Ocean air masses dominate the land-surface atmospheric water cycles in the coastal areas of Liaodong Bay: Insights from stable isotopes

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Abstract

Long-term atmospheric water vapor hydrogen ($\delta 2H$), oxygen ($\delta 18O$), and deuterium excess (d-excess) can provide unique insights into the land-atmosphere coupling processes. The in-situ measurements of atmospheric water vapor $\delta 2H$, $\delta 18O$, and d-excess were conducted above a reed wetland of Liaodong Bay (2019-2020). We found significant inter-annual variations in atmospheric water vapor isotopes between the two growing (May-September) seasons. The $\delta 2H$, $\delta 18O$, and d-excess of atmospheric water vapor exhibited different seasonal and diurnal cycles respect to the vertical (i.e., 1 m, 3 m, and 5 m) measurement heights, especially in 2019. The isotopic differences of atmospheric water vapor among vertical measurement heights were more evident in the daytime (8:00-20:00 LST) than at night (20:00-8:00 LST). Rainfall events had a direct impact on the diurnal patterns of water vapor isotopes, and the influences depended on rainfall intensities. However, only week correlations existed between water vapor isotopes and local meteorological factors ($R2 = 0.01$-0.16, $P < 0.001$), such as water vapor concentration (w), relative humidity (RH), and surface air temperature (Ta). Based on the back-air trajectory analyses, the spatial-temporal dynamics of atmospheric water vapor isotopes highly synchronized with monsoon activities. The dominant air masses in this region mainly arose from ocean sources, which contributed to $62.1 \pm 12.2\%$ (49.4-84.5%) of the total air moisture. High d-excess consistently followed the strong monsoon activities, suggesting predominating impacts of ocean air masses from the East Asian monsoon region. High-resolution measurements of atmospheric water vapor isotopes will improve our understanding of the hydrological cycles in coastal areas.

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1 **Ocean air masses dominate the land-surface atmospheric water cycles in**

2 **the coastal areas of Liaodong Bay: Insights from stable isotopes**

3

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16 **Key Points:**

17 • Spatial-temporal variations of water vapor isotopes are very different during
18 2019/2020 growing (May-September) seasons.

19 • Meteorological variables are not reliable indicators for water vapor δ^2H, δ^{18}O,
20 and d-excess at Panjin experimental station.

21 • Ocean air masses from East Asian monsoon dominate land-surface
22 atmospheric water vapor cycles in the coastal areas of Liaodong Bay.
23

Abstract

Long-term atmospheric water vapor hydrogen (δ^2H), oxygen (δ^{18}O), and deuterium excess (*d-excess*) can provide unique insights into the land-atmosphere coupling processes. The in-situ measurements of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess* were conducted above a reed wetland of Liaodong Bay (2019-2020). We found significant inter-annual variations in atmospheric water vapor isotopes between the two growing (May-September) seasons. The δ^2H, δ^{18}O, and *d-excess* of atmospheric water vapor exhibited different seasonal and diurnal cycles respect to the vertical (i.e., 1 m, 3 m, and 5 m) measurement heights, especially in 2019. The isotopic differences of atmospheric water vapor among vertical measurement heights were more evident in the daytime (8:00-20:00 LST) than at night (20:00-8:00 LST). Rainfall events had a direct impact on the diurnal patterns of water vapor isotopes, and the influences depended on rainfall intensities. However, only week correlations existed between water vapor isotopes and local meteorological factors ($R^2 = 0.01$-0.16, $P < 0.001$), such as water vapor concentration (w), relative humidity (RH), and surface air temperature (T_a). Based on the back-air trajectory analyses, the spatial-temporal dynamics of atmospheric water vapor isotopes highly synchronized with monsoon activities. The dominant air masses in this region mainly arose from ocean sources, which contributed to $62.1 \pm 12.2\%$ (49.4-84.5%) of the total air moisture. High *d-excess* consistently followed the strong monsoon activities, suggesting predominating impacts of ocean air masses from the East Asian monsoon region. High-resolution measurements of atmospheric water vapor isotopes will improve our understanding of the hydrological cycles in coastal areas.

Plain Language Summary

The coastal wetland regions in East Asia always have complex atmospheric hydrological processes, because they are influenced both by the westerly belt and the East Asian monsoon. Under such circumstances, still the question remains how do the multiple air masses affect the seasonal and diurnal patterns of atmospheric circulations? We implemented high temporal resolution (1Hz) measurements of atmospheric hydrogen (HDO/H$_1$H$_2{}^{18}$O) and oxygen (H$_2{}^{18}$O and H$_2{}^{16}$O) using an off-axis integrated cavity output spectroscopy (OA-ICOS) technology in a reed wetland. The deuterium excess (*d-excess* $= \delta^2$H $- 8 \times \delta^{18}$O) of atmospheric water vapor was further used as an indicator for identifying the moisture source locations (2019-2020). There were obvious seasonal and diurnal variations of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess*. However, the inter-annual variations in atmospheric water vapor isotopes were more notable in this study, mainly due to the stronger monsoon activities. For example, the landing of typhoon "Lekima" brought a very high level of atmospheric water vapor *d-excess* in 2019. Therefore, the local meteorological variables might not be sufficient predictors of the atmospheric water vapor isotopes in the coastal wetland regions.

64 **1 Introduction**

65   Measurements of atmospheric water vapor hydrogen (δ^2H), oxygen (δ^{18}O),
66 and deuterium excess (*d-excess*) can provide unique insights into the land-atmosphere
67 coupling processes (Gat, 1996; Lee et al., 2005; Vuille et al., 2003). The δ^2H, δ^{18}O,
68 and *d-excess* of water vapor (termed as the δ_{vapor} hereafter) can be used as natural
69 tracers of atmospheric water cycles (Bastrikov et al., 2014; Christner et al., 2017;
70 Munksgaard et al., 2020; Wen et al., 2008, 2010). Influenced by lower tropospheric
71 water variations (e.g., precipitation and vertical atmospheric mixing) and local
72 vegetation properties (e.g., soil evaporation and plant transpiration), the signatures of
73 land-surface water vapor δ_{vapor} contain subtle information concerning water
74 movements between the atmospheric boundary layer (ABL) and Earth's surfaces
75 (Huang & Wen, 2014; Laonamsai et al., 2021; Lee et al., 2006). Thus, there is a
76 growing interest in high-resolution measurements of atmospheric water vapor δ_{vapor}
77 from ecosystem to regional scales (Galewsky et al., 2016; Steen-Larsen et al., 2013;
78 Wei & Lee, 2019). Several studies have successfully completed the in-situ
79 atmospheric water vapor δ_{vapor} monitoring based on the technological advantages of
80 laser spectrometers (Aemisegger et al., 2014; Hu et al., 2014; Noone et al., 2012).
81 However, it is still necessary to conduct in-situ measurements of atmospheric water
82 vapor δ_{vapor} above near-surface ecosystems (Galewsky et al., 2016; Lee et al., 2005,
83 2007), compared with the condensed water isotopes that have formed a well-known
84 global network (e.g., Global Network of Isotopes in Precipitation, GNIP).

85   To the best of our knowledge, datasets of in-situ atmospheric water vapor
86 δ_{vapor} are reported across 49 sites worldwide. Those sites reflect the global land
87 surface in all forms, including oceans (e.g., Bonne et al., 2019; Galewsky et al., 2022;
88 Steen-Larsen et al., 2014a), forests (Aron et al., 2019; Bastrikov et al., 2014; Mercer
89 et al., 2020), grasslands (Hu et al., 2014; Parkes et al., 2017; Tremoy et al., 2014),
90 croplands (Griffis et al., 2016; Huang & Wen, 2014; Wen et al., 2012), ice sheets
91 (Bonne et al., 2020; Casado et al., 2016; Steen-Larsen et al., 2014b), cities (Christner
92 et al., 2017; Noone et al., 2012; Wang et al., 2021), and lakes (Cui et al., 2018; Hu et
93 al., 2021; Xiao et al., 2017). These studies confirm the great potential of in-situ water
94 vapor δ_{vapor} measurements to deconstruct the complex hydrological processes.
95 However, among the available data on atmospheric water vapor δ_{vapor}, the data from
96 coastal wetlands are scarce (Delattre et al., 2015; Lai et al., 2018). For example,
97 Delattre et al. (2015) showed that ground level atmospheric vapour composition can
98 record both local and regional isotopic signatures during 36 consecutive summer
99 days . The water vapor δ_{vapor} data reported by Lai et al. (2018) showed that, on daily
100 time scales (11-28 July, 2017), substantial rain recycling and large-scale atmospheric
101 water transport occur above a coastal mangrove forest in southern China, which is
102 subjected to the monsoons from South China Sea, Indian Ocean, Pacific Ocean, and
103 local land areas. Nevertheless, the brief campaigns of water vapor δ_{vapor} measurements
104 would restrain the best demonstration of atmospheric processes in the coastal
105 wetlands.

106 Previous studies have demonstrated that the small spatial and temporal variations of
107 atmospheric water vapor δ_{vapor} are affected mainly by processes of atmospheric
108 entrainments, land surface evapotranspiration (i.e., soil evaporation and plant
109 transpiration, ET), and vapor condensations (Huang & Wen, 2014; Lee et al., 2007;
110 Fiorella et al., 2019; Diekmann et al., 2021). Entrainment processes of the free
111 atmosphere will vertically deplete the ^{2}H and ^{18}O of water vapor near the land
112 surfaces (Devi et al., 2014; Kurita et al., 2012; Wei et al., 2015). Local ET will enrich
113 the ^{2}H and ^{18}O of near-surface atmosphere above the densely vegetated landscapes,
114 which usually plays a dominant role in the variations of water vapor δ_{vapor} (Lai &
115 Ehleringer, 2011; Zhang et al., 2011). The diurnal dynamics of atmospheric water
116 vapor $\delta vapor$ are closely associated with the vapor condensation processes (e.g.,
117 precipitation, dew and fog), which is mainly caused by the equilibrium phase changes
118 of local water vapor during the synoptic events (Bailey et al., 2015; Farlin et al., 2013;
119 Wen et al., 2012). On large spatial scales, air mass advection is considered as a
120 critical factor contributing to the temporal variability in atmospheric water vapor δ_{vapor}
121 (Dahinden et al., 2021; Galewsky et al., 2011; Steen-Larsen et al., 2015).

122 Despite high-resolution monitoring efforts over the past two decades,
123 decoupling the atmospheric water vapor δ_{vapor} variability across various timescales
124 remains challenging (Bagheri et al., 2019; Berkelhammer et al., 2013; Lee et al.,
125 2005; Dahinden et al., 2021). The deuterium excess (*d-excess* $= \delta^2H - 8 \times \delta^{18}O$) of
126 atmospheric water vapor provides a new insight into the source identification of
127 atmospheric moistures (Dansgaard, 1964; Merlivat & Jouzel, 1979; Welp et al.,
128 2012). The theoretical basis of this application is that the *d-excess* of water vapor is
129 closely linked to the environmental conditions during the kinetic fractionation
130 processes (Araguas-Araguas et al., 2000; Craig, 1961). Hence, the strong sensitivity
131 of *d-excess* to local atmosphere relative humidity (RH) can place better constraints on
132 the water transport processes than the analyses of water vapor δ^2H and $\delta^{18}O$ alone
133 (Lai et al., 2018; Wei & Lee, 2019). Previous work has traced both the ocean moisture
134 sources (Dahinden et al., 2021; Gonzalez et al., 2016; Salamalikis et al., 2015) and
135 continental moisture recycling (Aemisegger et al., 2014; Fiorella et al., 2019). To
136 better resemble the transmission path of large-scale air masses, tools of Hybrid
137 Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) and TrajStat models
138 have been widely used in conjunction with water vapor isotopes in recent years
139 (Bagheri et al., 2019; Fiorella et al., 2018; Gonzalez et al., 2016; Salamalikis et al.,
140 2015). It is foreseeable that long-term water vapor d-excess measurements will
141 improve our understanding of atmospheric processes and the associated mechanisms
142 in the coastal wetlands.

143 Liaodong Bay, a high-latitude continental bay (37.1-41.0° N, 117.6-121.2° E),
144 has the largest size and northernmost semi-enclosed seaports in China. It contains a
145 wetland area of approximately 5300 km^2 (Luo et al., 2021). According to the 2nd
146 National Wetland Survey Statistics Report (NFGA, 2010), the reed wetlands in this
147 region are well-preserved and among the largest in extent (~ 2500 km^2) in the world.
148 Those offshore wetlands are located in the transition zones between continents and
149 oceans, which are vulnerable to natural and anthropogenic activities, such as urban

150 and agricultural runoff. To fill the gaps in knowledge regarding the mechanisms of
151 water cycle processes, we conducted two-year (2019-2020) measurements of
152 atmospheric water vapor δ^2H, δ^{18}O, and *d-excess* in the reed wetlands of Liaodong
153 Bay. The present study aims to (i) investigate the spatial-temporal dynamics of
154 atmospheric water vapor isotopes above the coastal wetland, and (ii) identify the
155 contributing factors that affect the isotopic characteristics of atmosphere in Liaodong
156 Bay. We hypothesize that (1) isotopic gradients exist for atmospheric water vapor
157 measurements along the monitoring heights due to the growth of reeds, and (2) moist
158 air masses from the East Asian monsoon strongly affects the atmospheric water vapor
159 isotopes.

2 Materials and Methods

160

161   2.1 Study site

162   The observations were carried out at Panjin Wetland Field Science
163 Experimental Station (40° 56′ 40″ N, 121° 56′ 36″ E, and elevation 2.1 m), located in
164 the north of Liaodong Bay. This station is a member of the National Climatic
165 Observatory of China Meteorological Administration (CMA), which is adjacent to the
166 Liaohe River Delta wetlands, and 12 km to the Bohai Sea (Figure 1a and 1b). This
167 area is characterized by the semi-humid temperate monsoon climate, influenced by
168 the westerly belt and the East Asian monsoon. The southwest East Asian monsoon
169 prevails from May to September, which brings abundant rainfall between July and
170 September (Huang et al., 2018). The regional meteorological records (1961-2010)
171 indicate that the mean air temperature and annual precipitation are 9.1 °C and 643.9
172 mm, respectively. Approximately 170 days of frost-free weather occur throughout the
173 year. The annual evaporation is about 516.0-720.3 mm (2012-2015). The research site
174 (150 m × 150 m) is situated in the center of a reed marsh (~ 780 km2), with a
175 vegetation coverage of more than 90% (Wang et al., 2016). Meteorological data of
176 surface air temperature (T_a), relative humidity (RH), and total precipitation (P)
177 obtained from an automatic weather station (Model A753WS, Adcon Telemetry Inc.,
178 Santa Rosa, CA). The leaf area index (LAI) and height of the reeds were collected for
179 fifteen days intervals during the growing season (May-September). During the study
180 periods of 2019 and 2020, the maximum LAI and maximum height were 5.1 m^2 m^{-2}
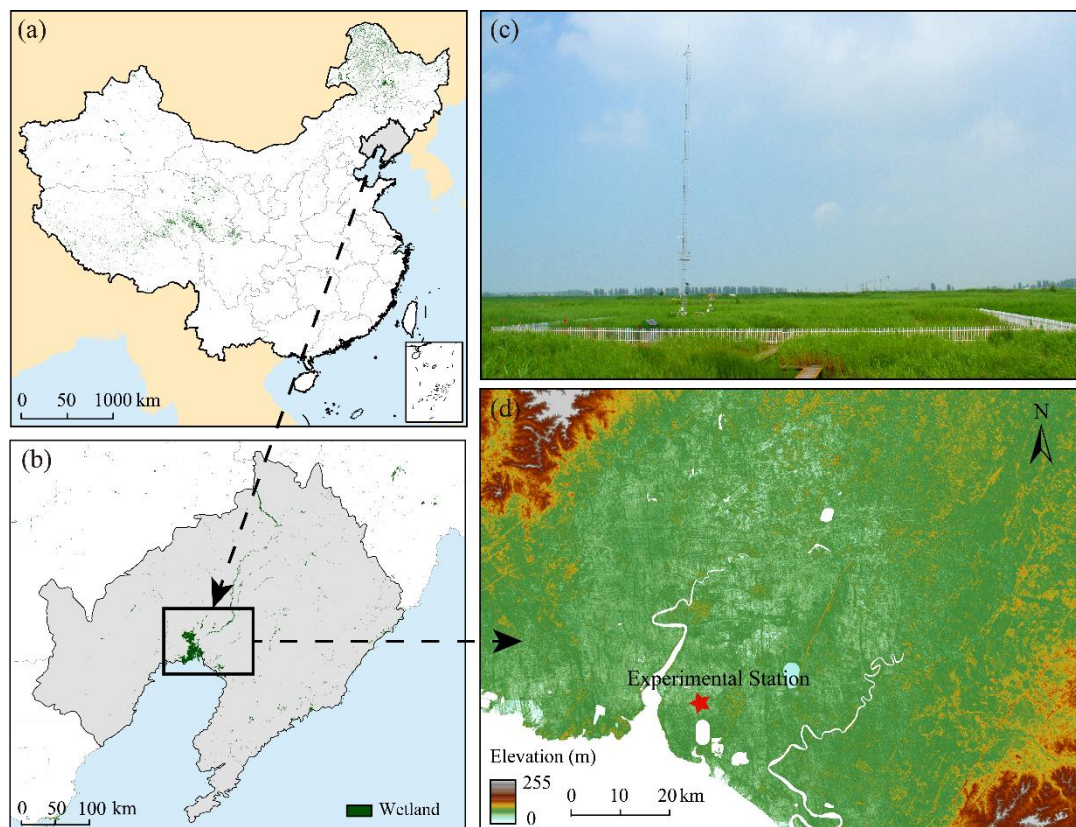181 and 2.5 m, respectively.

Figure 1. Maps showing the locations of Liaodong Bay (**a**, **b**) and Panjin experimental station (**c**, **d**) in this study. Elevation data was downloaded from the National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn).

2.2 In-Situ measurement of water vapor isotopes

The in-situ system used to measure the atmospheric water vapor δ^2H and δ^{18}O consisted of a water vapor isotope analyzer (WVIA), a water vapor isotope standard source (WVISS), and an air sampling system (ASS). The WVIA was used to measure water vapor isotopes (at a frequency of 1 Hz) based on the off-axis integrated cavity output spectroscopy (OA-ICOS; Model TIWA-912, Los Gatos Research, Mountain View, CA, USA). The analyzer has a near-infrared diode laser scanning absorption lines (~ 1.4 μb) for $H_2^{16}O$, $H_2^{18}O$, and $H_1H_2^{16}O$ (HDO), whose precision was approximately 0.4‰ for δ^2H and 0.08‰ for δ^{18}O (Steen-Larsen et al., 2013; Wen et al., 2012). The WVISS is an online calibration device that generates fixed concentrations of continuous vapor streams (Model 908-004-902, Los Gatos Research, Mountain View, CA, USA). In this study, ultrapure liquid water with known isotopic values was nebulized (at a rate of 2-10 L min^{-1}) to produce three designated gradients of standard streams (S$_1$, S$_2$, and S$_3$, 300s each) covering the water vapor concentration of ambient air. There is no isotopic fractionation since the nebulizer and hot chamber (2 L) of WVISS will ensure instant evaporation (heated to 80 °C) of all liquid water. The ASS was mounted on a 30 m height tower (Figure 1c) and used to pump ambient air from four heights (1, 3, 10, and 15 m) with 300s spent

205   on each height. To reduce the residence time of ambient air in the inlet lines (i.e.,

206   "memory effects"), the sampling lines were pumped at approximately 2 L min^{-1} using

207   a commercial multiplexer (Model MC-2000-8, Lica United Technology Limited Inc.,

208   Beijing, CHN). Teflon pipes were used in conjunction with individual heating tapes

209   and jackets to prevent possible vapor condensation in the sampling tubes (Lee et al.,

210   2005; Sturm & Knohl, 2010). Filters were installed at the entrances of the air-intake

211   lines to prevent sucking liquid water into the instrument (Model 300-01961, LI-COR

212   Inc., Lincoln, NE, USA). The switching sequence was S_1, S_2, S_3, and ambient air,

213   with 15 minutes on the standard streams and 220 minutes on ambient air. The WVIA

214   and WVISS were placed in an air-conditioning room to minimize the temperature-

215   driven drifts.

216   While using the OA-ICOS for high-precision measurements of atmospheric

217   water vapor δ^2H and δ^{18}O, measurement bias can occur because of the instrumental

218   concentration-dependence and time-drift (Bastrikov et al., 2014; Wen et al., 2008,

219   2012). Here, we followed a user-configurable "two-point calibration" protocol

220   described by Wen et al. (2012), Huang & Wen (2014) and Xiao et al. (2017). Every

221   220 minutes (i.e., ~ 3.7 h) after the ambient (1, 3, 10, and 15 m) air measurements,

222   two of the three standards (S_1, S_2, and S_3) spanning the water vapor concentration of

223   ambient air were used to linearly calibrate atmospheric water vapor measurements.

224   The isotopic values of the liquid calibration standards were measured using a liquid

225   water isotope analyzer (Model GLA 431-TLWIA, Los Gatos Research, Mountain

226   View, CA, USA), which were scaled to the Vienna Standard Mean Ocean Water

227   (VSMOW) scale. For all the raw δ^2H and δ^{18}O measurements, the first 180 of 300 s

228   spent measuring a given standard stream or an ambient vapor were discarded from the

229   analysis to eliminate the possible memory effects. Then, the "two-point" linear

230   interpolation was implemented using the following formula (Wen et al., 2012; Huang

231   & Wen, 2014):

232
$$\delta_{\text{vapor}} = \delta_{s1} + \frac{(\delta_{s2} - \delta_{s1})}{(X_{s2} - X_{s1})} \times (X_{\text{air}} - X_{s1}) \tag{1}$$

233   where δ_{vapor} is the isotopic ratio (^{2}H/^{1}H, or ^{18}O/^{16}O) of one ambient air (i.e., 1,

234   3, 10, and 15 m), δ_{s1} and δ_{s2} are the single-point corrected ambient airs that are

235   normalized to a reference humidity (i.e., X_{s1} and X_{s2}), X_{s1}, X_{s2} and X_{s1} are water

236   vapor concentrations of the two selected standard streams (S_1, S_2, and S_3) and the

237   ambient air, respectively.

238   The isotopic data collected at 1 m, 3 m, and 15 m in height were used for

239   representing the lower, middle, and upper canopy during the 2019-2020 growing

240   (May-September) seasons. The second-order parameter deuterium excess (*d-excess* =

241   δ^2H $- 8 \times \delta^{18}$O) is defined as the deviation from the linear relationship between ^{2}H/^{1}H

242   and ^{18}O/^{16}O in the Global Meteoric Water Line (GMWL) having a mean slope of 8

243   (Dansgaard, 1964; Merlivat & Jouzel, 1979). All data reported were block-averaged

244   to hourly intervals.

245   2.3 Back-air mass trajectory analyses

246   The Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT)
247 model was used to track changes in isotopic composition and moisture sources
248 (Christner et al., 2018; Munksgaard et al., 2020). The HYSPLIT model
249 (https://ready.arl.noaa.gov/HYSPLIT.php) was developed by the National Oceanic
250 and Atmospheric Administration-Air Resources Laboratory (NOAA-ARL). Inputs of
251 the HYSPLIT model include the cloud height, wind direction, temperature, and
252 surface pressure, which are available from the Global Data Assimilation System
253 (GDAS) meteorological data. In this study, the spatial resolution of the HYSPLIT
254 model was set to $1° \times 1°$, and the starting height was set to 500 m above ground level.
255 The 48-hour back-tracking analysis (close to the time that water vapor is present in
256 the air) was performed hourly for the experimental site from May to September 2019
257 and 2020. The angular distance of the TrajStat model
258 (http://www.meteothinker.com/downloads/index.html) was used to cluster the
259 trajectories of air mass reaching the experimental station:

260
$$D = \frac{1}{n} \sum_{i=1}^{n} \left(0.5 \frac{A_i + B_i - C_i}{\sqrt{A_i B_i}} \right) \qquad (2)$$

261   where D is the average angular distance between two backward trajectories, A
262 and B are the squares of the straight-line distances between the trajectory points and
263 the experimental site, and C denotes the square of the straight-line distance between
264 the two trajectory points.

265   The Concentration Weighted Trajectory (CWT) method was used to identify
266 the potential source regions contributing to the variability of atmospheric water vapor
267 *d-excess* at the experimental site (Li et al., 2020; Salamalikis et al., 2015). The
268 rearward trajectories were assigned by the equally sized $i \times j$ grid cells. The sample
269 concentrations accompanying trajectories that traversed each grid cell were averaged
270 to provide each grid cell with a weighted concentration. The calculation of this
271 method could be found in Li et al. (2020):

272
$$C_{ij} = \frac{1}{\sum_{l=1}^{M} \tau_{ijl}} \sum_{l=1}^{M} c_l \tau_{ijl} \qquad (3)$$

273   where Cij is the average *d-excess* concentration in the ij^{th} cell, *l* is the
274 trajectory index, *M* is the total number of the trajectories, cl is the concentration (*d-*
275 *excess*) of the trajectory *l*, and τ_{ijl} is the time spent in the ij^{th} cell by the trajectory *l*.
276 The weight function (W*ij*) was further introduced (WCWT*ij* = C*ij* $\times$ W*ij*) to reduce
277 uncertainty because the error of CWT increases with the distance between the grid
278 and the experimental station.

279   2.4 Statistical analyses

280   The isotopic data of atmospheric water vapor were calibrated based on the
281 "two-point calibration" protocol using Matrix Laboratory (MATLAB, version 9.2.0,
282 The MathWorks, Inc. Natick, USA). The normality and homogeneity of all data were
283 checked using IBM SPSS statistical software (Version 22.0, SPSS Inc., Chicago,
284 USA). One-way analysis of variance (ANOVA) and multiple means comparisons
285 (LSD) were used to highlight differences in data between months and vertical strata.
286 Considering the possible errors of the two variables, we used geometric mean
287 regression (GMR) to assess the relationships between atmospheric water vapor
288 isotopes and meteorological data with two probability levels of $P \leq 0.05$ and $P \leq$
289 0.001.

290 **3 Results**

291   3.1 Long time scale variations

292   Figure 2 shows the seasonal variations in hourly measured atmospheric water
293 vapor δ^2H, $\delta^{18}O$, and *d-excess* at lower (1 m), middle (3 m), and upper (15 m)
294 measurement heights during the 2019-2020 growing (May-September) seasons. The
295 meteorological data of water vapor concentration (*w*), leaf area index (LAI), relative
296 humidity (RH), total precipitation (P), and surface air temperature (T_a) are also
297 presented for the Panjin experimental station. The WVIA analyzer was under repairs
298 from June 20 to July 10, 2019, and from August 24 to September 9, 2020. For the rest
299 of the study periods, only short gaps occurred in the in-situ measurements of
300 atmospheric water vapor δ^2H, $\delta^{18}O$, and *d-excess* due to the occasional system
301 downtimes (e.g., electricity interruption and/or analyzer breakdown). The monthly
302 average of the above isotopic values of atmospheric water vapor and meteorological
303 data are summarized in Table 1.

304   The δ^2H, $\delta^{18}O$, and *d-excess* of atmospheric water vapor underwent
305 pronounced inter-annual and annual changes with months and vertical measurement
306 heights (Figure 2). Significant differences existed in atmospheric water vapor δ^2H (P
307 < 0.001), $\delta^{18}O$ (P < 0.05), and *d-excess* (P < 0.001) between 2019 and 2020. The
308 mean isotopic values of atmospheric water vapor were higher in 2019 (δ^2H: − 108.4 ±
309 21.4‰, $\delta^{18}O$: − 16.64 ± 3.13‰, and *d-excess*: 26.3 ± 11.7‰) than in 2020 (− 120.7 ±
310 20.2‰, − 16.98 ± 2.93‰ and 13.3 ± 8.4‰). Variation amplitudes (i.e., maximums −
311 minimums) of the water vapor δ^2H, $\delta^{18}O$, and *d-excess* were 153.8‰, 27.69‰, and
312 82.5‰ in 2019, and were 124.5‰, 20.78‰, and 77.7‰ in 2020. The δ^2H and $\delta^{18}O$ of
313 atmospheric water vapor gradually decreased with the vertical measurement heights
314 from 1 m to 3 m and 15 m in both 2019 and 2020. In contrast, the *d-excess* of water
315 vapor increased from the lower (1 m) to the upper (15 m) canopy during the two years
316 of study periods. The difference in atmospheric water vapor δ^2H, $\delta^{18}O$, and *d-excess*
317 was only significant between 1 m and 15 m (P < 0.05) in 2019. The isotopic values of
318 atmospheric water vapor changed drastically between 1 m and 15 m (P < 0.001) in
319 2020; and the atmospheric water vapor $\delta^{18}O$ and *d-excess* differed significantly
320 between 1 m and 3 m (P < 0.001) in 2020.

321

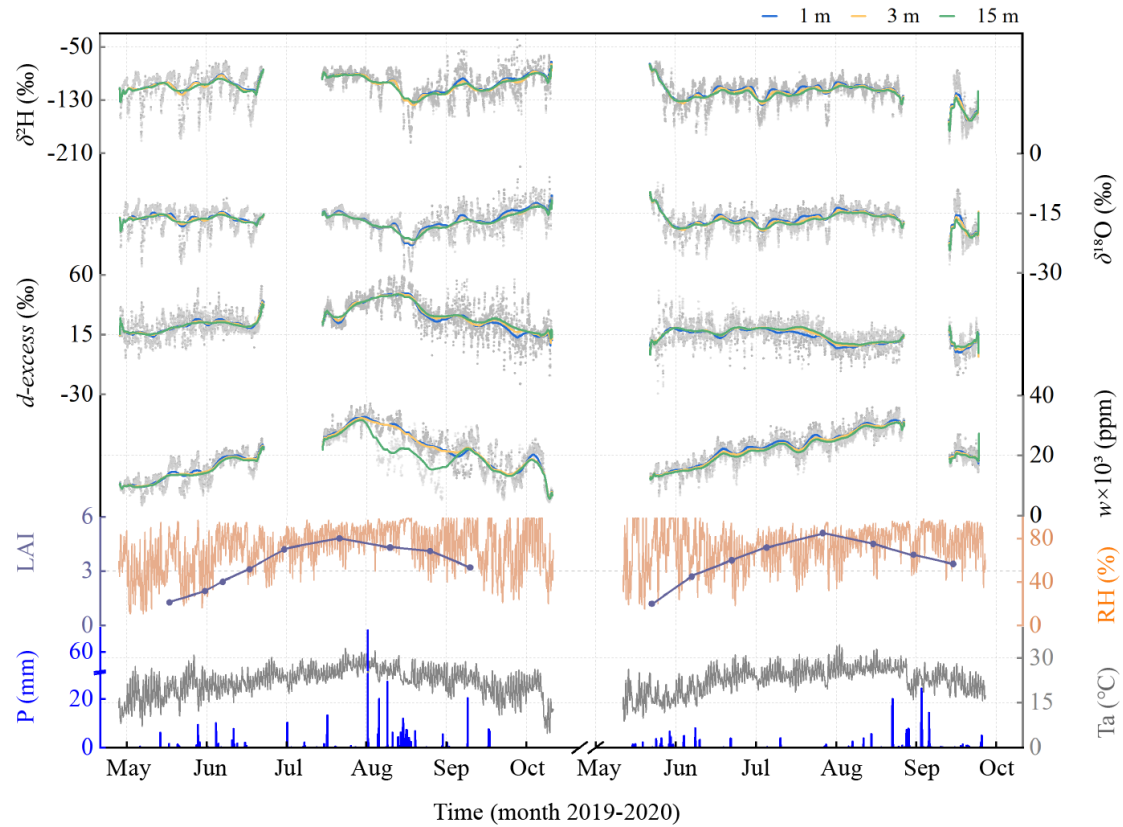**Figure 2.** Time series of hourly atmospheric water vapor δ^2H, $\delta^{18}O$, and *d-excess*, water vapor concentration (*w*), leaf area index (LAI), relative humidity (RH), precipitation (P), and surface air temperature (T_a) during the 2019-2020 growing (May-September) seasons. The Gaussian smoothing curves are shown for the in-situ atmospheric water vapor measurements at heights of 1 m (blue lines), 3 m (yellow lines), and 15 m (green lines).

The *w* of atmospheric water vapor was highest in August with single-peaked curves of seasonal variations (Figure 2). However, the peak of water vapor *w* in 2019 (36959.8 ppm) was delayed for 25 days compared to the peak (36090.8 ppm) in 2020. Furthermore, there were apparent differences in the atmospheric water vapor *w* between 1 m (or 3 m) and 15 m in 2019 ($P < 0.001$). During the growing (May-September) seasons, the LAI of reeds were 3.3 ± 1.2 in 2019 and 3.6 ± 1.2 in 2020. The mean RH in 2019 and 2020 were 70.7 ± 19.7 and 72.6 ± 17.5, respectively. The total rainfall was 37.6% lower in 2020 (414.1 mm) compared to 2019 (663.8 mm), indicating a weak summer monsoon year in 2020. The T_a of the experimental station was relatively constant with mean values of 21.9 ± 4.7 °C in 2019 and 22.8 ± 4.3 °C in 2020 during the study periods.

339 **Table 1** Monthly average values of Water Vapor Concentration (w), Leaf Area Index (LAI), Relative Humidity (RH), Total
340 Precipitation (P), Surface Air Temperature (T_a), and Isotopic Values of Atmospheric Water Vapor (δ^2H, $\delta^{18}O$, and *d-excess*) in
341 Liaodong Bay, China, from May-September 2019 and 2020

Month	w (ppm)[a]	LAI ($m^2\,m^{-2}$)	RH (%)	P (mm)	T_a (°C)	δ^2H (‰)			$\delta^{18}O$ (‰)			*d-excess* (‰)		
						1 m	3 m	15 m	1 m	3 m	15 m	1 m	3 m	15 m
May	12045.5	1.6	54.1	66.1	18.3	−111.1	−111.8	−112.5	−16.31	−16.40	−16.49	19.4	19.4	19.4
Jun	18875.6	3.3	69.4	44.9	22.0	−104.4	−105.8	−107.2	−16.10	−16.25	−16.31	24.4	24.2	23.3
Jul	29870.6	4.4	78.	55.8	25.6	− 97.2	−97.5	−98.3	−12.79	−12.88	−13.00	33.7	34.1	34.2
Aug	25471.5	4.0	82.6	424.1	24.9	−113.2	−114.3	−115.0	−18.54	−18.77	−18.87	35.2	35.8	35.9
Sep	18040.9	3.2	70.1	107.9	26.0	−102.6	−104.9	−104.5	−15.47	−15.91	−16.02	21.2	22.2	23.4
May	14714.6	1.8	70.2	85.9	16.7	−117.9	−118.8	−119.2	−16.75	−16.93	−16.96	15.9	16.4	16.3
Jun	20746.6	3.4	64.6	29.2	23.1	−118.3	−120.3	−122.4	−16.99	−17.34	−17.61	17.6	18.4	18.6
Jul	25200.8	4.5	70.7	11.5	25.4	−113.1	−114.8	−116.3	−15.60	−16.03	−16.34	11.7	13.3	14.6
Aug	30488.3	4.2	80.6	253	25.5	−115.0	−115.7	−116.7	−15.46	−15.60	−15.76	8.6	9.0	9.4
Sep	20180.2	3.3	77.6	34.8	21.7	−144.3	−146.1	−148.7	−18.73	−19.09	−19.54	5.6	6.6	7.6

342 [a] The monthly w of atmospheric water vapor was calculated based on the average of data from the lower (1 m), middle (3 m), and
343 upper (15 m) canopy.
344

345   3.2 Long time scale variations

346   Figure 3 presents the diurnal variations of atmospheric water vapor δ^2H, δ^{18}O, and *d-*
347   *excess* measured at heights of 1 m, 3 m, and 15 m. A clear diurnal cycle of water vapor δ^2H,
348   δ^{18}O, and *d-excess* existed in both 2019 and 2020. The atmospheric water vapor δ^2H and δ^{18}O
349   generally increased from 9:00 (LST) to 18:00 (LST). Simultaneously, the δ^2H and δ^{18}O of water
350   vapor progressively declined to their minimum around 8:00-9:00 (LST) on the next day (Figure
351   3a-d). The diurnal variations of atmospheric water vapor δ^2H and δ^{18}O were less pronounced in
352   2020 than in 2019. Nonetheless, the diurnal variations of atmospheric water vapor *d-excess* were
353   pretty clear in both years of 2019 and 2020, which had an opposite diurnal trend to that of
354   atmospheric water vapor δ^2H and δ^{18}O (Figure 3e-f). The isotopic differences of atmospheric
355   water vapor across measurement heights (i.e., 1, 3, and 15 m) were more evident in the daytime
356   (8:00-20:00 LST) than at night (20:00-8:00 LST). This phenomenon appeared extremely typical
357   in 2020, during which the atmosphere water vapor δ^2H and δ^{18}O declined progressively with the
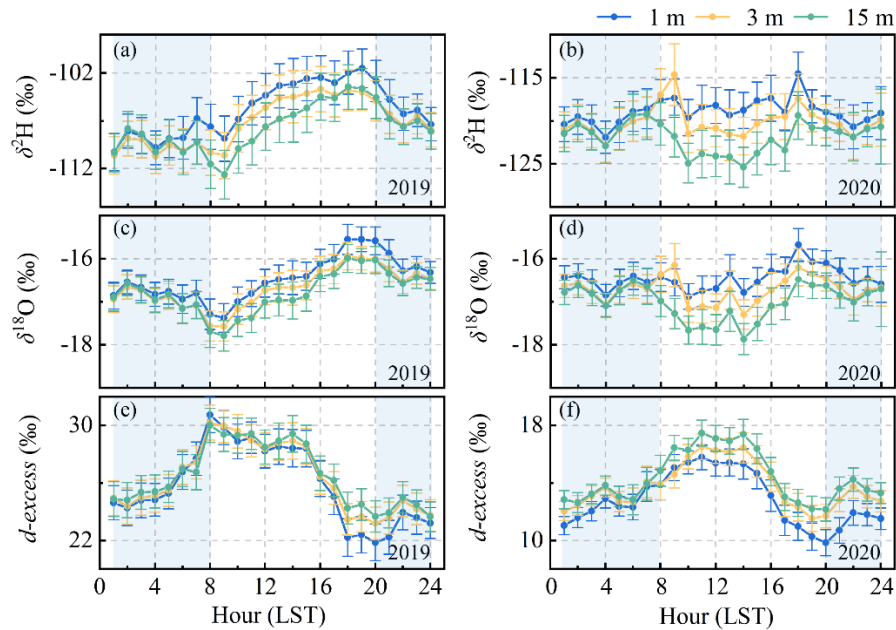358   increase of heights ($P < 0.05$).

359

360   **Figure 3.** Twenty-four-hour variations of atmospheric water vapor δ^2H (**a**, **b**), δ^{18}O (**c**, **d**), and *d-*
361   *excess* (**e**, **f**) measured at heights of 1 m (blue lines), 3 m (yellow lines), and 15 m (green lines)
362   during the 2019-2020 growing (May-September) seasons. Error bars represent standard errors of
363   the isotopic data in every hour. Shadow areas indicate the periods of time at night (20:00-8:00
364   LST).

365   Figure 4 illustrates the impacts of rainfall processes on the diurnal cycles of atmospheric
366   water vapor δ^2H, δ^{18}O, and *d-excess* at 15 m height. Six rainfall events of different rainfall
367   amounts (P = 2.6-141.1 mm) were selected during the 2019-2020 growing (May-September)
368   seasons. The duration (D) of these rainfall events ranged from 11 h to 100 h. The δ^2H, δ^{18}O, and
369   *d-excess* of atmospheric water vapor increased slightly after two small rainfall events (P = 2.6-
370   4.5 mm, in Figure 4a-b). The peak-to-peak variations of atmospheric water vapor δ^2H, δ^{18}O, and
371   *d-excess* were 31.8-51.6‰, 3.08-7.02‰, and 12.7-26.2‰, respectively. With the increase in

372 intensity and duration of rainfall, the isotopic values of atmospheric water vapor also increased
373 during the rainfall processes (Figure 4c-d). However, the isotopic values of atmospheric water
374 vapor declined after a 20 h continuous rainfall event. The variability of atmospheric water vapor
375 in these moderate rainfall events (P = 30.9-33.4 mm) increased to 68.4-70.8‰ for δ^2H, 7.15-
376 8.87‰ for δ^{18}O, and 20.3-34.3‰ for *d-excess*. The δ^2H, δ^{18}O, and *d-excess* of atmospheric water
377 vapor decreased drastically during the heavy rainfall events as expected (Figure 4e-f). The
378 isotopic variations of atmospheric water vapor in heavy rainfall events (P = 68.4-141.1 mm)
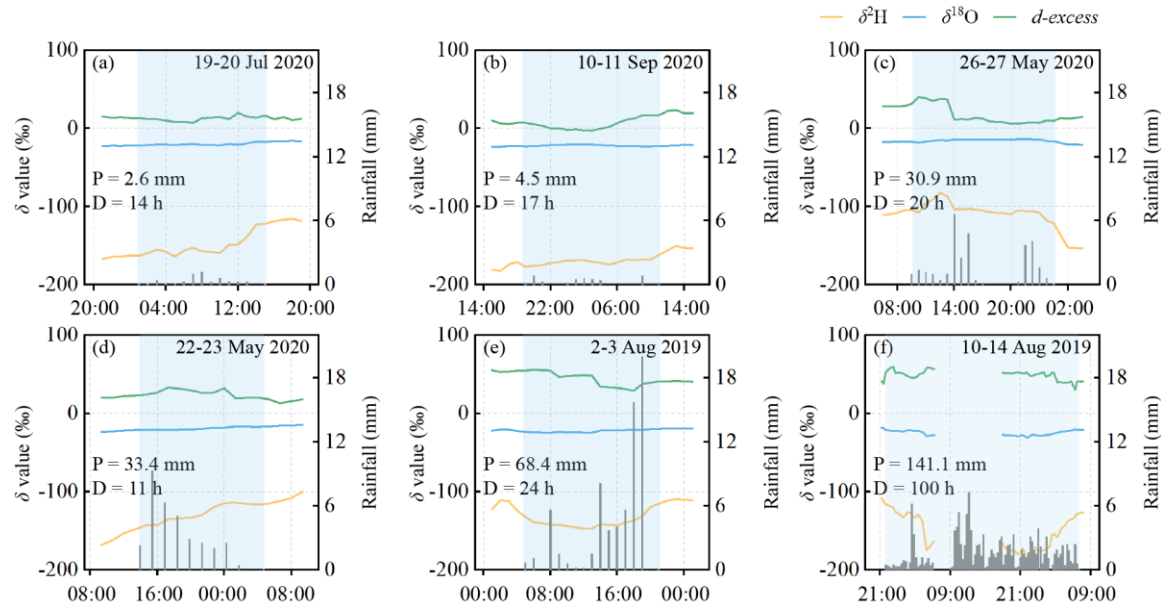379 were 37.4-66.8‰ for δ^2H, 3.41-5.70‰ for δ^{18}O, and 22.5-26.8‰ for *d-excess*.

Figure 4. Impacts of rainfall processes on the diurnal cycles of atmospheric water vapor δ^2H,
δ^{18}O, and *d-excess* at 15 m height (**a-f**) during the (2019-2020) study periods. Rainfall amount
(P) and rainfall duration (D) are plotted on each panel for reference. Shadow areas indicate the
periods of rainfall events.

3.3 Relationships with meteorological variables

386 Figure 5 depicts the linear dependency of δ^2H on δ^{18}O for atmospheric water vapor
387 during the 2019-2020 growing (May-September) seasons. The hourly measurement of three (i.e.,
388 1 m, 3 m, and 15 m) canopy layers were merged to reflect the impacts of rainfall events on the
389 co-variations between δ^2H on δ^{18}O of atmospheric water vapor. This treatment was adopted due
390 to the similar functions among different heights (*SI Appendix A*, Figure S1). In 2019, the δ^2H and
391 δ^{18}O of atmospheric water vapor mainly occupied the dual-isotope plots from the global meteoric
392 water line (GMWL: δ^2H = 8 × δ^{18}O + 10) to its left sides (Figure 5a). Slopes of the atmospheric
393 water vapor lines in 2019 were 6.4 ± 0.2 (R^2 = 0.87, P < 0.001) and 6.2 ± 0.1 (R^2 = 0.76, P <
394 0.001) during the rainfall and non-rainfall periods, respectively. In 2020, the δ^2H and δ^{18}O of
395 atmospheric water vapor were plotted right on the GMWL (Figure 5b). Slopes of the
396 atmospheric water vapor lines in 2020 were 7.4 ± 0.2 (R^2 = 0.89, P < 0.001) and 6.4 ± 0.1 (R^2 =
397 0.87, P < 0.001) during the rainfall and non-rainfall periods, respectively. The intercepts of the
398 atmospheric water vapor lines were less than 10 for both years, ranging from 2.8 to 4.5 during
399 the rainfall periods, and from – 13.8 to – 3.8 during the non-rainfall periods.
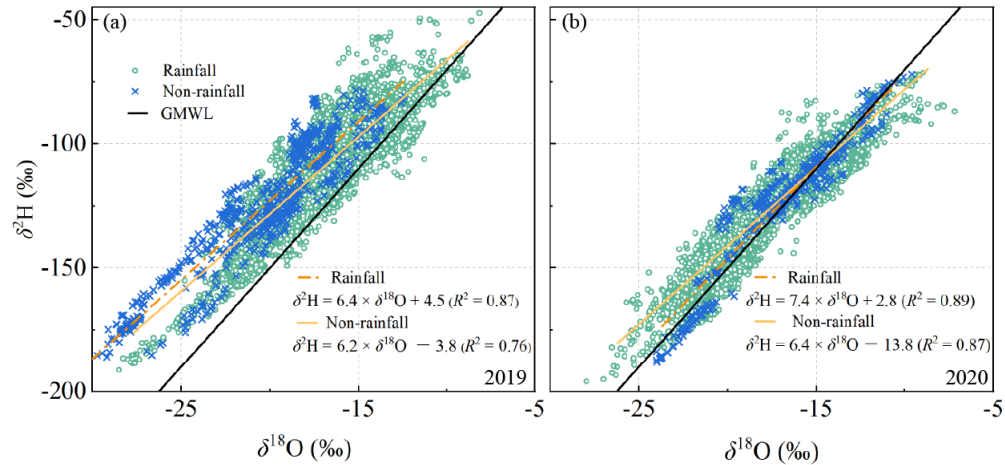
Figure 5. Isotopic values of δ^2H as a function of $\delta^{18}O$ in atmospheric water vapor during the 2019 (**a**) and 2020 (**b**) growing (May-September) seasons. Data of atmospheric water vapor δ^2H and $\delta^{18}O$ are divided into two groups representing the periods with rainfall and non-rainfall events. The global meteoric water line (GMWL: $\delta^2H = 8 \times \delta^{18}O + 10$) is also plotted on each panel for reference.

Figure 6 shows the relationships between the δ^2H, $\delta^{18}O$ and *d-excess* of atmospheric water vapor and local meteorological factors. The δ^2H and $\delta^{18}O$ of atmospheric water vapor were positively correlated with the water vapor concentration (*w*) (Figure 6a, 6d, 6g, and 6j). In contrast, their *d-excess* were negatively correlated with *w* in 2019 ($R^2 = 0.05$, $P < 0.001$, measurement undertaken at height of 15 m, in Figure 6m) and 2020 ($R^2 = 0.11$-0.16, $P < 0.001$, in Figure 6p). The atmospheric water vapor δ^2H, $\delta^{18}O$ and *d-excess* were weakly dependent on the relative humidity (RH) during the study periods ($R^2 = 0.01$-0.11, $P < 0.001$, in Figure 6b, 6e, 6h, 6k, 6n, and 6q). The δ^2H, $\delta^{18}O$ of atmospheric water vapor exhibited positive dependences on surface air temperature (T_a) in 2020 ($R^2 = 0.05$-0.07, $P < 0.001$, in Figure 6f and 6l). The atmospheric water vapor d-excess in 2020 was negatively correlated with T_a ($R^2 = 0.01$-0.02, $P < 0.001$, in Figure 6r). However, no significant correlation occurred between the atmospheric water vapor isotopes and T_a in 2019 (Figure 6c, 6i, and 6o).
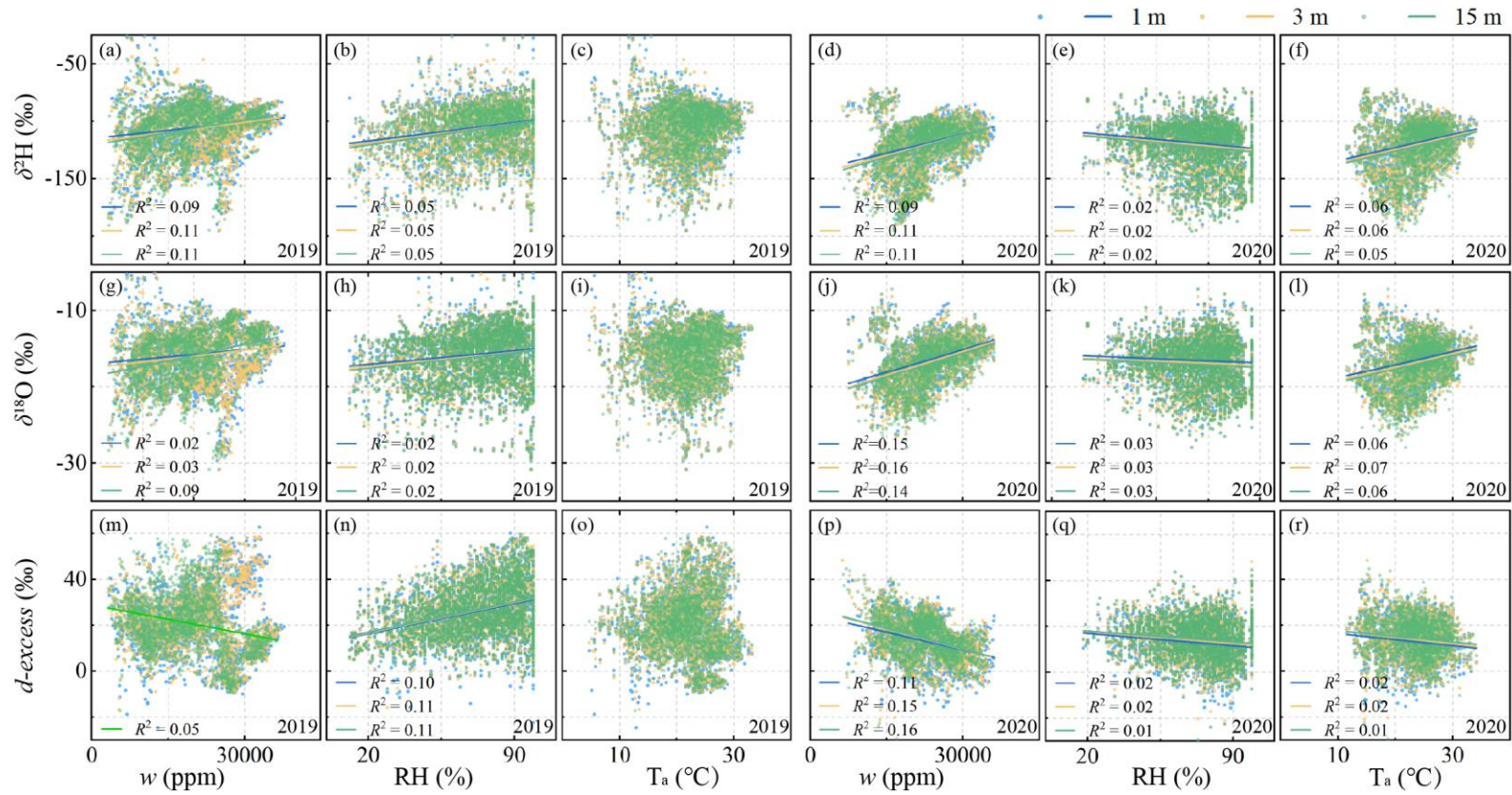
Figure 6. Correlations of the water vapor concentration (*w*), relative humidity (RH), and surface air temperature (T_a) with the atmospheric water vapor δ^2H (**a-f**), δ^{18}O (**g-l**), and *d-excess* (**m-r**) during the (2019-2020) study periods. The regression curves represent the in-situ atmospheric water vapor measurements at heights of 1 m (blue lines), 3 m (yellow lines), and 15 m (green lines).

Figure 7. Back trajectory frequencies clustered according to the directions of air masses and the concentration fields of atmospheric water vapor *d-excess* during the 2019 (**a-e**) and 2020 (**f-j**) growing (May-September) seasons. Red star indicates the location of Panjin experimental station. Orange lines are the clusters of air masses during the preceding 48 h at 500 m height above the ground, and blue shading is the potential source of atmospheric water vapor *d-excess* in each month.

428   3.4 Large scale atmosphere circulations

429   Figure 7 shows the concentration fields of atmospheric water vapor *d-excess* along the
430   backward trajectories at Panjin experimental station. The 48-hourly backward trajectories of air
431   masses were calculated for the 2019-2020 growing (May-September) seasons. For all five
432   months, 3659 and 3515 trajectories were clustered in 2019 and 2020, respectively (*SI Appendix*
433   *A*, Figure *S2*). Then, we identified three-five major moisture source sectors that affected the
434   experimental station. The dominant air masses in this region generally came from ocean sources,
435   contributing more than 50% to the total air moisture except in June 2020 (49.4%). The transport
436   paths of ocean air masses could be further clustered into two sectors, i.e., Southwest-South (SW-
437   S) and South-Southeast (S-SE) directions. At the beginning of the monsoon season (May-June),
438   the trajectory paths of air masses usually originated from ocean surfaces and the northern interior
439   (Figure 7a-b and 7f-g). The ocean air masses gradually dominated during the peak monsoon
440   season (July-August). The contribution proportions of ocean air masses reached the maxima in
441   July 2019 (73.2%, in Figure 7c) and in August 2020 (84.5%, in Figure 7i). The influence of
442   summer monsoon on local air masses weakened in September 2019, with a contribution
443   proportion of 59.9% (Figure 7e). However, the ocean air masses had a prolonged impact (70.5%)
444   on atmospheric water vapor *d-excess* at the experimental station in September 2020 (Figure 7j).

445   The back-air mass trajectory analysis indicates that seasonal dynamic in moisture sources
446   was a main driving factor of the atmospheric water vapor *d-excess* variability (Figure 7). The
447   spatial distribution of atmospheric water vapor *d-excess* at this experimental station was closely
448   linked with the monsoon activities in East Asia. Most of trajectory paths were accompanied by
449   relatively higher atmospheric water vapor *d-excess* in 2019 than in 2020. This phenomenon was
450   particularly evident in 2019 (Figure 7a-e), where high-value of atmospheric water vapor *d-excess*
451   commonly distributed around the coastal regions. Lower proportion of air masses arose from the
452   ocean sources between August and September in 2019 (50-59.9%, in Figure 7d-e) than in 2020
453   (70.5-84.5%, in Figure 7i-j). However, the intensity of the East Asian monsoon was weak in
454   2020, which brought less rainfall to the atmospheric water cycles in Liaodong Bay. Therefore,
455   the air masses from the interiors of North China had more significant impacts (i.e., more negative
456   values) on the atmospheric water vapor *d-excess* in 2020 than in 2019. The secondary moisture
457   sources of inland air masses played a vital role in the seasonal variations of atmospheric water
458   vapor *d-excess* in the weak summer monsoon year.

459

4 Discussion

461   Based on the in-situ measurement techniques, this study revealed the isotopic signatures of
462   atmospheric water vapor (Figure 2-4), as well as the driving forces of the atmospheric water
463   vapor isotopes (Figure 5-7) for a reed wetland of Liaodong Bay, Northeast China. The
464   meteorological factors (e.g., water vapor concentration, relative humidity, and air temperature)
465   were incapable of predicting the variations of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess*
466   in this region. The different seasonal and diurnal patterns of water vapor isotopes could be
467   attributed to the stronger monsoon activities in 2019 than in 2020. These findings would broaden
468   our understanding of hydrological cycles in the coastal wetlands.

469   4.1 Temporal dynamics of water vapor isotopes at different heights

470   The long- (i.e., seasonal scale) and short- (i.e., diurnal scale) term characteristics of
471   atmospheric water vapor isotopes showed significant variations at heights of 1 m, 3 m, and 15 m
472   (Figure 2 and 3). The temporal dynamics of water vapor δ^2H, δ^{18}O, and *d-excess* are usually
473   controlled by the atmospheric processes (Lee et al., 2005; Wen et al., 2008), local
474   evapotranspiration (Aron et al., 2019; Huang & Wen, 2014), and synoptic events (Berkelhammer
475   et al., 2013; Wu et al., 2019). For instance, Steen-Larsen et al. (2013) suggested that the intra-
476   seasonal variations of water vapor isotopes mainly result from the interplay between large-scale
477   moisture advection, boundary layer dynamics, and local moisture fluxes above the Greenland Ice
478   Sheet. The magnitude of changes in surface water vapor *d-excess* can be as high as 40‰ or
479   greater during several episodes (Steen-Larsen et al., 2013). Huang & Wen (2014) reported that
480   the atmospheric water vapor δ^2H, δ^{18}O, and *d-excess* are dominated by the typical arid and
481   continental climates, which will not show clear seasonal cycles in the inland region of Northwest
482   China. As a typical coastal wetland under the influence of the East Asian Monsoon, our results
483   showed that the temporal patterns of water vapor isotopes were strikingly different between the
484   years of study periods. Moreover, some departures of atmospheric water vapor isotopes were
485   observed among the three measurement heights. This might be interpreted as the enrichment
486   effects of local evapotranspiration, which gradually improves the atmospheric water vapor
487   isotopes with the increasing plant physiological activities (Hu et al., 2021; Welp et al., 2012).

488   The seasonal variations of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess* in the reed
489   wetlands of Liaodong Bay were different from those of the other research site (Fiorella et al.,
490   2018; Laonamsai et al., 2021; Lee et al., 2006; Wen et al., 2010). Apart from the noticeable
491   seasonal changes occurring in each year, there were distinct inter-annual cycles for atmospheric
492   water vapor isotopes between 2019 and 2020 (Figure 2). The mean isotopic values of
493   atmospheric water vapor ranged from − 120.7‰ to − 108.4‰ for δ^2H, from − 16.98‰ to −
494   16.64‰ for δ^{18}O, and from 13.3‰ to 26.3‰ (Table 1), which were higher than the results
495   reported by Wen et al. (2010) and Zhang et al. (2011) in inland areas of China. Especially in
496   2019, the δ^2H and δ^{18}O of atmospheric water vapor fluctuated seasonally with lower values in
497   the prevailing monsoon season (i.e., August-September). The seasonal pattern of atmospheric
498   water vapor δ^2H and δ^{18}O made a complete reversal of the water vapor concentration (*w*) trend
499   (Figure 2). In fact, the summer monsoon was earlier in 2019 and brought more rainfall than in
500   2020. In 2019, the typhoon "Lekima" was reported to land in Southwest coast of China (4-10
501   August) with a wind speed of 51.4 m s^{-1}, which then moved northwards and made a second
502   landfall in Liaodong Bay (Wang et al., 2021). Some studies reported that a significant decrease
503   in precipitation and atmospheric isotopes can happen during the tropical typhoons (Bonne et al.,
504   2019; Conroy et al., 2016). The abrupt decline of atmospheric water vapor *w* at 15 m height
505   could also be attributed to the high condensation efficiency and strong entrainment activity
506   during the typhoon event in 2019.

507   The interactions between atmospheric entrainment and local evapotranspiration typically
508   dominate the diurnal cycles of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess* (Aron et al.,
509   2019; Huang & Wen, 2014; Lee et al., 2007; Zhao et al., 2014). Our results showed that the δ^2H
510   and δ^{18}O of atmosphere were lower in the early morning (8:00-9:00 LST) than in the late
511   afternoon (16:00-18:00 LST). On the contrary, the atmospheric water vapor *d-excess* exhibited
512   an "inverted U-shaped diurnal pattern" in 2019 and 2020 (Figure 3). The downward trends in
513   atmospheric water vapor δ^2H and δ^{18}O can be attributed to the rapid increase of free air in ABL

514 when plant transpiration activity is relatively low in the morning (Huang & Wen, 2014). The
515 enrichment roles of local evapotranspiration surpassed the depletion effects of atmospheric
516 entrainment in the late afternoon. Such positive impacts of local evapotranspiration on
517 atmosphere isotopes were marked significantly in the lower (1 m) canopy than in the middle (3
518 m) and upper (15 m) heights (Figure 3). Apparently, the rainfall process was one of the main
519 factors contributing to the diurnal dynamics of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess*
520 (Figure 4). The isotopic fractionation caused by the sub-cloud secondary evaporation enriches
521 the residual rainfall, which in turn can make the enrichment of atmospheric isotopes during small
522 rainfall events (Vuille et al., 2003; Wu et al., 2021). However, the rainout effects of rainfall
523 would result in the continuous depletion of atmospheric isotopes according to the Rayleigh
524 distillation mechanisms (Gat, 1996; Lee et al., 2005; Wen et al., 2010).

525   4.2 Controlling factors of water vapor isotopes above coastal wetlands

526   The global meteoric water line (GMWL: δ^2H = 8 × δ^{18}O + 10) indicates the isotopic co-
527 variations in marine water that has not been exposed to evaporation fractionation (Craig, 1961;
528 Gat, 1996). As the marine air masses move over the coastal regions and towards the inland, the
529 air parcels will be mixed with continental water vapor sources and influenced by geographic
530 parameters such as the distances from coasts, altitudes, rainfall processes, and temperatures
531 (Christner et al., 2018; Gat, 1996; Merlivat & Jouzel, 1979). The slopes of atmospheric water
532 vapor lines (6.2-7.4) were lower than that of GMWL (Figure 5), which were determined by the
533 non-equilibrium fractionation (i.e., the existence of kinetic effects) within air parcels. Similarly,
534 Bastrikov et al. (2014) reported that the overall slopes of atmospheric water vapor lines are 5.6-
535 7.7 among different seasons in western Siberia (Kourovka). Li et al. (2020) highlighted that the
536 slopes of atmospheric water vapor lines change from 7.0 to 7.6 during a six-year period in
537 Eastern China. The high intercept (i.e., *d-excess*) of atmospheric water vapor lines in 2019
538 suggested that the isotopic changes in air masses which were very sensitive to the moisture
539 source conditions (Aemisegger et al., 2014; Delattre et al., 2015; Fiorella et al., 2018).

540   The results of this study also showed that the relationships between local meteorological
541 factors and atmospheric water vapor isotopes were weak or nonexistent at Panjin experimental
542 station (Figure 6). This finding was inconsistent with previous observations in the inland areas of
543 China**.** For example, Zhang et al. (2011) noted that the water vapor concentration (*w*) can be an
544 excellent predictor of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess* based on the Rayleigh
545 distillation. However, the weak correlations between atmospheric water vapor isotopes and
546 relative humidity (RH) were found in other studies (Li et al., 2020; Salamalikis et al., 2015). An
547 earlier study by Lee et al. (2006) in New England found that the atmospheric *w* is a better
548 indicator for atmospheric water vapor isotopes than air temperature (T$_a$) on short time scales.
549 These studies have established a certain level of correlation between atmospheric water vapor
550 isotopes and local meteorological factors (e.g., *w*, T$_a$, and RH) during the non-monsoon season
551 (Lee et al., 2005; Li et al., 2020; Noone et al., 2012). In contrast, Wen et al. (2010) found that the
552 *w* becomes a poor predictor of the atmospheric water vapor δ^2H, δ^{18}O, and *d-excess* during the
553 summer monsoon season. Similar to this study, weak correlations were also found by Li et al.
554 (2020) and Wang et al. (2021) during the peak monsoon activities.

555   Unlike the δ^2H and δ^{18}O whose temporal variations are commonly overwhelmed by the
556 Rayleigh distillation and/or the rainout history of air masses, the atmospheric water vapor *d-*
557 *excess* of an air mass is a nearly constant tracer during the transport processes (Welp et al., 2012;

558   Wei et al., 2019). Therefore, the *d-excess* of atmospheric water vapor is widely used as a
559   conservative indicator for identifying the moisture source locations (Aemisegger et al., 2014;
560   Steen-Larsen et al., 2015; Uemura et al., 2008; Xu et al., 2022). Panjin experimental station was
561   situated on the special borderland between the North China Plain and Bohai Sea (Figure 1),
562   which was also located within the edge of the East Asian monsoon region (Luo et al., 2021;
563   Wang et al., 2021). With the sea in three directions, the atmospheric water vapor *d-excess* in this
564   study was significantly affected by the ocean air masses (Figure 7). The high values of
565   atmospheric water vapor *d-excess* consistently appeared in the peak (i.e., July-August) monsoon
566   season. The results of the present study further confirmed that the ocean air masses dominated
567   the temporal variations of atmospheric water vapor *d-excess* (Figures 2, 3, and 7) when a super
568   typhoon "Lekima" happened in 2019 (details in Section 4.1). Lai et al. (2018) examined the
569   atmospheric water cycling above a coastal mangrove forest in Southern China. They also found
570   that the substantial increase of atmospheric water vapor *d-excess* is related to the passage of a
571   tropical typhoon "Talas" (Lai et al., 2018). In the Qinghai-Tibetan Plateau of central Asia, Wu et
572   al. (2019) revealed that high *d-excess* values of atmospheric water vapor were influenced by
573   local moisture mixing during the monsoon season. A recent study noted that high values of
574   atmospheric water vapor *d-excess* appear before the monsoon onset and after the monsoon
575   season at Lhasa in Southern Tibetan Plateau (Tian et al., 2020). Indeed, air masses from cold and
576   dry areas can also bring a relatively high atmospheric water vapor *d-excess* (Uemura et al., 2008;
577   Xu et al., 2022). Further mechanism studies are expected to provide more rational explanations
578   for the above-mentioned processes in coastal wetlands.

579

5 Conclusions

581   The inter-annual variations of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess* were
582   significantly different between 2019 and 2020. On a seasonal time scale, the mean isotopic
583   values of atmospheric water vapor in 2019 were significantly higher than that in 2020.
584   Meanwhile, the δ^2H and δ^{18}O of atmospheric water vapor gradually decreased from the lower (1
585   m), to the middle (3 m) and upper (15 m) canopy both 2019 and 2020. A clear diurnal cycle of
586   atmospheric water vapor isotopes existed during the study periods, which was more pronounced
587   in 2019 than in 2020. The diurnal isotopic differences of atmospheric water vapor among
588   measurement heights (i.e., 1, 3, and 15 m) were more evident in the daytime (8:00-20:00 LST)
589   than at night (20:00-8:00 LST). Rainfall events had a significant impact on the diurnal dynamics
590   of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess*, depending on the rainfall intensity (i.e.,
591   amount and duration). The correlations between atmospheric water vapor isotopes and local
592   meteorological factors were weak or nonexistent in the study region. Instead, the spatial-
593   temporal dynamics of atmospheric water vapor isotopes were highly consistent with the
594   monsoon activities. The moisture in air masses could be clustered into three to-five primary
595   sources, with over 60% from the ocean sources. High *d-excess* values reflected the
596   predominating influences of ocean air masses on atmospheric water vapor cycles in the coastal
597   regions.

598

Acknowledgments

612

613   **Open Research**

614   Data for this study consist of water isotopes and environmental variables that are available at
615   https://doi.org/10.11888/Atmos.tpdc.272899
616

References

Aemisegger, F., Pfahl, S., Sodemann, H., Lehner, I., Seneviratne, S. I., & Wernli, H. (2014). Deuterium excess as a proxy for continental moisture recycling and plant transpiration. *Atmospheric Chemistry and Physics*, *14*(8), 4029-4054. https://doi.org/10.5194/acp-14-4029-2014

Araguas-Araguas, L., Froehlich, K., Rozanski, K. (2000). Deuterium and oxygen-18 isotope composition of precipitation and atmospheric moisture. *Hydrological Processes*, *14*(8), 1341-1355. https://doi.org/10.1002/1099-1085(20000615)14:8<1341::Aid-hyp983>3.0.Co;2-z

Aron, P. G., Poulsen, C.J., Fiorella, R. P., & Matheny, A. M. (2019). Stable water isotopes reveal effects of intermediate disturbance and canopy structure on forest water cycling. *Journal of Geophysical Research: Biogeosciences*, *124*(10), 2958-2975. https://doi.org/10.1029/2019jg005118

Bagheri, R., Bagheri, F., Karami, G. H., & Jafari, H. (2019). Chemo-isotopes (^{18}O & ^{2}H) signatures and HYSPLIT model application: Clues to the atmospheric moisture and air mass origins. *Atmospheric Environment*, *215*, 116892. https://doi.org/10.1016/j.atmosenv.2019.116892

Bailey, A., Noone, D., Berkelhammer, M., Steen-Larsen, H. C., & Sato, P. (2015). The stability and calibration of water vapor isotope ratio measurements during long-term deployments. *Atmospheric Measurement Techniques*, 4521-4538. https://doi.org/10.5194/amt-8-4521-2015

Bastrikov, V., Steen-Larsen, H. C., Masson-Delmotte, V., Gribanov, K., Cattani, O., Jouzel, J., & Zakharov, V. (2014). Continuous measurements of atmospheric water vapour isotopes in

640   western Siberia (Kourovka). *Atmospheric Measurement Techniques*, *7*(6), 1763-1776.

641   https://doi.org/10.5194/amt-7-1763-2014

642   Berkelhammer, M., Hu, J., Bailey, A., Noone, D. C., Still, C. J., Barnard, H., et al. (2013). The

643   nocturnal water cycle in an open-canopy forest. *Journal of Geophysical Research:*

644   *Atmospheres*, *118*(17), 10225-10242. https://doi.org/10.1002/jgrd.50701

645   Bonne, J. L., Behrens, M., Meyer, H., Kipfstuhl, S., Rabe, B., Schönicke, L., et al. (2019).

646   Resolving the controls of water vapour isotopes in the Atlantic sector. *Nature*

647   *Communications*, *10*(1), 1-10. https://doi.org/10.1038/s41467-019-09242-6

648   Bonne, J. L., Meyer, H., Behrens, M., Boike, J., Kipfstuhl, S., Rabe, B. et al. (2020). Moisture

649   origin as a driver of temporal variabilities of the water vapour isotopic composition in the

650   Lena River Delta, Siberia. *Atmospheric Chemistry and Physics*, *20*(17), 10493-10511.

651   https://doi.org/10.5194/acp-20-10493-2020

652   Casado, M., Cauquoin, A., Masson-Delmotte, V., Genthon, C., Kerstel, E., Kassi, S., et al.

653   (2016). Continuous measurements of isotopic composition of water vapour on the East

654   Antarctic Plateau. *Atmospheric Chemistry and Physics*, *16*(13), 8521-8538.

655   https://doi.org/10.5194/acp-16-8521-2016

656   Christner, E., Aemisegger, F., Pfahl, S., Werner, M., Cauquoin, A., Schneider, M. et al. (2018).

657   The climatological impacts of continental surface evaporation, rainout, and subcloud

658   processes on δD of water vapor and precipitation in Europe. *Journal of Geophysical*

659   *Research: Atmospheres*, *123*(8), 4390-4409. https://doi.org/10.1002/2017jd027260

660   Christner, E., Kohler, M., & Schneider, M. (2017). The influence of snow sublimation and

661   meltwater evaporation on δD of water vapor in the atmospheric boundary layer of central

662   Europe. *Atmospheric Chemistry and Physics*, *17*(2), 1207-1225.

663   https://doi.org/10.5194/acp-17-1207-2017

664   Conroy, J. L., Noone, D., Cobb, M. K., Moerman, J. W., & Konecky, B. L. (2016). Paired stable

665   isotopologues in precipitation and vapor: A case study of the amount effect within western

666   tropical Pacific storms. *Journal of Geophysical Research: Atmospheres*, *121*(7), 3290-3303.

667   https://doi.org/10.1002/2015jd023844

668   Craig, H. (1961). Isotopic variations in meteoric waters. *Science*, *133*(346), 1702-1703.

669   https://doi.org/10.1126/science.133.3465.1702

670   Cui, J. P., Tian, L. D., & Gibson, J. J. (2018). When to conduct an isotopic survey for lake water

671   balance evaluation in highly seasonal climates. *Hydrological Processes*, *32*(3), 379-387.

672   https://doi.org/10.1002/hyp.11420

673   Dahinden, F., Aemisegger, F., Wernli, H., Schneider, M. Diekmann, C.J., Ertl, B., et al. (2021).

674   Disentangling different moisture transport pathways over the eastern subtropical North

675   Atlantic using multi-platform isotope observations and high-resolution numerical

676   modelling. *Atmospheric Chemistry and Physics*, *21*(21), 16319-16347.

677   https://doi.org/10.5194/acp-21-16319-2021

678   Dansgaard W. (1964). Stable isotopes in precipitation. *Tellus*, *16*(4): 436-468.

679   https://doi.org/10.3402/tellusa.v16i4.8993

680   Delattre, H., Vallet-Coulomb C., & Sonzogni, C. (2015). Deuterium excess in the atmospheric

681   water vapour of a Mediterranean coastal wetland: regional vs. local signatures. *Atmospheric*

682   *Chemistry and Physics*, *15*(17), 10167-10181. https://doi.org/10.5194/acp-15-10167-2015

683   Devi, P., Jain, A. K., Rao, M. S., & Kumar B. (2014). Experimental study on isotope

684   fractionation of evaporating water of different initial isotopic composition. *Journal of*

685   *Radioanalytical and Nuclear Chemistry*, *302*(2), https://doi.org/10.1007/s10967-014-3368-7

686   Diekmann, C. J., Schneider, M., Knippertz, P., Vries, A. J., Pfahl, S., Aemisegger, F., et al.

687   (2021). A lagrangian perspective on stable water isotopes during the West African

688   Monsoon. *Journal of Geophysical Research: Atmospheres*, *126*(19), e2021JD034895.

689   https://doi.org/10.1029/2021jd034895

690   Farlin, J., Lai, C. T., & Yoshimura, K. (2013). Influence of synoptic weather events on the

691   isotopic composition of atmospheric moisture in a coastal city of the western United States.

692   *Water Resources Research*, *49*(6), 3685-3696. https://doi.org/10.1002/wrcr.20305

693   Fiorella, R. P., Poulsen, C. J. & Matheny, A. M. (2018). Seasonal patterns of water cycling in a

694   deep, continental mountain valley inferred from stable water vapor isotopes. *Journal of*

695   *Geophysical Research: Atmospheres*, *123*(14), 7271-7291.

696   https://doi.org/10.1029/2017jd028093

697   Fiorella, R. P., West, J. B., & Bowen, G. J. (2019). Biased estimates of the isotope ratios of

698   steady-state evaporation from the assumption of equilibrium between vapour and

699   precipitation. *Hydrological Processes*, *33*(19), 2576-2590.

700   https://doi.org/10.1002/hyp.13531

701   Galewsky, J., Jensen, M. P., & Delp, J. (2022). Marine boundary layer decoupling and the stable

702   isotopic composition of water vapor. *Journal of Geophysical Research: Atmospheres*,

703   *127*(3), e2021JD035470. https://doi.org/10.1029/2021jd035470

704   Galewsky, J., Rella, C., Sharp, Z., Samuels, K., & Ward, D. (2011). Surface measurements of

705   upper tropospheric water vapor isotopic composition on the Chajnantor Plateau, Chile.

706   *Geophysical Research Letters*, *38*(17), L17803. https://doi.org/10.1029/2011gl048557

707   Galewsky, J. Steen-Larsen, H. C., Field, R. D., Worden, J., Risi, C., & Schneider, M. (2016).

708   Stable isotopes in atmospheric water vapor and applications to the hydrologic cycle.

709   *Reviews of Geophysics*, *54*(4), 809-865. https://doi.org/10.1002/2015rg000512

710   Gat, J. R. (1996). Oxygen and hydrogen isotopes in the hydrologic cycle. *Annual Review of*

711   *Earth and Planetary Sciences*, *24*, 225-262. https://doi.org/10.1146/annurev.earth.24.1.225

712   Gonzalez, Y., Schneider, M., Rodriguez, S., Christner, E., Garcia, O. E., Cuevas, E., et al.

713   (2016). Detecting moisture transport pathways to the subtropical North Atlantic free

714   troposphere using paired H_2O-δD in situ measurements. *Atmospheric Chemistry and*

715   *Physics*, *16*(7), 4251-4269. https://doi.org/10.5194/acp-16-4251-2016

716   Griffis, T. J., Wood, J. D., Baker, J. M., Lee, X. H., Xiao, K., Chen, Z. C., et al. (2016).

717   Investigating the source, transport, and isotope composition of water vapor in the planetary

718   boundary layer. *Atmospheric Chemistry and Physics*, *16*(8), 5139-5157.

719   https://doi.org/10.5194/acp-16-5139-2016

720   Hu, Y. B., Xiao, W., Wei, Z. W., Welp, L. R., Wen, X. F., & Lee, X. H. (2021). Determining the

721   isotopic composition of surface water vapor flux from high-frequency observations using

722   flux-gradient and keeling plot methods. *Earth and Space Science*, *8*(3), e2020EA001304.

723   https://doi.org/10.1029/2020ea001304

724   Hu, Z. M., Wen, X. F., Sun, X. M., Li, L. H., Yu, G. R., Lee, X. H. & Li S. G. (2014).

725   Partitioning of evapotranspiration through oxygen isotopic measurements of water pools

726 and fluxes in a temperate grassland. *Journal of Geophysical Research: Biogeosciences*,

727 *119*(3), 358-371. https://doi.org/10.1002/2013jg002367

728 Huang, L. J., & Wen, X F. (2014). Temporal variations of atmospheric water vapor δD and δ^{18}O

729 above an arid artificial oasis cropland in the Heihe River Basin. *Journal of Geophysical*

730 *Research: Atmospheres*, *119*(19), 11456-11476. https://doi.org/10.1002/2014jd021891

731 Huang, Y. Y., Wang, B., Li, X. F., & Wang, H. J. (2018). Changes in the influence of the

732 western Pacific subtropical high on Asian summer monsoon rainfall in the late 1990s.

733 *Climate Dynamics*, *51*(1-2), 443-455. https://doi.org/10.1007/s00382-017-3933-1

734 Kurita, N., Newman, B. D., Araguas-Araguas, L. J., & Aggarwal, P. (2012). Evaluation of

735 continuous water vapor δD and δ^{18}O measurements by off-axis integrated cavity output

736 spectroscopy. *Atmospheric Measurement Techniques*, *5*(8), 2069-2080.

737 https://doi.org/10.5194/amt-5-2069-2012

738 Lai, C.T., & Ehleringer, J. (2011). Deuterium excess reveals diurnal sources of water vapor in

739 forest air. *Oecologia*, *165*(1), 213-223. https://doi.org/10.1007/s00442-010-1721-2

740 Lai, X., Wright, J. S., Huang, W. Y., Liang, J., Lin, G. H., & Zhu, S. X. (2018). Contributions of

741 atmospheric transport and rain-vapor exchange to near-surface water vapor in the Zhanjiang

742 Mangrove Reserve, southern China: an isotopic perspective. *Atmosphere*, *9*(9), 365.

743 https://doi.org/10.3390/atmos9090365

744 Laonamsai, J., Ichiyanagi, K., Patsinghasanee, S., & Kamdee, K. (2021). Controls on stable

745 isotopic characteristics of water vapour over Thailand. *Hydrological Processes*, *35*(7),

746 e14202. https://doi.org/10.1002/hyp.14202

747 Lee, X. H, Sargent, S., Smith, R., & Tanner, B. (2005). In situ measurement of the water vapor

748 $^{18}O/^{16}O$ isotope ratio for atmospheric and ecological applications. *Journal of Atmospheric*

749 *and Oceanic Technology*, *22*(8), 1305-1305. https://doi.org/10.1175/JTECH9001.1a

750 Lee, X. H., Smith, R., & Williams, J. (2006). Water vapour $^{18}O/^{16}O$ isotope ratio in surface air in

751 New England, USA. *Tellus Series B-Chemical and Physical Meteorology*, *58*(4), 293-304.

752 https://doi.org/10.1111/j.1600-0889.2006.00191.x

753 Lee, X. H., Kim, K., & Smith R. (2007). Temporal variations of the $^{18}O/^{16}O$ signal of the whole-

754 canopy transpiration in a temperate forest. *Global Biogeochemical Cycles*, *21*, GB3013.

755 https://doi.org/10.1029/2006gb002871

756 Li, Y. J., An, W. L., Pang, H. X., Wu, S. Y., Tang, Y. Y., Zhang, W. B., & Hou, S.G. (2020).

757 Variations of stable isotopic composition in atmospheric water vapor and their controlling

758 factors-a 6-year continuous sampling study in Nanjing, eastern China. *Journal of*

759 *Geophysical Research: Atmospheres*, *125*, e2019JD031697.

760 https://doi.org/10.1029/2019jd031697

761 Luo, J. S., Sun, Y. H., Wang, Y. G., Xie, Z. H., & Meng, L. D. (2021). Cenozoic tectonic

762 evolution of the eastern Liaodong Bay sub-basin, Bohai Bay basin, eastern China-

763 Constraints from seismic data. *Marine and Petroleum Geology*, *134*, 105346.

764 https://doi.org/10.1016/j.marpetgeo.2021.105346

765 Mao, D.H., He, X.Y., Wang, Z.M., Tian, Y.L., Xiang, H.X., Yu, H., et al. (2019). Diverse

766 policies leading to contrasting impacts on land cover and ecosystem services in Northeast

767 China. Journal of Cleaner Production, *240*, 117961.

768 https://doi.org/10.1016/j.jclepro.2019.117961

Mao, D.H., Wang, Z.M., Du, B.J., Li, L., Tian, Y.L., Zeng, Y., et al. (2020). National wetland mapping in China: A new product resulting from object based and hierarchical classification of Landsat 8 OLI images. ISPRS Journal of Photogrammetry and Remote Sensing, 164, 11-25 https://doi.org/10.1016/j.isprsjprs.2020.03.020

Mercer, J. J., Liefert, D. T., & Williams, D. G. (2020). Atmospheric vapour and precipitation are not in isotopic equilibrium in a continental mountain environment. *Hydrological Processes*, *34*(14), 3078-3101. https://doi.org/10.1002/hyp.13775

Merlivat, L., & Jouzel, J. (1979). Global climatic interpeeretation of the deuterium ^{18}O relationship for precipitation. *Journal of Geophysical Research: Oceans*, *84*(C8), 5029-5033. https://doi.org/10.1029/jc084ic08p05029

Munksgaard, N. C., Zwart, C., Haig, J., Cernusak, L. A., & Bird, M. I. (2020). Coupled rainfall and water vapour stable isotope time series reveal tropical atmospheric processes on multiple timescales. *Hydrological Processes*, *34*(1), 111-124. https://doi.org/10.1002/hyp.13576

NFGA. (2010). National Wetland Survey Statistics Report. National Foresttry and Grassland Administration (in Chinese). https://www.forestry.gov.cn

Noone, D. (2012). Pairing measurements of the water vapor isotope ratio with humidity to deduce atmospheric moistening and dehydration in the tropical midtroposphere. *Journal of Climate*, *25*(13), 4476-4494. https://doi.org/10.1175/jcli-d-11-00582.1

Parkes, S. D., McCabe, M. F., Griffiths, A. D., Wang, L. X., Chambers, S., Ershadi, A., et al. (2017). Response of water vapour *D-excess* to land-atmosphere interactions in a semi-arid environment. *Hydrology and Earth System Sciences*, *21*(1), 533-548. https://doi.org/10.5194/hess-21-533-2017

792 Salamalikis, V., Argiriou, A. A., & Dotsika, E. (2015). Stable isotopic composition of

793   atmospheric water vapor in Patras, Greece: a concentration weighted trajectory approach.

794   *Atmospheric Research*, *152*, 93-104. https://doi.org/10.1016/j.atmosres.2014.02.021

795 Steen-Larsen, H. C., Johnsen, S. J., Masson-Delmotte, V., Stenni, B., Risi, C., Sodemann, H., et

796   al. (2013). Continuous monitoring of summer surface water vapor isotopic composition

797   above the Greenland Ice Sheet. *Atmospheric Chemistry and Physics*, *13*(9), 4815-4828.

798   https://doi.org/10.5194/acp-13-4815-2013

799 Steen-Larsen, H. C., Masson-Delmotte, V., Hirabayashi, M., Winkler, R., Satow, K., Prie, F., et

800   al. (2014b). What controls the isotopic composition of Greenland surface snow? *Climate of

801   the Past*, *10*(1), 377-392. https://doi.org/10.5194/cp-10-377-2014

802 Steen-Larsen, H. C., Sveinbjörnsdottir, A. E., Jonsson, T., Ritter, F., Bonne, J. L., Masson-

803   Delmotte, V., et al. (2015). Moisture sources and synoptic to seasonal variability of North

804   Atlantic water vapor isotopic composition. *Journal of Geophysical Research: Atmospheres*,

805   *120*(12), 5757-5774. https://doi.org/10.1002/2015jd023234

806 Steen-Larsen, H. C., Sveinbjornsdottir, A. E., Peters, A. J., Masson-Delmotte, V., Guishard, M.

807   P., Hsiao, G., et al. (2014a). Climatic controls on water vapor deuterium excess in the

808   marine boundary layer of the North Atlantic based on 500 days of in situ, continuous

809   measurements. *Atmospheric Chemistry and Physics*, *14*(15), 7741-7756.

810   https://doi.org/10.5194/acp-14-7741-2014

811 Sturm, P., & Knohl, A. (2010). Water vapor δ^2H and $\delta^{18}O$ measurements using off-axis

812   integrated cavity output spectroscopy. *Atmospheric Measurement Techniques*, *3*(1), 67-77.

813   https://doi.org/10.5194/amt-3-67-2010

814 Tian, L. D., Yu, W. S., Schuster, P. F., Wen, R., Cai, Z. Y., Wang, D., et al. (2020). Control of

815   seasonal water vapor isotope variations at Lhasa, southern Tibetan Plateau. *Journal of*

816   *Hydrology*, *580*, 124237. https://doi.org/10.1016/j.jhydrol.2019.124237

817 Tremoy, G., Vimeux, F., Vimeux, F., Souley, I., Risi, C., Favreau, G., & Oi, M. (2014).

818   Clustering mesoscale convective systems with laser-based water vapor delta O-18

819   monitoring in Niamey (Niger). *Journal of Geophysical Research: Atmospheres*, *119*(9),

820   5079-5103. https://doi.org/10.1002/2013jd020968

821 Uemura, R., Matsui, Y., Yoshimura, K., Motoyama, H., & Yoshida, N. (2008). Evidence of

822   deuterium excess in water vapor as an indicator of ocean surface conditions. *Journal of*

823   *Geophysical Research: Atmospheres*, *113*, D19114. https://doi.org/10.1029/2008jd010209

824 Vuille, M., Bradley, R. S., Werner, M., Healy, R., & Keimig, F. (2003). Modeling δ^{18}O in

825   precipitation over the tropical Americas: interannual variability and climatic controls.

826   *Journal of Geophysical Research: Atmospheres*, *108*(D6), 4174.

827   https://doi.org/10.1029/2001jd002038

828 Wang, G. D., Wang, M., Lu, X. G., & Jiang, M. (2016). Surface elevation change and

829   susceptibility of coastal wetlands to sea level rise in Liaohe Delta, China. *Estuarine Coastal*

830   *and Shelf Science*, *180*, 204-211. https://doi.org/10.1016/j.ecss.2016.07.011

831 Wang, G. Y., Lan, H. M., & Liu, Z. F. (2021). Stable isotope record of super typhoon Lekima

832   (2019). *Atmospheric Research*, *264*, 264, 105822.

833   https://doi.org/10.1016/j.atmosres.2021.105822

834 Wei, Z. W., & Lee, X. H. (2019). The utility of near-surface water vapor deuterium excess as an

835   indicator of atmospheric moisture source. *Journal of Hydrology*, *577*, 123923.

836   https://doi.org/10.1016/j.jhydrol.2019.123923

837   Wei, Z. W., Yoshimura, K., Okazaki, A., Kim, W., Liu, Z. F., & Yokoi, M. (2015). Partitioning

838   of evapotranspiration using high-frequency water vapor isotopic measurement over a rice

839   paddy field. *Water Resources Research*, *51*(5), 3716-3729.

840   https://doi.org/10.1002/2014wr016737

841   Welp, L. R., Lee, X. H., Griffis, T. J., Wen, X. F., Xiao, W., Li, S. G., et al. (2012). A meta-

842   analysis of water vapor deuterium-excess in the midlatitude atmospheric surface layer.

843   *Global Biogeochemical Cycles*, *26*, GB3021. https://doi.org/10.1029/2011gb004246

844   Wen, X. F., Lee, X. H., Sun, X. M., Wang, J. L., Hu, Z. M., Li, S.G., & Yu, G.R. (2012). Dew

845   water isotopic ratios and their relationships to ecosystem water pools and fluxes in a

846   cropland and a grassland in China. *Oecologia, 168*(2), 549-561.

847   https://doi.org/10.1007/s00442-011-2091-0

848   Wen, X. F., Sun, X. M., Zhang, S. C., Yu, G. R., Sargent, S. D., & Lee, X. H. (2008).

849   Continuous measurement of water vapor D/H and $^{18}O/^{16}O$ isotope ratios in the atmosphere.

850   *Journal of Hydrology*, *349*(3-4), 489-500. https://doi.org/10.1016/j.jhydrol.2007.11.021

851   Wen, X. F., Zhang, S. C., Sun, X. M., Yu, G. R., & Lee, X. H. (2010). Water vapor and

852   precipitation isotope ratios in Beijing, China. *Journal of Geophysical Research:*

853   *Atmospheres*, *115*, D1103. https://doi.org/10.1029/2009jd012408

854   Wu, H. W, Li, X. Y., Zhang, J. M., Li, J., Liu, J. Z., Tian, L. H., & Fu, C.S. (2019). Stable

855   isotopes of atmospheric water vapour and precipitation in the northeast Qinghai-Tibetan

856   Plateau. *Hydrological Processes*, *33*(23), 2997-3009. https://doi.org/10.1002/hyp.13541

857   Wu, X. X., Chen, F. L., Liu, X. Y, Wang, S. J., Zhang, M. J., Zhu, G. F., et al. (2021). The

858   significance of hydrogen and oxygen stable isotopes in the water vapor source in Dingxi

859   area. *Water*, *13*(17), 2374. https://doi.org/10.3390/w13172374

860 Xiao, W., Lee, X. H., Hu, Y. B., Liu, S. D., Wang, W., Wen, X. F., et al. (2017). An

861   experimental investigation of kinetic fractionation of open-water evaporation over a large

862   lake. *Journal of Geophysical Research: Atmospheres*, *122*(21), 11651-11663.

863   https://doi.org/10.1002/2017jd026774

864 Xu, T., Pang, H. X., Zhan, Z. J., Zhang, W. B., Guo, H. W., Wu, S. Y., & Hou, S. G. (2022).

865   Water vapor isotopes indicating rapid shift among multiple moisture sources for the 2018-

866   2019 winter extreme precipitation events in southeastern China. *Hydrology and Earth*

867   *System Sciences*, *26*(1), 117-127. https://doi.org/10.5194/hess-26-117-2022

868 Zhang, S. C., Sun X. M., Wang J. L., Yu, G. R., Wen, X. F. (2011). Short-term variations of

869   vapor isotope ratios reveal the influence of atmospheric processes. *Journal of Geographical*

870   *Sciences*, *21*(3), 401-416. https://doi.org/10.1007/s11442-011-0853-6

871 Zhao, L., Wang, L., Liu, X., Xiao, H., Ruan, Y., & Zhou, M. (2014). The patterns and

872   implications of diurnal variations in the d-excess of plant water, shallow soil water and air

873   moisture. *Hydrology and Earth System Sciences*, *18*(10), 4129-4151.

874   https://doi.org/10.5194/hess-18-4129-2014

1   **Ocean air masses dominate the land-surface atmospheric water cycles in**

2   **the coastal areas of Liaodong Bay: Insights from stable isotopes**

3

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16   **Key Points:**

17   - Spatial-temporal variations of water vapor isotopes are very different during
18   2019/2020 growing (May-September) seasons.

19   - Meteorological variables are not reliable indicators for water vapor δ^2H, δ^{18}O,
20   and d-excess at Panjin experimental station.

21   - Ocean air masses from East Asian monsoon dominate land-surface
22   atmospheric water vapor cycles in the coastal areas of Liaodong Bay.
23

Abstract

Long-term atmospheric water vapor hydrogen (δ^2H), oxygen ($\delta^{18}O$), and deuterium excess (*d-excess*) can provide unique insights into the land-atmosphere coupling processes. The in-situ measurements of atmospheric water vapor δ^2H, $\delta^{18}O$, and *d-excess* were conducted above a reed wetland of Liaodong Bay (2019-2020). We found significant inter-annual variations in atmospheric water vapor isotopes between the two growing (May-September) seasons. The δ^2H, $\delta^{18}O$, and *d-excess* of atmospheric water vapor exhibited different seasonal and diurnal cycles respect to the vertical (i.e., 1 m, 3 m, and 5 m) measurement heights, especially in 2019. The isotopic differences of atmospheric water vapor among vertical measurement heights were more evident in the daytime (8:00-20:00 LST) than at night (20:00-8:00 LST). Rainfall events had a direct impact on the diurnal patterns of water vapor isotopes, and the influences depended on rainfall intensities. However, only week correlations existed between water vapor isotopes and local meteorological factors ($R^2 = 0.01$-0.16, $P < 0.001$), such as water vapor concentration (w), relative humidity (RH), and surface air temperature (T_a). Based on the back-air trajectory analyses, the spatial-temporal dynamics of atmospheric water vapor isotopes highly synchronized with monsoon activities. The dominant air masses in this region mainly arose from ocean sources, which contributed to $62.1 \pm 12.2\%$ (49.4-84.5%) of the total air moisture. High *d-excess* consistently followed the strong monsoon activities, suggesting predominating impacts of ocean air masses from the East Asian monsoon region. High-resolution measurements of atmospheric water vapor isotopes will improve our understanding of the hydrological cycles in coastal areas.

Plain Language Summary

The coastal wetland regions in East Asia always have complex atmospheric hydrological processes, because they are influenced both by the westerly belt and the East Asian monsoon. Under such circumstances, still the question remains how do the multiple air masses affect the seasonal and diurnal patterns of atmospheric circulations? We implemented high temporal resolution (1Hz) measurements of atmospheric hydrogen (HDO/$H_1H_2^{18}O$) and oxygen ($H_2^{18}O$ and $H_2^{16}O$) using an off-axis integrated cavity output spectroscopy (OA-ICOS) technology in a reed wetland. The deuterium excess (*d-excess* $= \delta^2H - 8 \times \delta^{18}O$) of atmospheric water vapor was further used as an indicator for identifying the moisture source locations (2019-2020). There were obvious seasonal and diurnal variations of atmospheric water vapor δ^2H, $\delta^{18}O$, and *d-excess*. However, the inter-annual variations in atmospheric water vapor isotopes were more notable in this study, mainly due to the stronger monsoon activities. For example, the landing of typhoon "Lekima" brought a very high level of atmospheric water vapor *d-excess* in 2019. Therefore, the local meteorological variables might not be sufficient predictors of the atmospheric water vapor isotopes in the coastal wetland regions.

1 Introduction

Measurements of atmospheric water vapor hydrogen (δ^2H), oxygen (δ^{18}O), and deuterium excess (*d-excess*) can provide unique insights into the land-atmosphere coupling processes (Gat, 1996; Lee et al., 2005; Vuille et al., 2003). The δ^2H, δ^{18}O, and *d-excess* of water vapor (termed as the δ_{vapor} hereafter) can be used as natural tracers of atmospheric water cycles (Bastrikov et al., 2014; Christner et al., 2017; Munksgaard et al., 2020; Wen et al., 2008, 2010). Influenced by lower tropospheric water variations (e.g., precipitation and vertical atmospheric mixing) and local vegetation properties (e.g., soil evaporation and plant transpiration), the signatures of land-surface water vapor δ_{vapor} contain subtle information concerning water movements between the atmospheric boundary layer (ABL) and Earth's surfaces (Huang & Wen, 2014; Laonamsai et al., 2021; Lee et al., 2006). Thus, there is a growing interest in high-resolution measurements of atmospheric water vapor δ_{vapor} from ecosystem to regional scales (Galewsky et al., 2016; Steen-Larsen et al., 2013; Wei & Lee, 2019). Several studies have successfully completed the in-situ atmospheric water vapor δ_{vapor} monitoring based on the technological advantages of laser spectrometers (Aemisegger et al., 2014; Hu et al., 2014; Noone et al., 2012). However, it is still necessary to conduct in-situ measurements of atmospheric water vapor δ_{vapor} above near-surface ecosystems (Galewsky et al., 2016; Lee et al., 2005, 2007), compared with the condensed water isotopes that have formed a well-known global network (e.g., Global Network of Isotopes in Precipitation, GNIP).

To the best of our knowledge, datasets of in-situ atmospheric water vapor δ_{vapor} are reported across 49 sites worldwide. Those sites reflect the global land surface in all forms, including oceans (e.g., Bonne et al., 2019; Galewsky et al., 2022; Steen-Larsen et al., 2014a), forests (Aron et al., 2019; Bastrikov et al., 2014; Mercer et al., 2020), grasslands (Hu et al., 2014; Parkes et al., 2017; Tremoy et al., 2014), croplands (Griffis et al., 2016; Huang & Wen, 2014; Wen et al., 2012), ice sheets (Bonne et al., 2020; Casado et al., 2016; Steen-Larsen et al., 2014b), cities (Christner et al., 2017; Noone et al., 2012; Wang et al., 2021), and lakes (Cui et al., 2018; Hu et al., 2021; Xiao et al., 2017). These studies confirm the great potential of in-situ water vapor δ_{vapor} measurements to deconstruct the complex hydrological processes. However, among the available data on atmospheric water vapor δ_{vapor}, the data from coastal wetlands are scarce (Delattre et al., 2015; Lai et al., 2018). For example, Delattre et al. (2015) showed that ground level atmospheric vapour composition can record both local and regional isotopic signatures during 36 consecutive summer days . The water vapor δ_{vapor} data reported by Lai et al. (2018) showed that, on daily time scales (11-28 July, 2017), substantial rain recycling and large-scale atmospheric water transport occur above a coastal mangrove forest in southern China, which is subjected to the monsoons from South China Sea, Indian Ocean, Pacific Ocean, and local land areas. Nevertheless, the brief campaigns of water vapor δ_{vapor} measurements would restrain the best demonstration of atmospheric processes in the coastal wetlands.

106 Previous studies have demonstrated that the small spatial and temporal variations of
107 atmospheric water vapor δ_{vapor} are affected mainly by processes of atmospheric
108 entrainments, land surface evapotranspiration (i.e., soil evaporation and plant
109 transpiration, ET), and vapor condensations (Huang & Wen, 2014; Lee et al., 2007;
110 Fiorella et al., 2019; Diekmann et al., 2021). Entrainment processes of the free
111 atmosphere will vertically deplete the ^{2}H and ^{18}O of water vapor near the land
112 surfaces (Devi et al., 2014; Kurita et al., 2012; Wei et al., 2015). Local ET will enrich
113 the ^{2}H and ^{18}O of near-surface atmosphere above the densely vegetated landscapes,
114 which usually plays a dominant role in the variations of water vapor δ_{vapor} (Lai &
115 Ehleringer, 2011; Zhang et al., 2011). The diurnal dynamics of atmospheric water
116 vapor δvapor are closely associated with the vapor condensation processes (e.g.,
117 precipitation, dew and fog), which is mainly caused by the equilibrium phase changes
118 of local water vapor during the synoptic events (Bailey et al., 2015; Farlin et al., 2013;
119 Wen et al., 2012). On large spatial scales, air mass advection is considered as a
120 critical factor contributing to the temporal variability in atmospheric water vapor δ_{vapor}
121 (Dahinden et al., 2021; Galewsky et al., 2011; Steen-Larsen et al., 2015).

122 Despite high-resolution monitoring efforts over the past two decades,
123 decoupling the atmospheric water vapor δ_{vapor} variability across various timescales
124 remains challenging (Bagheri et al., 2019; Berkelhammer et al., 2013; Lee et al.,
125 2005; Dahinden et al., 2021). The deuterium excess (*d-excess* $= \delta^2H - 8 \times \delta^{18}O$) of
126 atmospheric water vapor provides a new insight into the source identification of
127 atmospheric moistures (Dansgaard, 1964; Merlivat & Jouzel, 1979; Welp et al.,
128 2012). The theoretical basis of this application is that the *d-excess* of water vapor is
129 closely linked to the environmental conditions during the kinetic fractionation
130 processes (Araguas-Araguas et al., 2000; Craig, 1961). Hence, the strong sensitivity
131 of *d-excess* to local atmosphere relative humidity (RH) can place better constraints on
132 the water transport processes than the analyses of water vapor δ^2H and $\delta^{18}O$ alone
133 (Lai et al., 2018; Wei & Lee, 2019). Previous work has traced both the ocean moisture
134 sources (Dahinden et al., 2021; Gonzalez et al., 2016; Salamalikis et al., 2015) and
135 continental moisture recycling (Aemisegger et al., 2014; Fiorella et al., 2019). To
136 better resemble the transmission path of large-scale air masses, tools of Hybrid
137 Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) and TrajStat models
138 have been widely used in conjunction with water vapor isotopes in recent years
139 (Bagheri et al., 2019; Fiorella et al., 2018; Gonzalez et al., 2016; Salamalikis et al.,
140 2015). It is foreseeable that long-term water vapor d-excess measurements will
141 improve our understanding of atmospheric processes and the associated mechanisms
142 in the coastal wetlands.

143 Liaodong Bay, a high-latitude continental bay (37.1-41.0° N, 117.6-121.2° E),
144 has the largest size and northernmost semi-enclosed seaports in China. It contains a
145 wetland area of approximately 5300 km^2 (Luo et al., 2021). According to the 2nd
146 National Wetland Survey Statistics Report (NFGA, 2010), the reed wetlands in this
147 region are well-preserved and among the largest in extent (~ 2500 km^2) in the world.
148 Those offshore wetlands are located in the transition zones between continents and
149 oceans, which are vulnerable to natural and anthropogenic activities, such as urban

150 and agricultural runoff. To fill the gaps in knowledge regarding the mechanisms of
151 water cycle processes, we conducted two-year (2019-2020) measurements of
152 atmospheric water vapor δ^2H, $\delta^{18}O$, and *d-excess* in the reed wetlands of Liaodong
153 Bay. The present study aims to (i) investigate the spatial-temporal dynamics of
154 atmospheric water vapor isotopes above the coastal wetland, and (ii) identify the
155 contributing factors that affect the isotopic characteristics of atmosphere in Liaodong
156 Bay. We hypothesize that (1) isotopic gradients exist for atmospheric water vapor
157 measurements along the monitoring heights due to the growth of reeds, and (2) moist
158 air masses from the East Asian monsoon strongly affects the atmospheric water vapor
159 isotopes.

160 **2 Materials and Methods**

161   2.1 Study site

162   The observations were carried out at Panjin Wetland Field Science
163 Experimental Station (40° 56′ 40″ N, 121° 56′ 36″ E, and elevation 2.1 m), located in
164 the north of Liaodong Bay. This station is a member of the National Climatic
165 Observatory of China Meteorological Administration (CMA), which is adjacent to the
166 Liaohe River Delta wetlands, and 12 km to the Bohai Sea (Figure 1a and 1b). This
167 area is characterized by the semi-humid temperate monsoon climate, influenced by
168 the westerly belt and the East Asian monsoon. The southwest East Asian monsoon
169 prevails from May to September, which brings abundant rainfall between July and
170 September (Huang et al., 2018). The regional meteorological records (1961-2010)
171 indicate that the mean air temperature and annual precipitation are 9.1 °C and 643.9
172 mm, respectively. Approximately 170 days of frost-free weather occur throughout the
173 year. The annual evaporation is about 516.0-720.3 mm (2012-2015). The research site
174 (150 m × 150 m) is situated in the center of a reed marsh (~ 780 km2), with a
175 vegetation coverage of more than 90% (Wang et al., 2016). Meteorological data of
176 surface air temperature (T_a), relative humidity (RH), and total precipitation (P)
177 obtained from an automatic weather station (Model A753WS, Adcon Telemetry Inc.,
178 Santa Rosa, CA). The leaf area index (LAI) and height of the reeds were collected for
179 fifteen days intervals during the growing season (May-September). During the study
180 periods of 2019 and 2020, the maximum LAI and maximum height were 5.1 $m^2\,m^{-2}$
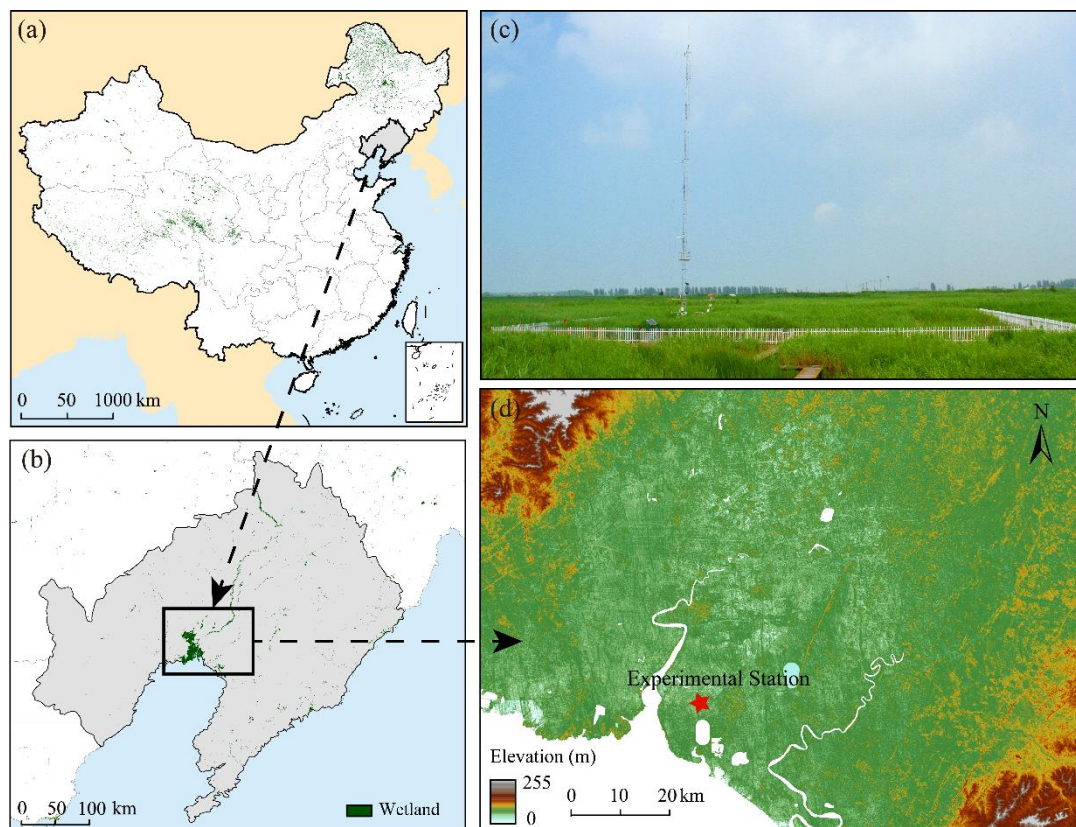181 and 2.5 m, respectively.

Figure 1. Maps showing the locations of Liaodong Bay (**a**, **b**) and Panjin experimental station (**c**, **d**) in this study. Elevation data was downloaded from the National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn).

2.2 In-Situ measurement of water vapor isotopes

The in-situ system used to measure the atmospheric water vapor δ^2H and δ^{18}O consisted of a water vapor isotope analyzer (WVIA), a water vapor isotope standard source (WVISS), and an air sampling system (ASS). The WVIA was used to measure water vapor isotopes (at a frequency of 1 Hz) based on the off-axis integrated cavity output spectroscopy (OA-ICOS; Model TIWA-912, Los Gatos Research, Mountain View, CA, USA). The analyzer has a near-infrared diode laser scanning absorption lines (~ 1.4 μb) for $H_2^{16}O$, $H_2^{18}O$, and $H_1H_2^{16}O$ (HDO), whose precision was approximately 0.4‰ for δ^2H and 0.08‰ for δ^{18}O (Steen-Larsen et al., 2013; Wen et al., 2012). The WVISS is an online calibration device that generates fixed concentrations of continuous vapor streams (Model 908-004-902, Los Gatos Research, Mountain View, CA, USA). In this study, ultrapure liquid water with known isotopic values was nebulized (at a rate of 2-10 L min^{-1}) to produce three designated gradients of standard streams (S$_1$, S$_2$, and S$_3$, 300s each) covering the water vapor concentration of ambient air. There is no isotopic fractionation since the nebulizer and hot chamber (2 L) of WVISS will ensure instant evaporation (heated to 80 °C) of all liquid water. The ASS was mounted on a 30 m height tower (Figure 1c) and used to pump ambient air from four heights (1, 3, 10, and 15 m) with 300s spent

205   on each height. To reduce the residence time of ambient air in the inlet lines (i.e.,
206   "memory effects"), the sampling lines were pumped at approximately 2 L min^{-1} using
207   a commercial multiplexer (Model MC-2000-8, Lica United Technology Limited Inc.,
208   Beijing, CHN). Teflon pipes were used in conjunction with individual heating tapes
209   and jackets to prevent possible vapor condensation in the sampling tubes (Lee et al.,
210   2005; Sturm & Knohl, 2010). Filters were installed at the entrances of the air-intake
211   lines to prevent sucking liquid water into the instrument (Model 300-01961, LI-COR
212   Inc., Lincoln, NE, USA). The switching sequence was S_1, S_2, S_3, and ambient air,
213   with 15 minutes on the standard streams and 220 minutes on ambient air. The WVIA
214   and WVISS were placed in an air-conditioning room to minimize the temperature-
215   driven drifts.

216   While using the OA-ICOS for high-precision measurements of atmospheric
217   water vapor δ^2H and $\delta^{18}O$, measurement bias can occur because of the instrumental
218   concentration-dependence and time-drift (Bastrikov et al., 2014; Wen et al., 2008,
219   2012). Here, we followed a user-configurable "two-point calibration" protocol
220   described by Wen et al. (2012), Huang & Wen (2014) and Xiao et al. (2017). Every
221   220 minutes (i.e., ~ 3.7 h) after the ambient (1, 3, 10, and 15 m) air measurements,
222   two of the three standards (S_1, S_2, and S_3) spanning the water vapor concentration of
223   ambient air were used to linearly calibrate atmospheric water vapor measurements.
224   The isotopic values of the liquid calibration standards were measured using a liquid
225   water isotope analyzer (Model GLA 431-TLWIA, Los Gatos Research, Mountain
226   View, CA, USA), which were scaled to the Vienna Standard Mean Ocean Water
227   (VSMOW) scale. For all the raw δ^2H and $\delta^{18}O$ measurements, the first 180 of 300 s
228   spent measuring a given standard stream or an ambient vapor were discarded from the
229   analysis to eliminate the possible memory effects. Then, the "two-point" linear
230   interpolation was implemented using the following formula (Wen et al., 2012; Huang
231   & Wen, 2014):

232
$$\delta_{vapor} = \delta_{s1} + \frac{(\delta_{s2} - \delta_{s1})}{(X_{s2} - X_{s1})} \times (X_{air} - X_{s1}) \tag{1}$$

233   where δ_{vapor} is the isotopic ratio ($^2H/^1H$, or $^{18}O/^{16}O$) of one ambient air (i.e., 1,
234   3, 10, and 15 m), δ_{s1} and δ_{s2} are the single-point corrected ambient airs that are
235   normalized to a reference humidity (i.e., X_{s1} and X_{s2}), X_{s1}, X_{s2} and X_{s1} are water
236   vapor concentrations of the two selected standard streams (S_1, S_2, and S_3) and the
237   ambient air, respectively.

238   The isotopic data collected at 1 m, 3 m, and 15 m in height were used for
239   representing the lower, middle, and upper canopy during the 2019-2020 growing
240   (May-September) seasons. The second-order parameter deuterium excess (*d-excess* =
241    $\delta^2H - 8 \times \delta^{18}O$) is defined as the deviation from the linear relationship between $^2H/^1H$
242   and $^{18}O/^{16}O$ in the Global Meteoric Water Line (GMWL) having a mean slope of 8
243   (Dansgaard, 1964; Merlivat & Jouzel, 1979). All data reported were block-averaged
244   to hourly intervals.

245　　　　　2.3 Back-air mass trajectory analyses

246　　　　　The Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT)
247　model was used to track changes in isotopic composition and moisture sources
248　(Christner et al., 2018; Munksgaard et al., 2020). The HYSPLIT model
249　(https://ready.arl.noaa.gov/HYSPLIT.php) was developed by the National Oceanic
250　and Atmospheric Administration-Air Resources Laboratory (NOAA-ARL). Inputs of
251　the HYSPLIT model include the cloud height, wind direction, temperature, and
252　surface pressure, which are available from the Global Data Assimilation System
253　(GDAS) meteorological data. In this study, the spatial resolution of the HYSPLIT
254　model was set to $1° \times 1°$, and the starting height was set to 500 m above ground level.
255　The 48-hour back-tracking analysis (close to the time that water vapor is present in
256　the air) was performed hourly for the experimental site from May to September 2019
257　and 2020. The angular distance of the TrajStat model
258　(http://www.meteothinker.com/downloads/index.html) was used to cluster the
259　trajectories of air mass reaching the experimental station:

$$260 \qquad D = \frac{1}{n} \sum_{i=1}^{n} \left(0.5 \frac{A_i + B_i - C_i}{\sqrt{A_i B_i}} \right) \qquad (2)$$

261　　　　　where D is the average angular distance between two backward trajectories, A
262　and B are the squares of the straight-line distances between the trajectory points and
263　the experimental site, and C denotes the square of the straight-line distance between
264　the two trajectory points.

265　　　　　The Concentration Weighted Trajectory (CWT) method was used to identify
266　the potential source regions contributing to the variability of atmospheric water vapor
267　*d-excess* at the experimental site (Li et al., 2020; Salamalikis et al., 2015). The
268　rearward trajectories were assigned by the equally sized $i \times j$ grid cells. The sample
269　concentrations accompanying trajectories that traversed each grid cell were averaged
270　to provide each grid cell with a weighted concentration. The calculation of this
271　method could be found in Li et al. (2020):

$$272 \qquad C_{ij} = \frac{1}{\sum_{l=1}^{M} \tau_{ijl}} \sum_{l=1}^{M} c_l \tau_{ijl} \qquad (3)$$

273　　　　　where Cij is the average *d-excess* concentration in the ij^{th} cell, *l* is the
274　trajectory index, *M* is the total number of the trajectories, cl is the concentration (*d-*
275　*excess*) of the trajectory *l*, and τ_{ijl} is the time spent in the ij^{th} cell by the trajectory *l*.
276　The weight function (W*ij*) was further introduced (WCWT*ij* = C*ij* $\times$ W*ij*) to reduce
277　uncertainty because the error of CWT increases with the distance between the grid
278　and the experimental station.

279   2.4 Statistical analyses

280   The isotopic data of atmospheric water vapor were calibrated based on the

281 "two-point calibration" protocol using Matrix Laboratory (MATLAB, version 9.2.0,

282 The MathWorks, Inc. Natick, USA). The normality and homogeneity of all data were

283 checked using IBM SPSS statistical software (Version 22.0, SPSS Inc., Chicago,

284 USA). One-way analysis of variance (ANOVA) and multiple means comparisons

285 (LSD) were used to highlight differences in data between months and vertical strata.

286 Considering the possible errors of the two variables, we used geometric mean

287 regression (GMR) to assess the relationships between atmospheric water vapor

288 isotopes and meteorological data with two probability levels of $P \leq 0.05$ and $P \leq$

289 0.001.

290 **3 Results**

291   3.1 Long time scale variations

292   Figure 2 shows the seasonal variations in hourly measured atmospheric water

293 vapor δ^2H, δ^{18}O, and *d-excess* at lower (1 m), middle (3 m), and upper (15 m)

294 measurement heights during the 2019-2020 growing (May-September) seasons. The

295 meteorological data of water vapor concentration (*w*), leaf area index (LAI), relative

296 humidity (RH), total precipitation (P), and surface air temperature (T$_a$) are also

297 presented for the Panjin experimental station. The WVIA analyzer was under repairs

298 from June 20 to July 10, 2019, and from August 24 to September 9, 2020. For the rest

299 of the study periods, only short gaps occurred in the in-situ measurements of

300 atmospheric water vapor δ^2H, δ^{18}O, and *d-excess* due to the occasional system

301 downtimes (e.g., electricity interruption and/or analyzer breakdown). The monthly

302 average of the above isotopic values of atmospheric water vapor and meteorological

303 data are summarized in Table 1.

304   The δ^2H, δ^{18}O, and *d-excess* of atmospheric water vapor underwent

305 pronounced inter-annual and annual changes with months and vertical measurement

306 heights (Figure 2). Significant differences existed in atmospheric water vapor δ^2H (P

307 < 0.001), δ^{18}O (P < 0.05), and *d-excess* (P < 0.001) between 2019 and 2020. The

308 mean isotopic values of atmospheric water vapor were higher in 2019 (δ^2H: − 108.4 ±

309 21.4‰, δ^{18}O: − 16.64 ± 3.13‰, and *d-excess*: 26.3 ± 11.7‰) than in 2020 (− 120.7 ±

310 20.2‰, − 16.98 ± 2.93‰ and 13.3 ± 8.4‰). Variation amplitudes (i.e., maximums −

311 minimums) of the water vapor δ^2H, δ^{18}O, and *d-excess* were 153.8‰, 27.69‰, and

312 82.5‰ in 2019, and were 124.5‰, 20.78‰, and 77.7‰ in 2020. The δ^2H and δ^{18}O of

313 atmospheric water vapor gradually decreased with the vertical measurement heights

314 from 1 m to 3 m and 15 m in both 2019 and 2020. In contrast, the *d-excess* of water

315 vapor increased from the lower (1 m) to the upper (15 m) canopy during the two years

316 of study periods. The difference in atmospheric water vapor δ^2H, δ^{18}O, and *d-excess*

317 was only significant between 1 m and 15 m (P < 0.05) in 2019. The isotopic values of

318 atmospheric water vapor changed drastically between 1 m and 15 m (P < 0.001) in

319 2020; and the atmospheric water vapor δ^{18}O and *d-excess* differed significantly
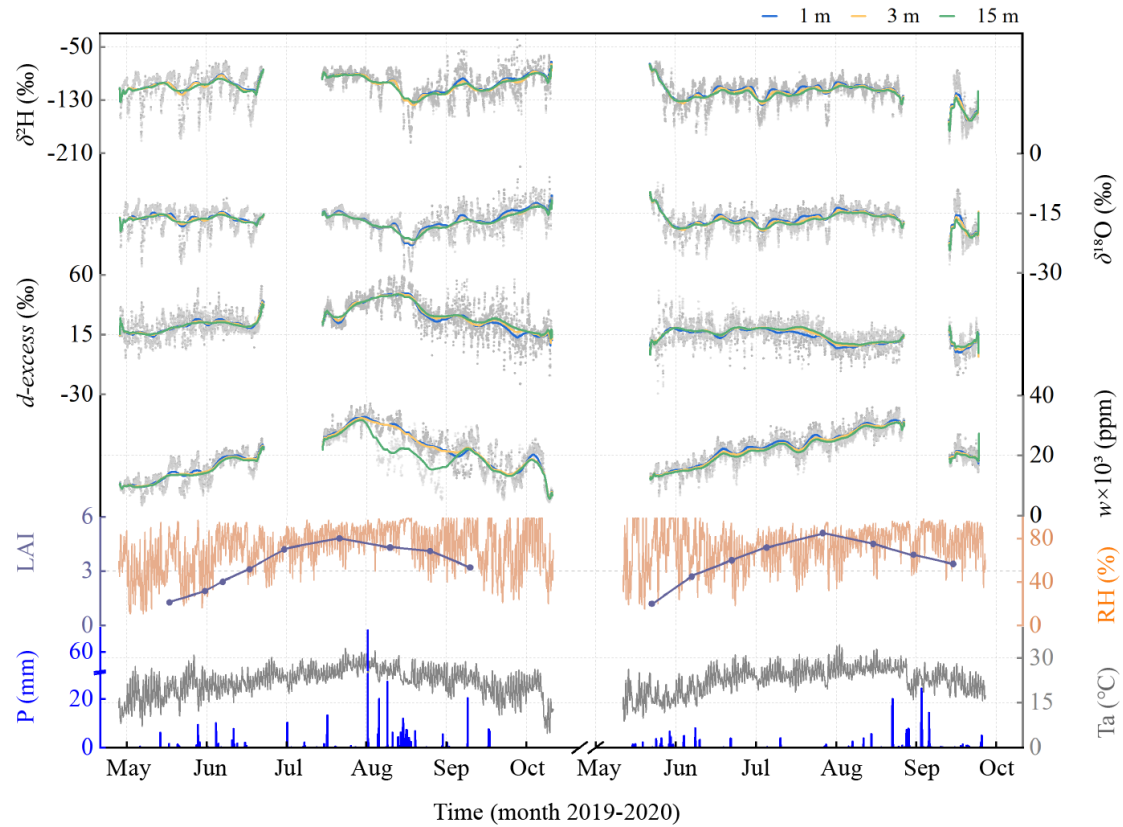
320 between 1 m and 3 m (P < 0.001) in 2020.

321

Figure 2. Time series of hourly atmospheric water vapor δ^2H, δ^{18}O, and *d-excess*, water vapor concentration (*w*), leaf area index (LAI), relative humidity (RH), precipitation (P), and surface air temperature (T$_a$) during the 2019-2020 growing (May-September) seasons. The Gaussian smoothing curves are shown for the in-situ atmospheric water vapor measurements at heights of 1 m (blue lines), 3 m (yellow lines), and 15 m (green lines).

The *w* of atmospheric water vapor was highest in August with single-peaked curves of seasonal variations (Figure 2). However, the peak of water vapor *w* in 2019 (36959.8 ppm) was delayed for 25 days compared to the peak (36090.8 ppm) in 2020. Furthermore, there were apparent differences in the atmospheric water vapor *w* between 1 m (or 3 m) and 15 m in 2019 (*P* < 0.001). During the growing (May-September) seasons, the LAI of reeds were 3.3 ± 1.2 in 2019 and 3.6 ± 1.2 in 2020. The mean RH in 2019 and 2020 were 70.7 ± 19.7 and 72.6 ± 17.5, respectively. The total rainfall was 37.6% lower in 2020 (414.1 mm) compared to 2019 (663.8 mm), indicating a weak summer monsoon year in 2020. The T$_a$ of the experimental station was relatively constant with mean values of 21.9 ± 4.7 °C in 2019 and 22.8 ± 4.3 °C in 2020 during the study periods.

339 **Table 1** Monthly average values of Water Vapor Concentration (w), Leaf Area Index (LAI), Relative Humidity (RH), Total
340 Precipitation (P), Surface Air Temperature (T_a), and Isotopic Values of Atmospheric Water Vapor (δ^2H, $\delta^{18}O$, and *d-excess*) in
341 Liaodong Bay, China, from May-September 2019 and 2020

Month	w (ppm)[a]	LAI ($m^2\,m^{-2}$)	RH (%)	P (mm)	T_a (°C)	δ^2H (‰)			$\delta^{18}O$ (‰)			*d-excess* (‰)		
						1 m	3 m	15 m	1 m	3 m	15 m	1 m	3 m	15 m
May	12045.5	1.6	54.1	66.1	18.3	−111.1	−111.8	−112.5	−16.31	−16.40	−16.49	19.4	19.4	19.4
Jun	18875.6	3.3	69.4	44.9	22.0	−104.4	−105.8	−107.2	−16.10	−16.25	−16.31	24.4	24.2	23.3
Jul	29870.6	4.4	78.	55.8	25.6	−97.2	−97.5	−98.3	−12.79	−12.88	−13.00	33.7	34.1	34.2
Aug	25471.5	4.0	82.6	424.1	24.9	−113.2	−114.3	−115.0	−18.54	−18.77	−18.87	35.2	35.8	35.9
Sep	18040.9	3.2	70.1	107.9	26.0	−102.6	−104.9	−104.5	−15.47	−15.91	−16.02	21.2	22.2	23.4
May	14714.6	1.8	70.2	85.9	16.7	−117.9	−118.8	−119.2	−16.75	−16.93	−16.96	15.9	16.4	16.3
Jun	20746.6	3.4	64.6	29.2	23.1	−118.3	−120.3	−122.4	−16.99	−17.34	−17.61	17.6	18.4	18.6
Jul	25200.8	4.5	70.7	11.5	25.4	−113.1	−114.8	−116.3	−15.60	−16.03	−16.34	11.7	13.3	14.6
Aug	30488.3	4.2	80.6	253	25.5	−115.0	−115.7	−116.7	−15.46	−15.60	−15.76	8.6	9.0	9.4
Sep	20180.2	3.3	77.6	34.8	21.7	−144.3	−146.1	−148.7	−18.73	−19.09	−19.54	5.6	6.6	7.6

342 [a] The monthly w of atmospheric water vapor was calculated based on the average of data from the lower (1 m), middle (3 m), and
343 upper (15 m) canopy.
344

345   3.2 Long time scale variations

346   Figure 3 presents the diurnal variations of atmospheric water vapor δ^2H, δ^{18}O, and *d-*
347 *excess* measured at heights of 1 m, 3 m, and 15 m. A clear diurnal cycle of water vapor δ^2H,
348 δ^{18}O, and *d-excess* existed in both 2019 and 2020. The atmospheric water vapor δ^2H and δ^{18}O
349 generally increased from 9:00 (LST) to 18:00 (LST). Simultaneously, the δ^2H and δ^{18}O of water
350 vapor progressively declined to their minimum around 8:00-9:00 (LST) on the next day (Figure
351 3a-d). The diurnal variations of atmospheric water vapor δ^2H and δ^{18}O were less pronounced in
352 2020 than in 2019. Nonetheless, the diurnal variations of atmospheric water vapor *d-excess* were
353 pretty clear in both years of 2019 and 2020, which had an opposite diurnal trend to that of
354 atmospheric water vapor δ^2H and δ^{18}O (Figure 3e-f). The isotopic differences of atmospheric
355 water vapor across measurement heights (i.e., 1, 3, and 15 m) were more evident in the daytime
356 (8:00-20:00 LST) than at night (20:00-8:00 LST). This phenomenon appeared extremely typical
357 in 2020, during which the atmosphere water vapor δ^2H and δ^{18}O declined progressively with the
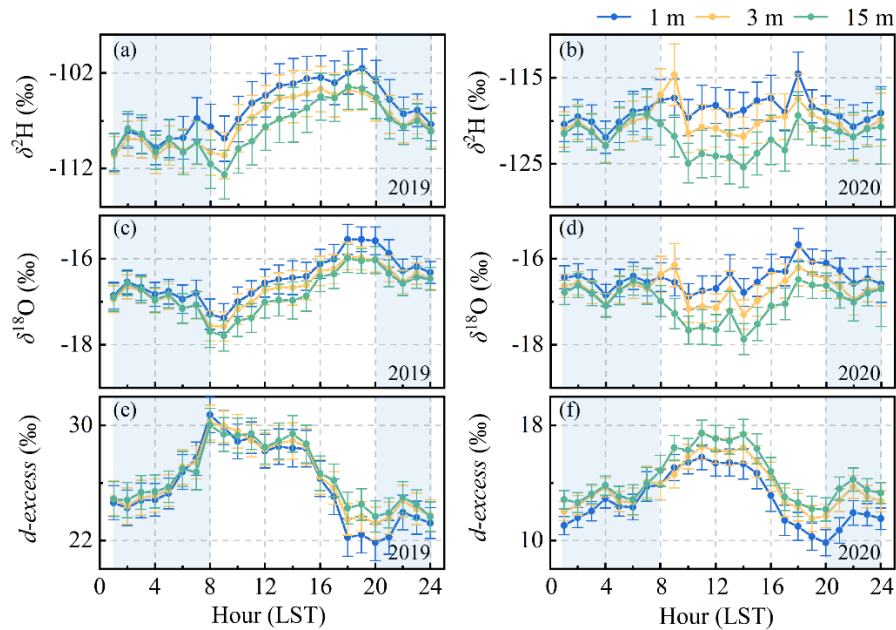358 increase of heights ($P < 0.05$).

359

360 **Figure 3.** Twenty-four-hour variations of atmospheric water vapor δ^2H (**a**, **b**), δ^{18}O (**c**, **d**), and *d-*
361 *excess* (**e**, **f**) measured at heights of 1 m (blue lines), 3 m (yellow lines), and 15 m (green lines)
362 during the 2019-2020 growing (May-September) seasons. Error bars represent standard errors of
363 the isotopic data in every hour. Shadow areas indicate the periods of time at night (20:00-8:00
364 LST).

365   Figure 4 illustrates the impacts of rainfall processes on the diurnal cycles of atmospheric
366 water vapor δ^2H, δ^{18}O, and *d-excess* at 15 m height. Six rainfall events of different rainfall
367 amounts (P = 2.6-141.1 mm) were selected during the 2019-2020 growing (May-September)
368 seasons. The duration (D) of these rainfall events ranged from 11 h to 100 h. The δ^2H, δ^{18}O, and
369 *d-excess* of atmospheric water vapor increased slightly after two small rainfall events (P = 2.6-
370 4.5 mm, in Figure 4a-b). The peak-to-peak variations of atmospheric water vapor δ^2H, δ^{18}O, and
371 *d-excess* were 31.8-51.6‰, 3.08-7.02‰, and 12.7-26.2‰, respectively. With the increase in

intensity and duration of rainfall, the isotopic values of atmospheric water vapor also increased during the rainfall processes (Figure 4c-d). However, the isotopic values of atmospheric water vapor declined after a 20 h continuous rainfall event. The variability of atmospheric water vapor in these moderate rainfall events (P = 30.9-33.4 mm) increased to 68.4-70.8‰ for δ^2H, 7.15-8.87‰ for δ^{18}O, and 20.3-34.3‰ for *d-excess*. The δ^2H, δ^{18}O, and *d-excess* of atmospheric water vapor decreased drastically during the heavy rainfall events as expected (Figure 4e-f). The isotopic variations of atmospheric water vapor in heavy rainfall events (P = 68.4-141.1 mm) were 37.4-66.8‰ for δ^2H, 3.41-5.70‰ for δ^{18}O, and 22.5-26.8‰ for *d-excess*.

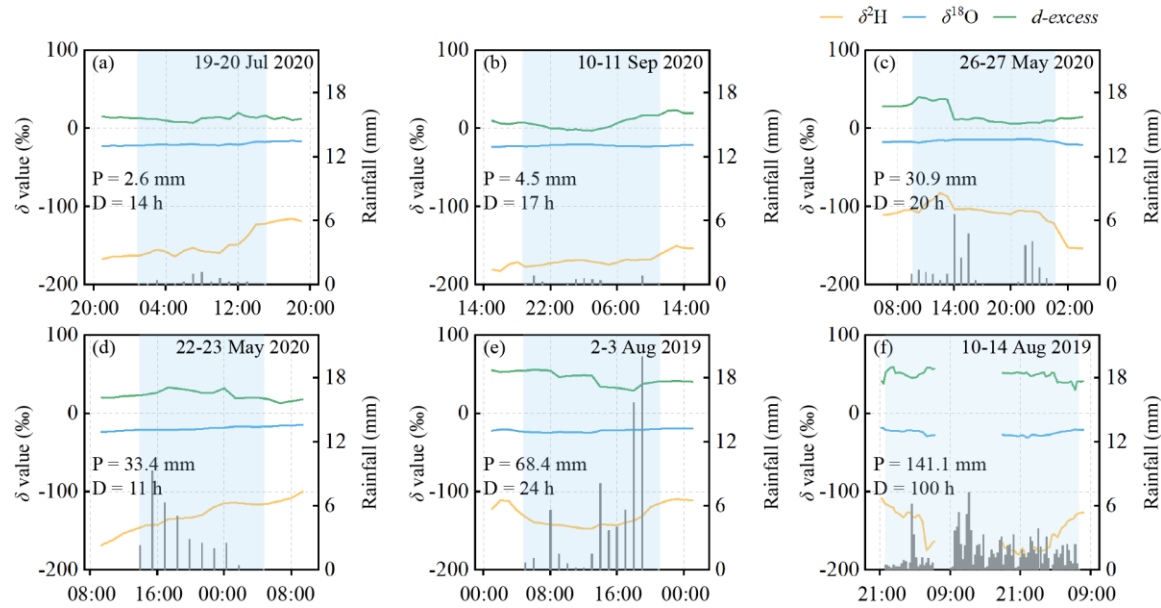**Figure 4.** Impacts of rainfall processes on the diurnal cycles of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess* at 15 m height (**a-f**) during the (2019-2020) study periods. Rainfall amount (P) and rainfall duration (D) are plotted on each panel for reference. Shadow areas indicate the periods of rainfall events.

3.3 Relationships with meteorological variables

Figure 5 depicts the linear dependency of δ^2H on δ^{18}O for atmospheric water vapor during the 2019-2020 growing (May-September) seasons. The hourly measurement of three (i.e., 1 m, 3 m, and 15 m) canopy layers were merged to reflect the impacts of rainfall events on the co-variations between δ^2H on δ^{18}O of atmospheric water vapor. This treatment was adopted due to the similar functions among different heights (*SI Appendix A*, Figure S1). In 2019, the δ^2H and δ^{18}O of atmospheric water vapor mainly occupied the dual-isotope plots from the global meteoric water line (GMWL: δ^2H = 8 × δ^{18}O + 10) to its left sides (Figure 5a). Slopes of the atmospheric water vapor lines in 2019 were 6.4 ± 0.2 (R^2 = 0.87, P < 0.001) and 6.2 ± 0.1 (R^2 = 0.76, P < 0.001) during the rainfall and non-rainfall periods, respectively. In 2020, the δ^2H and δ^{18}O of atmospheric water vapor were plotted right on the GMWL (Figure 5b). Slopes of the atmospheric water vapor lines in 2020 were 7.4 ± 0.2 (R^2 = 0.89, P < 0.001) and 6.4 ± 0.1 (R^2 = 0.87, P < 0.001) during the rainfall and non-rainfall periods, respectively. The intercepts of the atmospheric water vapor lines were less than 10 for both years, ranging from 2.8 to 4.5 during the rainfall periods, and from – 13.8 to – 3.8 during the non-rainfall periods.
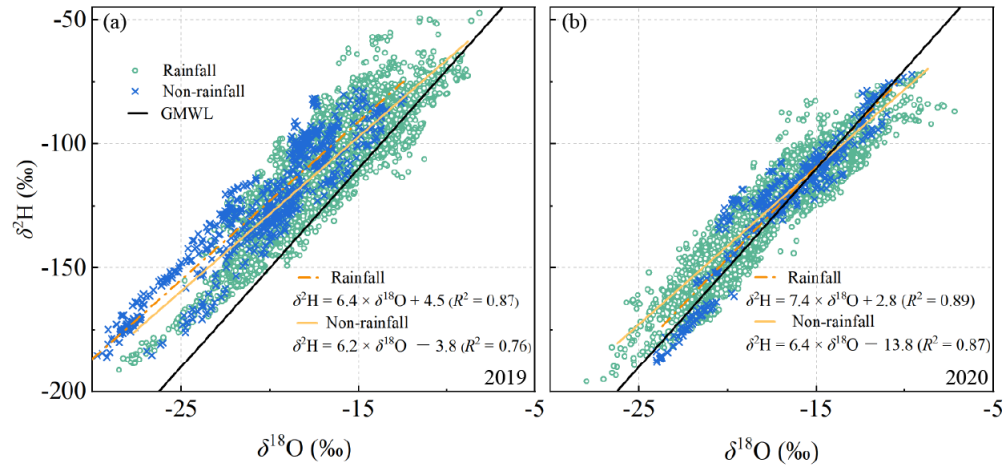
Figure 5. Isotopic values of δ^2H as a function of $\delta^{18}O$ in atmospheric water vapor during the 2019 (**a**) and 2020 (**b**) growing (May-September) seasons. Data of atmospheric water vapor δ^2H and $\delta^{18}O$ are divided into two groups representing the periods with rainfall and non-rainfall events. The global meteoric water line (GMWL: $\delta^2H = 8 \times \delta^{18}O + 10$) is also plotted on each panel for reference.

Figure 6 shows the relationships between the δ^2H, $\delta^{18}O$ and *d-excess* of atmospheric water vapor and local meteorological factors. The δ^2H and $\delta^{18}O$ of atmospheric water vapor were positively correlated with the water vapor concentration (w) (Figure 6a, 6d, 6g, and 6j). In contrast, their *d-excess* were negatively correlated with w in 2019 ($R^2 = 0.05$, $P < 0.001$, measurement undertaken at height of 15 m, in Figure 6m) and 2020 ($R^2 = 0.11$-0.16, $P < 0.001$, in Figure 6p). The atmospheric water vapor δ^2H, $\delta^{18}O$ and *d-excess* were weakly dependent on the relative humidity (RH) during the study periods ($R^2 = 0.01$-0.11, $P < 0.001$, in Figure 6b, 6e, 6h, 6k, 6n, and 6q). The δ^2H, $\delta^{18}O$ of atmospheric water vapor exhibited positive dependences on surface air temperature (T_a) in 2020 ($R^2 = 0.05$-0.07, $P < 0.001$, in Figure 6f and 6l). The atmospheric water vapor d-excess in 2020 was negatively correlated with T_a ($R^2 = 0.01$-0.02, $P < 0.001$, in Figure 6r). However, no significant correlation occurred between the atmospheric water vapor isotopes and T_a in 2019 (Figure 6c, 6i, and 6o).

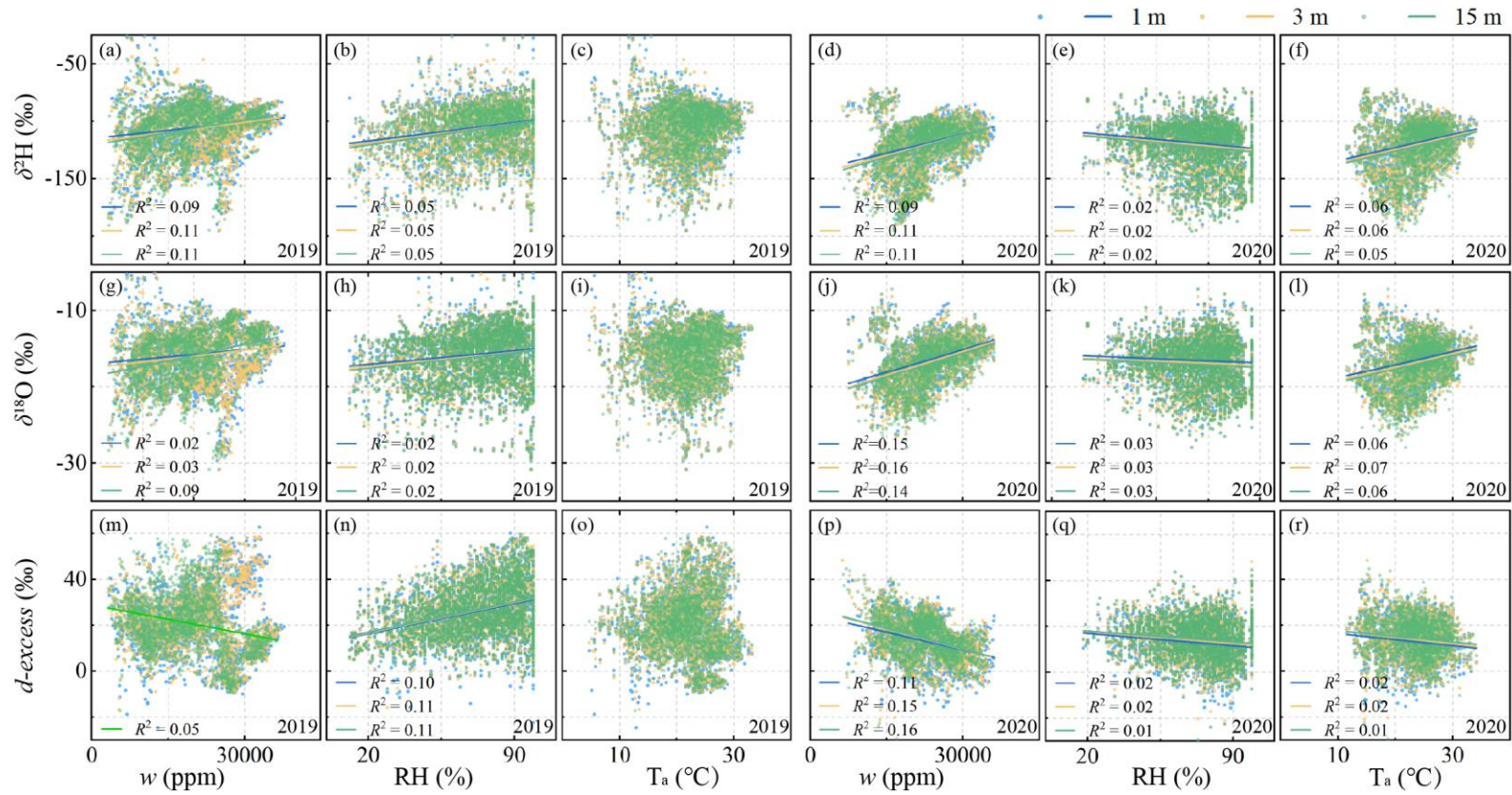**Figure 6.** Correlations of the water vapor concentration (*w*), relative humidity (RH), and surface air temperature (T$_a$) with the atmospheric water vapor δ^2H (**a-f**), δ^{18}O (**g-l**), and *d-excess* (**m-r**) during the (2019-2020) study periods. The regression curves represent the in-situ atmospheric water vapor measurements at heights of 1 m (blue lines), 3 m (yellow lines), and 15 m (green lines).

Figure 7. Back trajectory frequencies clustered according to the directions of air masses and the concentration fields of atmospheric water vapor *d-excess* during the 2019 (**a-e**) and 2020 (**f-j**) growing (May-September) seasons. Red star indicates the location of Panjin experimental station. Orange lines are the clusters of air masses during the preceding 48 h at 500 m height above the ground, and blue shading is the potential source of atmospheric water vapor *d-excess* in each month.

428   3.4 Large scale atmosphere circulations

429   Figure 7 shows the concentration fields of atmospheric water vapor *d-excess* along the
430   backward trajectories at Panjin experimental station. The 48-hourly backward trajectories of air
431   masses were calculated for the 2019-2020 growing (May-September) seasons. For all five
432   months, 3659 and 3515 trajectories were clustered in 2019 and 2020, respectively (*SI Appendix*
433   *A*, Figure *S2*). Then, we identified three-five major moisture source sectors that affected the
434   experimental station. The dominant air masses in this region generally came from ocean sources,
435   contributing more than 50% to the total air moisture except in June 2020 (49.4%). The transport
436   paths of ocean air masses could be further clustered into two sectors, i.e., Southwest-South (SW-
437   S) and South-Southeast (S-SE) directions. At the beginning of the monsoon season (May-June),
438   the trajectory paths of air masses usually originated from ocean surfaces and the northern interior
439   (Figure 7a-b and 7f-g). The ocean air masses gradually dominated during the peak monsoon
440   season (July-August). The contribution proportions of ocean air masses reached the maxima in
441   July 2019 (73.2%, in Figure 7c) and in August 2020 (84.5%, in Figure 7i). The influence of
442   summer monsoon on local air masses weakened in September 2019, with a contribution
443   proportion of 59.9% (Figure 7e). However, the ocean air masses had a prolonged impact (70.5%)
444   on atmospheric water vapor *d-excess* at the experimental station in September 2020 (Figure 7j).

445   The back-air mass trajectory analysis indicates that seasonal dynamic in moisture sources
446   was a main driving factor of the atmospheric water vapor *d-excess* variability (Figure 7). The
447   spatial distribution of atmospheric water vapor *d-excess* at this experimental station was closely
448   linked with the monsoon activities in East Asia. Most of trajectory paths were accompanied by
449   relatively higher atmospheric water vapor *d-excess* in 2019 than in 2020. This phenomenon was
450   particularly evident in 2019 (Figure 7a-e), where high-value of atmospheric water vapor *d-excess*
451   commonly distributed around the coastal regions. Lower proportion of air masses arose from the
452   ocean sources between August and September in 2019 (50-59.9%, in Figure 7d-e) than in 2020
453   (70.5-84.5%, in Figure 7i-j). However, the intensity of the East Asian monsoon was weak in
454   2020, which brought less rainfall to the atmospheric water cycles in Liaodong Bay. Therefore,
455   the air masses from the interiors of North China had more significant impacts (i.e., more negative
456   values) on the atmospheric water vapor *d-excess* in 2020 than in 2019. The secondary moisture
457   sources of inland air masses played a vital role in the seasonal variations of atmospheric water
458   vapor *d-excess* in the weak summer monsoon year.

459

4 Discussion

461   Based on the in-situ measurement techniques, this study revealed the isotopic signatures of
462   atmospheric water vapor (Figure 2-4), as well as the driving forces of the atmospheric water
463   vapor isotopes (Figure 5-7) for a reed wetland of Liaodong Bay, Northeast China. The
464   meteorological factors (e.g., water vapor concentration, relative humidity, and air temperature)
465   were incapable of predicting the variations of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess*
466   in this region. The different seasonal and diurnal patterns of water vapor isotopes could be
467   attributed to the stronger monsoon activities in 2019 than in 2020. These findings would broaden
468   our understanding of hydrological cycles in the coastal wetlands.

469   4.1 Temporal dynamics of water vapor isotopes at different heights

470   The long- (i.e., seasonal scale) and short- (i.e., diurnal scale) term characteristics of
471 atmospheric water vapor isotopes showed significant variations at heights of 1 m, 3 m, and 15 m
472 (Figure 2 and 3). The temporal dynamics of water vapor δ^2H, $\delta^{18}O$, and *d-excess* are usually
473 controlled by the atmospheric processes (Lee et al., 2005; Wen et al., 2008), local
474 evapotranspiration (Aron et al., 2019; Huang & Wen, 2014), and synoptic events (Berkelhammer
475 et al., 2013; Wu et al., 2019). For instance, Steen-Larsen et al. (2013) suggested that the intra-
476 seasonal variations of water vapor isotopes mainly result from the interplay between large-scale
477 moisture advection, boundary layer dynamics, and local moisture fluxes above the Greenland Ice
478 Sheet. The magnitude of changes in surface water vapor *d-excess* can be as high as 40‰ or
479 greater during several episodes (Steen-Larsen et al., 2013). Huang & Wen (2014) reported that
480 the atmospheric water vapor δ^2H, $\delta^{18}O$, and *d-excess* are dominated by the typical arid and
481 continental climates, which will not show clear seasonal cycles in the inland region of Northwest
482 China. As a typical coastal wetland under the influence of the East Asian Monsoon, our results
483 showed that the temporal patterns of water vapor isotopes were strikingly different between the
484 years of study periods. Moreover, some departures of atmospheric water vapor isotopes were
485 observed among the three measurement heights. This might be interpreted as the enrichment
486 effects of local evapotranspiration, which gradually improves the atmospheric water vapor
487 isotopes with the increasing plant physiological activities (Hu et al., 2021; Welp et al., 2012).

488   The seasonal variations of atmospheric water vapor δ^2H, $\delta^{18}O$, and *d-excess* in the reed
489 wetlands of Liaodong Bay were different from those of the other research site (Fiorella et al.,
490 2018; Laonamsai et al., 2021; Lee et al., 2006; Wen et al., 2010). Apart from the noticeable
491 seasonal changes occurring in each year, there were distinct inter-annual cycles for atmospheric
492 water vapor isotopes between 2019 and 2020 (Figure 2). The mean isotopic values of
493 atmospheric water vapor ranged from − 120.7‰ to − 108.4‰ for δ^2H, from − 16.98‰ to −
494 16.64‰ for $\delta^{18}O$, and from 13.3‰ to 26.3‰ (Table 1), which were higher than the results
495 reported by Wen et al. (2010) and Zhang et al. (2011) in inland areas of China. Especially in
496 2019, the δ^2H and $\delta^{18}O$ of atmospheric water vapor fluctuated seasonally with lower values in
497 the prevailing monsoon season (i.e., August-September). The seasonal pattern of atmospheric
498 water vapor δ^2H and $\delta^{18}O$ made a complete reversal of the water vapor concentration (*w*) trend
499 (Figure 2). In fact, the summer monsoon was earlier in 2019 and brought more rainfall than in
500 2020. In 2019, the typhoon "Lekima" was reported to land in Southwest coast of China (4-10
501 August) with a wind speed of 51.4 m s^{-1}, which then moved northwards and made a second
502 landfall in Liaodong Bay (Wang et al., 2021). Some studies reported that a significant decrease
503 in precipitation and atmospheric isotopes can happen during the tropical typhoons (Bonne et al.,
504 2019; Conroy et al., 2016). The abrupt decline of atmospheric water vapor *w* at 15 m height
505 could also be attributed to the high condensation efficiency and strong entrainment activity
506 during the typhoon event in 2019.

507   The interactions between atmospheric entrainment and local evapotranspiration typically
508 dominate the diurnal cycles of atmospheric water vapor δ^2H, $\delta^{18}O$, and *d-excess* (Aron et al.,
509 2019; Huang & Wen, 2014; Lee et al., 2007; Zhao et al., 2014). Our results showed that the δ^2H
510 and $\delta^{18}O$ of atmosphere were lower in the early morning (8:00-9:00 LST) than in the late
511 afternoon (16:00-18:00 LST). On the contrary, the atmospheric water vapor *d-excess* exhibited
512 an "inverted U-shaped diurnal pattern" in 2019 and 2020 (Figure 3). The downward trends in
513 atmospheric water vapor δ^2H and $\delta^{18}O$ can be attributed to the rapid increase of free air in ABL

514   when plant transpiration activity is relatively low in the morning (Huang & Wen, 2014). The
515   enrichment roles of local evapotranspiration surpassed the depletion effects of atmospheric
516   entrainment in the late afternoon. Such positive impacts of local evapotranspiration on
517   atmosphere isotopes were marked significantly in the lower (1 m) canopy than in the middle (3
518   m) and upper (15 m) heights (Figure 3). Apparently, the rainfall process was one of the main
519   factors contributing to the diurnal dynamics of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess*
520   (Figure 4). The isotopic fractionation caused by the sub-cloud secondary evaporation enriches
521   the residual rainfall, which in turn can make the enrichment of atmospheric isotopes during small
522   rainfall events (Vuille et al., 2003; Wu et al., 2021). However, the rainout effects of rainfall
523   would result in the continuous depletion of atmospheric isotopes according to the Rayleigh
524   distillation mechanisms (Gat, 1996; Lee et al., 2005; Wen et al., 2010).

525   4.2 Controlling factors of water vapor isotopes above coastal wetlands

526   The global meteoric water line (GMWL: δ^2H = 8 × δ^{18}O + 10) indicates the isotopic co-
527   variations in marine water that has not been exposed to evaporation fractionation (Craig, 1961;
528   Gat, 1996). As the marine air masses move over the coastal regions and towards the inland, the
529   air parcels will be mixed with continental water vapor sources and influenced by geographic
530   parameters such as the distances from coasts, altitudes, rainfall processes, and temperatures
531   (Christner et al., 2018; Gat, 1996; Merlivat & Jouzel, 1979). The slopes of atmospheric water
532   vapor lines (6.2-7.4) were lower than that of GMWL (Figure 5), which were determined by the
533   non-equilibrium fractionation (i.e., the existence of kinetic effects) within air parcels. Similarly,
534   Bastrikov et al. (2014) reported that the overall slopes of atmospheric water vapor lines are 5.6-
535   7.7 among different seasons in western Siberia (Kourovka). Li et al. (2020) highlighted that the
536   slopes of atmospheric water vapor lines change from 7.0 to 7.6 during a six-year period in
537   Eastern China. The high intercept (i.e., *d-excess*) of atmospheric water vapor lines in 2019
538   suggested that the isotopic changes in air masses which were very sensitive to the moisture
539   source conditions (Aemisegger et al., 2014; Delattre et al., 2015; Fiorella et al., 2018).

540   The results of this study also showed that the relationships between local meteorological
541   factors and atmospheric water vapor isotopes were weak or nonexistent at Panjin experimental
542   station (Figure 6). This finding was inconsistent with previous observations in the inland areas of
543   China. For example, Zhang et al. (2011) noted that the water vapor concentration (*w*) can be an
544   excellent predictor of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess* based on the Rayleigh
545   distillation. However, the weak correlations between atmospheric water vapor isotopes and
546   relative humidity (RH) were found in other studies (Li et al., 2020; Salamalikis et al., 2015). An
547   earlier study by Lee et al. (2006) in New England found that the atmospheric *w* is a better
548   indicator for atmospheric water vapor isotopes than air temperature (T_a) on short time scales.
549   These studies have established a certain level of correlation between atmospheric water vapor
550   isotopes and local meteorological factors (e.g., *w*, T_a, and RH) during the non-monsoon season
551   (Lee et al., 2005; Li et al., 2020; Noone et al., 2012). In contrast, Wen et al. (2010) found that the
552   *w* becomes a poor predictor of the atmospheric water vapor δ^2H, δ^{18}O, and *d-excess* during the
553   summer monsoon season. Similar to this study, weak correlations were also found by Li et al.
554   (2020) and Wang et al. (2021) during the peak monsoon activities.

555   Unlike the δ^2H and δ^{18}O whose temporal variations are commonly overwhelmed by the
556   Rayleigh distillation and/or the rainout history of air masses, the atmospheric water vapor *d-*
557   *excess* of an air mass is a nearly constant tracer during the transport processes (Welp et al., 2012;

558   Wei et al., 2019). Therefore, the *d-excess* of atmospheric water vapor is widely used as a
559   conservative indicator for identifying the moisture source locations (Aemisegger et al., 2014;
560   Steen-Larsen et al., 2015; Uemura et al., 2008; Xu et al., 2022). Panjin experimental station was
561   situated on the special borderland between the North China Plain and Bohai Sea (Figure 1),
562   which was also located within the edge of the East Asian monsoon region (Luo et al., 2021;
563   Wang et al., 2021). With the sea in three directions, the atmospheric water vapor *d-excess* in this
564   study was significantly affected by the ocean air masses (Figure 7). The high values of
565   atmospheric water vapor *d-excess* consistently appeared in the peak (i.e., July-August) monsoon
566   season. The results of the present study further confirmed that the ocean air masses dominated
567   the temporal variations of atmospheric water vapor *d-excess* (Figures 2, 3, and 7) when a super
568   typhoon "Lekima" happened in 2019 (details in Section 4.1). Lai et al. (2018) examined the
569   atmospheric water cycling above a coastal mangrove forest in Southern China. They also found
570   that the substantial increase of atmospheric water vapor *d-excess* is related to the passage of a
571   tropical typhoon "Talas" (Lai et al., 2018). In the Qinghai-Tibetan Plateau of central Asia, Wu et
572   al. (2019) revealed that high *d-excess* values of atmospheric water vapor were influenced by
573   local moisture mixing during the monsoon season. A recent study noted that high values of
574   atmospheric water vapor *d-excess* appear before the monsoon onset and after the monsoon
575   season at Lhasa in Southern Tibetan Plateau (Tian et al., 2020). Indeed, air masses from cold and
576   dry areas can also bring a relatively high atmospheric water vapor *d-excess* (Uemura et al., 2008;
577   Xu et al., 2022). Further mechanism studies are expected to provide more rational explanations
578   for the above-mentioned processes in coastal wetlands.

579

5 Conclusions

581   The inter-annual variations of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess* were
582   significantly different between 2019 and 2020. On a seasonal time scale, the mean isotopic
583   values of atmospheric water vapor in 2019 were significantly higher than that in 2020.
584   Meanwhile, the δ^2H and δ^{18}O of atmospheric water vapor gradually decreased from the lower (1
585   m), to the middle (3 m) and upper (15 m) canopy both 2019 and 2020. A clear diurnal cycle of
586   atmospheric water vapor isotopes existed during the study periods, which was more pronounced
587   in 2019 than in 2020. The diurnal isotopic differences of atmospheric water vapor among
588   measurement heights (i.e., 1, 3, and 15 m) were more evident in the daytime (8:00-20:00 LST)
589   than at night (20:00-8:00 LST). Rainfall events had a significant impact on the diurnal dynamics
590   of atmospheric water vapor δ^2H, δ^{18}O, and *d-excess*, depending on the rainfall intensity (i.e.,
591   amount and duration). The correlations between atmospheric water vapor isotopes and local
592   meteorological factors were weak or nonexistent in the study region. Instead, the spatial-
593   temporal dynamics of atmospheric water vapor isotopes were highly consistent with the
594   monsoon activities. The moisture in air masses could be clustered into three to-five primary
595   sources, with over 60% from the ocean sources. High *d-excess* values reflected the
596   predominating influences of ocean air masses on atmospheric water vapor cycles in the coastal
597   regions.

598

Acknowledgments

612

613   **Open Research**

614   Data for this study consist of water isotopes and environmental variables that are available at
615   https://doi.org/10.11888/Atmos.tpdc.272899
616

617 **References**

618 Aemisegger, F., Pfahl, S., Sodemann, H., Lehner, I., Seneviratne, S. I., & Wernli, H. (2014).

619 Deuterium excess as a proxy for continental moisture recycling and plant transpiration.

620 *Atmospheric Chemistry and Physics*, *14*(8), 4029-4054. https://doi.org/10.5194/acp-14-

621 4029-2014

622 Araguas-Araguas, L., Froehlich, K., Rozanski, K. (2000). Deuterium and oxygen-18 isotope

623 composition of precipitation and atmospheric moisture. *Hydrological Processes*, *14*(8),

624 1341-1355. https://doi.org/10.1002/1099-1085(20000615)14:8<1341::Aid-

625 hyp983>3.0.Co;2-z

626 Aron, P. G., Poulsen, C.J., Fiorella, R. P., & Matheny, A. M. (2019). Stable water isotopes reveal

627 effects of intermediate disturbance and canopy structure on forest water cycling. *Journal of*

628 *Geophysical Research: Biogeosciences*, *124*(10), 2958-2975.

629 https://doi.org/10.1029/2019jg005118

630 Bagheri, R., Bagheri, F., Karami, G. H., & Jafari, H. (2019). Chemo-isotopes (^{18}O & ^{2}H)

631 signatures and HYSPLIT model application: Clues to the atmospheric moisture and air mass

632 origins. *Atmospheric Environment*, *215*, 116892.

633 https://doi.org/10.1016/j.atmosenv.2019.116892

634 Bailey, A., Noone, D., Berkelhammer, M., Steen-Larsen, H. C., & Sato, P. (2015). The stability

635 and calibration of water vapor isotope ratio measurements during long-term deployments.

636 *Atmospheric Measurement Techniques*, 4521-4538. https://doi.org/10.5194/amt-8-4521-

637 2015

638 Bastrikov, V., Steen-Larsen, H. C., Masson-Delmotte, V., Gribanov, K., Cattani, O., Jouzel, J., &

639 Zakharov, V. (2014). Continuous measurements of atmospheric water vapour isotopes in

640   western Siberia (Kourovka). *Atmospheric Measurement Techniques*, *7*(6), 1763-1776.

641   https://doi.org/10.5194/amt-7-1763-2014

642   Berkelhammer, M., Hu, J., Bailey, A., Noone, D. C., Still, C. J., Barnard, H., et al. (2013). The

643   nocturnal water cycle in an open-canopy forest. *Journal of Geophysical Research:*

644   *Atmospheres*, *118*(17), 10225-10242. https://doi.org/10.1002/jgrd.50701

645   Bonne, J. L., Behrens, M., Meyer, H., Kipfstuhl, S., Rabe, B., Schönicke, L., et al. (2019).

646   Resolving the controls of water vapour isotopes in the Atlantic sector. *Nature*

647   *Communications*, *10*(1), 1-10. https://doi.org/10.1038/s41467-019-09242-6

648   Bonne, J. L., Meyer, H., Behrens, M., Boike, J., Kipfstuhl, S., Rabe, B. et al. (2020). Moisture

649   origin as a driver of temporal variabilities of the water vapour isotopic composition in the

650   Lena River Delta, Siberia. *Atmospheric Chemistry and Physics*, *20*(17), 10493-10511.

651   https://doi.org/10.5194/acp-20-10493-2020

652   Casado, M., Cauquoin, A., Masson-Delmotte, V., Genthon, C., Kerstel, E., Kassi, S., et al.

653   (2016). Continuous measurements of isotopic composition of water vapour on the East

654   Antarctic Plateau. *Atmospheric Chemistry and Physics*, *16*(13), 8521-8538.

655   https://doi.org/10.5194/acp-16-8521-2016

656   Christner, E., Aemisegger, F., Pfahl, S., Werner, M., Cauquoin, A., Schneider, M. et al. (2018).

657   The climatological impacts of continental surface evaporation, rainout, and subcloud

658   processes on δD of water vapor and precipitation in Europe. *Journal of Geophysical*

659   *Research: Atmospheres*, *123*(8), 4390-4409. https://doi.org/10.1002/2017jd027260

660   Christner, E., Kohler, M., & Schneider, M. (2017). The influence of snow sublimation and

661   meltwater evaporation on δD of water vapor in the atmospheric boundary layer of central

662   Europe. *Atmospheric Chemistry and Physics*, *17*(2), 1207-1225.

663   https://doi.org/10.5194/acp-17-1207-2017

664 Conroy, J. L., Noone, D., Cobb, M. K., Moerman, J. W., & Konecky, B. L. (2016). Paired stable

665   isotopologues in precipitation and vapor: A case study of the amount effect within western

666   tropical Pacific storms. *Journal of Geophysical Research: Atmospheres*, *121*(7), 3290-3303.

667   https://doi.org/10.1002/2015jd023844

668 Craig, H. (1961). Isotopic variations in meteoric waters. *Science*, *133*(346), 1702-1703.

669   https://doi.org/10.1126/science.133.3465.1702

670 Cui, J. P., Tian, L. D., & Gibson, J. J. (2018). When to conduct an isotopic survey for lake water

671   balance evaluation in highly seasonal climates. *Hydrological Processes*, *32*(3), 379-387.

672   https://doi.org/10.1002/hyp.11420

673 Dahinden, F., Aemisegger, F., Wernli, H., Schneider, M. Diekmann, C.J., Ertl, B., et al. (2021).

674   Disentangling different moisture transport pathways over the eastern subtropical North

675   Atlantic using multi-platform isotope observations and high-resolution numerical

676   modelling. *Atmospheric Chemistry and Physics*, *21*(21), 16319-16347.

677   https://doi.org/10.5194/acp-21-16319-2021

678 Dansgaard W. (1964). Stable isotopes in precipitation. *Tellus*, *16*(4): 436-468.

679   https://doi.org/10.3402/tellusa.v16i4.8993

680 Delattre, H., Vallet-Coulomb C., & Sonzogni, C. (2015). Deuterium excess in the atmospheric

681   water vapour of a Mediterranean coastal wetland: regional vs. local signatures. *Atmospheric*

682   *Chemistry and Physics*, *15*(17), 10167-10181. https://doi.org/10.5194/acp-15-10167-2015

683 Devi, P., Jain, A. K., Rao, M. S., & Kumar B. (2014). Experimental study on isotope

684   fractionation of evaporating water of different initial isotopic composition. *Journal of*

685   *Radioanalytical and Nuclear Chemistry*, *302*(2), https://doi.org/10.1007/s10967-014-3368-7

686 Diekmann, C. J., Schneider, M., Knippertz, P., Vries, A. J., Pfahl, S., Aemisegger, F., et al.

687   (2021). A lagrangian perspective on stable water isotopes during the West African

688   Monsoon. *Journal of Geophysical Research: Atmospheres*, *126*(19), e2021JD034895.

689   https://doi.org/10.1029/2021jd034895

690 Farlin, J., Lai, C. T., & Yoshimura, K. (2013). Influence of synoptic weather events on the

691   isotopic composition of atmospheric moisture in a coastal city of the western United States.

692   *Water Resources Research*, *49*(6), 3685-3696. https://doi.org/10.1002/wrcr.20305

693 Fiorella, R. P., Poulsen, C. J. & Matheny, A. M. (2018). Seasonal patterns of water cycling in a

694   deep, continental mountain valley inferred from stable water vapor isotopes. *Journal of*

695   *Geophysical Research: Atmospheres*, *123*(14), 7271-7291.

696   https://doi.org/10.1029/2017jd028093

697 Fiorella, R. P., West, J. B., & Bowen, G. J. (2019). Biased estimates of the isotope ratios of

698   steady-state evaporation from the assumption of equilibrium between vapour and

699   precipitation. *Hydrological Processes*, *33*(19), 2576-2590.

700   https://doi.org/10.1002/hyp.13531

701 Galewsky, J., Jensen, M. P., & Delp, J. (2022). Marine boundary layer decoupling and the stable

702   isotopic composition of water vapor. *Journal of Geophysical Research: Atmospheres*,

703   *127*(3), e2021JD035470. https://doi.org/10.1029/2021jd035470

704   Galewsky, J., Rella, C., Sharp, Z., Samuels, K., & Ward, D. (2011). Surface measurements of

705   upper tropospheric water vapor isotopic composition on the Chajnantor Plateau, Chile.

706   *Geophysical Research Letters*, *38*(17), L17803. https://doi.org/10.1029/2011gl048557

707   Galewsky, J. Steen-Larsen, H. C., Field, R. D., Worden, J., Risi, C., & Schneider, M. (2016).

708   Stable isotopes in atmospheric water vapor and applications to the hydrologic cycle.

709   *Reviews of Geophysics*, *54*(4), 809-865. https://doi.org/10.1002/2015rg000512

710   Gat, J. R. (1996). Oxygen and hydrogen isotopes in the hydrologic cycle. *Annual Review of*

711   *Earth and Planetary Sciences*, *24*, 225-262. https://doi.org/10.1146/annurev.earth.24.1.225

712   Gonzalez, Y., Schneider, M., Rodriguez, S., Christner, E., Garcia, O. E., Cuevas, E., et al.

713   (2016). Detecting moisture transport pathways to the subtropical North Atlantic free

714   troposphere using paired H_2O-δD in situ measurements. *Atmospheric Chemistry and*

715   *Physics*, *16*(7), 4251-4269. https://doi.org/10.5194/acp-16-4251-2016

716   Griffis, T. J., Wood, J. D., Baker, J. M., Lee, X. H., Xiao, K., Chen, Z. C., et al. (2016).

717   Investigating the source, transport, and isotope composition of water vapor in the planetary

718   boundary layer. *Atmospheric Chemistry and Physics*, *16*(8), 5139-5157.

719   https://doi.org/10.5194/acp-16-5139-2016

720   Hu, Y. B., Xiao, W., Wei, Z. W., Welp, L. R., Wen, X. F., & Lee, X. H. (2021). Determining the

721   isotopic composition of surface water vapor flux from high-frequency observations using

722   flux-gradient and keeling plot methods. *Earth and Space Science*, *8*(3), e2020EA001304.

723   https://doi.org/10.1029/2020ea001304

724   Hu, Z. M., Wen, X. F., Sun, X. M., Li, L. H., Yu, G. R., Lee, X. H. & Li S. G. (2014).

725   Partitioning of evapotranspiration through oxygen isotopic measurements of water pools

726   and fluxes in a temperate grassland. *Journal of Geophysical Research: Biogeosciences*,

727   *119*(3), 358-371. https://doi.org/10.1002/2013jg002367

728 Huang, L. J., & Wen, X F. (2014). Temporal variations of atmospheric water vapor δD and δ^{18}O

729   above an arid artificial oasis cropland in the Heihe River Basin. *Journal of Geophysical*

730   *Research: Atmospheres*, *119*(19), 11456-11476. https://doi.org/10.1002/2014jd021891

731 Huang, Y. Y., Wang, B., Li, X. F., & Wang, H. J. (2018). Changes in the influence of the

732   western Pacific subtropical high on Asian summer monsoon rainfall in the late 1990s.

733   *Climate Dynamics*, *51*(1-2), 443-455. https://doi.org/10.1007/s00382-017-3933-1

734 Kurita, N., Newman, B. D., Araguas-Araguas, L. J., & Aggarwal, P. (2012). Evaluation of

735   continuous water vapor δD and δ^{18}O measurements by off-axis integrated cavity output

736   spectroscopy. *Atmospheric Measurement Techniques*, *5*(8), 2069-2080.

737   https://doi.org/10.5194/amt-5-2069-2012

738 Lai, C.T., & Ehleringer, J. (2011). Deuterium excess reveals diurnal sources of water vapor in

739   forest air. *Oecologia*, *165*(1), 213-223. https://doi.org/10.1007/s00442-010-1721-2

740 Lai, X., Wright, J. S., Huang, W. Y., Liang, J., Lin, G. H., & Zhu, S. X. (2018). Contributions of

741   atmospheric transport and rain-vapor exchange to near-surface water vapor in the Zhanjiang

742   Mangrove Reserve, southern China: an isotopic perspective. *Atmosphere*, *9*(9), 365.

743   https://doi.org/10.3390/atmos9090365

744 Laonamsai, J., Ichiyanagi, K., Patsinghasanee, S., & Kamdee, K. (2021). Controls on stable

745   isotopic characteristics of water vapour over Thailand. *Hydrological Processes*, *35*(7),

746   e14202. https://doi.org/10.1002/hyp.14202

747   Lee, X. H, Sargent, S., Smith, R., & Tanner, B. (2005). In situ measurement of the water vapor

748     $^{18}O/^{16}O$ isotope ratio for atmospheric and ecological applications. *Journal of Atmospheric*

749   *and Oceanic Technology*, *22*(8), 1305-1305. https://doi.org/10.1175/JTECH9001.1a

750   Lee, X. H., Smith, R., & Williams, J. (2006). Water vapour $^{18}O/^{16}O$ isotope ratio in surface air in

751   New England, USA. *Tellus Series B-Chemical and Physical Meteorology*, *58*(4), 293-304.

752   https://doi.org/10.1111/j.1600-0889.2006.00191.x

753   Lee, X. H., Kim, K., & Smith R. (2007). Temporal variations of the $^{18}O/^{16}O$ signal of the whole-

754   canopy transpiration in a temperate forest. *Global Biogeochemical Cycles*, *21*, GB3013.

755   https://doi.org/10.1029/2006gb002871

756   Li, Y. J., An, W. L., Pang, H. X., Wu, S. Y., Tang, Y. Y., Zhang, W. B., & Hou, S.G. (2020).

757   Variations of stable isotopic composition in atmospheric water vapor and their controlling

758   factors-a 6-year continuous sampling study in Nanjing, eastern China. *Journal of*

759   *Geophysical Research: Atmospheres*, *125*, e2019JD031697.

760   https://doi.org/10.1029/2019jd031697

761   Luo, J. S., Sun, Y. H., Wang, Y. G., Xie, Z. H., & Meng, L. D. (2021). Cenozoic tectonic

762   evolution of the eastern Liaodong Bay sub-basin, Bohai Bay basin, eastern China-

763   Constraints from seismic data. *Marine and Petroleum Geology*, *134*, 105346.

764   https://doi.org/10.1016/j.marpetgeo.2021.105346

765   Mao, D.H., He, X.Y., Wang, Z.M., Tian, Y.L., Xiang, H.X., Yu, H., et al. (2019). Diverse

766   policies leading to contrasting impacts on land cover and ecosystem services in Northeast

767   China. Journal of Cleaner Production, *240*, 117961.

768   https://doi.org/10.1016/j.jclepro.2019.117961

769   Mao, D.H., Wang, Z.M., Du, B.J., Li, L., Tian, Y.L., Zeng, Y., et al. (2020). National wetland

770   mapping in China: A new product resulting from object based and hierarchical classification

771   of Landsat 8 OLI images. ISPRS Journal of Photogrammetry and Remote Sensing, 164, 11-

772   25 https://doi.org/10.1016/j.isprsjprs.2020.03.020

773   Mercer, J. J., Liefert, D. T., & Williams, D. G. (2020). Atmospheric vapour and precipitation are

774   not in isotopic equilibrium in a continental mountain environment. *Hydrological Processes*,

775   *34*(14), 3078-3101. https://doi.org/10.1002/hyp.13775

776   Merlivat, L., & Jouzel, J. (1979). Global climatic interpereptation of the deuterium ^{18}O

777   relationship for precipitation. *Journal of Geophysical Research: Oceans*, *84*(C8), 5029-

778   5033. https://doi.org/10.1029/jc084ic08p05029

779   Munksgaard, N. C., Zwart, C., Haig, J., Cernusak, L. A., & Bird, M. I. (2020). Coupled rainfall

780   and water vapour stable isotope time series reveal tropical atmospheric processes on

781   multiple timescales. *Hydrological Processes*, *34*(1), 111-124.

782   https://doi.org/10.1002/hyp.13576

783   NFGA. (2010). National Wetland Survey Statistics Report. National Foresttry and Grassland

784   Administration (in Chinese). https://www.forestry.gov.cn

785   Noone, D. (2012). Pairing measurements of the water vapor isotope ratio with humidity to

786   deduce atmospheric moistening and dehydration in the tropical midtroposphere. *Journal of

787   Climate*, *25*(13), 4476-4494. https://doi.org/10.1175/jcli-d-11-00582.1

788   Parkes, S. D., McCabe, M. F., Griffiths, A. D., Wang, L. X., Chambers, S., Ershadi, A., et al.

789   (2017). Response of water vapour *D-excess* to land-atmosphere interactions in a semi-arid

790   environment. *Hydrology and Earth System Sciences*, *21*(1), 533-548.

791   https://doi.org/10.5194/hess-21-533-2017

792   Salamalikis, V., Argiriou, A. A., & Dotsika, E. (2015). Stable isotopic composition of

793   atmospheric water vapor in Patras, Greece: a concentration weighted trajectory approach.

794   *Atmospheric Research*, *152*, 93-104. https://doi.org/10.1016/j.atmosres.2014.02.021

795   Steen-Larsen, H. C., Johnsen, S. J., Masson-Delmotte, V., Stenni, B., Risi, C., Sodemann, H., et

796   al. (2013). Continuous monitoring of summer surface water vapor isotopic composition

797   above the Greenland Ice Sheet. *Atmospheric Chemistry and Physics*, *13*(9), 4815-4828.

798   https://doi.org/10.5194/acp-13-4815-2013

799   Steen-Larsen, H. C., Masson-Delmotte, V., Hirabayashi, M., Winkler, R., Satow, K., Prie, F., et

800   al. (2014b). What controls the isotopic composition of Greenland surface snow? *Climate of*

801   *the Past*, *10*(1), 377-392. https://doi.org/10.5194/cp-10-377-2014

802   Steen-Larsen, H. C., Sveinbjörnsdottir, A. E., Jonsson, T., Ritter, F., Bonne, J. L., Masson-

803   Delmotte, V., et al. (2015). Moisture sources and synoptic to seasonal variability of North

804   Atlantic water vapor isotopic composition. *Journal of Geophysical Research: Atmospheres*,

805   *120*(12), 5757-5774. https://doi.org/10.1002/2015jd023234

806   Steen-Larsen, H. C., Sveinbjornsdottir, A. E., Peters, A. J., Masson-Delmotte, V., Guishard, M.

807   P., Hsiao, G., et al. (2014a). Climatic controls on water vapor deuterium excess in the

808   marine boundary layer of the North Atlantic based on 500 days of in situ, continuous

809   measurements. *Atmospheric Chemistry and Physics*, *14*(15), 7741-7756.

810   https://doi.org/10.5194/acp-14-7741-2014

811   Sturm, P., & Knohl, A. (2010). Water vapor δ^2H and δ^{18}O measurements using off-axis

812   integrated cavity output spectroscopy. *Atmospheric Measurement Techniques*, *3*(1), 67-77.

813   https://doi.org/10.5194/amt-3-67-2010

814   Tian, L. D., Yu, W. S., Schuster, P. F., Wen, R., Cai, Z. Y., Wang, D., et al. (2020). Control of

815   seasonal water vapor isotope variations at Lhasa, southern Tibetan Plateau. *Journal of*

816   *Hydrology*, *580*, 124237. https://doi.org/10.1016/j.jhydrol.2019.124237

817   Tremoy, G., Vimeux, F., Vimeux, F., Souley, I., Risi, C., Favreau, G., & Oi, M. (2014).

818   Clustering mesoscale convective systems with laser-based water vapor delta O-18

819   monitoring in Niamey (Niger). *Journal of Geophysical Research: Atmospheres*, *119*(9),

820   5079-5103. https://doi.org/10.1002/2013jd020968

821   Uemura, R., Matsui, Y., Yoshimura, K., Motoyama, H., & Yoshida, N. (2008). Evidence of

822   deuterium excess in water vapor as an indicator of ocean surface conditions. *Journal of*

823   *Geophysical Research: Atmospheres*, *113*, D19114. https://doi.org/10.1029/2008jd010209

824   Vuille, M., Bradley, R. S., Werner, M., Healy, R., & Keimig, F. (2003). Modeling δ^{18}O in

825   precipitation over the tropical Americas: interannual variability and climatic controls.

826   *Journal of Geophysical Research: Atmospheres*, *108*(D6), 4174.

827   https://doi.org/10.1029/2001jd002038

828   Wang, G. D., Wang, M., Lu, X. G., & Jiang, M. (2016). Surface elevation change and

829   susceptibility of coastal wetlands to sea level rise in Liaohe Delta, China. *Estuarine Coastal*

830   *and Shelf Science*, *180*, 204-211. https://doi.org/10.1016/j.ecss.2016.07.011

831   Wang, G. Y., Lan, H. M., & Liu, Z. F. (2021). Stable isotope record of super typhoon Lekima

832   (2019). *Atmospheric Research*, *264*, 264, 105822.

833   https://doi.org/10.1016/j.atmosres.2021.105822

834   Wei, Z. W., & Lee, X. H. (2019). The utility of near-surface water vapor deuterium excess as an

835   indicator of atmospheric moisture source. *Journal of Hydrology*, *577*, 123923.

836   https://doi.org/10.1016/j.jhydrol.2019.123923

837 Wei, Z. W., Yoshimura, K., Okazaki, A., Kim, W., Liu, Z. F., & Yokoi, M. (2015). Partitioning

838   of evapotranspiration using high-frequency water vapor isotopic measurement over a rice

839   paddy field. *Water Resources Research*, *51*(5), 3716-3729.

840   https://doi.org/10.1002/2014wr016737

841 Welp, L. R., Lee, X. H., Griffis, T. J., Wen, X. F., Xiao, W., Li, S. G., et al. (2012). A meta-

842   analysis of water vapor deuterium-excess in the midlatitude atmospheric surface layer.

843   *Global Biogeochemical Cycles*, *26*, GB3021. https://doi.org/10.1029/2011gb004246

844 Wen, X. F., Lee, X. H., Sun, X. M., Wang, J. L., Hu, Z. M., Li, S.G., & Yu, G.R. (2012). Dew

845   water isotopic ratios and their relationships to ecosystem water pools and fluxes in a

846   cropland and a grassland in China. *Oecologia, 168*(2), 549-561.

847   https://doi.org/10.1007/s00442-011-2091-0

848 Wen, X. F., Sun, X. M., Zhang, S. C., Yu, G. R., Sargent, S. D., & Lee, X. H. (2008).

849   Continuous measurement of water vapor D/H and $^{18}O/^{16}O$ isotope ratios in the atmosphere.

850   *Journal of Hydrology*, *349*(3-4), 489-500. https://doi.org/10.1016/j.jhydrol.2007.11.021

851 Wen, X. F., Zhang, S. C., Sun, X. M., Yu, G. R., & Lee, X. H. (2010). Water vapor and

852   precipitation isotope ratios in Beijing, China. *Journal of Geophysical Research:*

853   *Atmospheres*, *115*, D1103. https://doi.org/10.1029/2009jd012408

854 Wu, H. W, Li, X. Y., Zhang, J. M., Li, J., Liu, J. Z., Tian, L. H., & Fu, C.S. (2019). Stable

855   isotopes of atmospheric water vapour and precipitation in the northeast Qinghai-Tibetan

856   Plateau. *Hydrological Processes*, *33*(23), 2997-3009. https://doi.org/10.1002/hyp.13541

857 Wu, X. X., Chen, F. L., Liu, X. Y, Wang, S. J., Zhang, M. J., Zhu, G. F., et al. (2021). The

858   significance of hydrogen and oxygen stable isotopes in the water vapor source in Dingxi

859   area. *Water*, *13*(17), 2374. https://doi.org/10.3390/w13172374

Xiao, W., Lee, X. H., Hu, Y. B., Liu, S. D., Wang, W., Wen, X. F., et al. (2017). An experimental investigation of kinetic fractionation of open-water evaporation over a large lake. *Journal of Geophysical Research: Atmospheres*, *122*(21), 11651-11663. https://doi.org/10.1002/2017jd026774

Xu, T., Pang, H. X., Zhan, Z. J., Zhang, W. B., Guo, H. W., Wu, S. Y., & Hou, S. G. (2022). Water vapor isotopes indicating rapid shift among multiple moisture sources for the 2018-2019 winter extreme precipitation events in southeastern China. *Hydrology and Earth System Sciences*, *26*(1), 117-127. https://doi.org/10.5194/hess-26-117-2022

Zhang, S. C., Sun X. M., Wang J. L., Yu, G. R., Wen, X. F. (2011). Short-term variations of vapor isotope ratios reveal the influence of atmospheric processes. *Journal of Geographical Sciences*, *21*(3), 401-416. https://doi.org/10.1007/s11442-011-0853-6

Zhao, L., Wang, L., Liu, X., Xiao, H., Ruan, Y., & Zhou, M. (2014). The patterns and implications of diurnal variations in the d-excess of plant water, shallow soil water and air moisture. *Hydrology and Earth System Sciences*, *18*(10), 4129-4151. https://doi.org/10.5194/hess-18-4129-2014