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A new local meteoric water line for Inuvik (NT, Canada)

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Abstract. The paper presents a new local meteoric water line (LMWL) of stable oxygen and hydrogen isotopes in precipitation from Inuvik in the western Canadian Arctic. Data were obtained over 37 months between August 2015 and August 2018 resulting in 134 measurements of the isotopic composition of both types of precipitation, snow and rain. For 33 months of the sampling period each month is represented at least two times from different years. The new LMWL from Inuvik is characterized by a slope of 7.39 and an intercept of −6.70 and fills a data gap in the western Arctic, where isotopic composition data of precipitation are scarce and stem predominantly from before the year 1990. Regional studies of meteorology, hydrology, environmental geochemistry and paleoclimate will likely benefit from the new Inuvik LMWL. Data are available on the PANGAEA repository under https://doi.org/10.1594/PANGAEA.935027 (Fritz et al., 2021).

1 Introduction

The global annual average relationship between hydrogen (δ^2H or δD) and oxygen (δ^{18}O) isotope ratios in natural meteoric waters is captured by the global meteoric water line (GMWL) that was developed by assembling numerous local annual mean records worldwide (Craig, 1961) and is expressed by Eq. (1):

$$\delta^2\mathrm{H} = 8 \times \delta^{18}\mathrm{O} + 10‰. \quad (1)$$

The GMWL is widely used as baseline in environmental geochemistry, meteorology, hydrology and hydrogeology to trace the water cycle before and after recharge and to use isotopic fractionation processes in the water pathway to infer source characteristics and transport mechanisms. The relationship of δ^{18}O and δ^2H in meteoric waters is controlled by mass-dependent fractionation of oxygen and hydrogen isotopes between evaporation from ocean seawater and condensation from vapour, which strongly depends on altitude, latitude, seasonality and continentality of a given location (e.g. Clark, 2013; Dansgaard, 1964; Gat, 1996).

A meteoric water line calculated for a given area is called local meteoric water line (LMWL) with emphasis on the spatial variability in isotopic compositions of meteoric waters as investigated by Rozanski et al. (1993) by comparing the δ^{18}O–δ^2H relationships of monthly-scale samples at selected sites of the Global Network of Isotopes in Precipitation (GNIP) (IAEA/WMO, 2020). Thus, an LMWL represents the covariation in oxygen and hydrogen stable isotope ratios for a distinct area and observation period and has practical utility as a hydrologic framework and benchmark for evaluating hydroclimatic processes such as in isotope-enabled climate models (e.g. Werner et al., 2016). As a simplified, intuitive and site-specific representation of the average isotopic relationship in meteoric waters, coupled with information about the seasonal range of isotope composition in precipitation, an LMWL offers a reference for interpreting the isotope ratios measured in terrestrial waters and ice.

An LMWL can deviate from the GMWL both in slope and intercept of the linear regression in a δ^{18}O–δ^2H co-isotope plot. Such deviation largely results from differences in humidity (e.g. Putman et al., 2019) that are represented by

Figure 1. Map with WMO stations in the western Arctic, where GNIP data and LMWLs exist (i.e. Inuvik, Utqiaġvik (Barrow), Mayo and Cambridge Bay). Map by Sebastian Laboor (Alfred Wegener Institute, AWI, Potsdam, Germany).

the second-order parameter deuterium excess (d; Dansgaard, 1964), expressed by Eq. (2):

$$d = \delta^2\mathrm{H} - 8 \times \delta^{18}\mathrm{O}. \quad (2)$$

Deuterium excess is an indicator for non-equilibrium fractionation processes that might occur during phase transitions of water. It has been established as a function of relative humidity in the moisture source regions. The statistical linear relationship of δ^2H to δ^{18}O varies both temporally and spatially, and the variation in the slope may hold information about the seasonal climatology of the site (Craig, 1961; Rozanski et al., 1993).

A correlation between air temperature (T) and precipitation δ^{18}O was recognized and can be used to study surface air temperature change over time (Merlivat and Jouzel, 1979) using preserved ancient meteoric water such as in glacial ice (e.g. Dansgaard, 1964; Jouzel et al., 2003) or in permafrost-bound ground ice (e.g. Meyer et al., 2015; Opel et al., 2018; Wetterich et al., 2021) to reconstruct paleoclimate. Such studies benefit from known modern hydroclimatic conditions as expressed in LMWLs (e.g. Porter et al., 2019; Porter and Opel, 2020).

Although increasingly used, LMWLs from remote areas are rare, especially in the Arctic, as it requires long-term and regular sampling, analysing, and data processing (Putman et al., 2019). For example, in the western Arctic where extensive paleoclimatic research on (buried) glacial ice (e.g. Lacelle et al., 2007; Fritz et al., 2011; Coulombe et al., 2019), permafrost ground ice (e.g. Meyer et al., 2010; Fritz et al., 2011, 2012; St-Jean et al., 2011; Holland et al., 2020) and permafrost hydrology (e.g. Utting et al., 2012, 2013; Kokelj et al., 2015) takes place, the respective reference LMWLs to compare isotopic records with are based on scarce data covering only small periods of data acquisition before the year 1990 at only a few locations (Fig. 1). The present data collection aims (1) to update and extend the previous Inuvik LMWL and, thus, (2) to improve the regional framework for meteorological, hydrological and paleoclimate applications of precipitation stable isotopes of modern and past environments. Special emphasis is given to the central role of Inuvik for research in the western Canadian Arctic.

2 Material and methods

Inuvik (68.3° N, 133.5° W; Fig. 1) is located at the east channel of the Mackenzie River delta in the Northwest Territories (NT) in Canada. The current World Meteorological Organization (WMO) station (number: 719570) in Inuvik is located at the international airport at an elevation of 68 m above sea level (m a.s.l.).

The regular sampling of meteoric water for subsequent stable isotope analysis was conducted between August 2015 and August 2018 at the Aurora Research Institute (Western Arctic Research Centre, 191 Mackenzie Road, Inuvik, NT X0E 0T0, Canada) in the town of Inuvik.

A precipitation gauge was constructed as a PVC funnel with 30 cm diameter on top and fitting into a vertical PVC pipe with a diameter of 10 cm. A 250 mL HDPE bottle is located behind the sleeve in the vertical PVC tubes, directly under the funnel, which collects the water. The funnel and a 250 mL collection bottle fit tightly together to avoid secondary evaporation. The collection bottle can be taken out or replaced through the sleeve. Threaded rods in the inside of the PVC pipes run into the ground for stabilization. Ropes and stakes stabilize the rain gauge against wind.

The rain gauge collection bottle was regularly checked and carefully emptied after every rain or snowfall event. Sampled precipitation was transferred into 15 or 30 mL narrow-neck LDPE bottles, depending on the amount of water aiming at no remaining air in the bottle. Snow was scraped out from the funnel of the precipitation gauge after each snow event. The snow was placed into a larger (250 mL) bottle and melted. The meltwater was then poured into a LDPE sample bottle. Samples were stored dark and cool at the Western Arctic Research Centre (ARI) in Inuvik at $+4$ °C prior to analysis. Storage duration and sample container material might have an effect on the isotopic composition and thus on data quality and comparability. In a storage test study by Spangenberg (2012) over 659 d, the potential isotopic variations in LDPE bottles (10 and 50 mL), which are similar to the LDPE sample bottles used in our study (15, 30 mL), range from about 0.5 ‰ to 1.0 ‰ in δ^{18}O and from about 1.9 ‰ to 3.0 ‰ in δ^2H and show no trend over time. In our study the maximum period between sampling and analysis was less than 12 months (< 365 d). This maximum period was defined between the precipitation sampling on site in Inuvik and the sample pick-up, transport and subsequent analysis every summer. This means that our samples never reached the storage duration tested in the experimental study

Table 1. Summary of precipitation events by month and year.

Month	Year				Monthly
	2015	2016	2017	2018	sum
1	–	1	3	1	5
2	–	0	5	2	7
3	–	1	2	1	4
4	–	5	1	2	8
5	–	0	2	6	8
6	–	3	2	3	8
7	–	4	3	7	14
8	4	11	8	14	37
9	12	6	7	–	25
10	4	1	1	–	6
11	2	4	0	–	6
12	2	4	0	–	6
Yearly sum	24	40	34	36	

by Spangenberg (2012), which was 659 d. Given the minor effects of the LDPE material on the isotopic composition on monthly timescales, the container material we used (Kautex narrow-neck LDPE) provides some practical advantages for sampling in high latitudes. Those are (1) that the material is flexible to ensure complete filling without remaining air in the headspace, (2) that the material does not break upon freezing or mechanical stress, and (3) that complete and very tight closure of the lid avoids exchange with ambient air and sample loss due to evaporation. This ensures that neither evaporation nor other substantial fractionation processes altered the isotopic composition significantly.

The oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) stable isotope compositions of precipitation were measured in the Stable Isotope Facility of the Alfred Wegener Institute in Potsdam (Germany), using a Finnigan MAT Delta-S mass spectrometer ($1\sigma < 0.1$ ‰ for $\delta^{18}O$, $1\sigma < 0.8$ ‰ for $\delta^{2}H$; Meyer et al., 2000). Values are given as per mil (‰) difference from the Vienna Standard Mean Ocean Water (VSMOW) standard. A total of 135 samples were obtained and analysed from the monitoring period between August 2015 and August 2018 of which 134 samples were considered in this study. One sample from February 2016 was excluded from the data set and from interpretation due to its highly unusual isotopic composition ($\delta^{18}O$ of −21.04 ‰, $\delta^{2}H$ of −186.1 ‰, d of −17.8 ‰). We consider two possible explanations, which are (1) an incorrectly labelled date on the sample bottle or (2) sublimation and according kinetic fractionation of the snow sample. As the February 2016 sample was the only one in the entire sample set showing such anomalous values, while being stored and processed as all other samples, we decided to note the values for completeness but to exclude them from interpretation due to the untraceable origin of these erroneous values.

Table 2. Basic statistics of stable water isotope data based on monthly means.

	$\delta^{18}O$ [‰]	$\delta^{2}H$ [‰]	d [‰]
Mean	−20.46	−158.0	5.7
Median	−20.30	−155.3	5.8
Min	−29.00	−221.1	−2.4
Max	−13.89	−96.7	14.4
25 % quantile	−24.56	−184.6	3.4
75 % quantile	−16.43	−127.8	8.4
n	33	33	33

3 Data structure

The total of 134 valid data points represent 33 months of the entire monitoring period of 37 months (Table 1). The 4 months without data during the observation period are February and May in 2016 and November and December in 2017. Consequently, each month in the data set is represented at least two times from different years. Eight months of the year(s) are represented at least three times from different years. The sample number per month varies between 0 and up to 14 samples (e.g. August 2018; Table 1).

The currently available GNIP data set for Inuvik precipitation originates from the 1980s. Data acquisition took place between 1986 and 1989. During this 4-year period, only 14 monthly observations of both $\delta^{2}H$ and $\delta^{18}O$ are available. The month of June is not represented in the previous Inuvik LMWL data set at all. All remaining months are represented at least once, while December, January and February are represented twice.

The GNIP data (IAEA/WMO, 2020) provide monthly means of stable isotopes in precipitation. In order to keep comparability, we also present monthly means of the Inuvik LMWL, although the entire database is freely available at PANGAEA (Fritz et al., 2021).

4 Data availability

Original data are available on PANGAEA under https://doi.org/10.1594/PANGAEA.935027 (Fritz et al., 2021).

5 Data analysis

5.1 Climate and stable isotope data during the observation period

The meteorological monitoring data for the observation period are available from the WMO station (number: 719570) in Inuvik (Environment and Climate Change Canada, 2021a; Fig. 2). The long-term average annual air temperature is −8.2 °C, and the annual air temperature amplitude amounts

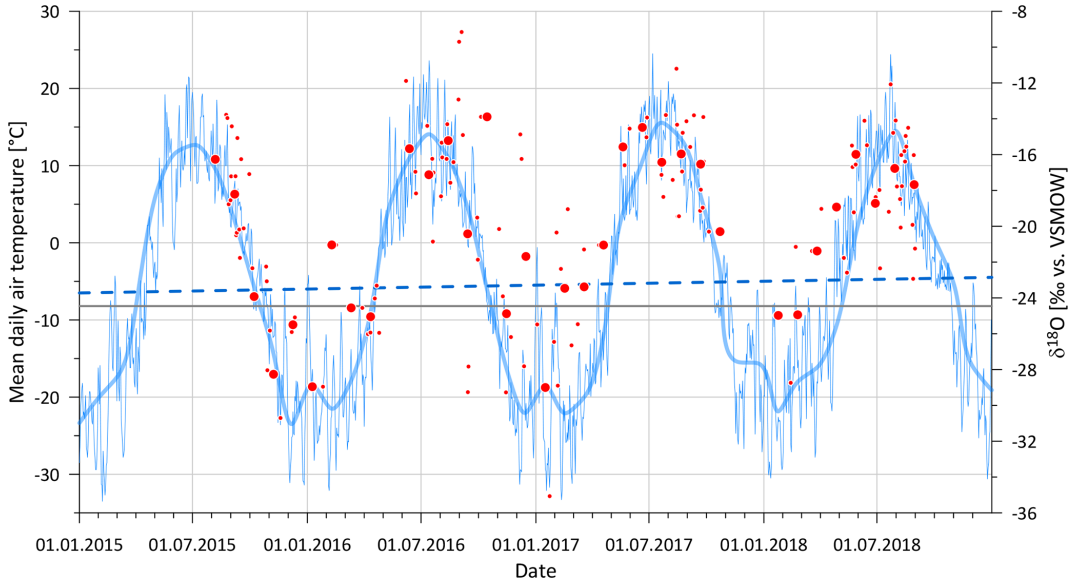

Figure 2. Air temperatures from Inuvik (NT, Canada) together with δ^{18}O values in precipitation during the sampling period from August 2015 to August 2018. Thin blue line shows mean daily air temperatures and the thick blue line shows monthly averages. Small red dots show all δ^{18}O data points. Large red dots show δ^{18}O monthly averages. Grey line illustrates long-term average of air temperatures (1981–2010). Blue dashed line illustrates air temperature trend from 2015 to 2018.

to 41 °C with coldest mean temperatures in January and warmest mean temperatures in July (1981–2010; Environment and Climate Change Canada, 2021b). The mean annual precipitation sums up to 241 mm and snow depth reaches up to 159 cm. During the observation period, the average annual air temperature was −5.5 °C with an increasing trend towards today (Fig. 2). The maximum temperature amplitude between 2015 and 2018 was 58 °C. The stable isotope composition of meteoric water expressed as monthly means varies over about 15 ‰ between −29.0 ‰ and −13.9 ‰ in δ^{18}O (mean of −20.5 ‰) and over about 124 ‰ between −221 ‰ and −97 ‰ in δ^{2}H (mean of −158 ‰). Deuterium excess ranges from −2.4 ‰ to 14.4 ‰ (mean of 5.7 ‰ , Table 2). The seasonal pattern in air temperatures is largely delineated by the stable isotope composition of precipitation with lower δ^{18}O and δ^{2}H values representing lower air temperatures (Fig. 2).

5.2 The new local meteoric water line from Inuvik

The LMWL representing Inuvik precipitation between August 2015 and August 2018 is shown in Fig. 3a in comparison to the previous LMWL covering 1986 to 1989 (Fig. 3b). Further LMWLs from the western Arctic that are from Utqiaġvik (Barrow), Mayo and Cambridge Bay are summarized in Table 3. The slope of the new Inuvik LMWL is 7.39 and the intercept is −6.70. In comparison, the previous Inuvik LMWL shows values of 7.33 for the slope and −3.55 for the intercept (Fig. 3) underlining the long-term local singularity of stable isotope composition in meteoric water. The relationship between δ^{2}H and d in the Inuvik precipitation isotopic composition is expressed by Eq. (3):

$$d = -0.07 \times \delta^{2}\mathrm{H} - 4.92, \quad (3)$$

with a moderate correlation of $R^2 = 0.47$ (Fig. 4). In general, low δ^{2}H values, which are largely explained by low air temperatures, are associated with higher d values (e.g. Porter et al., 2016). The mean annual d for Inuvik is 5.7 ‰ compared to the global average of 10 ‰. The greatest difference between the new Inuvik LMWL and the previous Inuvik LMWL is associated with d values. The data set from between 1986 and 1989 contains only positive d values that range between 3.6 and 34.4, with a mean of 14.9. In contrast, our d data from between 2015 and 2018 contain a considerable number of negative values (Fig. 4), and they have a smaller range and a much lower average (Table 2). Unpaired t tests for different parameters between new and old Inuvik LMWL data sets confirm that the new and the old LMWLs from Inuvik are statistically different from each other (δ^{18}O: $t(45) = 4.23$, $p < .001$; δ^{2}H: $t(45) = 3.80$, $p < .001$; deuterium excess: $t(45) = -5.16$, $p < .00001$; critical t value: 1.68). Other regional LMWL statistics differ distinctly from Inuvik (Table 3) emphasizing regional peculiarities.

The slight deviation of the new Inuvik LMWL slope when compared to that of the GMWL might either reflect regionally specific isotopic fractionation in equilibrium of distinct ranges in temperature and/or isotopic composition. It might further point to seasonal precipitation that is characterized by non-equilibrium processes (Putman et al., 2019). The latter

Table 3. Available monthly-based LMWLs from the western Arctic.

Location	WMO number	Coordinates	Elevation [m a.s.l.]	Period of data acquisition	Number of data points	LMWL equation
Inuvik – new	719570	68.3° N, 133.5° W	68	2015–2018	33	$\delta D = 7.39 \times \delta^{18}O - 6.70$
Inuvik – old	719570	68.3° N, 133.5° W	68	1986–1989	14	$\delta D = 7.33 \times \delta^{18}O - 3.55$
Utqiaġvik (Barrow)	943040	71.4° N, 156.5° W	4	1962–1969	47	$\delta D = 7.12 \times \delta^{18}O - 9.06$
Mayo	719650	63.6° N, 135.9° W	519	1985–1989	37	$\delta D = 6.27 \times \delta^{18}O - 36.86$
Cambridge Bay	719250	69.1° N, 105.1° W	31	1989–1993	58	$\delta D = 7.66 \times \delta^{18}O + 0.83$

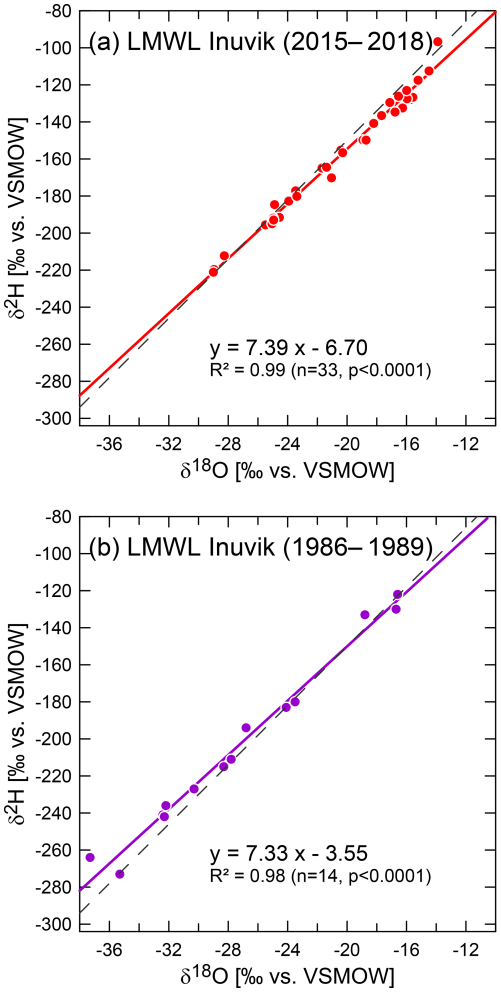

Figure 3. Co-isotope plots of $\delta^{18}O$ and $\delta^{2}H$ of precipitation for Inuvik (NT, Canada). **(a)** New ($n = 34$, 2015–2018) local meteoric water line. **(b)** Old ($n = 14$, 1986–1989) local meteoric water line. Dashed line represents the global meteoric water line.

might affect the new Inuvik LMWL as snow from mixed-phase cloud processes controlled by Rayleigh distillation is likely to contribute to the annual Inuvik precipitation. This is seen in high d values of cold-season precipitation (Fig. 4) and in a slope below the GMWL slope of 8 (Fig. 3). Moreover, low d values during warm-season precipitation might be indicative of a contribution of recycled moisture from continental sources (compare Bonne et al., 2020). The wide ranges over about 15 ‰ in $\delta^{18}O$ and about 124 ‰ in $\delta^{2}H$ of monthly means of the new Inuvik data set and the substantially greater sample size if compared to the old Inuvik LMWL enable a well-defined new LMWL. Putman et al. (2019) applied data quality criteria for LMWL calculations requiring time series that include at least three samples in each 3-month meteorological season to represent seasonality, while the length of the observation period depends on the timescale of the process of interest. In this context, the new Inuvik LMWL is regarded as valid representation of the isotopic composition of regional precipitation.

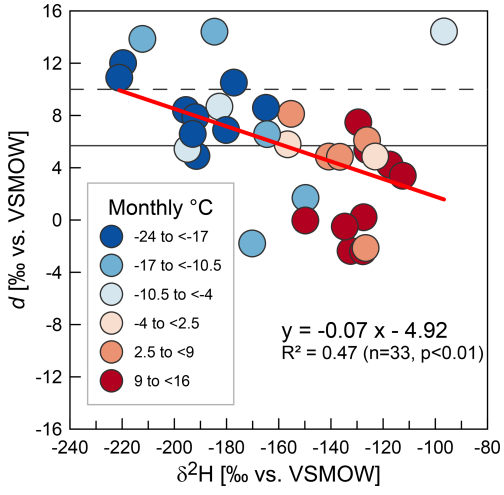

Figure 4. Relationship between hydrogen isotope ratios ($\delta^{2}H$) and deuterium excess d (monthly means). The solid horizontal line indicates mean d from Inuvik (this study), whereas the dashed line indicates global average d. Bubble colour indicates air temperature ranges (monthly mean) at the time of sampling. Red line represents the linear trend.

Author contributions. MF designed the study and analysed the data. HM conceptualized the sampling device and analysed the samples at the Stable Isotope Facility at the AWI. MF and SW wrote the paper with contributions from HM and JM.

Competing interests. The contact author has declared that neither they nor their co-authors have any competing interests.

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