AI isn’t as clever as it seems. I mainly used it for inspiration and coding help. Glaciers will have gone, and some water will have gone down the glacial rivers. Glaciers will be lost until they fully replace humans, and for sure not for field work.

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Ein Bild, das draußen, Himmel, Wasser, polare Eiskappe enthält.

KI-generierte Inhalte können fehlerhaft sein.Ein Bild, das draußen, Himmel, Schuhwerk, Wolke enthält.

KI-generierte Inhalte können fehlerhaft sein.

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List of Abbreviations (in logical/order of appearance)

UMR University of Marburg

OM organic matter

POM particulate organic matter

DOM dissolved organic matter

~~SOM solid organic material~~

OC organic carbon

DOC dissolved organic carbon

POC particulate organic carbon

BDOC bioavailable dissolved organic carbon

VJR Vestari-Jökulsá River

AJR Austari-Jökulsá River

VR Virkisá River

TOC

Research projects (UMR 2025)

Longitudinal variation of macroinvertebrate assemblages in Icelandic arctic glacier-fed and snow-fed streams: changes and their environmental drivers – a comparison after 26 years

PhD student: Alicia Knauft

*Funded by the German Research Foundation; Duration: 2021-2024; Project and cooperation partners: Prof. S. Pálsson (University of Iceland), J. S. Ólafsson (Marine and Freshwater Research Institute, Reykjavik), Dr C. Fasching (University of Marburg)*

Elucidating the temporal variability of glacial organic carbon concentration and composition toward determining carbon export via discharge separation and machine learning techniques (Falljökull, Iceland)

PhD student: Ann-Kathrin Wild

*Funded by the German Research Foundation; Duration: 2021-2024; Project and cooperation partners: Prof. Dr G. Gíslason, (University of Iceland), Prof. Dr A. Hartmann (TU Dresden), Þ. Þorsteinsson (Icelandic MET Office)*

# Introduction

# Background and Context

- Overview of the importance of studying dissolved organic carbon (DOC) and biodegradable dissolved organic carbon (BDOC) in glacial rivers.

- The role of glacial meltwaters in global carbon cycles.

- Introduction to Vestari-Jökulsa and Virkisa rivers.

Ein Bild, das Text, Karte, Atlas, Screenshot enthält.

Automatisch generierte Beschreibung

Fig. 1: location of the two rivers with the respective sampling sites

topographical map of Iceland.

<https://gatt.natt.is/geonetwork/srv/eng/catalog.search#/metadata/e6712430-a63c-4ae5-9158-c89d16da6361>

Coordinate system EPSG:3057 - ISN93 / Lambert 1993

# Significance of the Study

- Discuss the contribution to physical geography and environmental sciences.

- Implications for understanding carbon dynamics in glacial environments.

Iceland’s glaciers are under-studied in terms of DOC and BDOC dynamics, with little focus on regional river systems like Vestari-Jökulsá and Virkisá.

Structure of the Thesis - Briefly outline the content of each chapter.

In addition, both the Hofsjökull and Vatnajökull ice caps are among the best studied and have the longest running mass balance monitoring programmes in Iceland. So, despite their relatively modest contribution to the global glacier and ice cap volume - which stands at only a few per cent - glaciers in Iceland are of significant scientific interest due to being very well-monitored and the insights they offer into the response of glaciers in maritime climate zones to climate change. (Aðalgeirsdóttir et al. 2006)

Projections indicate that within a century, the ice caps will have diminished by half and will have fully disappeared within two centuries if the warming rate remains constant. It is also notable that the reduction in volume will be qualitative comparable for the two ice caps, exhibiting a gradual initial decrease that will accelerate with a greater increase in temperature. (Aðalgeirsdóttir et al. 2006)

# Research Objectives and Questions

- Clearly state the aims of the study.

- Formulate specific research questions or hypotheses.

Compare DOC and BDOC between two Icelandic glacial rivers, investigating how catchment features affect carbon dynamics.

Pex.

* How do carbon fluxes (DOC loads) from each catchment compare when normalized by catchment area?
* What landscape or glaciological factors might explain any observed differences?

# **Literature Review**

The study of glacial DOC represents a relatively recent area of research. The dynamics of DOC and BDOC vary geographically, and the present review will mention studies conducted in Greenland, Svalbard, Alaska, Canada, Asia, Antarctica, the Alps, and Iceland. Glacial DOC contributes to the global carbon cycle, and this research aims to add to the understanding Icelandic glacial DOC export.

# Dissolved Organic Carbon (DOC)

In water, organic material (OM) is present in dissolved (DOM) form, which originates i.a. from decaying plants, soil and microbial biomass, as well as leachate, but also in the *solid phase of soils and sediments* (SOM). While the alterations in SOM composition take time (p.ex. ageing

of sediments), chemical properties and composition of DOM are subject to faster change and are influenced by hydrology with snowmelt for example (Gabor et al. 2014).

OM in natural waters has been classified as either, dissolved or particulate organic carbon by filtration (typically with 0.2-1.2 μm filters). This distinction is a practical/ operational rather than a natural one. (Aiken 2014)

# Biodegradable dissolved Organic Carbon (BDOC)

* how BDOC differs from total DOC.
* Discuss microbial processing of DOC and how its composition affects **biodegradability**.

**Lutz et al. (2015)** – Microbial influence on DOC bioavailability in Icelandic glacial environments​

**Stibal et al. (2008)** – Microbial primary production in Svalbard glaciers and its impact on DOC cycling- wants further studies

**~~Holt et al. (2024)~~** ~~– Microbial preference for young carbon in glacial DOC​​~~

- Definition and its role in aquatic ecosystems.

- Methods of measuring BDOC.

# DOC and BDOC in Glacial Rivers

DOC in glacial rivers is impacted by different factors i.e. hydrology, temperature, microbial activity and seasonal discharge variations. That way, DOC varies not only seasonally in glacial fed rivers (Spencer et al. 2014; Chifflard et al. 2024) but also diurnal (Chifflard et al. 2024).

# Sources of DOC in glacial rivers

Externally derived (allochthonous) sources include the deposition of organic material from the atmosphere, such as anthropogenic aerosols (Fossil fuel combustion byproducts / biomass burning byproducts), or natural organic materials (poles, soil particles and plant residues) transported by wind. In addition, wind-borne material from proglacial soils and vegetation in proximity to glaciers has been identified. (Holt, Kellerman et al., 2023; Holt, McKenna et al., 2024)

Internal derived (autochthonous) sources are microbial production (supraglacial and subglacial) as well as glacier overrun and leaching of subglacial organic material. (Holt, Kellerman et al 2023; Holt, McKenna et al 2024)

Another process is photochemical degradation, where ultraviolet radiation converts aromatic organic compounds into simpler, aliphatic compounds (Holt, Kellerman et al. (Holt, Kellerman et al. 2021)

The relative interaction of these different sources and processes determines the concentration, composition and age of the DOC pool in glaciers. Regional differences in the sources of anthropogenic emissions and in-situ production lead to global diversity in the composition of glacier DOM. (Holt, McKenna et al 2024), (Behnke et al. 2021; Holt, Kellerman et al. 2021; Holt, Kellerman et al. 2023; Holt, McKenna et al. 2024; Hood et al. 2009; Musilova et al. 2017; Smith et al. 2017; Spencer, Vermilyea et al. 2014; Stubbins et al. 2012; etc.)

# DOC in glacial rivers around the world/in different locations

As elaborated above, there exists a global diversity in the composition of glacier DOM. That’s why various studies on DOC and BDOC in glacial rivers did not only focus on different aspects like the composition, sources and exports but were also centred on different geographical locations:

Hood et al. (2009, 2020) and Behnke et al. (2021) focused on **Alaskan** glaciers as DOC sources.

Like Bhatia et al. (2010, 2011, 2013), Kellerman et al. (2020, 2021) concentrated on the molecular composition and the seasonal dynamics of the DOC fluxes of the **Greenland Ice Sheet**. And Lawson et al. (2014) identified the Ice Sheet as a significant DOC source.

Kulinski et al. (2014) addressed the DOC transport into Arctic fjords on **Svalbard**, while Zhu et al. (2016) researched the high bioavailable properties of the exported DOC there.

Yu et al. (2021) compared glacial and permafrost DOC fluxes from the **Tibetan Plateau**, while Zhang et al. (2018) noted the anthropogenic influences on the DOC depositions there.

Smith et al. (2017) studied DOC in **Antarctic** glaciers.

Concerning **Alpine** glaciers, Singer et al. (2012) studied the bioavailability of DOC, while Boix et al. (2019) focus on climate-driven DOC shifts.

For **Iceland**, Chifflard et al. (2019, 2024) elaborated on DOC flux estimates (2019) with distinct seasonal/diurnal variability in DOC composition (2024).

# Analysing DOC and BDOC in Glacial Rivers

The DOC concentrations in various studies mentioned above, were mainly determined by high-temperature combustion in different models of Total Organic Carbon Analyser. For the characterisation of the DOM quality Fluorescence spectroscopic methods were also used in some studies which will be the subject of this chapter.

Most of the compounds of DOM and SOM can be differentiated by their light absorbing, chromophoric, or also light emitting, fluorophoric properties. To the chromophoric fractions of organic material count the humics: yellow to brown colour influenced by the content of aromatic carbon moieties, from plant litter and soil and to a lesser extent microbial biomass. Another one is the proteinaceous material, frequently including fluorescent amino acids, to be precise, tryptophan and tyrosine, from decomposition of plant material and extracellular microbial products (Gabor et al. 2014).

DOM composition influences the location of excitation and emission peaks. The excitation spectrum of DOM fluorescence ranges from 250 to 400 nm, with a corresponding emission spectrum ranging from 350 to 500 nm. (Stedmon & Bro 2008)

Fluorescence, recorded across a range of emission wavelengths while exciting the sample at various wavelengths, results in three-dimensional scans known as excitation–emission matrices (EEMs) (Gabor et al. 2014).

### Different fluorescence indices

By analysing the wavelength ranges of absorption and emission most chemical information on the origin and the chemical quality of DOM can be obtained. For this reason, **different fluorescence indices** have been developed (Gabor et al. 2014):

Generally, concerning the humic-like fluorescence signal (peak C), these indices assess either the location or the magnitude or compare its intensity to that of a microbially derived, or protein-like, peak (peak T and/or M). (Gabor et al. 2014)

For marine environments, the fluorescence properties of DOM proved valuable for its characterization, even at low DOC levels (Coble, 1996). **Coble** identified typical fluorophores found in both marine and coastal waters, categorizing five distinct fluorescence peaks as either protein-like or humic-like (Table 1) (Gabor et al. 2014). Building on this research, aquatic scientists developed fluorescence indices to help interpret changes in the quality of (DOM) in natural waters (Gabor et al. 2014).

Concerning the age of DOM, Parlanti et al. (2000) established the “**freshness index**” (Gabor et al. 2014) and demonstrated that fluorescence can be applied to measure the level of biological activity but also to identify its various stages (Parlanti et al. 2000) and renamed the **peaks of Coble** (1996) (detected fluorescence peak areas in an excitation–emission spectrum of aquatic DOM, Table 1).

Table 1: detected fluorescence peak areas

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Component** | **ex (nm)** | **em (nm)** | **Coble (1996)** | **Parlanti et al. (2000)** |
| Humic-like | 330–350 | 420–480 | C | α |
| Humic-like | 250–260 | 380–480 | A | α’ |
| Marine humic-like | 310–320 | 380–420 | M | β |
| Tyrosine-like, protein-like | 270–280 | 300–320 | B | ɣ |
| Tryptophan-like, protein-like/phenol-like | 270–280 | 320–350 | T | δ |

With: em = emission wavelengths, ex = excitation wavelengths, (Parlanti et al. 2000)

From there, Huguet et al. 2009, concerning riverine, or more specifically estuarine environments developed the **β/α,** thenrenamed **BIX Index,** (Gabor et al. 2014) the “index of recent autochthonous contribution (BIX)” (Huguet et al. 2009), to identify the β fluorophore which indicates biological activity is occurring (Huguet et al. 2009). High BIX values (>1) indicate that dissolved organic matter (DOM) primarily originates from local biological processes and represents recently produced organic material. Conversely, lower BIX values (0.6–0.7) reflect reduced DOM generation within natural aquatic systems (Table 2). (Huguet et al. 2009)

Table 2: BIX-Index

|  |  |
| --- | --- |
| **BIX values** | **DOM characteristics** |
| 0.6–0.7 | Low autochthonous component |
| 0.7–0.8 | Intermediate autochthonous component |
| 0.8–1 | Strong autochthonous component |
| >1 | Biological or aquatic bacterial origin |

(Properties of DOM linked to the variability in BIX values (from the Mediterranean Sea, Huguet et al. 2009 after Parlanti et al. 2006)

Zsolnay et al. (1999) introduced a **humification index**, **HIX index** which links greater humification to longer emission wavelengths and lower H/C ratios, and reflects how extensively the organic matter was humified (Gabor et al. 2014 :311) The HIX is a reliable method for evaluating how humified organic matter is (Ohno 2002) and assess how extensively DOM in soil has matured (Table 3) (Huguet et al. 2009).

Table 3: Humification Index

|  |  |
| --- | --- |
| **HIX values** | **DOM characteristics** |
| >16 | Strong humic character/ important terrigenous contribution |
| 6–10 | Important humic character and weak recent autochthonous component |
| 4–6 | Weak humic character and important recent autochthonous component |
| <4 | Biological or aquatic bacterial origin |

Properties of DOM linked to the variability in HIX values (from the Seine, Loire and Gironde estuaries, Huguet et al. 2009 after Vacher 2004)

In natural water bodies, DOM is largely made up of aquatic fulvic acids which are heterogenous and organic. McKnight et al. 2001 established a **fluorescence index (FI)** to qualify the original source and chemical characteristics of dissolved fulvic acid. (In contrast, concerning the origin of the nonhumic components of DOM, the FI is possibly not of use and other data is needed.) The emission peak of fluorophores in fulvic acids of microbial origin appear at shorter wavelengths then the one of fluorophores in fulvic acids of terrestrial origin. The FI is based on the ratio of fluorescence emission intensities measured at 450 nm and 500 nm wavelength (with excitation at 370 nm), to differentiate the origins of aquatic fulvic acids. (McKnight et al. 2001 :39:47). In their study, McKnight et al. 2001 obtained ~1,9 as value for fulvic acids originating from microbes, and of ~1.4 for terrestrial origin (Table 4).

Table 4: Fluorescence Index

|  |  |
| --- | --- |
| **FI value** | **DOM characteristics** |
| ~1,9 | microbially derived fulvic acids |
| ~1.4 | terrestrially derived fulvic acids |

McKnight et al. (2001) also pointed out that the range of index values would vary depending on the instrument used.

Additionally is mentioned here the chromophoric index, the Specific UV absorbance (SUVA). It is defined as the UV absorbance of a water sample at a given wavelength normalized for dissolved organic carbon (DOC) concentration. SUVA254, (L mg⁻¹ m⁻¹), is calculated by dividing the water sample's absorbance at 254 nm by its DOC concentration (mg L-1). It reflects the overall aromatic character of the sample. (Gabor et al. 2014 :304, Weishaar et al. 2003)

### Analysing the EEMs

A common way of presenting DOM fluorescence data is with excitation–emission matrices (EEMs). Statistical multivariate data analysis techniques like the **parallel factor analysis (PARAFAC;** Stedmon et al. 2003, 2008), analyse the entire EEM datasets to pinpoint spectral features and assess how different excitation/emission regions contribute to the overall fluorescence profile. (Aiken 2014) PARAFAC assists in analysing fluorescent DOM by breaking down the fluorescence matrices into distinct, independent components. (Stedmon et al. 2003)

The advantage of PARAFAC is if the model is accurate, it will produce results that have real chemical significance. (Murphy et al. 2014)

canonical decomposition or CANDECOMP

PARAFAC is one of the multi-dimensional methods designed to work with data arranged in three or more dimensions as for example, fluorescence EEMs—which are structured by sample, excitation wavelength, and emission wavelength. (Murphy et al. 2013)

PARAFAC yields a model that captures both the quantitative and qualitative aspects of the dataset, unravelling the complex fluorescence signal into its constituent components—each defined by its own excitation and emission spectrum. (Stedmon & Bro 2008)

It serves as a powerful method for profiling and measuring shifts in DOM fluorescence, thereby allowing different fractions to be tracked in natural environments. (Cory & McKnight 2005)

Concerning the interpretation of the data, it is impossible to convert the fluorescence of every component into a concentration, as the component identity is not known. The peak fluorescence intensity of each component can be determined and expressed in the same calibration units—such as Raman units. The greater fluorescence signal in one component, may indicate higher fluorescence, not concentration, as fluorescence depends also on unknown molar absorptivity and quantum efficiency. Quantitative and qualitative differences among samples are revealed by comparing the relative fluorescence intensities of each component and their ratios. (Stedmon & Bro 2008)

Lawson

# Overview of Icelandic Glaciers and glacial rivers

Despite its high latitude, Iceland experiences a relatively mild climate, largely due to a branch of the Gulf Stream that flows along its southern and western shores. Precipitation levels vary widely across the country, with the southern regions being generally warmer and wetter. The greatest amounts of precipitation are typically recorded on the island’s glaciers. (Helgason & Nijssen 2024 :2743). So due to high precipitation and low evaporation, Iceland’s annual river runoff is estimated to be nearly four times the global average (Gíslason, 2008).

The central highlands make up around 40% of the island’s total area, while glaciers and ice caps cover approximately 10%. Vatnajökull, Europe’s largest ice cap outside the polar regions (~7700 km²), lies in the island’s southeast. Two additional ice caps, Langjökull (~835 km²) and Hofsjökull (~810 km²), are situated in the central highlands, while Mýrdalsjökull (~598 km²), is situated near the central southern coast of Iceland. (Helgason & Nijssen 2024 :2743; Hannesdóttir et al. 2020)

Being two largest of the four major icecaps in Iceland, **Hofsjökull** (900 km2) and **Vatnajökull** (8100 km2) cover ca. 10% of the country. Hofsjökull, situated in Iceland’s central highlands, spans elevations from 600 to 1800 meters above sea level and overlays a volcanic caldera. While Vatnajökull stretches along the southeastern coast, with a peak elevation of over 2000 meters. (Aðalgeirsdóttir et al. 2006).

Glacial meltwater contributes to at least one-third of Iceland’s total runoff, supplying the country’s major rivers (Björnsson & Pálsson 2008).

By the end of this century, river runoff in the region is expected to rise by approximately 50%; however, it will decline thereafter as the ice caps continue to shrink. This anticipated surge in glacial runoff represents one of the most significant hydrological impacts of future climate change in Iceland. (Aðalgeirsdóttir et al. 2006)

As far as the outlet glaciers of the two glacier rivers that are the subject of this study are concerned, the northern outlet glacier at Hofsjökull will generally be less susceptible to climate warming than the southern outlet glacier at Vatnajökull ice cap, as it reaches lower altitudes Projections indicate that both the ice caps and the outlet glaciers are set to disappear over the course of the next two centuries, with the climate warming, first retreating slowly and then faster. (Aðalgeirsdóttir et al. 2006).

Not only are glacier-fed rivers the most extensive ones but also the ones with the greatest discharge, marked by dark, cloudy waters rich in suspended sediments, while other types of rivers have generally clear water. These glacial rivers start to swell in June, with summer floods transporting large volumes of sediment. (Louvat et al. 2008 :682)

Glacier rivers are characterised by specific biotic and abiotic conditions, such as no primary organic production, with inputs originating exclusively from allochthonous sources. Moreover, there is extremely low temperatures with minimal diurnal temperature range. They also exhibit high water velocity, substratum instability and a considerable abundance of transported material, including gravel, sand and stones. (Steffan 1971: 485) These eroded sediments from the glaciers present a significant challenge to the accurate measurement of hydrological data. In addition to the corruption of sensors by burying and jamming, the formation of braided channels and highly erodible riverbeds further complicates the processes. (Bergur 2012: 8)

Kjartansson (1945) **grouped Icelandic rivers** into three categories according to their origin: glacial, direct-runoff, and spring-fed rivers, with many rivers representing a combination of these types. (Helgason & Nijssen 2024 :2744)

Rist (1990) introduced a classification system through which rivers in Iceland can be categorized by the extent of the origin and source of their runoff; with D - direct runoff, J - glacial runoff, L - groundwater and S if they flow through a lake. The first letter is indicating the primary source of runoff (Jónsdóttir et al. 2008 :428)

Petersen et al. (1995 :329) classified lowland rivers in Iceland as alpine, noting that their environmental conditions are like those found in alpine regions of central Europe, or as arctic.

# Study Sites

The selection of the two glacial rivers, Vestari-Jökulsá and Virkisá (Fig. 1) combines the study sites of two research projects currently being conducted by the Soil and Water Ecosystems working group at the University of Marburg's Department of Geography. At the Vestari-Jökulsá river (VJR), located in the northern region of Iceland, longitudinal changes in macroinvertebrate assemblages are studied[[1]](#footnote-1) (Fig. 2). Concerning the Virkisá River (VR) in the south of the island, the variability of the concentration and composition of organic carbon is being assessed and modelled[[2]](#footnote-2) (Fig. 3). (UMR 2025)

# Vestari-Jökulsá River

The Vestari-Jökulsá River (or West-Jökulsá) originates from the Sátujökull Glacier, an outlet glacier north-west of the Hofsjökull Ice cap in the central highlands of Iceland (Fig. 1).

Hofsjökull, among the country's most extensive ice caps, covers an active central volcano that features a caldera filled with ice, with its peak exceeding 1,600m.a.s.l. (Björnsson & Pálsson 2008 :369). Sátujökull is a surge-type glacier (Evans et al. 2010, Ingólfsson et al. 2017 :54)

The origin of the VJR is D+J+L (Crochet 2015 :8), with D - direct runoff, J - glacial runoff and L – groundwater (classification by Rist (1990), see above).

The river's course, from the glacier (on ca. 900m.a.s.l.) to its confluence with the Austari-Jökulsá River (AJR) (on ca. 160m.a.s.l.) (Free Map Tools 2024), is characterised by a slope that ranges from 5-10 ‰ for most of its journey (in the upper, middle and lowland reaches (below 200m.a.s.l.)). Except for the transition between the Highland plateau and the lowland valley, where the slope increases to approximately 20 ‰ (Gislason et al. 2000 :411).

It is possible that some topographic activity under the ice cap of Hofsjökull before the beginning of the Holocene caused the river to be diverted from its traditional course in Vesturdalur valley, the valley it originally carved out, into the Goðdaladalur valley, where it now flows in a deep canyon (Hjartarson 2003 :182). The VJR belongs to the main river system Héraðsvötn (Hróðmarsson et al. 2009).

The river catchment is 820 km² at the lowest gauging station (VHM-145) on the VJR (shortly before the conjunction with the AJR) in the lowland valley, which is situated at ca. 45 km from the glacier (Gislason et al. 2000 :412). For most of the river's course, the banks and surroundings are barren and are only covered (grasses, sedges and mosses) when the river flows through the lowlands (Gislason et al. 2000 :414).

The catchment area at the Gauging station VHM-145, which is located approximately where the confluence of the VJR and AJR are. The Watershed drains 850km2, has a mean altitude of 753m.a.s.l. and is mainly characterized by little or no vegetation (63%), grassland (15%) and moss (9%) while 11% of the area glacierized (with a mean glacier latitude of 1269m.a.s.l.) are (wetland and lakes constitute less than 2% of the area) (Crochet 2013 :73).

As the area lies within the glacier's precipitation shadow, the climate is relatively mild by Icelandic standards (Hjartarson 2003 :8)

The VJR has a fixed logger for water level measurements at Goðdalabrú, the Water level gauge 145 (vhm145) (Hróðmarsson et al. 2009).

The annual mean streamflow AQ of the VJR, is 20.6 m3/s (year 1971–2000) (Crochet 2013 :79) The positive significant trend in annual mean streamflow is related to increased glacier melt due to rising temperatures (Helgason et al. 2025).

Concerning the degree of anthropogenic impact, (degree of gauge impact) the catchment attribute is u - no influence (Helgason et al. sup. 2025 :28, adapted from Klingler et al., 2021) Criteria for the different degrees of gauge impact-> no influence (Helgason & Nijssen 2024 :2767).

VJR has carved canyons into the bedrock (Hjartarson 2003 :48) while it traverses first late Pleistocene hyaloclastites, late Pleistocene lavas and then tertiary bedrock (Hjartarson & Saemundsson 2014).

# Virkisá River

The Virkisá River (VR) originates from the Virkisjökull-Falljökull glacier, a high-mass-turnover outlet glacier (Bradwell et al. 2013: 971), draining the Öræfajökull ice cap covering the Öræfajökull stratovolcano (Everest et al. 2017 :937; Mackay et al. 2019 :1835) The accumulation of ice at the summit (∼2000m.a.s.l.) is predominantly drained by this channel (Mackay 2019: 1835). The Öræfajökull ice cap itself is the southern part of the Vatnajökull ice cap (Phillips et al. 2013: 1546)

Virkisjökull-Falljökull can be described as a double glacier, splitting at approximately 1200m.a.s.l., comprising the northern arm, Virkisjökull, and the southern arm, Falljökull. (Everest et al. 2017 :937; Mackay et al. 2018 :2178; Flett 2016 :70). The two glaciers encircle Rauðikambur Nunatak (ca. 600m.a.s.l) (Bradwell et al.2013: 961; Phillips et al. 2013: 1546).

Melting at the glacier terminus can occur at any time of the year, but most mass loss happens during the summer, with the ablation season generally lasting from May to late September. (Flett 2016 :70)

Both glaciers exhibit a considerable quantity of debris-laden ice at their fronts. (Everest et al. 2017: 937) which have their margins at the proglacial lake. On the eastern side the glacier terminus drains via the proglacial foreland surface (Flett et al. 2017: 1667) forming an unconsolidated bed, into the lake. (*Fig. 3*)

On the western side of the VR the topography is hummocky under which a body of old glacier ice. The landscape, formed by slump scars and sinkholes indicating slow collapse processes, is characterised as ice-stagnation topography. (Everest & Bradwell 2003)

The glacial lakebed is composed of buried ice. Sedimentation and changes in water level are the result of two processes: the input of meltwater and rainwater from the surface, and the outflow of water through the buried ice at the bottom of the lake. (Everest et al. 2017: 939)

When buried ice is melting it will have an impact on the catchment hydrology. Concerning the ice-floored lake It is not known at which velocity this ice core will melt and impact significantly the bathymetry of the lake itself. (Flett 2016; Everest & Bradwell 2003)

The low permeability of the bedrock on the opposite side of the lake results in a restriction of discharge within a relatively stable riverbed of the Virkisá river. (Flett et al. 2017: 1667)

The headwater of the Virkisá river is formed by this proglacial lake (Mackay et al. 2019: 1835)

The catchment area has an extent of roughly 31 km² (Flett et al. 2017: 1667; MacDonald et al. 2016: 152).

The glacial lake, by acting as a sediment trap, impacts the river incision into the outwash plains and increases the erosion of the coast. (Flett 2016; Jóhannesson & Sigurðarson, 2005)

Virkisá runs from the glacier terminus across the highly permeable outwash plain, Skeiðarásandur, covering about 30 km before reaching the sea (Flett 2016 :60).

The river initially flows between push moraines and predominantly bedrock and then crosses unconsolidated glacial outwash sediments. The thin soils that may have developed in these conditions are unable to support other vegetation than mainly mosses, grasses and shrubs. (Mackay 2019: 1836; Mackay et al. 2018: 2178)

Virkisjökull is both a significant tourist destination and a grazing area, with the surrounding sandur and slopes used for sheep pasture. (Flett 2016 :79)

The climate is a relatively mild oceanic climate. (MacDonald 2016: 152)

The Öræfi region has a relatively mild maritime climate, marked by a small annual temperature range of about 11°C and approximately 150 days of precipitation in the form of rain or snow each year (Einarsson, 1984). Annual precipitation on the eastern side can reach up to 3000 mm. Although there is no distinct seasonal trend, the months of October, December, and January tend to be the wettest at sea level in this area. (Flett, 2016)

Due to the prevailing North-Northeast winds over the ice cap, the Virkisjökull catchment may lie within a pronounced rain shadow, leading to substantial local variation in conditions around Öræfajökull. Therefore, caution is needed when using precipitation data from areas directly east or west of the Virkisjökull catchment. (Flett 2016 :79)

As it is the case with other glaciers in Iceland, the Virkisjökull-Falljökull is retreating (MacDonald 2016: 152), though not dynamically but by different geomorphological processes it is irregularly reducing in size, deteriorating and collapsing (Bradwell et al. 2013: 972; Phillips et al. 2013: 1545).

These findings suggest that the pro-glacial river at Virkisjökull is highly sensitive to meltwater input, driven by an efficient network of well-developed conduits in both the subglacial and pro-glacial zones. The comparable flow velocities of meltwater within the glacier and the river underscore the effectiveness of this conduit system in rapidly transporting water. (Flett 2016 :276)

Seasonal fluctuations in glacier melt are the primary driver of river flow in the Virkisjökull catchment. The catchment’s geomorphology not only enables through storage a base flow year-round, even in times of insignificant melting but also the reduction of flow, depending on the season, for a day. (Flett, 2016 :277)

# Comparative Characteristics

*AK - Comparison of the two rivers in terms of size, glacial input, and environmental settings.*

*Maybe a little table extra ? oder ist das schon abgehandelt da ich die rel genau beschreibe ?*

Vergleiche:

Icecaps verschiedene

Länge der Flüsse

Kurzer Fluss, langer Fluss

Einfluss Tidenhub ??

Könnte Tabelle:  
 mit der Zusammenfassung der Unterschiede und der **Gleichheiten**.

# Methodology

As part of this work, a variety of field data was collected and subsequently analysed.

# Sampling points

In the following the respective sampling sites at each river are presented.

# Vestari-Jökulsá River

The Vestari-Jökulsá river (VJR) is formed by three branches, eastern-, middle- and western branch. While the first sampling site **WJ00** is being located on the glacier snout (Fig. 2), the following, sites **WJ01-WJ05**, are located on the eastern branch in the first 5km of the river, on approximately 900m.a.s.l. to 820m.a.s.l. (Free Map Tools 2024). This branch is separated from the other branches by a hyaloclastite mountain ridge (Krókafell, 966m.a.s.l) (Gislason et al. 2000 :412). The area's cut by a fissure zone, linked to a volcano under the glacier (Adalsteinsson et al. 2000).

Adalsteinsson et al. (2000) distinguished variations in the mineral concentration of the three branches that constitute the VJR, indicating that in the western and middle branch the glacial melt water interfered with the volcanic area where carbon dioxide upwelling takes place (Sigurdsson 1990). Regarding the middle reaches (sampling point **WJ10**) in July, Adalsteinsson et al. (2000) ascribed the lower mineral content then in September to the influence of melt water, given the high mineral content in the groundwater inflow.

Adalsteinsson et al. (2000) reported that, for the middle reaches of the VJR, glacial meltwater constituted approximately 50%, and 20% in the lower reaches. Groundwater contributed 50% of the discharge, significantly higher than the average 10% for glacial rivers in Iceland (Sigurdsson 1990).

The decrease in glacial downstream components in the lower VJR reaches is balanced by high water speed which keeps suspended sediment levels high. This may affect primary production more than the chemical composition or the origin of the water. (Adalsteinsson et al. 2000 :739)

Due to the difficult accessibility of the river in certain parts (i.a. deep riverbed), limited infrastructure (few roads in the highlands, prohibition to drive off-road (EAI, 2023)) and for logistical reasons, the sampling sites correspond the sampling sites of the current PhD thesis there (Knauft UMR, to be published). Therefor the next sampling site, **WJ10** is located ca. 23km from the glacier. Approximately 7km after this sample point, the VJR is first joined from the east by the non-glacial Midhlutará river. Then, almost 1km after the sampling site **WJ11** and 2,5km before the last sampling site **WJ12**, is the confluence with the Hofsá river located (which partly also originates from the Sátujökull glacier). These last sampling sites **WJ11** and **WJ12** are located at ca. 200m.a.s.l. (Free Map Tools 2024)

Ein Bild, das Text, Karte, Diagramm enthält.

Automatisch generierte Beschreibung

Fig. 2: Vestari-Jökulsá river with the sampling sites

# Virkisá River

At the Virkisá River, the sampling points (Fig. 3) were placed at approximately equal intervals of the river, based on previous master thesis. Two sampling points, **S1** and **S2**, are located between the glacier and the lake, the other sampling points, **S3 – S7,** are found along the river, behind the lake, on average around 500 metres apart.

(height above sea level distance from glacier snout)

Ein Bild, das Karte, Screenshot, Erde, Digitales Compositing enthält.

Automatisch generierte Beschreibung

Fig. 3: Sample location at the Viskria river

“The glacier margin is no longer undergoing dynamic retreat but is now undergoing non-uniform downwasting, decay and collapse through a range of geomorphological processes” Bradwell, T., Sigurðsson, O. & Everest, J. 2013

# Research Design

To ensure consistency and comparability with previous work, the research design was closely aligned with established projects within the working group (UMR 2025). As described in chapter 2.6, the sampling sites at the VJR followed a PhD project, and at the VR a preceding master’s thesis. Also, the data collection and analytical procedures are commonly used in PhD projects as well as various Bachelor and Master theses and were, moreover, shaped by the available equipment and established workflows in the soil laboratory of the department of geography at the University of Marburg.

# Sample Collection and Data Analysis

These procedures are described in this chapter.

# Water sampling

At the Vestari-Jökulsá river sampling took place in July 2024, from the 17.07.2024 to the 23.07.2024 (Appendix III). The samples at the Virkisá River were taken shortly after that period, the 27.07.2024 and the 28.07.2024 (Appendix IV). This period was followed by a relatively heavy rainfall event in the region, which also caused the Virkisá river to rise visibly. As part of a student seminar at Philipps University in Marburg, further water samples were then taken from Virkisá. The seminar took place between 6.- 9. August 2024. In the following, these samples will be referred to, as samples “after the rainfall event”; while the samples taken during the first period, in July, will be referred to, as samples taken before the rainfall event.

The sampling locations are visible in figure 2.

Due to the length of the VJR, the resultant distance between the sampling points (see *Fig. 3*)and above all the distinct diurnal discharge behaviour of glacier rivers (cf. above) a distinction was made between samples taken in the morning (VM) and afternoon (NM) at both rivers. At the period of the sample collection, the sun is at its zenith (solar noon) in the Icelandic sky at ca. 13:10 – 13:20 local time (Time and date 2025), thus delineating the boundary between the morning and afternoon sampling periods.

For statistical relevance and due to logistical restrains 2 bottles (DURAN® Laboratory Bottle, 500ml) of **water samples** were collected. (before collection, each time, they were rinsed three times thoroughly with river water at the new sampling location). Either on-site or in the field laboratory (see Appendix I, in the evening of the same day, depending on weather conditions), the water samples were prepared, as described in the following paragraph:

For the **DOC samples**, ca. 40 ml of water was filtered through two Whatman® 934-AH glass microfibre filter discs with a pore size of 0.7 μm, following Fasching Chifflard (2024 :3). Based on the works of Fasching et al. 2016, Fasching and Battin 2011, Hood et al. 2015, Singer et al. 2012 and Chifflard et al. 2019 two filters are used for the filtering of DOC and BDOC to obtain a near-sterile sample.

The filters were combusted in advance at 450°C for 4 hours in the muffle stove. (After filtration, these filters will be used for the determination of particulate organic carbon POC. These results will not form part of the present work.)

Muffling and acid cleaning (with 0.1 N HCl) was also performed on the 40 ml vials. Due to the specific conditions in Iceland (low temperatures and the associated possible freezing of the samples), the vials are filled with headspace.

For determination of the bioavailable DOC, **BDOC** samples were prepared as follows: 4 ml of unfiltered water was filled up to approximately 40 ml vial with filtered water. After a period of 14 days, these samples were again filtered through 2 glass fibre filters (treated, as described above, Whatman GF/F, pore sizes 0.7 μm). (These filters are being disposed of.)

All samples were stored in a cool and dark place (kitchen refrigerator or, in the highlands outside) to minimise biological activity (Zhu et al. 2024).

For the analysis, the samples were brought to the Soil Laboratory at the University Marburg.

# Laboratory analyses

At UMR, the filtered samples' DOC concentration was determined using a **Total Organic Carbon Analyser** (TOC, Shimadzu 2021, Appendix IIa)), which combusts the organic matter at high temperatures and then thermally detects the resulting CO2. (Chifflard et al. 2024) The TOC was set up and calibrated using distilled water after approx. every 10 samples, in accordance with the standard operating procedures of the laboratory at the UMR soil lab.

Bioavailable DOC, BDOC (%), is calculated as the percentage change in average DOC concentration over the 14‑day incubation period, relative to the initial average DOC (left in the refrigerator, in the dark) of 12 days with the inocula composed of unfiltered sample water as described in a), above. (Fasching and Battin, 2010; Fellman, Spencer et al. 2010) It is expressed as the percentage of the initial DOC calculated relative to the average DOC concentration over the incubation period.

Fluorescence measurements were carried out with the **Spectrofluorophotometer** Shimadzu RF-6000 (2024, Appendix IIc)). Measurements were performed at a scan rate of 12,000 nm per minute with a 1 cm quartz cuvette (following the methodology described by Singer et al. 2012). Fluorescence intensity data were collected to construct excitation-emission matrices (EEMs) using excitation wavelengths covering 200 to 450 nm, with 5 nm intervals, and emission wavelengths between 250 and 700 nm with 2 nm intervals. The corresponding absorbance data was used for correcting the inner filter effect. (Chifflard et al. 2024)

The performance of the instruments was supervised by measuring the Raman peak intensity of distilled water at the start of different measurements (once per day) (no fluctuation >X%, variation of Raman peak <X%) (following Barker et al. 2013). The instrument-specific excitation and emission correction factors were used to correct all measured fluorescence intensities (Cory et al. 2010). The low DOC concentration (<1mg/L) (and absorbance at 320 nm <0.002) made inner filter effects correction obsolete. (high-intensity area attributed to the Rayleigh, normalized ???) (Barker et al. 2013).

For Absorbance measurements, the **Spectrophotometer** (Thermo Fisher 2013, Appendix IIb)) with 1 cm quartz cuvettes was employed (Appendix IV). (Chifflard et al. 2024)

Both, the Spectrofluorophotometer and the Spectrophotometer were calibrated with distilled water, that means the emission peak of distilled water was taken as the reference value. (Chifflard et al. 2024)

# CO2 sensor and Calculation of CO2 Fluxes

To obtain data on CO2 a sensor (constructed and borrowed from Annika Feld-Golinski, following Bastviken et al. 2015) was placed in the water at each sampling location for at least one hour. For these measurements, no differentiation in the daytime was made.

Prior to each measurement, the concentrations of air and CO₂ within the chamber were homogenized—either by manually agitating the chamber or allowing ambient wind to circulate the air. This step also served as a visual marker in the resulting curve to indicate the beginning of the measurement.

Due to the high discharges and flow velocities of the two rivers, care had to be taken to ensure that the measuring sonde did not break loose during the measurement. Consequently, it was flexibly secured with a rope, near the riverbank, often positioned behind rocks in the river, where the level of turbulence and wave activity was typically lower but the water still flowing for minimising the sedimentation of POC as these could bias the measurement (Lorke et al. 2015).

Following Boodoo et al. (2017) by using the ideal gas law (cf. Jablonka 2017 after Clapeyron 1834; Clausius 1857; Kronig 1856) and treating CO₂ as an ideal gas without corrections for non-ideal behaviour (Lorke et al. 2015) CO2 evasion fluxes (*f*CO2) were calculated.

First, the molar gas volume Vm was determined using the universal gas constant R (8.314 J mol−1 K−1), the absolute temperature T (in Kelvin) and the standard atmospheric pressure p of 1013.25 hPa was assumed for the calculations of the Fluxes at all sample sites.

Based on the chamber volume Vchamber (in L), the molar CO2 concentration [CO2]mol was calculated as:

Here, ΔCO2 (ppmv) is derived from the linear change in CO₂ concentration over a 10-minute period, which appeared appropriate for both rivers.

To ensure objectivity and reproducibility, the linear regression was applied to the best-fitting segment of the measurement (most linear section with the highest R²), selected automatically by a script (cf. supplementary data, Appendix I):

A sliding-window search over the CO₂ time series is implemented (sampling interval of the sensor: every 10 seconds). Windows of increasing length is tested (50, 60, 70 etc measuring points—while advancing the window start in 5-point increments, i.e., every 50 s, for practicability reasons). The window with the highest R² is selected; (in the case of same lengths, the longer window is preferred to favour stability). To standardized the analysis duration (and to minimise the possible influence of the sun by further heating the chamber) only the first 10 minutes (60 points) are chosen and all subsequent calculations are done with the data in this segment.

The relative molar mass of carbon RMMC (12.011 g · mol−1), the incubation time T (in hours), and the surface area A (in m2) covered by the chamber, the CO2 evasion fluxes *f*CO2 was calculated as:

# Complementary data

A calibrated **EXO2 Multiparameter Sonde** (YSI Inc. / Xylem Inc.)was used in-situ to obtain additional data on the water, like water temperature, concentration of dissolved oxygen and chlorophyll, specific conductivity, pH and turbidity (Appendices IId),VI).

**Hourly** **meteorological data** was obtained from the Icelandic Meteorological Office for two stations: the Sáta weather station, near the VJR, and the Skaftafell station, near the VR (see Figure 2, Appendix V).

For each river, meteorological conditions for the exact hour of water sampling were considered to best represent the immediate environmental conditions during data collection. However, as the weather stations are located at some distance from the sampling sites, and Icelandic weather patterns can vary considerably over short distances due to complex topography and rapid atmospheric changes (Crochet et al., 2007), the data may not fully capture the local conditions.

The **distance** of the individual sampling stations (Appendix IV) along the rivers to the respective glaciers was determined using the QGis software (QGIS Development Team, 2022) Appendix II.b.

The data from the laboratory as well as the data obtained in the field or from external sources (see the Chapters a),b) and c), Appendix VI), was compiled in a Master file (Appendix VI) and evaluated as described in the following chapters.

# Statistical analyses

As in the previous chapter, the coding, as well as all statistical analyses and visualizations, described below, were conducted in R (R Core Team 2025) within JupyterLab (Kluyver et al. 2016) using the R kernel (IRkernel project).

1. Descriptive statistics
2. Fluorescence Data Processing and PARAFAC Modelling

Fluorescence excitation–emission matrices (EEMs) were preprocessed (blank and scatter subtraction, inner filter effect correction and Raman normalization) and optical indices (BIX, HIX, FI, a254, a300, E2/E3, E4/E6, S275–295, S350–400, SR) were calculated.

To decompose the complex DOM fluorescence signal, a Parallel Factor Analysis (PARAFAC) model with five components was fitted using the R package staRdom (version 1.1.28, Pucher et al. 2019). The five extracted components represent independent fluorophore groups within the DOM pool and were validated following established guidelines (split-half validation, comparison to the OpenFluor (Murphy et al. 2014) database).

For each sample, component scores were expressed as relative contributions (in %) to enable comparison between treatments (DOC vs. BDOC) and across rivers.

*(R packages: staRdom, dplyr, tidyr, stringr, ggplot2)*

1. Principal Component Analysis

A Principal Component Analysis (PCA), (unrotated and varimax-rotated) was performed on selected environmental variables (using Pearson correlation matrices (Leyer & Wesche, 2008) and component number determination with Kaiser criterion, eigenvalues > 1 (Field et al. 2012). The carbon variables DOC, BDOC, and CO₂ flux were treated as supplementary variables (Graffelman & Aluja-Banet, 2003) and displayed in the biplots. These biplots showed sample scores (coloured by carbon concentrations and river identity) and variable loadings. Ellipses (95% CI, based on t-distribution) were added for the visualisation of groupings.

Furthermore, the contribution of each variable to the extracted components was assessed.

Finally, to test for systematic differences between the two rivers (Vestari-Jökulsá vs. Virkisá), MANOVA was applied to the factor scores of the selected components, univariate ANOVAs were performed for each factor separately to identify which factors contributed to between-river differences.

*(R packages: MVN, broom, dplyr, ggnewscale, ggplot2, ggrepel, psych, stringr, tidyr)*

# Results

In the following chapters the relevant results for the two study rivers, Vestari-Jökulsá and Virkisá are presented. The analysis focuses on the relevant carbon data; the DOC concentration, BDOC (see 3.3 b)) and the CO₂ fluxes (see chapter 3.3 c)). Data are evaluated i.e. in relation to spatial patterns, along longitudinal transects, temporal variations between morning and afternoon sampling, and in relation to physical, chemical, and biological parameters.

# Descriptive Statistics and overview of the carbon variables

Descriptive data of the carbon parameters measured in both rivers, Vestari-Jökulsá and Virkisá, for DOC, BDOC, and CO₂ fluxes is summarized in table 5. These values include minimum, maximum, median, mean, and standard deviation for each parameter. The data for Virkisá is also divided into results before and after a rainfall event which took place in between the two sampling periods (see chapter 3.3 a).

Table 5: carbon variables by river

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Group | Variable | **Minimum** | **Maximum** | **Median** | **Mean** | **Standard.**  **Deviation** | **N** |
| **Vestari-Jökulsá** | Average DOC | 0.07 | 0.28 | 0.14 | 0.15 | 0.05 | 18 |
| BDOC (%) | -37.4 | 62.98 | 27.46 | 23.09 | 25.93 | 14 |
| CO2\_Flux | -13.19 | 12.27 | -5.84 | -1.47 | 9.99 | 16 |
| **Virkisá** | Average DOC | 0.1 | 0.59 | 0.22 | 0.26 | 0.13 | 43 |
| BDOC (%) | -32.23 | 69.68 | 31.35 | 26.97 | 28.26 | 43 |
| CO2\_Flux | -108.84 | -17.59 | -56.82 | -58.55 | 30.46 | 17 |
| **Virkisá,** | Average DOC | 0.1 | 0.17 | 0.13 | 0.13 | 0.02 | 14 |
| **before rain event** | BDOC (%) | -32.23 | 25.46 | -1.66 | -4.54 | 17.67 | 14 |
| CO2\_Flux | -107.41 | -17.59 | -49.16 | -57.56 | 37.26 | 8 |
| **Virkisá,** | Average DOC | 0.16 | 0.59 | 0.29 | 0.32 | 0.12 | 29 |
| **after rain event** | BDOC (%) | 1.51 | 69.68 | 41.17 | 42.18 | 17.8 | 29 |
| CO2\_Flux | -108.84 | -31.83 | -56.82 | -59.43 | 25.27 | 9 |

The corresponding plots, Fig. 4, illustrate the results of DOC, BDOC and CO₂ flux for the Vestari-Jökulsá and data of the Virkisá before and after the rain event (see chapter 3.3 a)), to enable a visual comparison between the total carbon parameters of both rivers.

For ***DOC concentrations***, results for the Vestari-Jökulsá are centred around a median of 0.14 mg L⁻¹, with a narrow distribution and limited spread. Virkisá values before the rain show a similar narrow distribution with a slightly lower median, whereas values after the rain display a wider distribution and a higher median, reflecting increased variability.

For ***BDOC percentages***, Vestari-Jökulsá values are centred around a median near 27 %, with a moderately widespread. In the Virkisá, values before the rain have a median close to zero and a moderate spread. After the rain, both the median and the spread increase, with the median shifting to approximately 40 % and the distribution extending toward higher values.

For *CO₂ flux*, Vestari-Jökulsá values are consistently negative, with a median around −6 mg C m⁻² d⁻¹ and a narrow spread. In the Virkisá, values before and after the rain remain negative, but the distributions show greater variability. For both the median is around - 50 mg C m⁻² d⁻¹.

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Fig. 4: Violin and Boxplots of DOC, BDOC and CO2 Flux by river

Concerning the data of the Virkisá, data collected before and after a rain event associated with increased runoff, allow for a targeted examination of short-term changes of these parameters along the different sampling sites (visualised in figure 5). (For better comparison purposes, also the results prior to the rainfall event are visualised as box plots.)

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Fig. 5: Virkisá, carbon parameters: before and after the rain event across sampling sites

DOC concentrations were generally higher after the rain event, with the most pronounced increases observed at sampling sites 3, 4, and 5. Before the rain event, DOC values remained lower and more uniform across sites.

BDOC concentrations were also elevated in the post-rain samples compared to pre-rain conditions. Before the rain, BDOC results were lower at all sites, whereas several sites showed substantially higher values after the rain.

CO₂ fluxes were negative at all sites, both before and after the rain event. While the differences at the sampling sites 2 and 3 were the most pronounced.

Since there is only a small amount of data available for the Vestari-Jökulsá, only the data prior to the rain event will be considered for the Virkisá in the following analyses .

## *Spatial and Temporal Variations*

To characterize spatial and temporal variability in carbon dynamics, DOC, BDOC and CO2 Fluxes were assessed, as described above, along longitudinal transects of the river and at different times of day (morning and afternoon).

### *Longitudinal Patterns along the Rivers*

In the distance of approximately 3 km, it is possible to plot the DOC, BDOC and CO₂ fluxes at different sampling sites of the two rivers, Vestari-Jökulsá (site 1-4) and Virkisá (site 1-7), against the distance from the respective glacier in one single diagram, Figure 7.

For the Vestari-Jökulsá, the two results are visualised with points, while for the Virkisá, as there are multiple data (before and after rain event), the data is visualised with boxplots.

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Fig. 6: Carbon parameters of VJR and VR in distance from respective glacier

The DOC concentrations (upper panel) of the Virkisá exhibited a broader range across all sampling points, with several sites exceeding 0.4 mg L⁻¹. In contrast, DOC values in Vestari-Jökulsá remained lower overall and more uniform, with concentrations typically below 0.25 mg L⁻¹.

The BDOC concentrations (middle panel), where Virkisá displayed notable variation between sites and replicates. Several sites showed BDOC values above 0.25 mg L⁻¹. For the Vestari-Jökulsá, BDOC concentrations were generally lower and in some cases near or below zero.

The CO₂ fluxes (last panel), with all values remaining negative, indicating net CO₂ emission from water to atmosphere. The Virkisá data revealed considerable variability between replicates and sites, while Vestari-Jökulsá exhibited slightly less variation and consistently lower magnitudes of flux across sites.

The DOC concentrations measured along the Vestari-Jökulsá, plotted over the whole length of the river, that means the distance from the glacier terminus in meter, with separate profiles for morning and afternoon sampling, are visualised in Fig. 7.

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Fig. 7: DOC concentration along the Vestari-Jökulsá

A part of the sampling sites 3 and 10, in 820m and 24km distance, the DOC concentrations in the morning are slightly lower than the DOC concentrations in the afternoon but demonstrate overall a similar development. The relatively closely located sampling sites 1-5 (in 4,7km distance from the glacier) exhibit a decline in DOC concentrations until site 3, followed by an increase at site 4 (ca. 2,9 km) and then a lower concentration again at site 5 (4,7 km). In contrast to the two relatively constant lower values recorded at more then24 km distance from the glacier, at sites 10 and 11, the highest concentration is observed at Site 12, in more than 47 km from the glacier.

Concerning the Virkisá, the DOC concentration over the distance from its source (Fig. 8) exhibited a general increase downstream in the morning (a part of a relative decrease in site 2 and 6, 40m and 2,5km from the glacier). Afternoon concentrations were consistently lower than morning values and showed a less pronounced longitudinal trend, with a higher decrease from site 1 to site 2 (40m from the glacier).

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Fig. 8: DOC Concentration along the Virkisá

In addition to spatial gradients along the river course, temporal variability was examined through a comparison of morning and afternoon measurements.

### *Time of Day and Sampling Site*

The time of day when samples are taken, also leads to different results for the carbon parameters. The following Fig. 9 show the DOC, BDOC and CO₂ fluxes for better visualisation, at the different sampling sites in the morning and in the afternoon.

**Vestari-Jökulsá Virkisá**

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Fig. 9: Carbon parameters on the sampling sites of Vestari-Jökulsá left, Virkisá right

For the Vestari-Jökulsá, DOC concentrations (upper panel) varied across sampling sites and ranged from approximately 0.10 to 0.25 mg L⁻¹. Morning and afternoon values were generally similar.

For the Virkisá, the concentrations ranged from approximately 0.10 to 0.20 mg L⁻¹. Morning values showed a slight increase with downstream distance (apart of site 6), while afternoon values remained more stable across sites.

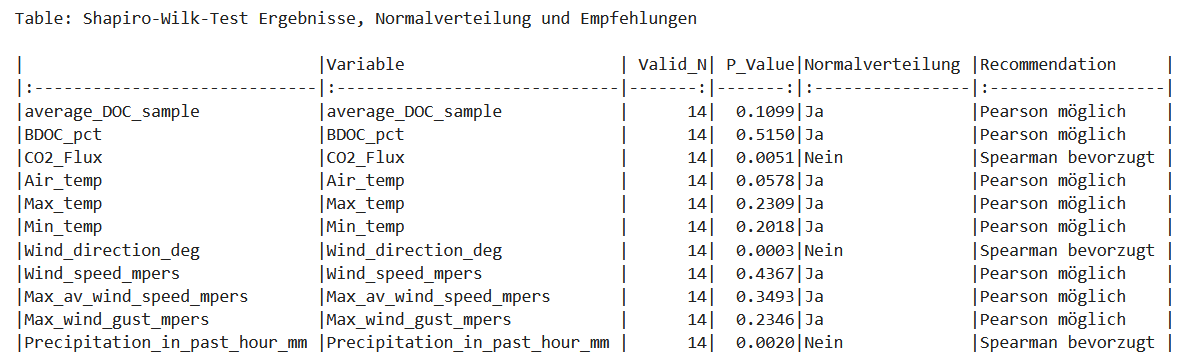
The BDOC (middle panel) at the Vestari-Jökulsá remained between approximately 0.6 and 1.1 along the river course. Minor variation between morning and afternoon measurements was observed, with site 3 showing the highest ratio values in the afternoon.

For the Virkisá, the BDOC (middle panel) varied between 0.75 and 1.5. Ratios tended to be slightly higher at downstream sites, with minor differences between morning and afternoon measurements.

Concerning the CO₂ fluxes (lower panel) at the Vestari-Jökulsá were negative at all sites, indicating net CO₂ emission to the atmosphere. Flux magnitudes varied little between morning and afternoon measurements and remained within a narrow range across all sampling points. At the Virkisá, the fluxes were also negative at all sampling sites. Magnitudes ranged from approximately −10 to −40 mg C m⁻² d⁻¹ and showed moderate variation between sites. Differences between morning and afternoon measurements were small.

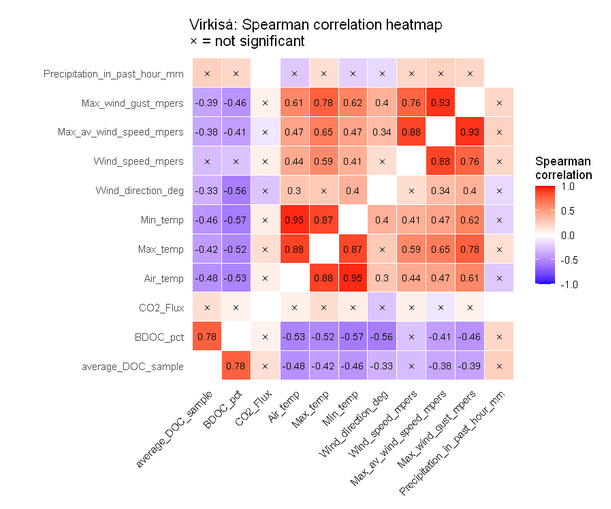
# Relationships with weather parameters

Correlation analysis - relationships between carbon variables and the weather



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# DOM Fluorescence Indices and Composition

Indices like BIX, HIX, and S275–295 indicated differences in DOM quality.

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Fig. 10: Vestari-Jökulsá, Component distribution

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Fig. 11: Virkisá, Component distribution

# Parafac

Table 6: excitation and emission of the components, their assignment to Coble peaks, fluorescence and other studies (i.a. OpenFluor\*)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Component number** | **Excitation maxima (nm)** | **Emission maxima (nm)** | **Coble (1996)**  **Fluorophore name** | **Description** | **Similar to** |
| **1** | 290 | 306 | b |  |  |
| **2** | 315 | 330 | m |  |  |
| **3** | 275 | 256 |  |  | Dainard et al. 2015\* ;  Chifflard et al. 2024 |
| **4** | 365 | 372 |  |  |  |
| **5** | 300 | 338 |  |  | Eder et al. 2022\* ; Maurischat et al. 2022\* |

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Fig. 12: Excitation-emission model of the five components

# Factor analysis

b) In der nachfolgenden Faktorenanalyse gehen wir von der Prämisse aus, dass der Kaiser-Meyer-Olkin-Index (KMO-Index) einen adäquaten Wert für die Angemessenheit der vorliegenden Stichprobe für eine Faktorenanalyse liefert. Dieser Wert sollte mindestens 0.70 groß sein, um eine gerade noch komfortable Faktorenanalyse mit den Stichprobendaten durchführen zu können. Liefert der KMO-Index einen Wert unter 0.60, dann sind die erhobenen Daten oder zu betrachteten Variablen nicht geeignet für eine Faktorenanalyse.

As mentioned above, part of the statistical evaluations was a factor analysis with the 'principal components analysis' (PCA) as factor extraction technique, without and with rotation, which examined as few relevant factors as possible capable to represent set of homogenous parameters (Reyment and Jöreskog, 1993) of the two rivers Vestari-Jökulsá and Virkisá. These parameters were predominantly e*nvironmental parameters (taken with the EXO2 Multiparameter Sonde) chlorophyll, oxygen, phycocyanin, turbidity, pH, air and water temperature as well as height above sea level and the components (comp.1 – comp.5)*

The carbon parameters, DOC, BDOC and CO2 fluxes, were then added in the PCA as supplementary variables.

An analysis using all the above parameters did not yield a positive definite correlation matrix (a prerequisite for factor analysis and for determining the KMO index). It led to an only positive semidefinite matrix (singularity) with a questionable sample suitability: KMO/MSA < 0.5) (Field et al. 2012), which was due to strict dependencies among the components 1-5.

Therefore, to obtain a positive definite correlation matrix and an acceptable KMO index with most of the parameters, some of these components had to be omitted, starting from the five component parameters (comp.1 – comp.5): The best value for the KMO index (KMO=0.696) was obtained after removing comp.1 and comp.5.

Furthermore, for the analysis, no incomplete cases were used (Total of 57 cases, 16 removed, due to no available data from the EXO2 Multiparameter Sonde (see 3.3d) above).

The variables with which the PCA was performed are listed in the following correlation matrix.

Table 7: Matrix of correlation coefficients among the variables examined (parameters/variables)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Chlorophyll** | **Oxygen** | **Phycocyanin** | **Turbidity** | **pH** | **Water temp.** | **Height amsl** | **Comp.2** | **Comp.3** | **Comp.4** | **Air temp.** |
| **Chlorophyll** | 1 | 0.554 | 0.88 | 0.224 | 0 | -0.158 | -0.5 | -0.4 | 0.471 | -0.361 | 0.65 |
| **Oxygen** | 0.554 | 1 | 0.56 | 0.136 | 0.152 | -0.642 | -0.623 | -0.677 | 0.701 | -0.6 | 0.518 |
| **Phycocyanin** | 0.88 | 0.56 | 1 | 0.391 | -0.039 | -0.328 | -0.37 | -0.344 | 0.565 | -0.288 | 0.628 |
| **Turbidity** | 0.224 | 0.136 | 0.391 | 1 | -0.025 | -0.249 | -0.061 | -0.093 | 0.227 | -0.034 | 0.196 |
| **pH** | 0 | 0.152 | -0.039 | -0.025 | 1 | 0.049 | -0.136 | -0.058 | 0.029 | -0.076 | 0.006 |
| **Water temp.** | -0.158 | -0.642 | -0.328 | -0.249 | 0.049 | 1 | 0.026 | 0.248 | -0.336 | 0.232 | -0.269 |
| **Height amsl** | -0.5 | -0.623 | -0.37 | -0.061 | -0.136 | 0.026 | 1 | 0.797 | -0.773 | 0.706 | -0.496 |
| **comp.2** | -0.4 | -0.677 | -0.344 | -0.093 | -0.058 | 0.248 | 0.797 | 1 | -0.83 | 0.945 | -0.379 |
| **comp.3** | 0.471 | 0.701 | 0.565 | 0.227 | 0.029 | -0.336 | -0.773 | -0.83 | 1 | -0.726 | 0.518 |
| **comp.4** | -0.361 | -0.6 | -0.288 | -0.034 | -0.076 | 0.232 | 0.706 | 0.945 | -0.726 | 1 | -0.3 |
| **Air temp.** | 0.65 | 0.518 | 0.628 | 0.196 | 0.006 | -0.269 | -0.496 | -0.379 | 0.518 | -0.3 | 1 |

The Kaiser-Meyer-Olkin measure of sampling adequacy (Kaiser, 1970) was 0.696, as mentioned above, which is slightly below the recommended threshold of 0.70 (0.7-0.8 good), suggesting mediocre (Kaiser, 1974), so in this case, acceptable sampling adequacy.

The Bartlett's Test of Sphericity shown below indicated suitability of the correlation coefficients of the selected variables for performing a factor analysis.

Bartlett's Test of Sphericity: χ²(55, N=27) = 375.74, p < 0.0001

Now, follow the results related to the number of meaningful components for the representation of the variables examined and the variance explained by them.

The PCA extracted an optimal number of three components (s. the red rectangle in Table 2) with eigenvalues higher or equal 1 (Kaiser, 1960; Kaiser’s criterion). Together they could explain approximately 73% of the total variance of the variables.

Table 8: table with the eigenvalues of the components

|  |  |  |  |
| --- | --- | --- | --- |
| **Component** | **Eigenvalues at the beginning** | | |
| **Total** | **% of variance** | **cumulative %** |
| **1** | 5.286 | 48.05 | 48.05 |
| **2** | 1.653 | 15.03 | 63.08 |
| **3** | 1.122 | 10.2 | 73.28 |
| **4** | 0.994 | 9.04 | 82.32 |
| **5** | 0.827 | 7.52 | 89.84 |
| **6** | 0.45 | 4.09 | 93.93 |
| **7** | 0.277 | 2.52 | 96.46 |
| **8** | 0.23 | 2.09 | 98.55 |
| **9** | 0.089 | 0.81 | 99.35 |
| **10** | 0.042 | 0.38 | 99.73 |
| **11** | 0.03 | 0.27 | 100 |
| Extraction method: principal component analysis | | | |

This was also confirmed by the scree plot (Fig. 13), which plots the eigenvalues of all possible factors (components) and illustrates graphically the result of the optimal number of factors (Cattell, 1966): Only the larger eigenvalues, on the “left” (in red), before the “break” of the curve are considered. (Field et al. 2012)

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Fig. 13: Scree plot illustrating the optimal choice of number of components

(Although parallel analysis, according to Iacobucci et al. 2022, would ‘significantly outperform’ the applied methods for determining the number of components, it was not considered because more detailed statistical discussions were not part of this work.)

The PCA provided also the factor loadings (the correlation coefficients of the individual variables with the individual factors, explaining as much of the variance of the variables as possible) (Field et al. 2012), which are listed in the following table 9.

Table 9: Correlation coefficients (factor loadings) of each factor with each of the examined variables

|  |  |  |  |
| --- | --- | --- | --- |
| Variables | Component matrix  (3 components extracted) | | |
| Factor 1 | Factor 2 | Factor 3 |
| Chlorophyll | 0.729971 | 0.412098 | 0.412434 |
| Oxygen | 0.853331 | 0.006239 | -0.291845 |
| Phycocyanin | 0.72623 | 0.565755 | 0.20678 |
| Turbidity | 0.270467 | 0.528207 | -0.199149 |
| pH | 0.074939 | -0.253388 | 0.109449 |
| Water temp. | -0.43396 | -0.30503 | 0.788225 |
| Height amsl | -0.805949 | 0.36966 | -0.254994 |
| comp.2 | -0.846649 | 0.451192 | 0.081611 |
| comp.3 | 0.888059 | -0.165983 | -0.060651 |
| comp.4 | -0.774678 | 0.492191 | 0.096584 |
| Air temp. | 0.68934 | 0.341434 | 0.257917 |

The correlation coefficients with absolute values > 0.50, show which variable is closely related to which factors. These variables can be grouped together for each factor, with the factor itself acting as the representative. The table below provides a clearer illustration of the variables that correlated strongly with each factor (correlation coefficients with absolute values > 0.50).

Table 10: Variables that belong to the respective factor, that can be represented by the 3 factors.

|  |  |  |  |
| --- | --- | --- | --- |
| Variable | Component matrix  after sorting the factor loadings with a value > 0.50 | | |
| Factor 1 | Factor 2 | Factor 3 |
| Chlorophyll | 0.73 |  |  |
| Oxygen | 0.853 |  |  |
| Phycocyanin | 0.726 |  |  |
| Turbidity |  | 0.528 |  |
| pH |  |  |  |
| Water temp. |  |  | 0.788 |
| Height amsl | 0.806 |  |  |
| comp.2 | 0.847 |  |  |
| comp.3 | 0.888 |  |  |
| comp.4 | 0.775 |  |  |
| Air temp. | 0.689 |  |  |
| Principal component analysis, with 3 components extracted | | | |

Factor 1 is most strongly associated with most of the variables: Chlorophyll, oxygen, phycocyanin, hight above sea level, air temperature and comp.2, comp.3 and comp.4. It can therefore be understood as the representative of this group.

Factor 2 shows strong correlations with the parameter phycocyanin and turbidity and can therefore be considered their representative.

The third factor (factor 3), which can only explain 10.2% of the total variance, is related to the variable turbidity.

To better understand the significance of the contribution of the individual variables to the factors the plots below could be helpful:

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Fig. 14: Contribution plots for the three components

The factor loadings also determined the proportion of the variance of the individual variables that can be explained by the three factors. The table below shows the original variance for each parameter in its standardised form, which is equal to 1 in this case, and the proportion of this variance that can be explained by a linear combination of the three factors. This shows how good the factors explained the original data (communalities closer to 1) (Field et al. 2012).

Table 11: Variances of parameters examined in their standardised form before / after factor extraction of the 3 factors

|  |  |  |
| --- | --- | --- |
| **Communalities** | | |
| **Standardised variables** | **Initial** | **Extraction** |
| Chlorophyll | 1 | 0.872784 |
| Oxygen | 1 | 0.813386 |
| Phycocyanin | 1 | 0.890247 |
| Turbidity | 1 | 0.391815 |
| pH | 1 | 0.0818 |
| Water temp. | 1 | 0.902664 |
| Height amsl | 1 | 0.851224 |
| comp.2 | 1 | 0.927048 |
| comp.3 | 1 | 0.819878 |
| comp.4 | 1 | 0.851706 |
| Air temp. | 1 | 0.658288 |
| Extraction method: principal component analysis | | |

Low communality on the other hand, as for pH and turbidity, mean that the variable is poorly represented by the factors.

Finally, the PCA was visualized a biplot, in which the variables are represented as vector arrows, and the individual samples taken are represented as points (Lepš & Šmilauer, 2003).

The first two principal components or factors are used which explain most of the total variance in the data. The difference between the plots below is only the coloration of the samples (see Fig. 15, Fig. 16 and Fig. 17).

The Ellipses visualise the samples with the different sampling periods that means, the sampling at the Vestari-Jökulsá river in the north, sampling at the Virkisá river before and after the rain event. The Ellipses represent 95% confidence intervals assuming multivariate normality (t-distribution). Normality tests indicated that this assumption was not fully met so ellipses should mainly be interpreted as descriptive part of the plot.

The quantities of the different carbon variables were used to colour the individual samples (points in the biplot) with different colour scales by river, as the measured quantities are quite different per river (see 4.1 above).

The samples, also carry the site numbers and are shaped, depending on the time of day of the sampling, for samples taken in the morning (VM) as a triangle and samples taken in the afternoon (NM) as a dot).

The carbon parameters, DOC, BDOC and CO2 fluxes, were then added as supplementary variables in the visualisation (in blue), onto the component space and did not influence the extraction of the components in the PCA (Husson et al. 2010). That means these supplementary variables were plotted afterwards by correlating (Pearson) each variable with the (unrotated/varimax-rotated, see later) components in the biplot (Graffelman & Aluja-Banet, 2003). (Even though correlations with the extracted components varied and were only moderately or weakly represented on the main axes).

Concerning the arrows of the supplementary variables and the arrows of the variables extracted by the PCA: the maximal linear association is reflected by the direction of the arrows, while the quality of the representation by the components is indicated by the length (Graffelman & Aluja-Banet, 2003).

In the biplot of the first two principal components (factors), several variables are clearly separated from each other. Turbidity, Phycocyanin, Chlorophyll, Air temperature and Oxygen and comp.3 load on the positive side and show a close alignment. Height amsl, comp.2 and comp.4, on the other hand, lie on the negative side of the same axis. PH is close to the origin because it is only weakly represented by the first two principal components. The samples are grouped along these gradients: on the left are samples with higher altitude and comp. values, on the right are samples with higher chlorophyll, Phycocyanin, turbidity and air temperature values.

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Fig. 15: unrotated PCA biplot PC1 & PC2, coloured by DOC quantities

The blue ellipse (samples taken in the week at the VJR, left side) groups samples that are strongly characterised by altitude and components 2 and 4 values.

The ellipse of the samples before the rain event, on the right, groups samples with high chlorophyll, phycocyanin, turbidity and air temperature values.

The ellipse with the samples after the rain, is more centred around pH values.

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Fig. 16: unrotated PCA biplot PC1 & PC2, coloured by BDOC quantities

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Fig. 17: unrotated PCA biplot PC1 & PC2, coloured by CO2  quantities

Determination of factor loadings after application of a rotation

The aim of the rotation principle in factor analysis is to maintain simpler and more easily interpretable factor loadings while retaining the factor solution achieved in the principal component analysis (Reyment and Jöreskog, 1993).

In the factor analysis of the present study the varimax method is selected and applied as the rotation technique. The aim of this method is to minimise the number of variables that have very high correlation coefficients (loadings) with a factor, as this increases and facilitates the interpretability of the factors (Field et al. 2012). After applying the Varimax rotation method, the factor loadings looked as follows:

Table 12: Variables that can be well represented by the three factors after applying a Varimax rotation.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Component matrix**  **after Varimax rotation**  **and sorting of factor loadings with a value > 0.50** | | |
| **Variable** | **Faktor 1** | **Faktor 2** | **Faktor 3** |
| Chlorophyll |  | 0.9 |  |
| Oxygen | 0.692 |  |  |
| Phycocyanin |  | 0.885 |  |
| Turbidity |  |  |  |
| pH |  |  |  |
| Water temp. |  |  | 0.916 |
| Height amsl | 0.817 |  |  |
| comp.2 | 0.944 |  |  |
| comp.3 | 0.795 |  |  |
| comp.4 | 0.916 |  |  |
| Air temp. |  | 0.752 |  |

The rotation contribution to the structure of the factors is illustrating in the following plots.

In the rotated biplot (Varimax rotation), the variables are grouped different:

Height amsl, comp.2 and comp.4 load on the positive side of Dim1/component 1.

Chlorophyll, phycocyanin and Air temperature are in the upper quadrant and are closely clustered.

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Fig. 18: varimax-rotated PCA biplot PC1 & PC2, coloured by DOC

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Fig. 19: varimax-rotated PCA biplot PC1 & PC2, coloured by BDOC quantities

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Fig. 20: varimax-rotated PCA biplot PC1 & PC2, coloured by CO2

Examination of the differences between the two rivers

Finally, the differences between the two rivers in the three factors, determined by the factor analysis using the principal components and Varimax rotation, were examined:

A Multivariate analysis of variance (MANOVA) was performed with the scores of the first three once unrotated and once rotated factors as dependent variables (PC1–PC3). The influencing variables were the rivers (VJR and VR). For testing the global effect of the rivers on the factor scores the Wilks' test of significance (lambda test) was used, whereas for the simple effects univariate F-Tests were performed.

Multivariate Analysis of Variance on the scores of unrotated factors

Dependent variables: Scores of Factor1, Factor2 and Factor3 (from factor analysis)

Factor: River (2 levels)

41 cases accepted.

EFFECT .. RIVER

Multivariate Tests of Significance (Wilks)

Wilks Lambda = 0.10331 F(3, 37) = 107.04405 p < 0.0001

------------------------------------------------------------------------------------

Univariate F-tests with (1; 39) D.F.

Variable Hypoth.SSError.SS Hypoth.MS Error.MS F Sig.

FAKTOR1 34.48126 5.51874 34.48126 0.14151 243.67326 < 0.0001

FAKTOR2 0.74660 39.25340 0.74660 1.00650 0.74178 0.3944

FAKTOR3 0.63959 39.36041 0.63959 1.00924 0.63373 0.4308

Multivariate Analysis of Variance on the scores of rotated factors

Dependent variables: Scores of Factor1, Factor2 and Factor3 (from factor analysis)

Factor: River (2 levels)

41 cases accepted.

EFFECT .. RIVER

Variant: Varimax rotated

Multivariate Tests of Significance (Wilks)

Wilks Lambda = 0.10331 F(3, 37) = 107.04405 p = < 0.0001

------------------------------------------------------------------------------------

Univariate F-tests with (1; 39) D.F.

Variable Hypoth.SSError.SS Hypoth.MS Error.MS F Sig.

FAKTOR1 26.70054 13.29946 26.70054 0.34101 78.29800 < 0.0001

FAKTOR2 6.32696 33.67304 6.32696 0.86341 7.32786 0.01002

FAKTOR3 2.83995 37.16005 2.83995 0.95282 2.98056 0.09218

Regarding the unrotated PCA, multivariate variance analyses revealed a significant global river effect both on the unrotated factor scores (Wilks: F(3, 37) = 107.04, p < 0.0001), and the Varimax-rotated factor scores as well (Wilks: F(3, 37) = 107.04, p < 0.0001).

~~Regarding the unrotated PCA, the variance analysis revealed a significant river effect (variant: unrotated; Wilks: F(3, 37) = 107.04, p < 0.0001), which only has a univariate effect on factor 1 (p < 0.05). For the Varimax-rotated PCA the univariate effect was on factor 1 and factor 2 (p < 0.05).~~

Univariate F-tests for the simple effects showed that by the scores of the unrotated factors the river effect was only significant on the Factor 1 (p < 0.001), i.e. Factor 1 differ significantly between the two rivers, whereas Factors 2 and 3 did not.

For the sores of the varimax-rotated factors the univariate tests revealed significant differences both in Factor 1 (p < 0.001) and Factor 2 (p = 0.01), while Factor 3 was not significantly different (p = 0.09).

For a better impression of the river effects on the factors the factor scores were displayed for each river separately in box plots. Box plots visuallysummarize the distribution characteristics: the minimum, first quartile (25th percentile), median (50th percentile), third quartile (75th percentile), maximum, interquartile range and whiskers extending the minimum and maximum values.

Ein Bild, das Screenshot, Diagramm, Pixel enthält.

KI-generierte Inhalte können fehlerhaft sein.

Fig. 21: Factor score by river (unrotated PCA)

Ein Bild, das Screenshot, Diagramm, Pixel enthält.

KI-generierte Inhalte können fehlerhaft sein.

Fig. 22: Factor score by river (varimax rotated PCA)

# Summary of Key Differences Between Rivers

The comparison revealed systematic differences in DOC levels, lability (BDOC%), and DOM quality, likely driven by catchment characteristics and glacier type.

# Discussion

Some parameters differed between morning and afternoon samples.

-> may reflect changes in temperature, light, or biological activity.

CO2

Von Chatty: In their flux calculations, Boodoo et al. (2017) estimate the molar volume of CO₂ using the ideal gas law in the form Vm=RTpVm​=pRT​, where RR is the universal gas constant and pp the atmospheric pressure. While CO₂ is not a perfectly ideal gas, this approximation is considered valid under ambient pressure and temperature conditions commonly found in field studies. The authors do not explicitly justify the use of the ideal gas law, but its application is implied in their method description.

# Interpretation of Results

- Explanation of what the findings indicate about DOC and BDOC levels in the two rivers.

Concerning the CO2 fluxes

The use of the ideal gas law and the assumption of a constant atmospheric pressure of 1013.25 hPa across all sites represent methodological simplifications applied in this study. While this simplification is commonly applied (e.g., Boodoo et al. 2017, Lorke et al. 2015), it may introduce minor inaccuracies, particularly at higher altitudes (e.g., ~900 m a.s.l. at the first 5 sampling points of VJR in the highlands). However, given the overall uncertainties in flux measurements, these effects are considered negligible in the context of this study. *Future work could improve accuracy by incorporating site-specific pressure data and corrections for non-ideal gas behavior, especially in more extreme environmental settings.*

It would be preferable to analyse also the fluorescence of the DOM samples without delay, but it is not logistically possible. (Barker et al. 2013)

*Observations*

*in reservoirs and river impoundments revealed that*

*the enhanced sedimentation of particulate organic matter can*

*make these zones emission hot spots*

# Comparison with Existing Literature

- How the results align or contrast with previous studies.

# Factors Influencing DOC and BDOC

- Discussion of environmental or climatic factors affecting the observed concentrations.

# Implications for Carbon Cycling

- The role of glacial rivers in regional and global carbon budgets.

- Potential impacts on downstream ecosystems.

Research indicates that, on a global scale, glaciers supply ancient, BDOC, downstream, into both riverine and oceanic trophic networks (e.g., Hood et al., 2009; Fellman et al., 2015; Holt, McKenna et al., 2024). Despite its aged character, the pronounced bioavailability of glacier DOC is likely driven largely by relatively young organic carbon produced in situ by microbial communities on the glacier surface. (Holt, Fellman et al. 2024)

As glaciers retreat and their contribution of glacier DOC decreases—while stream conditions increasingly favour microbial growth (e.g., Hood et al., 2015; Kohler et al., 2024)—the main source of bioavailable modern OC is expected to shift from glacier‑derived inputs (e.g., algal production on glacial surfaces) to in‑stream production. (Holt, Fellman et al. 2024)

Also, for example, vegetation expansion that follows the retreat of glaciers also results in alterations to the composition of the DOC. (Robinson et al. 2023)

# Limitations of the Study

- Reflection on methodological or data limitations.

- Impact of limitations on the study's conclusions.

# Conclusion

# Summary of Key Findings

- Recap of the main results and their significance.

# Answers to Research Questions

- Direct responses to the objectives and questions posed in Chapter 1.

# Recommendations for Future Research

- Suggestions for further studies to build on your findings.

# Final Remarks

- Concluding thoughts on the importance of the study.

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https://kort.gis.is/mapview/?app=kort&l=en&c=492934,338082&z=6.4&ls=4199,1056,3993,4355,4146,4056,1053&op=3993\_0.54,4355\_1,4146\_1,4056\_0.55&lo=8096\_2,3878\_12,3879\_509,3915\_510,3911\_13,4344\_30,4345\_948,4347\_949,4348\_950,4346\_951,4516\_952,4517\_953,3939\_516,3929\_567,3905\_37,4893\_40,4895\_827,4894\_828,3920\_593,3883\_43,3945\_602,4178\_517,4179\_518,3910\_49,4755\_57,3918\_652,3895\_64,6943\_66,6944\_716,3909\_68,3923\_662,3906\_83,3894\_120,6229\_125,6230\_1006,3930\_677,3890\_127,3913\_679,3907\_130,3893\_138,3935\_681,3928\_683,3943\_711,3921\_715,3908\_154,3926\_724,3932\_735,3898\_162,3933\_778,3888\_173,3901\_308,3892\_311,3919\_800,3886\_313,8140\_319,6231\_325,6232\_1007,3904\_327,3924\_803,3891\_433,3927\_814,3917\_823,3914\_826,3889\_447,3916\_844,3902\_475,3882\_482,3949\_874,3885\_499,5840\_507,3925\_947,3944\_962,3931\_991,3946\_999,3941\_1005,3922\_1048,4091\_963,4029\_875,3977\_964,4021\_876,3974\_1008,4036\_966,4004\_737,4359\_967,4001\_968,4022\_969,4003\_970,4170\_971,4047\_972,3979\_973,4006\_974,4177\_975,3980\_976,3982\_977,4007\_978,4015\_979,4008\_980,4020\_981,4099\_982,3967\_983,4026\_984,3995\_684,3984\_685,4000\_686,3993\_687,4355\_688,4071\_689,4013\_690,4098\_691,4066\_692,4002\_693,4009\_694,3990\_695,4028\_696,3985\_1009,3950\_1010,3951\_1011,3955\_1012,3952\_1013,4024\_1014,3956\_1015,3957\_1016,3986\_1017,3953\_1018,3987\_1019,3962\_1020,4065\_1021,5703\_1049,3958\_1050,3964\_779,7440\_780,4253\_781,4256\_1022,4258\_519,4257\_663,3968\_664,4084\_665,4259\_815,4260\_594,3999\_595,7442\_596,3969\_816,3961\_520,4109\_597,3998\_598,4261\_782,7456\_783,4005\_717,4262\_718,7446\_719,7445\_720,7449\_1023,7448\_1024,4263\_1051,4264\_1052,4416\_603,4417\_604,3971\_682,4418\_605,5618\_606,4909\_607,4419\_608,4191\_712,3972\_784,4336\_806,4335\_807,3975\_808,3983\_877,3996\_1025,5841\_829,4111\_521,4012\_830,4033\_846,4018\_847,4042\_848,4265\_849,4010\_850,4073\_851,4092\_852,7444\_853,4074\_854,4011\_855,4085\_856,4037\_857,3988\_858,4156\_859,4038\_860,4266\_861,7443\_862,4048\_863,4080\_831,4267\_832,7447\_864,4016\_785,4017\_786,4054\_609,4105\_610,7468\_611,4086\_612,4268\_613,4269\_614,4062\_615,4063\_616,4270\_617,7471\_618,7470\_619,7469\_620,4271\_621,7472\_622,4064\_623,4093\_624,4272\_625,4157\_626,4273\_627,7473\_628,7476\_629,7475\_630,7474\_631,4274\_632,4106\_633,7503\_634,7502\_635,7501\_636,7477\_637,4175\_638,7482\_639,4087\_640,4151\_641,4055\_787,4097\_992,7632\_704,4070\_705,4108\_706,4077\_707,7467\_878,7465\_879,7464\_880,7463\_881,4110\_882,4082\_883,4107\_884,4083\_885,4275\_886,4075\_887,4096\_708,4100\_709,4090\_710,5643\_954,5644\_955,5641\_956,6956\_957,6955\_958,6954\_959,6953\_960,6952\_961,7457\_522,4076\_523,4153\_524,7458\_525,3970\_526,4112\_527,4088\_528,4059\_529,4094\_530,4095\_531,7451\_532,7459\_533,4276\_534,4277\_535,3965\_536,7462\_537,7461\_538,7460\_539,4625\_888,4101\_540,5048\_666,4142\_721,4141\_722,4754\_723,3973\_680,4217\_757,4202\_758,4172\_759,4166\_760,4167\_761,4168\_762,4213\_763,4214\_764,4102\_765,4040\_766,3989\_767,4039\_768,4053\_769,4078\_770,4079\_771,4173\_772,4174\_773,4176\_774,4034\_833,3994\_775,4027\_993,4061\_834,4043\_817,4041\_541,4045\_642,3963\_599,4025\_776,3959\_994,4150\_667,4067\_643,4149\_835,4146\_818,4145\_889,4143\_542,4144\_543,4160\_777,4056\_995,4165\_996,4159\_997,4164\_890,4158\_891,4046\_892,4058\_893,4216\_836,4032\_837,4044\_838,4198\_839,4196\_840,4161\_668,4035\_669,3978\_670,4283\_671,3960\_644,4057\_645,4050\_600,4155\_601,4049\_819,4278\_820,4119\_821,4181\_822,8092\_672,4244\_673,4243\_674,4245\_544,4247\_545,4248\_1053,4246\_1054,4242\_1055,4249\_675,4052\_894,4187\_653,3997\_654,4781\_646,4780\_647,4777\_648,4756\_649,4775\_650,4774\_651,4215\_1026,3991\_1027,8108\_546,8103\_1028,4206\_1029,4229\_1030,8104\_454,8105\_455,4230\_1031,4228\_1032,4227\_1033,8098\_1034,4207\_1035,8106\_461,4205\_1036,4209\_678,4208\_824,4200\_825,4210\_1000,4197\_1001,4201\_1002,4183\_655,4370\_656,4185\_657,4369\_658,4189\_659,4188\_660,4186\_661,5060\_788,8110\_789,8111\_790,8112\_791,8109\_792,4193\_793,4192\_794,7438\_795,7439\_796,5624\_797,6857\_895,6858\_896,6859\_897,6860\_898,6861\_899,6872\_900,6871\_901,6862\_902,6863\_903,6864\_904,6865\_905,6868\_906,6867\_907,6873\_908,6869\_909,6870\_910,6874\_911,6875\_912,6876\_913,4194\_914,6877\_915,6878\_916,6879\_917,6880\_918,6881\_919,6884\_920,6883\_921,6885\_922,6891\_923,6890\_924,6889\_925,6888\_926,6887\_927,6886\_928,4195\_929,7710\_930,4948\_1037,4949\_1038,4339\_1039,4250\_1040,4204\_1041,5061\_1042,4212\_1043,4203\_1044,4252\_1045,4280\_1046,4219\_985,4233\_986,4222\_987,4223\_988,4224\_989,4235\_990,4237\_547,4236\_548,4238\_549,4225\_550,4226\_551,4239\_552,4240\_553,4220\_554,4221\_555,3992\_556,4232\_511,4218\_512,4231\_513,4946\_514,4234\_557,5166\_558,4211\_515,4241\_559,4279\_798,4068\_865,4295\_866,4285\_867,4291\_868,4293\_869,4072\_870,4287\_871,4284\_560,4286\_561,4281\_562,3966\_563,4282\_564,4294\_713,4289\_998,4292\_1047,4169\_676,4296\_799,4299\_931,4310\_841,8153\_932,4309\_933,4313\_842,4311\_934,4312\_843,4298\_935,4297\_872,4307\_873,4317\_936,4304\_937,4314\_938,4303\_939,4316\_940,4315\_941,4306\_942,4302\_943,4301\_944,4300\_945,4305\_946,4319\_725,5053\_726,5054\_727,4318\_728,5055\_729,5056\_730,4290\_731,5057\_732,5058\_733,4320\_734,8097\_714,8107\_565,8100\_471,8099\_566,8101\_473,8102\_474,8139\_809,8141\_810,8142\_811,8146\_812,8147\_813,8149\_1003,8150\_1004

<https://vatnavefsja.vedur.is/#/mainmap>

<https://vatnavefsja.vedur.is/#/mainmap>

<https://kort.gis.is/mapview/?app=kort&lang=is>

<https://kort.gis.is/mapview/?app=kort>

<https://atlas.lmi.is/mapview/?application=DEM>

<https://dem.gis.is/mapview/?application=DEM>

<https://vatnavefsja.vedur.is/#/mainmap>

<https://gatt.natt.is/geonetwork/srv/eng/catalog.search#/metadata/477cdfa0-9b78-449b-ad93-a048f059ba7d>

3Dmodell Öfajökull

<https://atlas.lmi.is/3dmodel/Oraefa_w_Names/Oraefa_20181102.html>

<https://www.lmi.is/is/landupplysingar/haedargogn/haedarlikon>

Bodenkarte

<https://loftgaedasja.gis.is/mapview/?application=loftgaedasja>

# Appendices

## Supplementary Code and Data

The source code and data used in this thesis are available in the following public GitHub repository:

**GitHub Repository**: <https://github.com/kokkaso/MA_supplementary_Data>

* CO₂ Flux Calculations

## List of instruments, materials and software

* 1. Instruments

1. TOC - Total organic carbon analyzer

Shimadzu Corporation (2021): Total organic carbon analyzer (TOC analyzer), TOC-L CPN,

<https://www.shimadzu.co.uk/products/total-organic-carbon-analysis/toc-analysis/toc-l-series/index.html> (Accessed: 5 March 2025)

1. Spectrophotometer

Thermo Fisher Scientific Inc. (2013): GENESYS 10S UV-Visible Spectrophotometer,

<https://www.thermofisher.com/de/de/home/industrial/spectroscopy-elemental-isotope-analysis/molecular-spectroscopy/uv-vis-spectrophotometry/instruments/genesys-uv-vis-spectrophotometer.html> (Accessed: 5 March 2025)

1. Spectrofluorophotometer

Shimadzu Corporation (2024): Spectrofl­uorophotometer RF-6000, Shimadzu

<https://www.shimadzu.de/products/molecular-spectroscopy/fluorescence/fluorescence-spectroscopy/rf-6000/index.html> (Accessed: 5 March 2025)

1. EXO2 Sonde

YSI Inc. / Xylem Inc.(2025): EXO2 multiparameter Water Quality Sonde,

<https://www.ysi.com/exo2> (Accessed: 5 March 2025)

* 1. Software

QGIS.org (2024) QGIS Geographic Information System (Version 3.34 - Florence). Open-Source Geospatial Foundation. Available at: https://qgis.org (Accessed: 6 March 2025).

R Core Team (2024) R: A language and environment for statistical computing. Version 4.3.2. R Foundation for Statistical Computing. Available at: https://www.R-project.org (Accessed: 6 March 2025).

RStudio Team (2024) RStudio: Integrated development environment for R. Version 2024.03.0. Posit Software, PBC. Available at: https://posit.co (Accessed: 6 March 2025).

Field laboratories (for the Vestari-Jökulsá in Ingólfsskáli, picture above; for the Virkisá, picture below)

Ein Bild, das Im Haus, Haus, Mobiliar, Kleidung enthält.

KI-generierte Inhalte können fehlerhaft sein.Ein Bild, das Mobiliar, Im Haus, Tisch, Kleidung enthält.

KI-generierte Inhalte können fehlerhaft sein.

* 1. Artificial Intelligence (AI) and Large Language Models (LLM)
     1. DeepL Translate, Deepl SE: <https://www.deepl.com/translator>

Translation support

* + 1. ChatGPT (OpenAI, 2025)

Inspiration and coding support

## Impressions sampling sites

* 1. Vestari-Jökulsá River
  2. Virkisá River

## Co2-Logger Result

* 1. Vestari-Jökulsá River
  2. Virkisa River

## Weather station Data

* 1. Sáta (17.07 - 23.07.2024)

Name: Sáta

Station Nr.: 3054

Type: Automatic weather station

Lat.; Lon.: 65,06278; -18,83833

height: 785 m.a.s.l.

1Air temperature (1 min. average) [°C]

Maximum temperature (highest 1 min. average of the last hour) [°C]

Minimum temperature (lowest 1 min. average of the last hour) [°C]

Wind direction (10 min. average) [°]. N: 0°, E: 90°, S: 180°, W: 270°

Wind speed (10 min. average) [m/s]

Maximum 10 min. average wind speed of the last hour [m/s]

Maximum wind gust (3 sec value) [m/s]

Precipitation in the past hour [mm] (unprocessed data)

Excel Table - C:\Users\sophia\Dropbox\MASTER\1\_Alicia\WETTER\wetterTabelle Alicia

Icelandic Meteorological Office 2025: Icelandic Meteorological Office Database, delivery no. 2025-03-10 11:04:16/IMO Self service of Weather observations

* 1. Skaftafell

Name: Skaftafell

Station Nr.: 6499

Type: Automatic weather station

Lat.; Lon.: 64,01437; -16,97212

height: 86 m.a.s.l.

1Air temperature (1 min. average) [°C]

Maximum temperature (highest 1 min. average of the last hour) [°C]

Minimum temperature (lowest 1 min. average of the last hour) [°C]

Wind direction (10 min. average) [°]. N: 0°, E: 90°, S: 180°, W: 270°

Wind speed (10 min. average) [m/s]

Maximum 10 min. average wind speed of the last hour [m/s]

Maximum wind gust (3 sec value) [m/s]

Precipitation in the past hour [mm] (unprocessed data)

Excel Table: - C:\Users\sophia\Dropbox\MASTER\3\_AnnKathrin\WETTER

Icelandic Meteorological Office 2024: Icelandic Meteorological Office Database, delivery no. 2024-10-29 12:53:51/IMO Self service of Weather observations

## Master table

# Declaration of Independence

**Declaration**

I hereby certify that I have written this work independently and have not used any sources or resources other than those specified.

The master's thesis has not yet been submitted to any other university in the current or a similar form and has not yet served any other examination purposes.

Ein Bild, das Schrift, Kalligrafie, Handschrift, Typografie enthält.

KI-generierte Inhalte können fehlerhaft sein.

Date: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ Signature: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

**Declaration of consent to access to the master’s thesis**

o I agree that my master’s thesis in the department/university archive may be viewed by third parties for academic purposes.



o I do not agree that my master’s thesis in the department/university archive may be viewed by third parties for scientific purposes.

Ein Bild, das Schrift, Kalligrafie, Handschrift, Typografie enthält.

KI-generierte Inhalte können fehlerhaft sein.

Date: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ Signature: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

ToDOs:

* Alle Schrift einfarbig machen, Überschriften schwarz machen

\*\*Explanation of the Structure:\*\*

- \*\*Abstract:\*\* Provides a snapshot of the entire study, allowing readers to quickly grasp the purpose and outcomes.

- \*\*Introduction:\*\* Sets the stage by introducing the topic, establishing the context, and stating the research objectives.

- \*\*Literature Review:\*\* Surveys existing research to position your study within the broader academic conversation.

- \*\*Study Area:\*\* Gives detailed information about the geographical and environmental settings of the rivers studied.

- \*\*Methodology:\*\* Describes how the research was conducted, ensuring transparency and reproducibility.

- \*\*Results:\*\* Presents the findings in a clear and organized manner, using visual aids where appropriate.

- \*\*Discussion:\*\* Interprets the results, linking them back to the research questions and existing literature.

- \*\*Conclusion:\*\* Summarizes the study, highlighting its contributions and suggesting future research directions.

- \*\*References and Appendices:\*\* Provide the necessary academic rigor and additional information for interested readers.

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1. Longitudinal variation of macroinvertebrate assemblages in Icelandic arctic glacier-fed and snow-fed streams: changes and their environmental drivers – a comparison after 26 years; PhD student: Alicia Knauft. [↑](#footnote-ref-1)
2. Elucidating the temporal variability of glacial organic carbon concentration and composition toward determining carbon export via discharge separation and machine learning techniques (Falljökull, Iceland); PhD student: Ann-Kathrin Wild. [↑](#footnote-ref-2)