

1 Arctic Sea Ice Loss Amplifies Local Evaporation Influence on Water Vapor Isotopes: 2 Insights from Cruise Observations

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7 **Abstract.** Rapid Arctic warming and sea ice retreat have increased atmospheric humidity, yet the relative contributions of
8 local evaporation and advected lower-latitude moisture remain poorly quantified. Here, we present high-resolution, ship-based
9 in-situ measurements of near-surface water vapor isotopes across diverse Arctic sea ice regimes. By integrating isotope
10 fractionation models with multi-source meteorological data, we show that sea ice changes act as a key modulator of Arctic
11 water vapor isotopic variations. Under ice-covered conditions, water vapor isotopes are strongly temperature-dependent,
12 exhibiting depleted $\delta^{18}\text{O}$ and elevated d-excess due to Rayleigh-dominated processes. As sea ice retreats, kinetic fractionation
13 from local evaporation becomes increasingly important, particularly at temperatures above $\sim 5^\circ\text{C}$, generating enriched $\delta^{18}\text{O}$,
14 elevated d-excess, and a characteristic “anti-temperature” effect. A Bayesian isotope mixing model quantifies the resulting
15 moisture source shift, showing local evaporation contributions rise from 18.6 % in ice-covered regions to 48.3 % in ice-free
16 regions, despite advected moisture remaining predominant. These findings establish a process-based isotope framework for
17 the Arctic hydrological cycle, complementing conventional meteorological diagnostics and offering valuable observational
18 constraints for interpreting paleo-isotope archives.

19 1 Introduction

20 Stable water vapor isotopes ($\delta^{18}\text{O}$ and δD) and their derived deuterium excess (d-excess, defined as $\delta\text{D} - 8 \times \delta^{18}\text{O}$) are widely
21 used as tracers for investigating hydrological processes and identifying moisture sources (Gat, 1996). These isotopes
22 fractionate during phase transitions such as evaporation, condensation, and sublimation, encoding information about
23 environmental conditions both at the moisture source and along the atmospheric transport pathways (Dansgaard, 1964;
24 Galewsky et al., 2016; Bowen et al., 2019). As such, analysis of these isotopic parameters in modern water vapor and
25 paleoclimate archives provides key insights into moisture sources and climatic dynamics across both modern (Kurita, 2011;
26 Kopeck et al., 2016; Wang et al., 2023) and paleoclimate contexts (Klein and Welker, 2016; Opel et al., 2013; Porter et al.,
27 2019). This dual perspective is particularly critical in the Arctic, which serves not only as a modern laboratory of rapid
28 hydrological change but also as a primary archive of past climate preserved in its ice sheets.
29 Recent Arctic amplification and sea ice loss have moistened the Arctic atmosphere (Min et al., 2008; Bengtsson et al., 2011;
30 Bintanja and Selten, 2014), yet the relative roles of local evaporation and poleward moisture transport remain contested. Some
31 studies attribute these changes to enhanced local evaporation over newly melt ocean (Bintanja and Selten, 2014; Boisvert and

32 Stroeve, 2015; Kopec et al., 2016), while others emphasize strengthened poleward transport of lower-latitude moisture
33 (Bengtsson et al., 2011; Zhang et al., 2013; Zhong et al., 2018). Resolving this debate is crucial because water vapor plays a
34 central role in Arctic radiative and hydrological feedbacks, influencing cloud cover, precipitation, and surface warming. Stable
35 water vapor isotopes provide a process-based diagnostic for disentangling and quantifying the relative contributions of these
36 two sources. Such insights are essential not only for improving the representation of hydrological processes in climate models,
37 thereby enabling more reliable projections (Barras and Simmonds, 2009; Gao et al., 2011; Sturm et al., 2010; Xi, 2014), but
38 also for interpreting isotopic signals preserved in paleoclimate archives such as ice cores (Klein et al., 2016; Opel et al., 2013;
39 Porter et al., 2019).

40 However, the application of stable isotopes in the Arctic remains challenging due to conflicting interpretations of isotopic
41 signals, particularly regarding the role of local evaporation. One line of evidence associates high d-excess and low $\delta^{18}\text{O}$ over
42 open water with strong evaporation under cold, dry air masses, as observed in both water vapor (Kurita, 2011; Steen-Larsen
43 et al., 2013; Bailey et al., 2021) and precipitation (Mellat et al., 2021). In contrast, Klein et al. (2015) showed that local
44 evaporation associated with sea ice loss leads to enriched $\delta^{18}\text{O}$ and suppressed d-excess in Arctic water vapor, relative to
45 advected lower-latitude moisture, a pattern that is also reflected in observed Arctic precipitation (Kopec et al., 2016; Song et
46 al., 2023). However, this interpretation is further complicated by recent evidence showing that low-latitude moisture can also
47 produce low vapor d-excess when influenced by synoptic-scale extratropical cyclones (Thurnherr and Aemisegger, 2022).

48 These divergent interpretations largely reflect the scarcity of spatially extensive, high-resolution vapor isotope observations
49 across the Arctic Ocean. Most existing studies are based on land-based observations, with limited coverage over the Arctic
50 Ocean, hindering efforts to disentangle complex isotope signals (Kurita, 2011; Kopec et al., 2016; Mellat et al., 2021). Klein
51 and Welker (2016) suggested the relative influence of local evaporation on water vapor isotopes may vary with sea ice extent
52 (SIE), proposing an anti-correlation between d-excess and SIE. However, subsequent studies have reported the opposite
53 relationship (Bonne et al., 2019). This persistent inconsistency underscores the need for broader, in-situ water vapor isotope
54 observations across diverse sea ice regimes.

55 To address this gap, we leverage a unique set of high-resolution, in-situ water vapor isotope measurements obtained during a
56 comprehensive summer expedition across the Arctic Ocean aboard the RV *Xuelong 2*. This dataset provides extensive spatial
57 coverage across the Arctic, spanning sea ice regimes from near-continuous cover to open water. By integrating these isotopic
58 observations with meteorological data, and applying isotope-based diagnostics along with Lagrangian trajectory analysis, this
59 study aims to: (1) map the spatial patterns of summer Arctic vapor isotopes in relation to diverse sea ice regimes, (2) identify
60 the primary mechanisms behind isotope variability under distinct sea ice conditions, and (3) quantify the partitioning between
61 locally evaporated and advected moisture sources across different Arctic regions.

62 2 Data and Methods

63 2.1 Water Vapor Isotope Measurements and Calibration

64 Continuous, in situ measurements of near-surface water vapor isotopes and humidity were conducted using a Picarro L-2130i
65 cavity ring-down spectroscopy (CRDS) analyzer. The instrument was housed in the meteorological room of the RV *Xuelong*
66 2. Ambient air was drawn from an inlet mounted on the balcony of the meteorological room, approximately 10 m above sea
67 level. To ensure data quality, the inlet was equipped with a specialized filter designed to avoid coarse particle contamination
68 and prevent icing. The sample air was delivered to the analyzer through a 5-meter inlet tube. Most of the tubing was routed
69 inside the meteorological room, where air conditioning maintained the temperature at ~20°C, preventing condensation without
70 additional heating.

71 All isotope values are reported in standard δ notation relative to the Vienna Standard Mean Ocean Water (VSMOW):

$$72 \quad \delta = \left(\frac{R_{\text{sample}}}{R_{\text{VSMOW}}} - 1 \right) \times 1000 \quad (1)$$

73 where R_{sample} and R_{VSMOW} are the isotope ratios ($^{18}\text{O}/^{16}\text{O}$ or $^2\text{H}/^1\text{H}$) of the sample and VSMOW, respectively. The
74 measurement precision was better than 0.04‰ for $\delta^{18}\text{O}$ and 0.5‰ for δD . The data were originally collected at 1-minute
75 intervals and have been resampled to hourly resolution for analysis. D-excess was calculated following Dansgaard (1964) as:

$$76 \quad d\text{-excess} = \delta\text{D} - 8 \times \delta^{18}\text{O} \quad (2)$$

77 Because the isotope measurements from the Picarro analyzer are subject to ambient water vapor concentration, a humidity-
78 dependent correction was applied to ensure consistency across varying atmospheric conditions. Calibration was performed
79 using a Standard Delivery Module (SDM). To define the calibration gradient, we used the analyzer's internal humidity
80 measurements, which closely agree with independent sensors (Wang et al., 2023; Bonne et al., 2019), without relying on
81 external references. Following Liu et al. (2014), two VSMOW-standard water samples were analyzed at three flow rates (0.015,
82 0.04, 0.07 $\mu\text{L/s}$) to generate three humidity levels of 5000, 15000, and 25000 ppm, and each step was maintained for 20 minutes.
83 A full calibration cycle was performed approximately every 22 hours during atmospheric measurements. To minimize memory
84 effects, the first 10 minutes and final 2 minutes of each calibration step were excluded. A correction function was derived from
85 the valid calibration data to express isotope bias as a function of humidity and was applied to all samples to normalize their
86 values to a reference humidity of 20000 ppm:

$$87 \quad \delta_{\text{measured}} - \delta_{\text{humidity calibration}} = f(\text{humidity}_{\text{measured}}) - f(20000) \quad (3)$$

$$88 \quad f_{\delta^{18}\text{O}}(\text{humidity}) = 0.2976\ln(x) - 11.969 \quad (4)$$

$$89 \quad f_{\text{D}}(\text{humidity}) = 0.2843\ln(x) - 30.892 \quad (5)$$

All vapor isotope measurements were then normalized to the VSMOW scale using two standard waters ($\delta^{18}\text{O} = -11.018 \text{ ‰}$, $\delta\text{D} = -78.051 \text{ ‰}$; $\delta^{18}\text{O} = -29.86 \text{ ‰}$, $\delta\text{D} = -222.86 \text{ ‰}$), whose isotope values match the expected range of water vapor isotopes in the Arctic. Both standards were pre-corrected for humidity-dependent bias, and a linear calibration function was established based on the measured versus true values of the two standards and applied to all samples to complete the VSMOW normalization.

2.2 Meteorological and sea ice data

Meteorological data, including air temperature (T), relative humidity (RH), and air pressure, were obtained from the onboard weather station of the RV *Xuelong 2*. Specific humidity (q) was calculated from the water vapor concentration measured by the Picarro instrument. All datasets were synchronized to the isotope measurement timestamps (UTC+8) and averaged to 1-minute resolution. Surface evaporation flux (E), representing the instantaneous vertical water vapor flux from the ocean surface, was obtained from the fifth-generation European Centre for Medium-Range Weather Forecasts reanalysis (ERA5; Hersbach et al. (2023)), available at 1-hour temporal and $0.5^\circ \times 0.5^\circ$ horizontal resolution.

The daily 4-km sea ice concentration (SIC) data were obtained from the National Snow and Ice Data Center (NSIDC), specifically from the MASIE-AMSR2 (MASAM2) blended product (Fetterer, 2023). This product integrates data from the Multisensor Analyzed Sea Ice Extent (MASIE) and the Advanced Microwave Scanning Radiometer 2 (AMSR2). To assess the influences of sea ice on water vapor isotopes and moisture source partitioning, the Arctic was classified into three sea ice regimes using contemporaneous SIC data (Fig. 2):

- I. Ice-free Region ($\text{SIC} < 0.4$): Areas below satellite detection threshold (MASAM-2 SIC = 0)
- II. Sea Ice Region ($\text{SIC} > 0.85$): Predominantly ice-covered areas
- III. Transition Region ($0.4 \leq \text{SIC} \leq 0.85$): Intermediate ice conditions

2.3 Theoretical Isotope Modelling of Ocean Evaporation

We employed the MJ79 model (Merlivat and Jouzel, 1979) to estimate the isotopic composition of water vapor evaporated from Arctic ocean, following the formulation of Bonne et al. (2019):

$$R_{BL} = \frac{R_{SW}}{\alpha_{eq} \times (\alpha_k + RH(1 - \alpha_k))} \quad , \quad (6)$$

where R_{BL} is the isotopic ratio of water vapor in the boundary layer, and R_{SW} is the isotopic ratio of surface seawater. RH is the relative humidity at the sea surface. α_{eq} and α_k are the equilibrium and kinetic fractionation coefficients, respectively. α_{eq} was calculated as a function of temperature, while α_k takes values of 1.0060 for $\delta^{18}\text{O}$ and 1.0053 for δD under smooth wind conditions, and 1.0035 for $\delta^{18}\text{O}$ and 1.0031 for δD under rough wind conditions (Bonne et al., 2019). Because surface seawater isotope values in the open Arctic Ocean are typically close to 0 ‰ (Namyatov et al., 2024, 2023), we prescribed $\delta^{18}\text{O}$ and δD of surface seawater as 0 ‰, from which R_{SW} was calculated and used as the model input.

120 2.4 Back-trajectory calculation

121 To identify moisture sources in the Arctic, we analyzed air mass trajectories using the Hybrid Single Particle Lagrangian
122 Integrated Trajectory (HYSPLIT) model (Stein et al., 2015). The model was driven by 0.5°×0.5° Global Data Assimilation
123 System (GDAS) meteorological fields from the National Oceanic and Atmospheric Administration (NOAA) Air Resources
124 Laboratory.

125 Ten-day backward trajectories were computed hourly along the cruise track at five vertical levels (10, 20, 30, 40, and 50 m
126 above the surface). This duration aligns with the typical residence time of atmospheric water vapor in polar regions (Gimeno
127 et al., 2021; Wallace and Hobbs, 2006) and is long enough to capture moisture transport from lower latitudes. The selected
128 vertical levels span the full range of the research vessel's measurements, enabling a more comprehensive representation of air
129 mass histories. Building on these trajectory calculations, moisture-weighted source contributions from the Pacific and Atlantic
130 sectors were quantified. All trajectories were batch-processed using the PySPLIT Python package (Warner, 2018).

131 2.5 Bayesian isotope mixing model

132 To quantify the contributions of different moisture sources to Arctic water vapor, we employed MixSIAR (Stock and Semmens,
133 2016a), an open-source Bayesian mixing model implemented in R. MixSIAR, developed from earlier MIXSIR and SIAR, has
134 been widely applied in ecological and environmental studies. According to Stock et al. (2018), the model framework can be
135 expressed as:

$$136 Y_j = \sum_k p_k u_{jk}^s, \quad (7)$$

137 where Y_j is the tracer value of the mixture for tracer j , p_k is the proportional contribution of source k , and u_{jk}^s is the mean tracer
138 value of source k . Given the substantial isotopic variability in Arctic water sources and its propagation into the vapor mixture,
139 we evaluated three error structures (residual, process, multiplicative) and adopted the process error structure as most
140 appropriate (Stock and Semmens, 2016b):

$$141 Y_{ij} \sim N\left(\sum_k p_k u_{jk}^s, \sum_k p_k^2 \omega_{jk}^{s2}\right) \quad (8)$$

142 where ω represents the source variance of the two stable isotope tracers. To estimate posterior probability distributions, the
143 model was run using Markov Chain Monte Carlo (MCMC) sampling with the "Normal" run length setting (chain length =
144 100,000; burn-in = 50,000; thinning = 50; 3 chains). Uninformative Dirichlet priors ($\alpha = 1$) were applied for the source
145 proportions. Model convergence was assessed using the Gelman-Rubin diagnostic ($R_{\text{hat}} < 1.05$) to ensure the reliability of the
146 estimated contributions.

147 To construct a representative lower-latitude moisture end-member, trajectory statistics were performed using a custom Python
148 script. Source end-member data were input as means and standard deviations. Air trajectories from Pacific (160°E-160°W)
149 and Atlantic (15°E-30°W) were integrated and weighted by the specific humidity of each backward trajectory at the time it
150 crossed the Arctic boundary (66.5°N). The weight W_k for each channel k was calculated as:

$$W_k = \frac{\sum_{i=1}^{N_k} q_{i,cross}}{\sum_{all} q_{i,cross}} \quad (9)$$

where $q_{i,cross}$ represents the specific humidity of trajectory i at the moment of crossing 66.5°N. The composite isotopic mean δ_{mix} was then derived using Eq. (10), and the mixed standard deviation σ_{mix} was calculated following the Gaussian error propagation rule (Eq. 11):

$$\delta_{mix} = \sum_k (W_k \cdot \delta_k) \quad (10)$$

$$\sigma_{mix} = \sqrt{\sum_k (W_k \cdot \sigma_k)^2} \quad (11)$$

A Rayleigh distillation correction was applied to the lower-latitude source end-member to account for isotopic depletion during poleward transport. The initial source region is defined as the North Pacific (50–60°N), with a saturation specific humidity of 6.6 g/kg (corresponding to ~8°C). Using the weighted approach described above, initial $\delta^{18}\text{O}$ and δD values of -17.68‰ and -134.42‰ were obtained. This air mass was modified according to a Rayleigh fractionation curve to a target humidity of 3.93 ± 1.84 g/kg, which represents the hourly mean saturation specific humidity across the Arctic domain resulting from rainout of lower-latitude water vapor along the trajectories. The calculated isotope values, representing the discrimination between the lower-latitude source and the Arctic background state due to Rayleigh fractionation, were incorporated into the MixSIAR model.

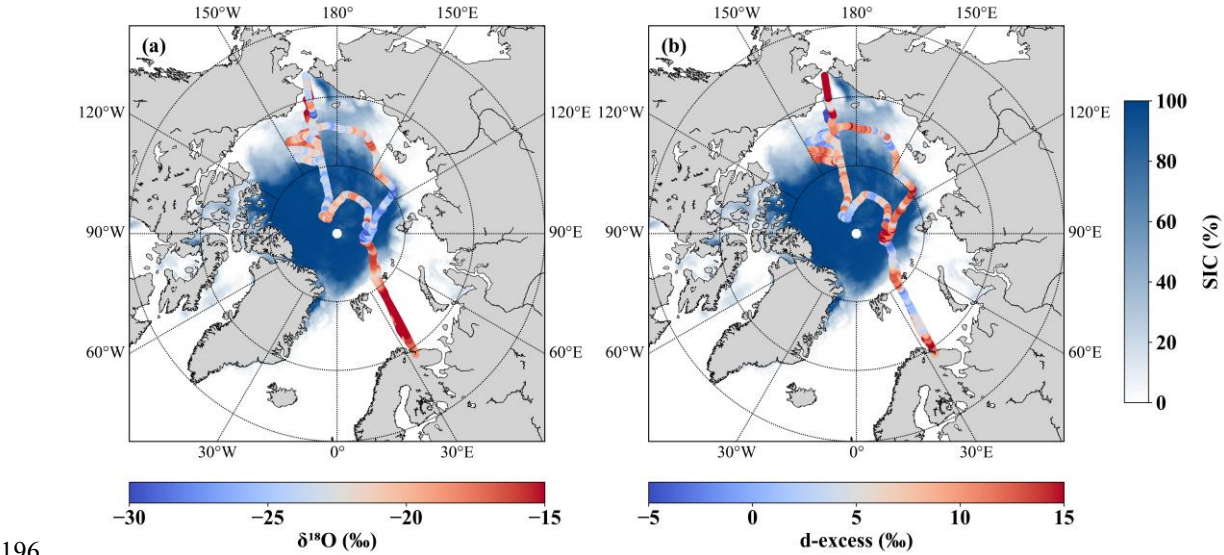
The local evaporation end-member was derived using hourly air temperature and relative humidity from shipboard observations in ice-free region as inputs for the MJ79 model (see section 2.3), implemented via a Python script. The model was run in batch mode to calculate the isotopic composition of vapor due to local evaporation. The resulting means and standard deviations were used to define the local evaporation end-member in the MixSIAR model.

3 Results

3.1 Water Vapor Isotope Variability Along the Cruise Track

Figure 1 shows the evolution of near-surface water vapor isotopes and sea ice coverage along the trans-Arctic RV *Xuelong 2* expedition track spanning the Chukchi Sea, central Arctic Basin, Barents Sea, and Laptev–East Siberian Seas, suggesting co-variability between them. $\delta^{18}\text{O}$ exhibited a pronounced spatial gradient along the cruise track, with the most enriched values (-10.8 ‰) in the ice-free Barents Sea, gradually becoming depleted poleward to the most depleted values (-34.19 ‰) in the heavily ice-covered central Arctic (SIC > 90 ‰), a pattern that inversely mirrors the gradient in sea ice coverage (Fig. 1a). This anti-phase variation between water vapor $\delta^{18}\text{O}$ and sea ice coverage is further confirmed by the $\delta^{18}\text{O}$ distributions across different sea-ice coverage regions (Fig. 2a), which reveal a systematic $\delta^{18}\text{O}$ enrichment from the Sea Ice Region (median = -23.97 ‰), through the Transition Region (-20.54 ‰), to the Ice-free Region (-18.83 ‰). These results suggest that sea ice changes can exert a strong influence on water vapor isotope composition of across the Arctic.

180 In contrast, the second-order parameter d-excess exhibits a more complex spatial pattern, with elevated values primarily
 181 observed both near coastal regions and in some localized zones of the ice-covered central basin (Fig. 1b). The highest values
 182 (23.31 ‰) were recorded in the central basin under steady sea ice cover, while the lowest (−8.35 ‰) occurred in the Chukchi
 183 Sea amid fluctuating sea ice (SIC varied from 40 % to 85 %). When grouped by SIC regimes, both the **Ice-free** and Sea Ice
 184 Regions sustained relatively higher d-excess values (median = 7.71 ‰ and 8.85 ‰, respectively), whereas the Transition
 185 Region yielded the lowest values (median = 5.46 ‰) (Fig. 2b). This distinct d-excess pattern across sea ice regimes points to
 186 the influence of sea ice changes on Arctic water vapor isotopic composition, likely through shifts in moisture sources and
 187 kinetic fractionation processes.
 188 To examine how sea ice changes modulate Arctic water vapor isotopes, we show the variations of $\delta^{18}\text{O}$ and d-excess in relation
 189 to temperature, humidity, and local evaporation along the cruise track (Fig. 3). A comparison across the three sea ice regimes
 190 reveals that $\delta^{18}\text{O}$ and d-excess exhibited pronounced, anti-phase fluctuations (Fig. 3b). Depleted $\delta^{18}\text{O}$ generally coincided with
 191 colder, drier air in the ice-covered central Arctic, while enriched values occurred in warm, moist sectors like the Barents
 192 Sea (Fig. 3d). The episodes of high d-excess were closely associated with conditions of reduced relative humidity and enhanced
 193 evaporation, particularly in the **Ice-free** Region (Fig. 3c), highlighting the growing role of kinetic fractionation under
 194 diminishing sea ice. These co-variations demonstrate that the sea ice regimes set the boundary conditions for the atmospheric
 195 controls—from equilibrium (temperature-driven) to kinetic (evaporation-driven)—on Arctic water vapor isotopes.



197 **Figure 1. Spatial distributions of water vapor $\delta^{18}\text{O}$ (a) and d-excess (b) along the cruise track. Colored dots indicate measured**
 198 **isotopic values (‰) and shading shows the mean sea ice concentration (SIC) during the observation period.**

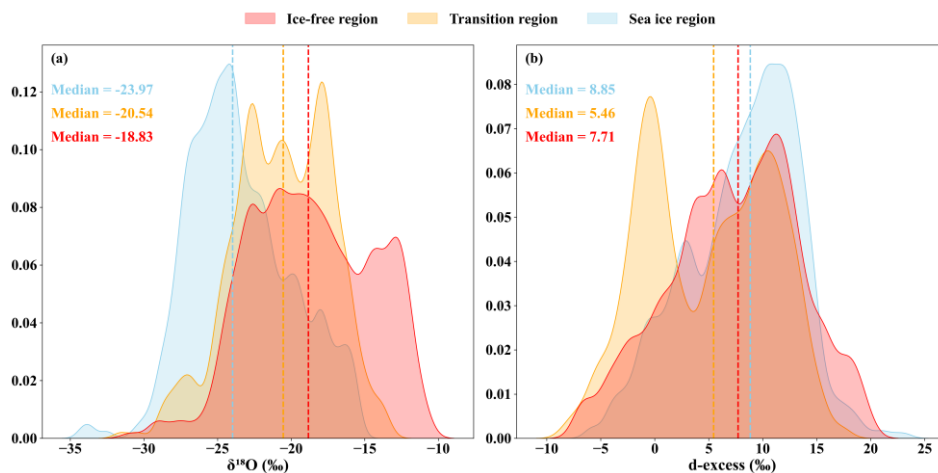


Figure 2. Probability density distributions of $\delta^{18}\text{O}$ (a) and d-excess (b) in the sea ice Ice-free (red), Transition (orange), and Sea Ice (blue) regions. Median values for each region are indicated.

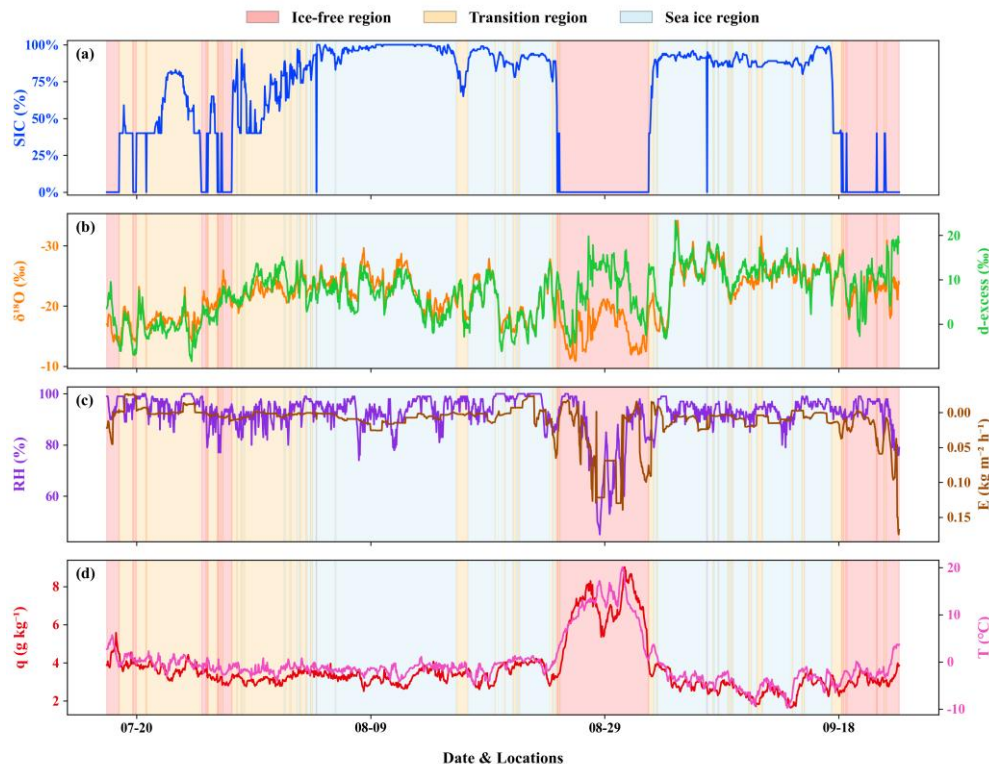


Figure 3. Temporal and spatial evolution of observed water vapor isotopes, SIC, and meteorological parameters along the cruise routes. (a) SIC (%); (b) $\delta^{18}\text{O}$ (‰) and d-excess (‰); (c) Relative humidity (RH; %) and Evaporation (E ; $\text{kg m}^{-2} \text{h}^{-1}$); (d) Specific humidity (q ; g kg^{-1}) and air temperature (T ; $^{\circ}\text{C}$). Background colors indicate the three different sea ice regimes.

206 3.2 Isotopic Responses to Temperature and Humidity across Arctic Sea Ice Regimes

207 To investigate isotopic responses to temperature and humidity, we first examined the relationship between $\delta^{18}\text{O}$ and air
208 temperature in the three distinct sea ice regions. As expected, $\delta^{18}\text{O}$ values exhibit significant positive correlations with
209 temperature in all regions (Fig. 4a), consistent with the classical “temperature effect” (Dansgaard, 1964). However, this
210 relationship weakens notably in the Ice-free Region and reverses when temperatures exceed 5 °C. Above this threshold, $\delta^{18}\text{O}$
211 becomes negatively correlated with temperature, indicating a departure from equilibrium-driven fractionation and the
212 emergence of dominant kinetic processes under warm, ice-free conditions.

213 In contrast, d-excess shows a more variable response to temperature. Significant negative correlations are observed in the Sea
214 Ice and Transition Regions ($r = -0.62$ and -0.49 , respectively; Fig. 4b), whereas the Ice-free Region exhibits a weak positive
215 correlation ($r = 0.19$; Fig. 4b). In the Ice-free Region, the correlation shifts from negative to positive when temperature is above
216 5 °C, highlighting a transition in the dominant fractionation regime. Although d-excess is theoretically not expected to directly
217 depend on temperature (Shao et al., 2021; Xiang et al., 2022), previous studies have shown that a positive correlation can
218 emerge as a signature of oceanic evaporation (Uemura et al., 2008). This suggests that correlation between d-excess and
219 temperature may serve as a diagnostic of the influence of local evaporation on Arctic water vapor (Brunello et al., 2023).
220 Collectively, these patterns indicate that fractionation mechanisms undergo fundamental shifts as sea ice retreats, with kinetic
221 effects increasingly dominating over open water.

222 Relative humidity (RH) further modulates isotopic fractionation by controlling the ambient saturation deficit (Bonne et al.,
223 2019). Across all sea ice regimes, d-excess exhibits a consistent negative correlation with RH (Fig. 5a), with the strongest
224 correlation in the Ice-free Region ($r = -0.52$, $p < 0.05$), followed by the Transition ($r = -0.37$) and Sea Ice Regions ($r = -0.33$).
225 A similar pattern is observed for the relationship between d-excess and surface evaporation (Fig. 5b), with the strongest positive
226 correlation in the Ice-free Region ($r = 0.51$) and weaker ones in the Transition ($r = 0.40$) and Sea Ice ($r = 0.24$) Regions. These
227 results indicate that as sea ice retreats, local evaporation increasingly governs the isotopic composition of Arctic water vapor,
228 consistent with the elevated d-excess observed in ice-free areas, while its influence remains relatively weak in ice-covered
229 regions.

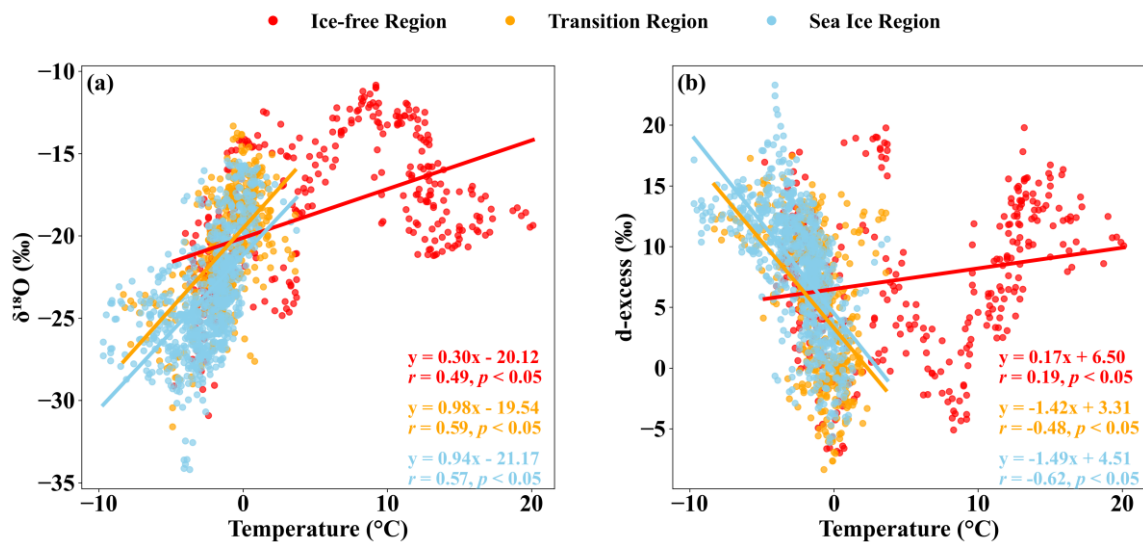


Figure 4. Relationships of water vapor isotopes with air temperature across three sea ice regimes. (a) $\delta^{18}\text{O}$ versus temperature; (b) d-excess versus temperature. Dots and linear regression lines are color-coded by regime: ice-free (red), transition (yellow), and sea ice (blue). Regression statistics are displayed in corresponding colors.

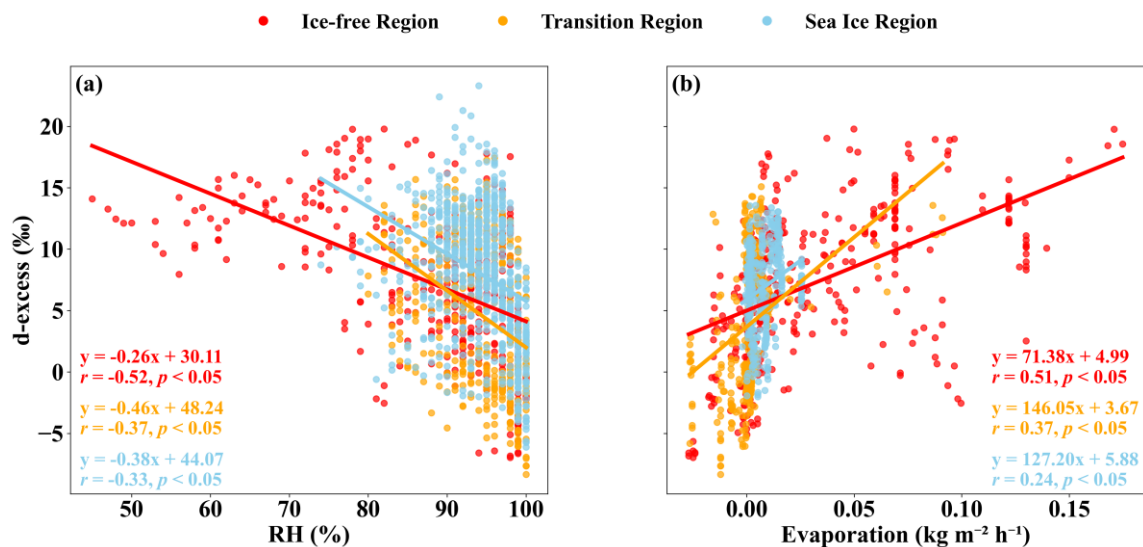
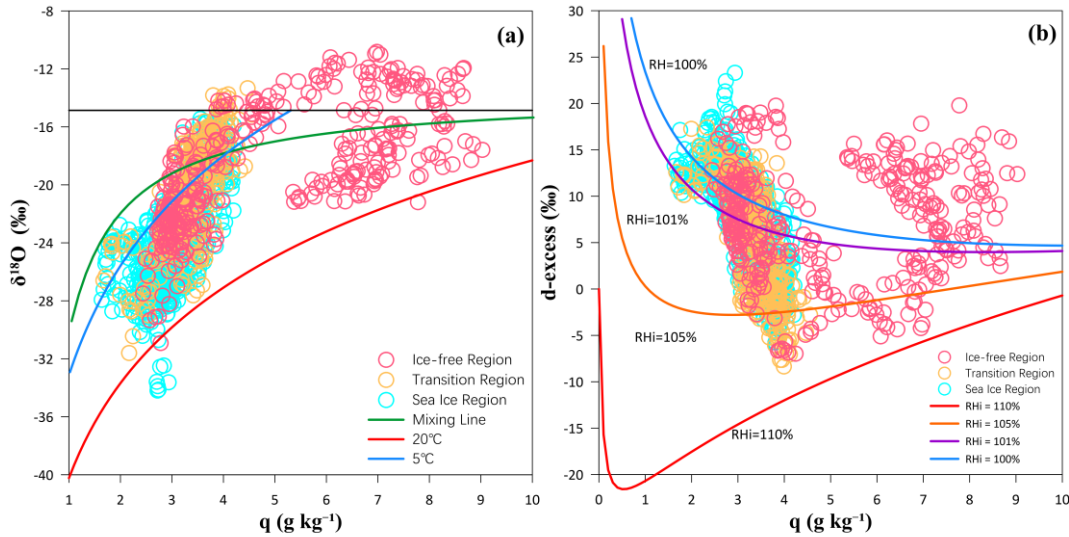


Figure 5. Relationships of d-excess with relative humidity and evaporation across three sea ice regimes. (a) d-excess versus relative humidity (RH); (b) d-excess versus evaporation flux. Dots and linear regression lines are color-coded by regime: ice-free (red), transition (yellow), and sea ice (blue). Regression statistics are displayed in corresponding colors.

3.3 Moisture Sources and Fractionation Processes across Arctic Sea Ice Regimes

To disentangle the influences of equilibrium and kinetic fractionation on Arctic water vapor isotopes, we employ q - δ diagrams as a diagnostic tool (Fig. 6a). Within a Rayleigh framework, $\delta^{18}\text{O}$ decreases systematically as vapor is progressively depleted through condensation during long-range transport, whereas d-excess remains relatively constant (Worden et al., 2007; Galewsky and Samuels-Crow, 2015; Noone, 2012). In the q - δ diagram, the idealized Rayleigh process forms a reference **curve** along which data distributions reflect the dominant influence of equilibrium fractionation. Data points deviating from this trajectory indicate additional physical processes: values above the curve often reflect admixture with other air masses (Wang et al., 2023), those below the mixing line reflect interactions between air masses of contrasting humidity (Galewsky and Samuels-Crow, 2015), and points below the Rayleigh curve typically signify local evaporation, such as from rain or open water (Worden et al., 2007). To specifically diagnose kinetic effects, we also examine a q -d-excess diagram (Fig. 6b), accounting for realistic polar conditions with Rayleigh curves modified for ice supersaturation ($\text{RH}_i = 100\text{--}110\%$). Under these conditions, kinetic fractionation suppresses d-excess below equilibrium predictions (Jouzel and Merlivat, 1984; Jensen and Pfister, 2005). Within this framework, points falling below the equilibrium curve primarily reflect d-excess suppression by ice-supersaturated cloud formation, whereas points above it indicate contributions from evaporation or sublimation (Samuels-Crow et al., 2014; Kopec et al., 2019). Collectively, these dual diagrams allow us to quantitatively distinguish the roles of long-range Rayleigh distillation, air-mass mixing, ice-phase microphysics, and local evaporation in shaping Arctic vapor isotopes across the sea ice regimes.



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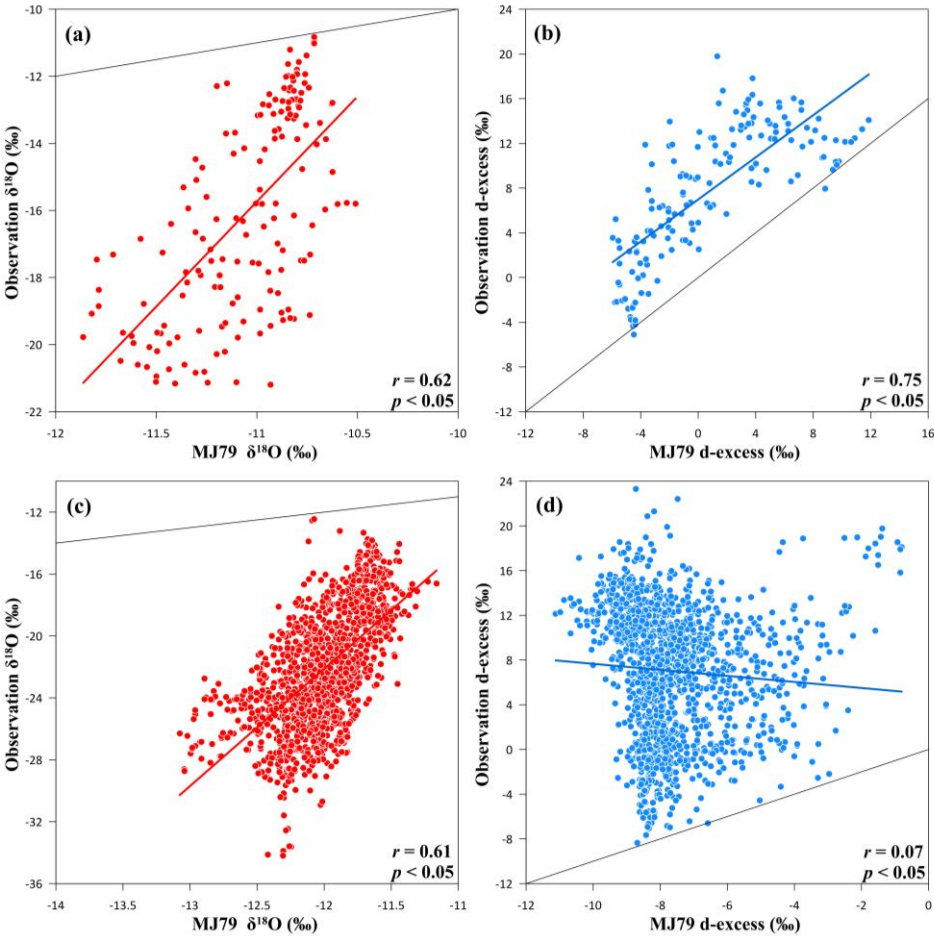
257 **Figure 6. Water vapor $\delta^{18}\text{O}$ (a) and d-excess (b) versus specific humidity (q). Data points are color-coded by sea ice regime.**
 258 **Theoretical Rayleigh distillation curves and mixing/supersaturation curves are shown in colored solid lines (see legends). The**
 259 **idealized Rayleigh curve shown in the graph was calculated based on an initial d-excess of 5.01‰ and $\delta^{18}\text{O}$ of -14.86‰ (the observed**
 260 **mean at $40\text{--}60^\circ\text{N}$). The initial specific humidity is 14.3 g kg^{-1} , corresponding to saturation over a 20°C surface water source (similar**
 261 **to the condition over $40\text{--}60^\circ\text{N}$ open sea).**

262 In the Sea Ice and Transition Regions, q - $\delta^{18}\text{O}$ observations cluster near or between the 5 °C and 20 °C Rayleigh curves (Fig. 6a),
 263 consistent with vapor originating from advection and progressive dehydration during long-range transport. The q -d-excess
 264 relationship in these regions follows the Rayleigh equilibrium pattern (Fig. 6b), supporting the interpretation that Rayleigh
 265 distillation, rather than local kinetic fractionation, primarily governs water vapor isotopic variation in these regions. This also
 266 explains the contrasting temperature correlations observed in Fig. 4: a positive correlation for $\delta^{18}\text{O}$ but a negative one for d-
 267 excess, reflecting the advection of warm, humid air from lower-latitude oceanic regions toward the Arctic.
 268 However, the decline in d-excess is steeper than predicted by the equilibrium Rayleigh curve, with many points falling below
 269 it (Fig. 6b). This deviation indicates additional kinetic fractionation, most likely from cloud formation under ice-supersaturated
 270 conditions, where the higher diffusivity of HDO compared to H_2^{16}O leads to stronger fractionation of deuterium, suppressing
 271 d-excess in surrounding vapour (Clark and Fritz, 2013; Jouzel and Merlivat, 1984). Our calculations show that RH with respect
 272 to ice (RH_i) exceeding 105 %—common in polar regions—can reduce d-excess by over 10 %. This supersaturation-induced
 273 decline in water vapor d-excess has also been observed during dew deposition (Thurnherr and Aemisegger, 2022), indicating
 274 that supersaturated conditions drive d-excess reduction regardless of the phase transition pathway. Conversely, a limited
 275 number of points above the Rayleigh curve likely reflect contributions from sublimation of snow or sea ice (Kopeck et al., 2019).
 276 Overall, the isotopic composition of water vapor in the Sea Ice and Transition Regions is primarily governed by Rayleigh
 277 fractionation during advective transport, while d-excess provides a distinct, sensitive record of local kinetic processes at the
 278 ice-atmosphere interface, such as supersaturation and sublimation. However, our interpretation of d-excess variations over sea
 279 ice is largely dependent on Rayleigh fractionation curves, with contributions from sublimation and processes under
 280 supersaturated conditions remaining poorly constrained.
 281 In contrast, the Ice-free region exhibits a breakdown of the organized Rayleigh behaviour. Observations show a broad scatter
 282 in both q - $\delta^{18}\text{O}$ and q -d-excess diagrams, indicating the interplay between advected and locally evaporated vapor under ice-free
 283 conditions. At lower specific humidity (< 5 g/kg), isotopic patterns resemble those of ice-covered regions (Fig. 6), suggesting
 284 a persistent influence of advective moisture. However, as humidity rises (> 5 g/kg)—which coincides with surface air
 285 temperatures exceeding ~5 °C—systematic deviations from Rayleigh behavior become evident, reflecting the growing
 286 dominance of local processes. In the q - $\delta^{18}\text{O}$ diagram, two distinct patterns emerge: one cluster is enriched well above the mean
 287 mid-latitude $\delta^{18}\text{O}$ value, indicating input from warm, isotopically heavy sources; the other falls below the 5°C Rayleigh curve,
 288 where its scattered, non-logarithmic distribution—though still bounded by the 20°C curve and the mixing line—points to
 289 strong kinetic fractionation. This divergence is systematically mirrored in the q -d-excess diagram (Fig. 6b), where values split
 290 both below and above the equilibrium curve. The co-occurrence of $\delta^{18}\text{O}$ enrichment and elevated d-excess in this high-humidity
 291 regime directly implicates kinetic fractionation during local evaporation as an important driver of Arctic water vapor isotopic
 292 composition under ice-free conditions.
 293 In summary, the isotopic composition of Arctic water vapor is governed by distinct processes that shift with the state of sea
 294 ice. In the Sea Ice and Transition Regions, isotope variations primarily reflect long-range Rayleigh distillation, partly
 295 modulated by kinetic effects from ice-phase processes such as supersaturation and sublimation. In the Ice-free Region, however,

296 this regime gives way to a fundamentally different balance, in which local evaporation over open water emerges as the key
 297 control. Together, these results highlight that the state of sea ice fundamentally shapes the balance between advective and local
 298 processes governing Arctic water vapor isotopes.

299 **3.4 Evaluating the Influence of Local Evaporation on Ice-free Region Water Vapor Isotopes**

300 To further evaluate the anomalous isotopic behavior identified with high temperature and humidity—where d-excess shows
 301 marked deviations from Rayleigh expectations under high-humidity conditions—we employed the MJ79 marine boundary-
 302 layer evaporation model (Merlivat and Jouzel, 1979; Bonne et al., 2019). The model was driven by observed surface
 303 temperature and relative humidity and accounts for both equilibrium fractionation, controlled by temperature, and kinetic
 304 fractionation, modulated by relative humidity. Following Bonne et al. (2019), we adopted kinetic fractionation factors
 305 representative of the rough-wind regime ($>7\text{ m s}^{-1}$) for all simulations.



306
 307 **Figure 7. Observed versus MJ79-simulated water vapor isotopes ($\delta^{18}\text{O}$ and d-excess) across sea ice regions under different**
 308 **temperature regimes: (a, b) $>5^\circ\text{C}$; (c, d) $<5^\circ\text{C}$. The black line denotes the 1:1 line ($y = x$).**

309 First set of simulations were restricted to samples with temperatures exceeding 5 °C, corresponding to ice-free, high
310 temperature-low relative humidity conditions where local evaporation is expected to dominate. Under these settings, the model
311 reproduces the observed isotopic variability reasonably well, with correlations of 0.62 for $\delta^{18}\text{O}$ and 0.75 for d-excess (Fig. 7a,
312 b). This agreement supports the interpretation that kinetic fractionation during local evaporation contributes substantially to
313 the isotopic composition of Arctic water vapor in the Ice-free Region. However, the model substantially overestimates the
314 observed values, consistent with a previous study by Bonne et al. (2019). This overestimation largely reflects the closure
315 assumption inherent in the MJ79 model, which treats local evaporation as the sole moisture source and neglects atmospheric
316 mixing.
317 In contrast, when the temperature is below 5 °C, although the simulation shows a reasonable correlation with the observed
318 $\delta^{18}\text{O}$ ($r = 0.61$), it fails to reproduce the d-excess variability ($r = 0.07$) (Fig. 7c, d). This failure of the model to represent d-
319 excess variability suggests that, under cold conditions, the moisture budget is dominated by non-local sources rather than local
320 evaporation. This further supports our interpretation that advective moisture transport dominates isotopic variations in ice-
321 covered regions.

322 3.5 Moisture Source Attribution from Lagrangian Trajectory Analysis

323 To test our isotope-based interpretation of moisture sources, we computed backward trajectories along the cruise track using
324 the HYSPLIT model (Fig. 8 and Figs. S2-4). The analysis reveals a clear dichotomy in air mass origins aligned with sea ice
325 regime. In the Sea Ice and Transition Regions, trajectories show air masses undergoing rapid cooling and dehydration during
326 poleward transport, as reflected by declining specific humidity and rising relative humidity. Under these cold, saturated
327 conditions, evaporation is suppressed, allowing Rayleigh distillation of advected moisture to emerge as the characteristic
328 process, consistent with the observed alignment to Rayleigh curves (Fig. 6). Moreover, the frequent recirculation within the
329 Arctic interior points to prolonged moisture residence under stable, cold conditions. This extended residency favors non-
330 equilibrium ice-phase processes, such as crystal formation and dew deposition under supersaturated conditions and sublimation,
331 providing a coherent explanation for the distinctive d-excess signals observed in these regions (Fig. 6b).

332 In the Ice-free Region, however, trajectories reveal two distinct source pathways, explaining its complex isotopic signals. Most
333 originate from lower latitudes, carrying warm, air northward across the Barents Sea. Elevated temperatures in the Barents Sea
334 create a large saturation vapor deficit (via the Clausius–Clapeyron relationship), which maintains low relative humidity despite
335 high specific humidity. These conditions promote strong evaporation over the ice-free ocean, contributing to the d-excess
336 enrichment observed in this region (Fig. 4) and confirming that local evaporation is a major driver of isotopic variability under
337 ice-free conditions. A smaller subset of air masses recirculates within the cold, saturated Arctic interior. Their limited
338 interaction with open water suppresses evaporation, preserving an advective signature similar to that of ice-covered regions.
339 Together, these dual air mass origins—one characterized by strong local evaporation and the other by advected moisture—
340 explain the coexistence of both isotopic end-members observed in the q – $\delta^{18}\text{O}$ and q –d-excess relationships.

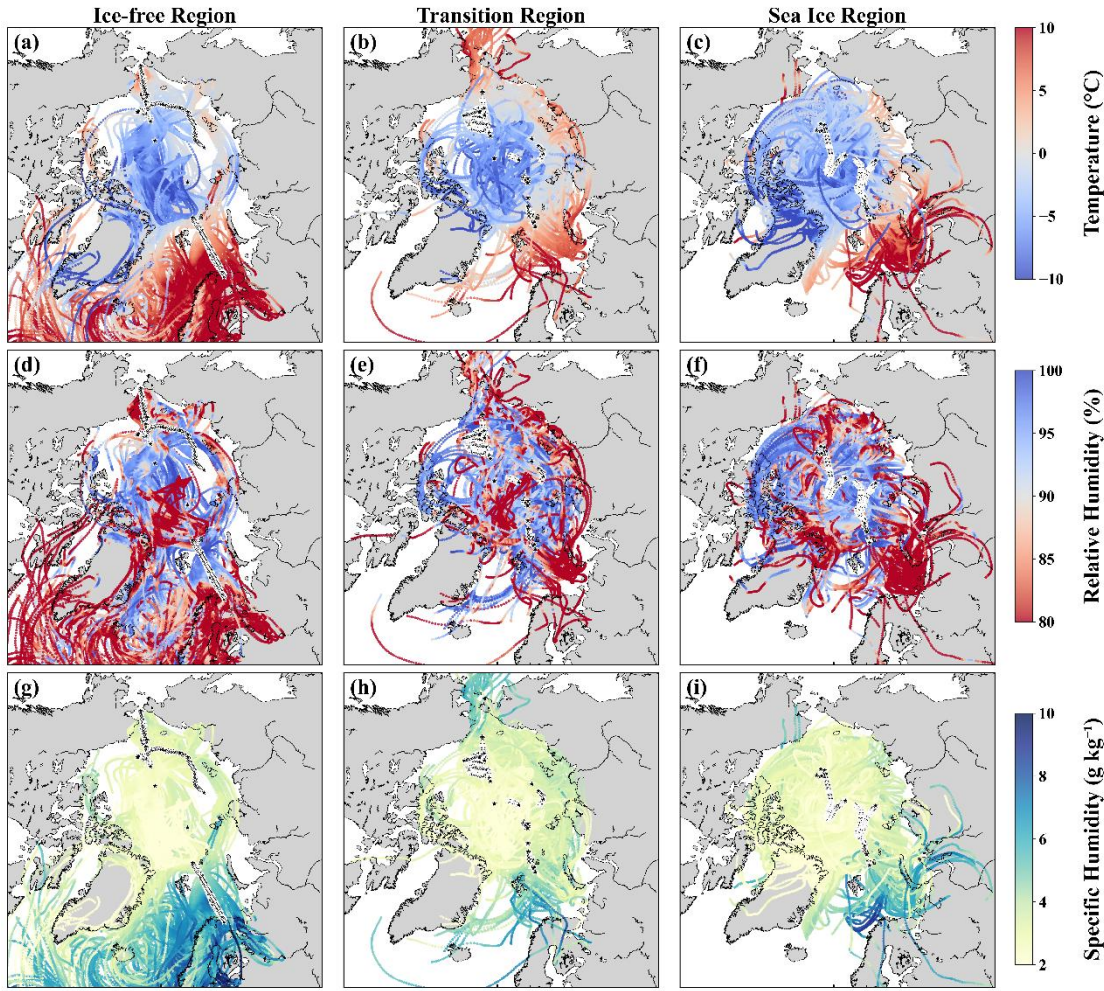
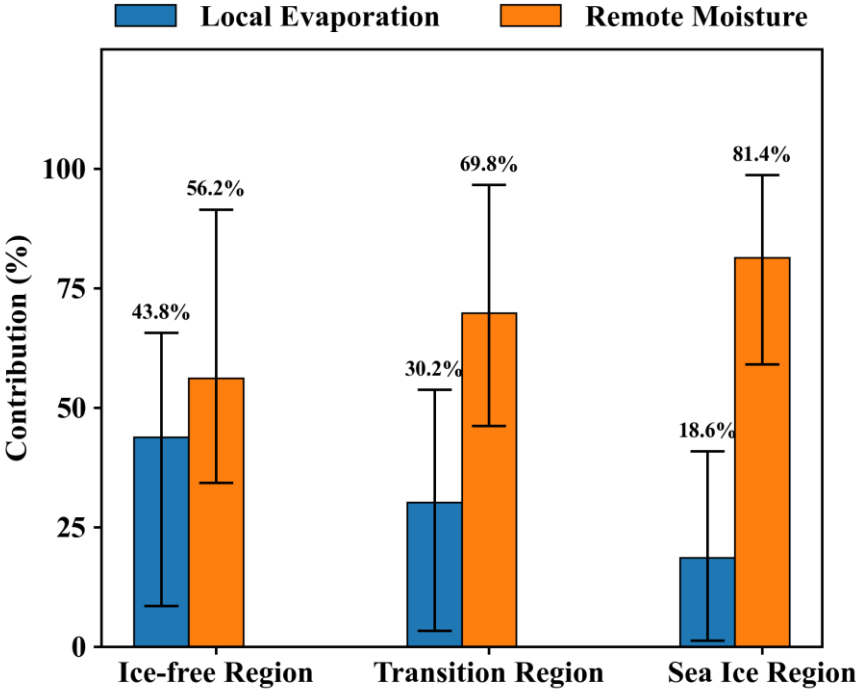


Figure 8. Ten-day HYSPLIT back trajectories from 10 m and associated meteorology by sea ice regime: ice-free (left), transition (middle), and sea ice (right). Rows show (a–c) air temperature (°C), (d–f) relative humidity (%), and (g–i) specific humidity (g kg⁻¹). Black stars denote start points.

3.6 Relative Contributions of Moisture Sources Across Arctic Sea Ice Regimes

To quantify the relative contributions of locally evaporated and advected moisture to Arctic boundary layer water vapor across different sea ice regimes, we apply the Bayesian isotope mixing model MixSIAR (Stock et al., 2018) to $\delta^{18}\text{O}$ and δD measurements. Locally evaporated moisture is derived from Arctic open-water evaporation, with $\delta^{18}\text{O} = -11.77 \pm 0.59 \text{ ‰}$ and $\delta\text{D} = -96.02 \pm 7.67 \text{ ‰}$, estimated using the MJ79 model (see Data and Methods). Advected lower-latitude moisture, as identified by HYSPLIT trajectories (Fig. 8), primarily originates from the North Atlantic and the North Pacific, with isotopic endmembers taken from Benetti et al. (2017) near 50–60°N for the Atlantic ($\delta^{18}\text{O} = -18.25 \pm 4.79 \text{ ‰}$, $\delta\text{D} = -138.53 \pm 34.75 \text{ ‰}$) and from our observations over 50–60°N for the Pacific ($\delta^{18}\text{O} = -15.54 \pm 1.67 \text{ ‰}$, $\delta\text{D} = -118.89 \pm 8.99 \text{ ‰}$). A weighted

353 average based on trajectory specific humidity (Atlantic = 79.07 % and Pacific = 20.93 %; see Data and Methods) is used to
 354 represent a single lower-latitude source ($\delta^{18}\text{O} = -17.68 \pm 3.8 \text{ ‰}$, $\delta\text{D} = -134.42 \pm 27.54 \text{ ‰}$). Calibrated vapor isotope
 355 measurements from each sea ice regime serve as the mixture input. A process error structure is applied to account for spatial
 356 variability and source uncertainty (see Data and Methods), and MixSIAR is run independently for each regime to estimate the
 357 probability distributions of source contributions.
 358 MixSIAR results reveal a clear spatial gradient in moisture source contributions across sea ice regimes (Fig. 9). Local
 359 evaporation contributes most in the Ice-free Region, with a mean of 43.8 % (95 % CI: 14.7–65.7 %), decreasing to 30.2 %
 360 (95 % CI: 13.8–53.8 %) in the Transition Region and 18.6 % (95 % CI: 11.1–40.9 %) in the Sea Ice Region. Although the
 361 absolute contribution of local evaporation is modest, it increases progressively with decreasing sea ice cover. Across all
 362 regimes, advected lower-latitude moisture remains the dominant source, accounting for 77–91 % of boundary-layer vapor.
 363 These findings indicate that, while long-range transport governs the Arctic vapor budget, local evaporation contributes a
 364 notable fraction in ice-free areas.



365
 366 **Figure 9. Contributions of local and low-latitude remote moisture estimated using a Bayesian isotope mixing model. Blue and orange**
 367 **bars indicate the proportions of local and low-latitude sources, respectively. Error bars denote the 95% credible intervals (2.5–**
 368 **97.5%), and the values above each bar represent the mean contributions.**

369 **4 Discussion and Conclusions**

370 **4.1 Water Vapor Isotopic Responses to Distinct Sea Ice Regimes**

371 Our sea-ice-based isotope framework resolves a longstanding Arctic paradox by showing that, although d-excess has
372 traditionally been treated predominantly as a source signature (Dansgaard, 1964), it is highly sensitive to boundary-layer
373 thermodynamics governed by sea-ice extent. Since the first polar vapor isotope measurements reported unexpectedly higher
374 d-excess in Arctic-sourced moisture compared with lower latitudes (Kurita, 2011), subsequent studies have alternately
375 documented both high (Kopec et al., 2019; Pang et al., 2019) and low (Samuels-Crow et al., 2014; Klein et al., 2015; Klein
376 and Welker, 2016; Brunello et al., 2023) values under similar surface conditions. These apparently conflicting results reflect
377 sampling across a continuum of ice-controlled humidity and kinetic fractionation regimes rather than intrinsic differences in
378 moisture sources.

379 Previous studies have reported conflicting relationships between polar vapor d-excess and sea ice. Bonne et al. (2019) found
380 a positive correlation with sea ice, whereas Klein and Welker (2016) reported a negative correlation. This divergence likely
381 stems from differences in the study domain, which sample distinct sea-ice regimes. Bonne et al. (2019) primarily analyzed
382 regions with sea-ice coverage greater than zero, corresponding to the transition-to-ice-covered regime in our study, where d-
383 excess increase with SIC (Fig. S1a). In contrast, Klein and Welker (2016) focused largely on the low-ice Bering Strait, an
384 environment analogous to our ice-free-to-transition region, in which the negative correlation reflects enhanced local
385 evaporation over open water (Fig. S1b). By spanning multiple sea-ice regimes, our observations reveal that d-excess does not
386 exhibit a simple monotonic relationship with sea ice, but instead shows a bimodal distribution, with elevated values in both
387 ice-covered and ice-free regions. This pattern reflects contrasting controlling mechanisms between the two regimes: the ice-
388 covered region is dominated by long-distance Rayleigh fractionation superimposed by sublimation, whereas the ice-free region
389 is governed primarily by local evaporation dynamics.

390 **4.2 Relationship between isotopes and local meteorological conditions**

391 A negative d-excess–RH relationship is widely observed at both regional (Uemura et al., 2008) and global scales (Pfahl and
392 Sodemann, 2014). In the Arctic, however, the relationship remains poorly constrained due to the paucity of isotopic
393 measurements. Our cross-Arctic water vapor isotope observations reveal an overall negative relationship between d-excess
394 and RH, but with a progressively weaker correlation from the ice-free region to the sea-ice-covered region, indicating a
395 diminishing influence of local evaporation as sea ice increases (Fig. 5). The slopes of the d-excess–RH relationship range from
396 -0.46‰ to -0.26‰ across the different Arctic regimes and are comparable to values reported at lower latitudes (e.g., -0.4‰ ;
397 Thurnherr et al. (2020)), highlighting the important role of local evaporation in shaping near-surface water-vapor d-excess.
398 However, it should be noted that RH in this study is derived from in situ air temperature rather than SST, which may partly
399 weaken the correlations and affect the estimated slopes. Nevertheless, because air temperature and SST co-vary closely over
400 the Arctic (Klein and Welker, 2016), the inter-regional contrasts in the d-excess–RH relationship identified here remain robust.

401 In contrast, our observations reveal pronounced differences in isotope–temperature relationships between the ice-free and ice-
402 covered regions. The $\delta^{18}\text{O}$ –temperature correlation weakens from the ice-covered region toward the ice-free region and
403 becomes clearly negative (the so-called anti-temperature effect) when temperatures exceed 5 °C in the ice-free region (Fig.
404 4a). This interpretation is further supported by the d-excess–temperature relationships, which show weak correlation in the
405 ice-free region but strong one in the ice-covered region (Fig. 4b). These patterns are consistent with previous observations over
406 open water (Bonne et al., 2019; Klein and Welker, 2016; Sodemann et al., 2024) and in the ice-covered region (Brunello et al.,
407 2023; Brunello et al., 2024), respectively. However, Brunello et al. (2024) and Sodemann et al. (2024) attributed the positive
408 $\delta^{18}\text{O}$ –temperature and negative d-excess–temperature relationships to warm air intrusions, based on observed positive RH–
409 temperature coupling. By contrast, our observations show a clear negative correlation between RH and temperature, indicating
410 that the observed isotope signals are primarily driven by spatial fractionation across the heterogeneous ice surface rather than
411 by synoptic-scale moist advection (Fig. 3). This difference likely reflects the contrasting observational frameworks, with our
412 short-duration transect sampling being less sensitive to episodic warm-air intrusions.

413 4.3 Quantifying the Shift in Moisture Sources

414 Stable water isotopes provide a quantitative framework to partition moisture source contributions across the study domain.
415 The contribution from local evaporation increases from 18.6 % in the Sea Ice Region to 43.8 % in the Ice-free Region,
416 demonstrating enhanced local recycling despite persistent advective dominance. This gradient aligns with observed surface
417 moisture flux trends (Boisvert and Stroeve, 2015) and contextualizes previous observationally or model-based estimates
418 ranging from 8 % (Domínguez et al., 2018) to over 35 % (Zhong et al., 2018). By providing a novel quantification based on
419 vapor isotopes, this study highlights the capacity of in-situ isotopic monitoring to resolve complex Arctic hydrological
420 processes.

421 Although we quantify the relative contributions of remotely advected and local evaporated moistures across different ice
422 regimes, there are at least two caveats should be noted. First, uncertainties arise from the determination of the end-members.
423 In particular, the remote end-member is constrained by limited low-latitude sampling and by the use of boundary humidity
424 rather than a full Lagrangian moisture budget, which may bias the estimated contribution of remote sources by neglecting
425 moisture turnover along transport pathways. In addition, although the MJ79 model serves as a standard local-evaporation end-
426 member, its closure assumption neglects atmospheric mixing and synoptic processes, which can lead to a systematic
427 overestimation of local isotope values (Bonne et al., 2019). Second, the Bayesian mixing model relies on the combined use of
428 $\delta^{18}\text{O}$ and δD , which are strongly correlated. This high correlation reduces the effective dimensionality of the isotopic
429 constraints, limiting the ability of the model to robustly distinguish between the two end members and introducing additional
430 uncertainty. Despite these caveats, our results demonstrate that local moisture contributions are intrinsically tied to sea-ice
431 state, providing quantitative support for a previously hypothesized feedback whereby sea-ice retreat promotes a more localized
432 Arctic water cycle, as recorded in both water-vapor (Bailey et al., 2021) and precipitation (Kopec et al., 2016) isotopes. These
433 results provide the first in-situ isotopic observational constraints for evaluating near-surface humidity, precipitation recycling,

434 and the fidelity of regional climate models.

435 **4.4 Implications for Arctic Hydroclimate Research**

436 Beyond contemporary implications, our findings necessitate refinements in paleoclimate interpretations from polar ice-core
437 records. The canonical $\delta^{18}\text{O}$ –temperature relationship, long used as a paleo-thermometer, is modulated by sea ice extent: under
438 extensive ice cover, strong positive correlations reflect temperature-driven advective distillation, whereas in Transition and
439 Ice-free Regions, the relationship weakens or reverses (“anti-temperature” effect), indicating that $\delta^{18}\text{O}$ integrates local
440 evaporation and humidity signals alongside temperature. Enriched $\delta^{18}\text{O}$ with elevated d-excess during warm, ice-reduced
441 periods (e.g., interglacials) reflects reorganized local moisture sources rather than temperature alone. We advocate a regime-
442 informed dual-proxy framework that leverages $\delta^{18}\text{O}$ –d-excess co-variation, interpreted through modern-observed sea ice
443 regimes, to disentangle past temperature and sea ice signals—thereby reconciling observational contradictions and bridging
444 modern process understanding with paleo-isotope interpretation.

445 While our study establishes a sea ice–mediated isotopic framework, several research frontiers warrant further investigation.
446 Extending observations across seasons and years will test the climatological robustness of the framework, while expanding
447 spatial coverage and incorporating additional tracers (e.g., ^{17}O -excess) will refine mechanistic attribution. Integrating the
448 framework into isotope-enabled climate models can evaluate model performance across both past and projected climates, and
449 applying it to ice-core records will help disentangle temperature and sea ice signals. Collectively, these efforts will advance
450 Arctic isotope science from descriptive regime characterization to predictive understanding of hydroclimate responses under
451 accelerating global change.

452 In summary, this study demonstrates that Arctic near-surface water vapor isotopes are systematically regulated by sea ice
453 regimes, which control moisture sources and fractionation pathways. Under extensive ice, advective Rayleigh distillation
454 dominates, producing a strong $\delta^{18}\text{O}$ –temperature correlation and elevated d-excess in colder regions. As sea ice retreats, local
455 evaporation over open water contributes more, imprinting a kinetic fingerprint of enriched $\delta^{18}\text{O}$ and elevated d-excess under
456 warm, dry conditions. This shift breaks down the canonical $\delta^{18}\text{O}$ –temperature relationship, giving rise to an “anti-temperature”
457 effect. Quantifying this regime shift, our Bayesian mixing model constrained by in-situ isotopes reveals that local evaporation
458 contributions rise from 18.6% in the Sea Ice Region to 43.8% in the Ice-free Region—demonstrating a 2.4-fold enhancement
459 of local recycling despite persistent advective dominance. These results establish sea ice as the dynamic regulator of Arctic
460 isotopic variability across the ice–open water transition, offering critical observational constraints for both contemporary
461 hydroclimate changes and paleoclimate reconstructions.

462 **Data and code availability**

463 The ERA5 data are publicly available at: <https://cds.climate.copernicus.eu/datasets> (last access : September 2025). The SIC
464 data were adopted from the National Snow and Ice Data Center (NSIDC) at: <https://nsidc.org/data/g10005/versions/2> (last

access : September 2025). The Global Data Assimilation System (GDAS) meteorological fields were obtained from NOAA's Air Resources Laboratory (<ftp://arlftp.arlhq.noaa.gov/pub/archives/gdas1/> (last access : September 2025)). The water vapor isotope dataset and the code to reproduce the figures in the main text will be available on the Zenodo research data repository after manuscript publication.

Author contributions

Yuankun Zhang and Zhongfang Liu designed the research. Yuankun Zhang, Dongsheng Li, Zhiqing Li and Hebin Shao performed the investigation, including the deployment and calibration of the ship-based instruments. Yuankun Zhang, Zhongfang Liu, and Dongsheng Li performed the analysis. All authors contributed to the discussion of the results and the final article. Yuankun Zhang drafted the paper with contributions from all co-authors. Zhongfang Liu checked and modified the paper.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgments

We gratefully acknowledge the open-source contributions of Stock and Semmens for the MixSIAR R package, NOAA for the HYSPLIT model, and Daniel Warner for the development and sharing of the pysplit package. Furthermore, we extend our sincere gratitude to all members of the 14th Chinese National Arctic Research Expedition, especially the crew and scientists aboard the RV *Xuelong 2*, for providing an exceptional operational environment and foundational support for the measurements conducted in this study.

Financial support

This work is supported by the National Natural Science Foundation of China (Grant 42025602).

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