Using stable water isotopes to understand ecohydrological pathways in changing Arctic watersheds

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Table of Contents

1. Introduction

The Arctic is not an isolated area but a key part of a global climate system, interacting with the rest of the world through a shared ocean, atmosphere, and social systems. Over the last century, however, the Arctic has experienced rapid and dramatic changes which occur and accelerate at a faster rate than in the mid-latitudes of the globe (Pörtner et al., 2019) . According to the 2019 IPCC report, polar regions are losing sea ice extent and thickness at an accelerating speed, sea levels all around the globe are rising, surface air has doubled its temperature, permafrost temperatures have reached record high levels and various other climate-related changes are occurring to Arctic ecosystems. These environmental changes will affect not only the Arctic but the whole planet and its inhabitants in multiple ways (Pörtner et al., 2019).

Ecohydrological cycle combines biological (living organisms) and abiotic (physical and chemical) processes, where a change in one process results in change in all of them. Understanding how water moves through time and space is crucial when trying to predict future water cycle dynamics and its impacts on the surrounding environment (Bowen et al., 2019). The hydrologic cycle consists of water evaporating form the oceans, rivers and lakes, rising into the atmosphere, cooling down and condensing, and finally returning as precipitation (Mu et al., 2011). Hydrological cycle is closely linked with the carbon cycle, which enters fresh waters mainly by dissolving directly from air as inorganic carbon or by vegetation that falls into the water (Cole et al., 2007) which, as a result of decomposition of dead organic matter (DOM), releases organic carbon in the stream (Prowse et al., 2006). Additionally, a large amount of organic carbon is stored in northern permafrost regions as immobile storage, as long as the permafrost stays stabile (Ma et al., 2019).

The consequences of climate change on the Arctic water system have high variability and widespread environmental impacts. While the rising of air temperatures and loss of pan-Arctic sea ice are fairly certain, effects on other climate variables such as precipitation and river discharge are still vastly unknown due to their dependence on each other and many simultaneously interacting processes (White et al., 2007). Additional issues rise with changes in seasonality and timing, as precipitation is shifting from snow to rain and snowmelt occurs earlier in the season indicating a structure shift in hydrologic cycles towards an earlier peak in spring floods (Pörtner et al., 2019).

One very powerful way to understand the fundamental hydrological processes and how they are interconnected is using stable water isotopes of hydrogen (^{2}H) and oxygen (^{18}O) and their compositions as hydrological tracers, as atmospheric processes and seasonal cycles produce natural variation in the isotopic ratios, and these ratios and compositions can be used to reflect the water source and history (Bowen et al., 2019). Measuring isotopic composition of water enables the identification of different water masses and tracing the history of their relationships (Gat, 1996). One of the earliest applications of stable isotope chemistry, in fact, was a study on hydrological cycles presented by W. Dansgaard, in which he studied waters from different sources and noticed variation in ^{18}O-values between fresh and marine waters, between fresh waters from different climates and between atmospheric water vapors from different precipitation temperatures (Dansgaard, 1954).

Stable isotope geochemistry is a well-established method for tracing environmental changes and it seems to be a promising method for exploring ecohydrological interactions as recent results reported by various authors indicate, for example studying moving precipitation events (von Freyberg et al., 2018), detecting snowmelt signals (Lyon et al., 2018) and uncovering how aquatic organisms change behavior due to climate change (Vander Zanden et al., 2016). As accessibility grows, databases become more comprehensive and technology develops, the importance and applicability of measuring stable water isotopes will keep growing in the future (Bowen et al., 2019).

The aim of this thesis is to determine whether stable water isotopes are suitable for understanding changes in ecohydrological pathways. This will be achieved by determining how stable water isotopes can be used to trace ecohydrological processes through space and time, understanding the patterns and drivers of ecological changes in Arctic watersheds and exploring how stable water isotopes can be applied to trace the interactions between water and ecological systems in Arctic watersheds.

2. Stable Isotope Hydrology

An isotope is an atom of an element with a given number of protons and neutrons. Unlike unstable radioactive isotopes that undergo spontaneous disintegration, stable isotopes remain indefinitely unchanged. Naturally occurring stable water isotopes of hydrogen and oxygen are ^{1}H,^{2}H, ^{16}O, ^{17}O and ^{18}O, the number indicating the differentiating number of neutrons in each atom. The proportional abundance of each of these isotopes varies throughout the hydrological cycle as different water sources have natural variation in their isotopic compositions. For example, the ^{18}O is heavy and rare in relation to the lighter, more common ^{16}O, as it has two more neutrons. This difference in composition and weight is significant because most biological or hydrologic processes prefer one isotopic form over the other and discriminate the alternative causing it to become locally depleted in abundance, for example how the water vapor phase accumulates the lighter isotopes, leaving the water it evaporated from with heavier isotopes (Bowen et al., 2019).

Fractionation, or the change in isotopic ratio due to mass selectivity, occurs most commonly with evaporation or other water phase change between solid, liquid and vapor. This change in isotopic composition provides a recognizable signature that can be traced back to different phases of the water cycle. The composition change results from differences in bonding energy, reaction rate or diffusivity of light/heavy isotopes (Bowen et al., 2019). The vapor phase preferentially accumulates the lighter isotopes, and as a result, water formed from evaporation is depleted of the heavy isotopes and therefore is isotopically lighter than the water from which it was derived (Gat, 1996). In case water phase changes involve the transport of water vapor (transport to/from sites of condensation/evaporation), the isotopic composition can be conventionally recorded as the dual-isotope composition of water, $\delta^{2}H$ and $\delta^{18}O$. This phenomenon affects hydrogen isotopes approximately eight times as much as oxygen and can be used to form a so-called deuterium-excess parameter (*d-excess* = $\delta^{2}H - 8\ \delta^{18}O$). This parameter can be used for example to investigate distribution of isotopes in local precipitation (Bowen et al., 2019). Water isotope data is traditionally given as relative deviation from an agreed standard called Standard Mean Ocean Water, or S.M.O.W., in which the ocean values for $\delta^{2}H$ and $\delta^{2}O$ are both exactly zero (Dansgaard, 1964).

Water isotopes can provide useful information for example on the origins of water, past climate and degree of evapotranspiration (Vander Zanden et al., 2016). The isotopic ratios of hydrogen and oxygen have been applied in researching hydrological cycles for over 60 years and have found extensive use as tracers. By measuring the isotopic composition of water, it is possible to identify different water masses from each other and trace their relationships (Bowen et al., 2019). For example, meteoric waters (waters derived from precipitation) are depleted of heavy isotopes compared to ocean water (Gat, 1996), the first meltwaters of a snowpack are isotopically depleted while the latter are isotopically enriched (Lyon et al., 2018), soil water isotopic ratios are distinct from the values measured from groundwater because of evaporation from the soil, and summer precipitation is usually found to be isotopically heavier than winter precipitation (Bowen et al., 2019). Lyon et al. (2018) used isotopes as tracers while studying shifts in isotopic compositions in an Arctic environment as seasons shifted from spring to summer, assessing isotopic composition and variability for inputs in precipitation (snow and rain) and outputs in stream water. The main goal was to explore how isotopic variability of stream waters evolve with the seasonal changes of snowpacks melting and precipitation input shifting from snow to rain. The results show that a considerable variability was found in the isotopic compositions inside catchment region in rivers that had input mostly from precipitation compared to input mostly from snowpack meltwater. The results were clear: the variation in isotopic values of the streams followed closely the variation observed in precipitation and upstream snowpacks, and the rivers followed the change in input sources religiously across the watershed. However, they noticed that a large portion of isotopic signals are yet to be detected for their similarity, for example high-elevation snow and early season rain showed very similar signals, and more studies are needed to reliably catch these differences (Lyon et al., 2018). von Freyberg et al. (2018) studied how storm characteristics affect the event and pre-event waters in the catchment. They used isotopes as tracers to track the waterflow through the catchment, were able to separate event and pre-event conditions, and concluded that for the majority of the storms, pre-event water dominates streamflow (von Freyberg et al., 2018). Furthermore, measuring isotopic variations in climatic archives such as ice cores or lake and ocean sediments are very useful in paleoclimatic studies, as it is possible to track the water history, reconstruct past hydrology and therefore predict future challenges related to climate change (Gat, 1996).

Gibson and Reid (2014), on the other hand, investigated water chains and water balance in the Arctic watersheds using water isotope mass balance with a multi-year dataset approach. The isotope mass balance determines evaporation and inflow ratio from measured isotopic composition of water body as well as estimated composition of inflow and is a valuable tool in assessing remote regions with limited baseline hydrologic data. The results showed how isotopic signals evolve along the watershed. The dataset captured both seasonal and interannual variability in the isotopic composition of waters which is especially important in snow-dominated regions where waters are exposed to inflow pulses during spring melt followed by short summers with high evaporation (Gibson & Reid, 2014).

Stable water isotopes are increasingly important when studying climate change induced phase changes from local watersheds to the snow-dominated Arctic regions. Using isotopes as tracers to detect specific hydrological fingerprints is invaluable when investigating past and present hydrology, and although the method is useful in any environment, it is particularly effective in remote and high altitude regions that would be difficult to study with other methods (Edwards et al., 2004). The development of technology has made isotopic studies even more comprehensive. Using satellite-based censors with the ability of measuring isotopes of water vapor at different levels in Earth’s atmosphere has opened up new opportunities for large-scale data collection (Bowen et al., 2019), and on-site devices that allow continuous measuring have excluded the usual complications of sample collection, human error, transport and storage issues that usually occur before analyzing is even possible to begin (von Freyberg et al., 2017).

3. Changing Water Cycle Dynamics in the Arctic

The drastic change Arctic environments are experiencing revolves largely around storage and cycle changes of fresh water. Taking the changes in temperature and precipitation that have been going on over the last two centuries into consideration, the stage of future fresh water availability is an open question in the Arctic regions (Barnett et al., 2005). The changes to freshwater hydrologic cycle are also closely related to the availability of permafrost. All in all, the consequences of climate change to Arctic freshwater systems have a large range and a larger significance (White et al., 2007).

The hydrologic cycle starts with water evaporating form the oceans, rivers and lakes, as well as the additional evaporation from soil surfaces, transpiration from plants and sublimation from snow surfaces. This evapotranspirated water vapor rises into the atmosphere, cools down and condenses, and finally returns as precipitation and flows to streams as runoff. Regionally, water cycles may also include a strong incoming and outgoing streamflow (Mu et al., 2011). The marine part of the hydrological cycle accounts for 90% of the annual water flux. This contains mainly evaporation from the ocean and the return flux in the form of precipitation back into the ocean. In the continental part of the cycle that accounts for 10% of the total flux, precipitation water is recycled with evapotranspiration, usually multiple times, before coming back to the ocean as river runoff. (Gat, 1996). The hydrological cycle is presented in Figure 1.

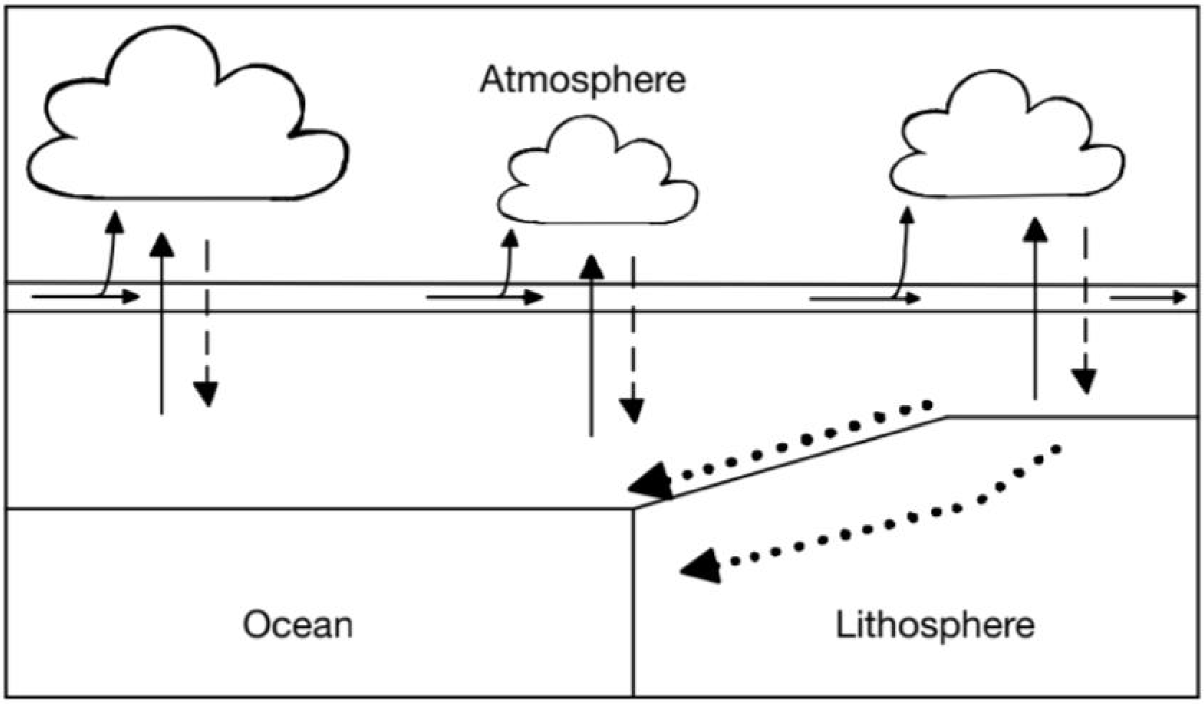

Figure 1. A schematic representation of the hydrological cycle. The full arrows represent evaporation, the dashed arrows precipitation and the dotted arrows runoff. Graph modeled after Gat, 1996.

Even though there are a lot of uncertainties concerning the climate change effects on the Arctic, it is relatively accepted that air temperatures are increasing. Warmer air, however, holds more water vapor and as the temperatures keep gradually rising, the air consequently contains increasing amounts of water vapor (White et al., 2007). Air temperatures will likely experience more climate-induced change than stream temperatures (Mustonen et al., 2018). The atmospheric moisture storage over the Arctic ocean has experienced, and will continue to experience, drastic change: precipitable water in the atmosphere has increased in the summer and decreased in the winter, however there have been no reports of significant change over the Arctic land. These changes are consistent with the observed surface air temperatures (White et al., 2007).

Sea ice serves as a thermal insulator between ocean and atmosphere and, most notably, reflects a large part of incoming solar radiation back to space. According to the 2019 IPCC report (Pörtner et al., 2019), the pan-Arctic sea ice cover, and more importantly its ongoing loss, can be used as a prominent indicator of climate change. The loss of Arctic sea ice is mostly due to two factors: later occurring freeze-up, and its most notable consequence, the delayed snowfall accumulation on sea ice. Freeze-up is annually delayed due to rise in near-surface temperatures. This allows warmer waters closer to the North Pole further accelerating the loss of sea ice and causing ocean stratification and altered marine primary production. Snowfall accumulation, on the other hand, inhibits sea ice melting because of its highly reflective nature, but the ongoing precipitation shift from snow to rain prevents this accumulation. The loss of sea ice and exposed ocean increases evaporation, which affects the whole Arctic by increased precipitation and overall warmer and wetter conditions (Pörtner et al., 2019).

In northern regions, according to Ma et al. (2019) and White et al. (2007), freshwater hydrologic processes and water availability are largely controlled by the presence or absence of permafrost, the ground that remains at or below 0°C. The effects of climate-induced permafrost thawing on the hydrological cycle depend on the thickness of permafrost as well as the thickness of the soil above the permafrost. This soil is called the active layer because it seasonally freezes and thaws. Studies conducted in Russia, Alaska and Canada indicate that active layers around the Arctic are thickening, which is significant because most of the ecological, biochemical and hydrological activity in the Arctic soils takes place in it. Diminishing permafrost allows the surface waters to interact with the underlying groundwater and therefore enables the soil moisture to infiltrate past the active layer into the groundwater, resulting in much dryer soils and, perhaps more significantly, the mobilization of major carbon stocks that have been stored in the permafrost and are now available for transportation into downstream rivers (Ma et al., 2019; White et al., 2007).

Snowpacks are a significant water source in the Arctic, and adding or removing snow cover fundamentally changes the ability of a snowpack to act as a water storage (Barnett et al., 2005). Rapidly melting snow and ice cause the extreme seasons of spring floods, which typically lead to largest annual river flow (Lyon et al., 2018) and cause differences in stream temperatures, as stream flows derived from snowmelt are colder in temperature than those derived from precipitation (Mustonen et al., 2018). The timing and magnitude of these flows have immense societal and ecological impacts as well as influence on the biochemical cycles of water pathways. As climate change is causing the diminishing of snowpacks as well as a shift in precipitation from snow to rain, the volume and the chemical compositions of stream waters are anticipated to change (Lyon et al., 2018), as the hydrological changes of river flows are affected mainly by the timing of snowmelt, rather than changes in the amount of precipitation (Mustonen et al., 2018). In Arctic locations where water source has previously been dominated by snowpacks, the altered streamflow timing, volume and chemistry will have considerable, and yet little-known, impacts on stream ecology (Lyon et al., 2018).

One very powerful way to detect changes in the fresh water hydrologic cycle is measuring river discharge, the volume of water flowing through a river. River discharge combines the study of evapotranspiration, precipitation and water storage changes over the entire watershed upstream of measuring station. Monitoring it allows to assess changes in water budget over a vast part of the Arctic by monitoring just a small number of big rivers with large watersheds. The longest record of river discharge measurements from Russia, started in 1930s, show an increase in river discharge from arctic rivers, most of which happened over the last few decades (White et al., 2007). In the case of large rivers, the effects of climate change must be evaluated for areas outside as well as inside of the Arctic (Prowse et al., 2006).

4. Changing Ecohydrological Dynamics in the Arctic

Northern regions are vulnerable to changes in the climate because of their short growing season, dependence on snowfall for moisture and cover, and a weak hydrologic resilience which is controlled by precipitation that falls into the catchment area, total evapotranspiration and snowpack depletion due to temperature increase (Foks et al., 2018). Climate change predictions for the Arctic regions have a large variance: only warming, only wetting, and both simultaneously. Each of the modeled future scenarios, however, predicts an intensification of atmospheric and hydrological processes, creating more extreme climate trends such as floods and droughts (Dean et al., 2016). Arctic freshwater systems are especially sensitive to climate change because of a large number of small ecohydrological components, such as tiny ponds and rivers including the fauna and flora that occupies them. The changes may result in gradual adjustment (the slow thaw of permafrost as its mean annual temperatures reach 0°C, lake stratification as temperature rises) or an abrupt crossing over the tipping point (larvae in the bottom of tundra lakes freezing to death when temperatures reach -18°C, organisms reaching thresholds for survival as pond temperatures rise) (Prowse et al., 2006).

To recapitulate, atmospheric processes control where, when and in which phase precipitation comes down. These processes combined with the hydrologic processes including the timing and place where water enters the stream, as well as where has the water been before entering, control the instream ecosystem processes. Where the water came from is a very important factor to the biological assembly in the river, because the origins and pathways of water have a major effect on the chemical composition of the river water and the amount of carbon in the river, which is influenced by the amount of dead organic matter (DOM) in the river. In addition to chemical composition and DOM and DOC levels, the increase in water temperatures affect and, in most cases, accelerate most biotic processes, increasing primary production (Prowse et al., 2006).

As mentioned, the original water source is the main factor affecting the chemical composition of the river, but other major factors are climate change induced shift from snow to rain in precipitation (Lyon et al., 2018), melting permafrost and deepening active layer (Prowse et al., 2006) and small soil water inputs that might have very small contributions to the volume of streamflow, but regardless have a large effect on the chemical composition of the stream (Foks et al., 2018). All in all, flow paths have a major effect on the downstream composition, which in turn affects the survival and productivity of organisms and therefore the ecosystem’s ability to resist climate change or atmospheric pollution. Changes to chemical composition include higher concentrations of nutrients, export of inorganic solutes such as nitrogen and phosphorus and changes in pH values of the river. The effects of changing chemical composition on organisms might include extended growing season (Foks et al., 2018) and increased productivity of the stream (Prowse et al., 2006).

Carbon cycles are closely linked with the hydrological cycle (Cole et al., 2007). Carbon enters fresh waters mainly by dissolving directly from air (inorganic carbon) or by vegetation that falls into the water (organic carbon) (Cole et al., 2007). Inorganic carbon is transformed into organic carbon by the autotrophs in the stream. Dissolved organic carbon (DOC) in the stream is the result of decomposition of dead organic matter (DOM). The rising amounts of carbon in the atmosphere and the warming of the climate can increase DOC concentrations in streams by climate-induced vegetation shifts in the Arctic from mostly lichens to mostly grasses that causes an increasing amount of particulate DOM in the runoff. DOC concentrations have historically been negatively correlated with latitude because of low DOM deposition. The increase in DOC also induces an increase in the microbial productivity and primary production of the streams (Prowse et al., 2006). A large amount of terrestrial carbon is stored in permafrost soils due to low-temperature conditions that shield the soil from microbial induced decomposition. Permafrost degradation and water infiltration will also result in a transport of dissolved organic carbon to streams and rivers and further increase the microbial activity in the streams (Ma et al., 2019)**.** The alterations in carbon quantities in aquatic environments increases the amount of primary production in heterotrophs (Mu et al., 2011) as well as increase in microbial activity (Ma et al., 2019), and therefore has vast effects on the organisms on all trophic levels that occupy the stream.

5. Connecting Stable Water Isotopes and Ecology

In the previous sections it was established that measuring the isotopic composition of water makes it possible to identify different water masses and trace their relationships and origins in space and time, as different water sources have natural variation in their isotopic compositions because the phase change of water between solid, liquid and vapor results in a change in the isotopic ratio of heavy isotopes and light isotopes. This change in isotopic composition provides a recognizable signature that can be traced back to different stages of the water cycle, and the water source and history can be identified: water originated from precipitation has different signal than water from snowmelt (Bowen et al., 2019). It was acknowledged that the changes that are happening in the hydrological cycle mainly revolve around storage and cycle changes of fresh water (White et al., 2007), and these changes were noticed especially in atmospheric water vapor, sea ice, permafrost, snow covers and stream flows. It was noted that these components are going through tremendous change and that an intensification of atmospheric and hydrological processes is predicted for the Arctic, creating more extreme climate trends (Dean et al., 2016), which could be studied and understood with isotopic surveillance. It was stated that these hydrological changes have consequent effects on the ecohydrological components of fresh waters, such as temperature, chemical composition, carbon and dead organic matter and these components in turn affect the primary production and hence the whole ecosystem in the stream.

Even though the vast majority of all isotopic studies focus solely on the hydrological side, isotopic data is not useful merely in hydrological studies. Recently, stable water isotopes have been introduced into ecological research, as purely hydrological studies cannot comprehensively explain the effects of climate change in different scales. Combining hydrological and ecological data merges to an even broader, even more comprehensive large-scale understanding of the interacting biotic and abiotic processes (Vander Zanden et al., 2016). The best results might be available by measuring isotopes from the stream to capture all the hydrological variabilities in the pathways and at the same time, from those same places, measuring some kind of biological activity. It might be of interest to look at these two different datasets and explore, and perhaps even expect, causations with isotopic fluctuations and the rates of primary production. If these causations are found, one could make very compelling conclusions about how climate-induced hydrological change affects the flora and fauna that occupy the stream, and what kind of changes can we expect as climate change extends and hydrological changes increase. Studies with similar ideas have already been conducted, for example by Bailey et al. (2018), in which ^{18}O values of precipitation preserved in diatoms in sediment were measured and compared to atmospheric events (Bailey et al., 2018). However, when studying real-time events, perhaps the best biological organisms for these research purposes would be microbes and how their communities and activities change, since they have a quick response to environmental changes as well as fast life and reproductive cycles. Changes to microbial communities, of course, bioaccumulate into change in all trophic levels.

Additionally, recent studies have suggested that stable water isotopes of δ^2H and δ^{18}O are potentially useful in building a more comprehensive understanding in aquatic and terrestrial food web studies. What makes hydrogen and oxygen especially useful in ecological food web studies is the linkage between spatial patterns of precipitation (δ^2H and δ^{18}O) values and the isotopic values in animal tissues. This combined knowledge makes it possible to track the movements of migratory aquatic animals (Vander Zanden et al., 2016). Animals that regularly move through the isotopic gradients develop isotopic signatures along the way, which can be detected from their tissues (deHart & Picco, 2015). The isotopic composition of tissue is influenced by diet which makes it possible to use these isotopes as tracers, investigating which resources the organism used in the past. The primary challenge of using H and O as ecological tracers in aquatic food web systems is the fact that these isotopes include information on both diet and water balance, meaning that the H and O fixed in the tissue might be a mixture from diet and body water (Vander Zanden et al., 2016). One powerful way to understand the effects of climate change on food webs and ecosystems would be to combine these isotopic food web studies with isotopic hydrologic studies, which might open up an interesting insight into what exactly is the hydrologic pressure that causes these animals to change their migration routes or feeding habits.

The effects of climate change to the ecohydrological processes are often not immediately noticeable in ecologic processes but they can be predicted, even in the early stages, with detecting change in stable water isotope compositions. Stable water isotope measurements have a lot to offer to improve ecological studies, either by including isotopic measurements of hydrological studies with an ecological ensemble, or by using them directly to study ecological processes by measuring hydrogen and oxygen isotopes from aquatic animal tissues.

6. Conclusions

Isotopic measurements of rainfall and streamflow are crucial when studying flow pathways. The most comprehensive results would be available by high-frequency measurements, but the workload and manpower required, combined with issues with the number of samples needed, sample storage, transport, subsequent laboratory analysis and the inevitable human error make that idea impossible when using traditional sampling methods. Indeed, often only just the time and effort required for sample managing are major limitations in the possible frequency and duration of sampling. Recent developments, however, have made it possible to measure water isotopes and chemical components in the field over extended periods of time (von Freyberg et al., 2017). Stable isotopes are measured from water samples with mass spectrometers (Bowen et al., 2019). One of the newer developments for this technique include Continuous Water Sampler (by Picarro Inc., USA) that allows quasi-continuous measurements for δ^2H and $\delta^{18}O$ when paired with wavelength-scanned cavity ring-down spectrometer analyzer (by Picarro Inc., USA). This technique allows measurements and sample analyzing straight at the study site (von Freyberg et al., 2017). Von Freyberg et al. (2017) were the first to use Continuous Water Sampler in the field and wanted to figure out how well the machine would perform compared to traditional sampling. Using Picarro equipment, they measured δ^2H and $\delta^{18}O$ -values on study site straight from the stream water and reported great performance and functionality. As mentioned, the usual issues of traditional sampling were irrelevant, but a small new issue was identified as a reliable energy source was required all the time. Their one-month dataset demonstrated how peak event-water contributions can easily be missed when using conventional snapshot sampling, which might result in an underestimation of event water fraction. Another major observation was how highly variable isotope responses were, making the capture of just right moments using traditional methods truly a challenge, even with episodic snapshot sampling.

The increase in near-surface temperatures caused by global warming will be responsible for alterations in the hydrological cycle in snow-dominated Arctic regions by seasonal shifts in streamflow. These alterations, depending on the exact location and system, will lead to both regional water shortages and therefore reductions in water availability in the dry season as well as to an increase in precipitation and overall wetness (Barnett et al., 2005; Dean et al., 2016). These severe changes are largely due to anthropogenic increases in greenhouse gases and the impacts that are unfolding are accumulative and, in some cases, irreversible. Additionally, the increasing amount of human impact makes the assessment of the state of rivers complicated, as development such as dams and flow regulation on major northern rivers adds to the complexity of determining which changes are climate-related (Pörtner et al., 2019). Overall, an intensification of atmospheric and hydrological processes and more extreme climate trends are predicted for the future (Barnett et al., 2005; Dean et al., 2016). The 2019 IPCC report predicts that by the end of the current century, the Arctic environment will appear significantly different from today. Future predictions have been made for different scenarios comparing the greenhouse gas emissions, and in case humans succeed in maintaining the global warming within 1.5°C, the magnitude of polar change will be significantly less (Pörtner et al., 2019).

Although the ecological landscape of the Arctic is irreplaceable with its large oceans, predominantly treeless permafrost areas and winter snow covers, what makes the area truly unique compared to other snow-covered regions of the world is the fact that the Arctic is a permanent home for about four million people. A large number of these people are indigenous, and while they as ethnic groups are the least accountable for human induced climate change, they are regardless the ones that will be affected the most (Pörtner et al., 2019). Stable water isotopes might provide a way to research the issues that affect the lifestyles of indigenous people such as disappearing sea and lake ice, diminishing fish populations and altering seasonal timing.

The examples in this thesis demonstrate that stable water isotopes of hydrogen and oxygen are immensely practical for understanding hydrological pathways and how they can be used in research. Whether used as tracers detecting snowmelt signals (Lyon et al., 2018), moving precipitation events (von Freyberg et al., 2018) or climate trends while capturing both seasonal and annual variation (Gibson & Reid, 2014), as environmental markers uncovering how organisms use resources, where they migrate and how their behavior is changing due to climate change (Vander Zanden et al., 2016), as a tool to reconstruct past climates to understand how the climate has changed in the past and what can be learned from it (Edwards et al., 2004), as a forensic approach with tracking the origins of various plant- and animal-based materials (Vander Zanden et al., 2016) or in comprehensive studies combining isotopic hydrological data and biological activity data, stable water isotopes have proved themselves a cost-efficient and nearly irreplaceable tool for ecohydrological research. It is very important to understand water isotope characteristics and to apply them to ecohydrological research to understand how every individual system of the ecohydrological cycle is functioning as well as how they are affected by the change around them. More large-scale isotopic studies are needed to comprehensively understand the effects of climate change in the Arctic regions in the global and regional scale.

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