

1 Working Title: **Seasonal and Spatial variation in the stable isotopic composition ($\delta^{18}\text{O}$
2 **and δD) of precipitation in south Florida****

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20

21 **Abstract**

22 Precipitation data collected from 5 sites in south Florida indicate a strong seasonal and
23 spatial variation in $\delta^{18}\text{O}$ and δD , despite the relatively limited geographic coverage and low-
24 lying elevation of each of the collection sites. Based upon the weighted-mean stable isotope
25 values, the sites were classified as coastal Atlantic, inland, and lower Florida Keys. The coastal
26 Atlantic sites had weighted-mean values of $\delta^{18}\text{O}$ and δD of -2.86‰ and -12.8‰ , respectively,
27 and exhibited a seasonal variation with lower δD and $\delta^{18}\text{O}$ values in the summer wet-season
28 precipitation ($\delta^{18}\text{O} = -3.38\text{‰}$, $\delta\text{D} = -16.5\text{‰}$) as compared to the winter-time precipitation
29 ($\delta^{18}\text{O} = -1.66\text{‰}$, $\delta\text{D} = -3.2\text{‰}$). The inland site was characterized as having the highest d-
30 excess value ($+13.3\text{‰}$), signifying a contribution of evaporated Everglades surface water to the
31 local atmospheric moisture. In spite of its lower latitude, the lower Keys site located at Long
32 Key had the lowest weighted mean stable isotope values ($\delta^{18}\text{O} = -3.64\text{‰}$, $\delta\text{D} = -20.2\text{‰}$) as
33 well as the lowest d-excess value of ($+8.8\text{‰}$). The lower δD and $\delta^{18}\text{O}$ values observed at the
34 Long Key site reflect the combined effects of oceanic vapor source, fractionation due to local
35 precipitation, and slower equilibration of the larger raindrops nucleated by a maritime aerosol.
36 Very low δD and $\delta^{18}\text{O}$ values ($\delta^{18}\text{O} < -6\text{‰}$, $\delta\text{D} < -40\text{‰}$) were observed just prior to the
37 passage of hurricanes from the Gulf of Mexico as well as during cold fronts from the north-west.
38 These results suggest that an oceanic vapor source region to the west, may be responsible for the
39 extremely low δD and $\delta^{18}\text{O}$ values observed during some tropical storms and cold fronts.

40 **1.1 Introduction**

41 Natural variations of $\delta^{18}\text{O}$ and δD in precipitation have been used in a variety of
42 hydrologic, ecological, and climate studies. As an integral part of the hydrologic cycle, $\delta^{18}\text{O}$ and
43 δD in precipitation was used as a tracer of groundwater recharge (Gat, 1971; Lee et al., 1999;
44 Price and Swart, 2006; Scholl et al., 1998), as well as a source of river water (Dutton et al., 2005;
45 Welker, 2000) and lake water (Gonfiantini, 1986; Hostetler and Benson, 1994). In ecological
46 studies, δD values of precipitation have been used to determine the migration patterns of birds
47 (Hobson et al., 2001; Hobson and Wassenaar, 1996) and other animals (Rubenstein and Hobson,
48 2004), as well as plant physiological functions (Ehleringer et al., 1991; Flanagan et al., 1992). In
49 climate studies, historical variations in $\delta^{18}\text{O}$ and δD of precipitation have been inferred as
50 preserved in tree cellulose (Anderson et al., 1998), ice cores (Dansgaard et al., 1993), and
51 carbonates (Hays and Grossman, 1991). The δD and $\delta^{18}\text{O}$ of precipitation can be used as an
52 indicator of climatic conditions as higher precipitation amounts tend to produce lower δD and
53 $\delta^{18}\text{O}$ values (Dansgaard, 1964). In addition, the δD and $\delta^{18}\text{O}$ of precipitation from hurricanes
54 and tropical storms tend to be very low (Lawrence and Gedzelman, 1996), as they act as efficient
55 fractionation chambers (Gedzelman et al., 2003; Trenberth, 2005). Meteorological opinion is
56 divided on the effects on Atlantic Tropical Cyclone (TC) numbers and intensity of global
57 warming (Emanuel 2005, Webster et al. 2005, Pileke et al. 2005, Pielke 2007) or natural cycles
58 (Goldenberg et al. 2001, Mann and Emanuel 2006). The 107 year (1900-2006) quantitative record
59 is too short relative to documented natural climatic variations and suffers from observational
60 lacunae before 1960 when meteorological satellites came into use (Landsea et al. 2006, Landsea
61 2007). Consequently, geological proxy records will prove essential as baselines for assessing
62 both anthropogenic changes in hurricane activity and natural variability in the unforced climate

63 (Liu 2004). There is an observed increase in surface sea temperature (Emanuel 2005, Webster et
64 al. 2005), which in turn is expected to lead to increased evaporation and atmospheric moisture.
65 This could lead to higher precipitation amounts and potentially to a change in the stable isotopic
66 signature of precipitation and subsequently surface waters and groundwaters of these regions.

67 The δD and $\delta^{18}O$ of precipitation is currently measured at over 300 stations across the
68 globe as part of the Global Network for Isotopes in Precipitation (GNIP), which is co-operated
69 by the International Atomic Energy Agency (IAEA) and the World Meteorological Organization
70 (WMO) (<http://isohis.iaea.org>). Despite the large number of stations in the GNIP, there are only
71 four active coastal sites (Cuba; Bermuda; Hatteras, North Carolina, and the Dominican Republic)
72 in the tropical Atlantic where hurricanes are frequent. Although a site in Miami, Florida is
73 currently part of the GNIP for tritium, it is not included for the stable isotopes of oxygen and
74 hydrogen. Amount-weighted annual precipitation maps produced from the GNIP data set have
75 the isotopic composition of precipitation in south Florida between -2 ‰ and -6 ‰ for $\delta^{18}O$,
76 and -6 ‰ to -38 ‰ for δD . Precipitation collected from the region and published to date
77 corresponded with the GNIP values (Price and Swart, 2006; Swart et al., 1989; Wilcox, 2004).
78 Each of those studies reported variability in the isotopic composition of precipitation in south
79 Florida, but there was no attempt to correlate precipitation $\delta^{18}O$ and δD values on a seasonal or
80 event driven basis. The objectives of this study were 1) to establish a long-term data set of the
81 oxygen and hydrogen isotopic composition of precipitation in south Florida in order to assist in
82 hydrologic and ecohydrologic studies being conducted in the region; 2) to document the
83 seasonal (short-term) and spatial variability in the stable isotopic composition of precipitation in
84 a semi-tropical, coastal region where temperature changes are minimal; and 3) to show the
85 influence of hurricanes on the isotopic composition of subtropical rainfall.

86 **1.2 South Florida Weather**

87 The Miami metropolitan area has a tropical, maritime climate (Trewartha 1954)
88 characterized by a June-October rainy season (Fig. 1). In summer and early fall, prevailing winds
89 blow from the southeast. The winds circle around the western end of the Bermuda High and
90 import Maritime-Tropical Air from the tropical North Atlantic. During this period, south Florida
91 weather is dominated by the diurnally forced sea-breeze, occasional easterly waves that originate
92 from Africa, and tropical cyclones that may drop tens of centimeters of precipitation in a single
93 event as they make landfall.

94 The months of November through May are characterized by a quasi-periodic alternation
95 of Maritime-Tropical Air with modified Continental-Polar Air from a high latitude North-
96 American source. The four- to eight- day middle-latitude cyclone cycle sets the tempo of the
97 weather. Most of the time, even in winter, Maritime Tropical air covers South Florida. As cold
98 fronts approach, the south-easterlies strengthen. Brief, but sometimes intense, precipitation
99 occurs as the front passes and the wind veers from the northwest or north and temperatures fall.
100 Many winters see episodes with single-digit (Celsius) temperatures, but frost is rare. In the days
101 after frontal passage the wind veers from the northeast, east, and finally from the southeast again.

102 Most of the moisture that falls as precipitation in southeast Florida originally evaporated
103 from the trade-wind belt of the tropical North Atlantic. Air entering the Trades of the African
104 coast has a low inversion capped by a strong surface mixed layer with much drier air above. As it
105 follows a westward trajectory, evaporation from the sea moistens the air below the inversion
106 while convectively generated turbulence raises the inversion by downward entrainment and
107 moistening of dry air from above (Riehl and Malkus 1957). Showers confined to the moist air
108 below the inversion further fractionate the stable isotopes toward low ratio values. During the

109 South Florida rainy season, upstream diurnal convection over the Bahamas and Greater Antilles
110 as well as nighttime convection offshore over the Gulf Stream enhance this effect.

111 Rarely during the cool season, when a deep, long-wave trough digs southward near
112 longitude 80° W, the resulting low-latitude westerlies bring moisture from the Gulf of Mexico,
113 Caribbean, or even the tropical Western Pacific. While local evapotranspiration rates are high
114 over the Florida peninsula in summer, air-mass residence times over the land are so short that
115 little moisture is recycled locally. Price and Swart (2006) have determined through a stable
116 isotope evaporation model, that evaporated seawater is the dominant contributor of atmospheric
117 moisture that moves over south Florida, and that evaporation of Everglades surface water
118 contributes between 7 and 12% of the local atmospheric vapor.

119

120 **2.0 Methods**

121 Precipitation samples were collected at five sites in south Florida (Fig. 2). Two sites
122 were located along the eastern coastline of south Florida; one on the roof of the Rosenstiel
123 School of Marine and Atmospheric Sciences (RSMAS) and the other at the headquarters of
124 Biscayne National Park (BNP). Two sites are located along the Florida Keys, one at Key Largo
125 and the other in Long Key. The precipitation collectors at BNP, Key Largo, and Long Key were
126 on docks positioned either over the water or adjacent to the coastline. The elevation of these
127 collectors were less than 2 m above mean sea level. The Redlands site is located approximately
128 16 km at an elevation of about 3 m above sea level. The RSMAS precipitation collector was
129 located about 100 m inland at an approximate elevation of 13 m.

130 At all but the Redlands site, precipitation was collected in a wet/dry collector made by
131 Aerochemitrics. This collector has two buckets, one to collect dry deposition and the other to

132 collected wet deposition (precipitation). Contents of the dry deposition bucket were not used in
133 this study. The collector was equipped with a sensor that when wet activated a mechanical arm
134 that moved a cover from the wet collection bucket to the dry collection bucket, thereby exposing
135 the wet collection bucket to receive precipitation. The sensor was heated and allowed for rapid
136 evaporation of atmospheric moisture that had collected on it at the end of a precipitation event,
137 and once dry, the mechanical arm moved back to cover the wet collection bucket. The cover
138 consisted of a foam pad encased in plastic wrap and formed a tight seal over the wet collection
139 bucket to prevent evaporation of the sample. On a weekly basis, water from the collector was
140 transferred to a 40 mL glass bottle and sealed with a rubber stopper and crimp cap. At the
141 Redlands site, precipitation was collected in a standard forestry 6-inch rain gauge on a daily basis
142 and then transferred to a dark, capped bottle that was kept indoors. On an approximately
143 monthly basis, water from this bottle was transferred to a smaller 120-mL plastic bottle with a
144 screw cap.

145 Precipitation amount was recorded at the RSMAS site by measuring volumetrically the
146 amount of water collected. At the Redlands site, precipitation amount was recorded from the 6-
147 inch forestry rain gauge. At the Key Largo site and Long Key sites, precipitation amount was
148 recorded by measuring with a ruler inside of the collection bucket, which had straight sides.
149 Precipitation amounts were missing from the BNP site, therefore, precipitation data recorded at
150 the Homestead Airforce Base (NOAA web site reference), approximately 1 mile inland of BNP
151 was used instead (Fig. 2). The precipitation amount was combined with the δD and $\delta^{18}O$ values
152 to determined amount-weighted mean values for each site.

153 This paper presents precipitation data collected at five sites in south Florida (Fig. 2) from
154 1997 through 2006. The collection times at each of the sites varied (Table. 1). The longest

155 record is from the RSMAS site with about five years of approximately weekly data spanning two
156 time periods from Dec. 1999 until Aug. 2001, and then between Aug. 2003 and Dec. 2006. Four
157 years of monthly precipitation samples were collected at the Redland site between Aug. 1997
158 and Aug. 2001. Three years of weekly precipitation data was collected at BNP between Sept.
159 2003 and Sept. 2006. Precipitation was collected for one year at the Key Largo and Long Key
160 sites; however, breakage of many of the sample bottles from Key Largo resulted in only 18
161 weekly samples available for isotope analysis. Concerns over losing the collectors at the Key
162 Largo, RSMAS and BNP sites in hurricane force winds, often prompted the removal of these
163 collectors several days prior to the approach of hurricanes. As a result, precipitation was not
164 collected during landfall of some hurricanes including hurricane Mitchell between November 3 –
165 19, 2001 and hurricanes Katrina and Wilma in August and October of 2005, respectively.

166 The number of samples collected at each of the sites was not evenly distributed
167 throughout the year. A lack of precipitation during the dry-season months of February through
168 April resulted in very few precipitation samples collected during these months. There were often
169 2 to 3 times as many precipitation samples available at each site during the rainy season months
170 of June through November, than for the dry season months. For example, of the 64 samples
171 analyzed from BNP, only 11, representing 17% of the samples, were collected between January
172 and May, with no precipitation samples collected in April. At the Redland site, 2 or fewer
173 samples were available for the months of December, March and April. Seasonal amount
174 weighted-mean values of $\delta^{18}\text{O}$, δD and d-excess were determined at four sites: Redlands,
175 RSMAS, BNP, and Long Key as at least 1 year of data was obtained from these sites. The data
176 from each site was grouped into wet-season (June through October) and dry season (November
177 through May). In order to determine the seasonal trends in the δD and $\delta^{18}\text{O}$ values, the RSMAS

178 data set (the site with the longest record) were averaged into weekly values using rectangular
179 interpolation methods and subjected to frequency analysis using Statistica.

180 A total of 286 samples of precipitation were analyzed in duplicate for $\delta^{18}\text{O}$ and δD at
181 RSMAS by mass spectrometry using modified methods of (Epstein and Mayda, 1953) and
182 (Coplen et al., 1991), respectively. The δD and $\delta^{18}\text{O}$ values are reported using the conventional
183 notation relative to the Vienna Standard Mean Ocean Water (VSMOW) standard. The mass
184 spectrometer used was a Europa Geo 20-20 equipped with an autosampler-equilibration unit
185 (Europa WES). Samples were analyzed in duplicate. The precision of these methods was ± 0.08
186 ‰ for $\delta^{18}\text{O}$ and ± 1.5 ‰ for δD . Deterium excess (d-excess or 'd') of each of the water
187 samples was estimated as $d = \delta\text{D} - 8\delta^{18}\text{O}$ (Dansgaard, 1964).

188 Climatologically data for south Florida was obtained from the National Climatic Data
189 Center (<http://www.ncdc.noaa.gov>). Long-term data (1971 – 2006) was obtained from Miami
190 International Airport. Precipitation and air temperature data were obtained from this site and
191 compared to isotopic data collected in this investigation.

192

193 **3.0 Results**

194 3.1 Stable isotopic variation by location

195 The $\delta^{18}\text{O}$ values of all the precipitation data ranged from -10.31 ‰ to $+1.53$ ‰, with
196 92 % of the values occurring between -4.5 ‰ and $+1.5$ ‰ (Tables 2-6). Precipitation δD values
197 ranged from -77.8 ‰ to $+21.0$ ‰, with 92% of the values occurring between -30 ‰ and $+20$ ‰.
198 The $\delta^{18}\text{O}$ and δD values plot close to the Global Meteoric Water Line (GMWL) as defined by
199 (Craig, 1961) as having a slope of 8 and an intercept of 10 (Fig. 3). A least square regression of
200 the data resulted in the equation:

201

202
$$\delta D = (7.4 \pm 0.2) \delta^{18}O + (8.62 \pm 0.49) \quad r^2 = 0.86 \quad n = 280; \quad (1)$$

203

204 while an orthogonal regression of the data resulted in the equation:

205

206
$$\delta D = (8.6 \pm 0.4) \delta^{18}O + (11.0 \pm 0.9) \quad r^2 = 0.86 \quad n = 280. \quad (2)$$

207

208 The weighted-mean values of all the data were $\delta^{18}O = -2.98 \pm 0.12 \text{ ‰}$ and $\delta D = -12.9 \pm 0.9 \text{ ‰}$
209 (Fig. 3).

210 Weighted-mean values of $\delta^{18}O$ and δD varied by site (Fig. 4). Precipitation collected at
211 the Long Key site had the lowest precipitation amount weighted-mean $\delta^{18}O$ and δD of -3.64 ‰
212 and -20.2 ‰ , respectively, and were significantly different than values obtained for the other
213 four sites. The weighted-mean stable isotope values for precipitation collected at RSMAS, BNP,
214 and Key Largo were similar and overlapped within their respective standard error. The
215 weighted-mean stable isotope value for the Redland site fell to the left of the GMWL (Fig. 4).

216

217 3.2 Stable isotope variation with time

218 Observation of the $\delta^{18}O$ values for each site with time, indicate events with large negative
219 shifts (Fig. 5). These events are identified by the names of tropical storms where appropriate or
220 by their dates of collection when there was no tropical cyclone. Some of these events, such as
221 Hurricane Irene (Oct. 1999) (Fig. 5) and the No-name storm (Oct. 2000) coincide with high
222 amounts of precipitation in which over 254 mm of precipitation fell within a 24-hour period.

223 However, the lowest stable isotope values were recorded from precipitation collected one and
224 two weeks prior to Hurricane Wilma making landfall on October 2005.

225 The results of the spectral analysis of the RSMAS data resulted in strong positive peaks
226 at 52 weeks, 31 to 33 weeks, and 12-14 weeks (Fig. 6) The 52 week period reflects an annual
227 variation in the $\delta^{18}\text{O}$ values, while the 31-33 week peak reflects differences between the isotopic
228 values of the precipitation in the wet and dry seasons. When the precipitation data were grouped
229 into wet and dry seasons, significantly lower values in $\delta^{18}\text{O}$ and δD were obtained at RSMAS
230 and BNP during the wet season as compared to the dry season (Table 7). The seasonal averaged
231 $\delta^{18}\text{O}$ and δD values for the Redland and Long Key sites were within the standard error for the
232 wet and dry seasons. Amount-weighted, annual values of $\delta^{18}\text{O}$ and δD were determined for those
233 sites with a complete year of data (Table 8). At the Redlands site, for the years 1998 through
234 2000, the most negative $\delta^{18}\text{O}$ and δD values were observed in 1999, while the least negative
235 values were observed in 1998. Precipitation collected at the RSMAS and BNP had the least
236 negative isotopic values in 2004, and the most negative values in 2005.

237 South Florida precipitation as measured at the Miami International Airport (MIA; NCDC
238 web site) indicates that during the 10 years of this study, annual precipitation varied from 138 cm
239 yr^{-1} in 2004 to 183 cm yr^{-1} in 2003 (Fig. 7). The 10-year average of 167 cm yr^{-1} , was higher than
240 the 30-year average (1976-2005) value of 155 cm yr^{-1} . In general, above average precipitation
241 occurred throughout the 10-year period except for 2004 (Fig. 7).

242

243 **4.0 Discussion**

244 ***4.1 Spatial Variability***

245 Dansgaard (1964) was the first to recognize that the δD and $\delta^{18}O$ composition of
246 precipitation was negatively correlated with temperature, latitude, altitude, distance from the
247 coast, and the amount of precipitation. Of those correlations, temperature and the continual loss
248 of moisture from an air mass as it moves away from its evaporative vapor source are considered
249 to be overriding factors (Yurtsever 1975; Gat 1996). However, mixing of different air masses
250 from local vapor sources (Gat and Matsui, 1991) as well as storm trajectory (Friedman et al.,
251 1992; Lawrence et al., 1982) also influence the isotopic signature of local precipitation.

252 Despite the relatively limited geographic coverage and low-lying elevation of each of the
253 collection sites, the precipitation data from the five sites monitored in south Florida can be
254 grouped into the 3 geographic classifications based upon their isotopic signatures: 1) coastal
255 Atlantic; 2) inland; and 3) lower Keys. These classifications are similar to the coastal,
256 continental, and marine sites, respectively, first defined by Rozanski et al. (1993) during the
257 review of the GNIP network. The coastal Atlantic sites in south Florida include RSMAS, BNP,
258 and Key Largo. These sites are characterized as having the highest mean $\delta^{18}O$ and δD values
259 (Table 1) that fall on or near the GMWL (Fig. 4) and are located within 100 m of the coastline.
260 The Redlands site is classified as an inland site. Although most common for inland sites to have
261 lower δD and $\delta^{18}O$ values than coastal sites due to “rain-out” of a moisture air mass as it moves
262 inland, this effect can be lessened with an intense recycling of water from within a basin by
263 evapotranspiration as observed in the Amazon Basin (Martinelli et al., 1996). The plotting of the
264 weighted-mean δD and $\delta^{18}O$ values of the Redland data to the left of the GMWL (Fig. 4) along
265 with a high d-excess value ($>13\text{‰}$), particularly in the wet season (Table 7) points to a

266 contribution of evaporated surface water from the Everglades to the local atmospheric moisture,
267 which can be as high as 12% (Price and Swart, 2006).

268 The δD and $\delta^{18}O$ composition of precipitation from Long Key is significantly more
269 negative compared to the other south Florida sites (Fig. 4). It also has the lowest d-excess value
270 of all the sites, particularly in the wet season (Table 7). This period of data collection at the Long
271 Key site, however, only partly overlaps the Key Largo station, and not at all with the other sites.
272 Low d-excess values ($<10 \text{ ‰}$) tend to be found over oceanic vapor source regions with high
273 annual relative humidity ($>85\%$) (Bowen and Revenaugh, 2003; Merlivat and Jouzel, 1979).
274 Annual relative humidity (R.H.) over the waters of the west Florida Shelf average near 75%
275 (Virmani and Weisberg, 2005), with lower R.H. values in the summertime due to higher air
276 temperatures. This average annual R.H is also similar to that measured at Miami airport of 74%
277 (www.ncdc.noaa.gov), therefore, higher R.H. values do not seem to be responsible for the lower
278 d-excess and lower isotopic values measured at Long Key. Higher precipitation amounts have
279 been correlated with lower isotope values (Dansgaard, 1964), however, precipitation amounts in
280 south Florida lesson towards the south. For instance, during the year that precipitation was
281 collected at Long Key (2002) precipitation amounts varied from north to south from 1,600 mm at
282 Miami International Airport to 1,510 mm in Key Largo and 993 mm at Long Key
283 (www.ncdc.noaa.gov/7.17.07). This is consistent with a sea-breeze effect causing more rain over
284 the mainland of Florida as compared to adjacent islands (Pielke, 1974).

285 The air passing over Long Key derives predominantly from the tropical North Atlantic. It
286 contains a maritime aerosol with $\sim 10^2$ condensation nuclei cm^{-3} exhibiting a wide range of
287 activities. Convective clouds forming in this air produce precipitation easily through the collision
288 coalescence at temperatures warmer than -10°C . The resulting large raindrops fall to the surface

289 quickly without opportunity to equilibrate with lower-tropospheric vapor. By contrast,
290 continental aerosols contain $\sim 10^3$ condensation nuclei cm^{-3} and produce precipitation primarily
291 through the Bergeron-Findeisen process. Although hydrometeors form at colder temperatures,
292 convective instability is generally too weak to produce hail. In these clouds, snow produced at
293 temperatures colder than -20°C , falls through the 0°C isotherm (at ~ 6 km) and melts to form
294 relatively small raindrops (Fletcher 1969). Because of their large area to volume ratios and slow
295 terminal velocities, they have a chance to equilibrate with lower-tropospheric isotope ratios. Also
296 precipitation over the ocean tends to occur in the late evening to early morning hours when
297 temperatures are cooler as compared to most land areas in the afternoon when precipitation peaks
298 (Yang and Smith, 2006). Both larger raindrops as well as the potential for more night-time
299 precipitation (Yang and Smith, 2006) may explain the lower isotopic signature of precipitation at
300 the Long Key site. Remember, that the observations at the Long Key site are based on only one
301 year of precipitation data, and additional monitoring may be necessary to confirm the results
302 presented here.

303

304 ***4.2 Seasonal Variability***

305 A seasonal variation in the δD and $\delta^{18}\text{O}$ signature of the precipitation in south Florida is
306 observed with lower values obtained during the wet season (Table 7). Lower air temperatures
307 are most commonly associated with lower δD and $\delta^{18}\text{O}$ values and are most responsible for
308 seasonal patterns observed in the isotopic values of precipitation in mid-latitude temperate
309 climates (Rozanski et al., 1993; Vreča et al., 2006). However, this is generally not the case in
310 tropical coastal settings where there is a minimal annual variation in air temperature (Rozanski et
311 al., 1993), nor is this the case in South Florida. Lower δD and $\delta^{18}\text{O}$ values tend to be found in

312 precipitation during the wet season (Table 7), from June through October, when the air
313 temperature is highest (Fig. 1), fractionation by regional upstream precipitation is most common,
314 and disequilibrium of larger hydrometeors as they fall through the lower troposphere is greatest.
315 In addition, lower isotope values in precipitation as a result of increased storm activity over the
316 ocean has been observed in the Tropics (Lawrence et al., 2004). The drop in δD and $\delta^{18}O$ values
317 in the beginning (May-June) and end (October-November) of the rainy season (Fig. 5) is
318 interesting and suggestive of different atmospheric sources during these months as compared to
319 the other rainy season months of July through September. Evaporation in south Florida is
320 highest in March through August, with the highest values typically observed in May (Abteu,
321 2001; Price et al., 2007). Surface water levels in the Everglades, however, often decline
322 throughout the winter dry season with the lowest levels in April or May (Harvey et al., 2004;
323 Price et al., 2003). Although evaporation rates are highest in May, there is often little to no
324 surface water available to contribute to the local atmospheric moisture. The first rains of the
325 wet-season that occur in May or sometimes June, therefore, must originate from an oceanic
326 source. Surface water levels increase from June through October allowing for its evaporation
327 and contribution to the local atmospheric moisture. Tropical cyclones are most common in
328 September and October, and the large negative isotopic values observed in precipitation from
329 these months are a result of these large oceanic forming cyclones passing over south Florida.

330 October cyclones often originate from the Gulf of Mexico, as opposed to the eastern
331 Atlantic and track eastward toward Florida. The Gulf of Mexico storms, such as hurricane Irene
332 (1999), the No-name storm (2000) and hurricane Wilma (2005) produced very low isotope
333 values of $\delta^{18}O < -6\text{‰}$ and $\delta D < -40\text{‰}$ (Fig. 5). The lowest stable isotope values were obtained
334 from precipitation collected at both the RSMAS and BNP sites, 1 to 2 weeks prior to the passage

335 of Hurricane Wilma. Hurricane Wilma was a category 5 storm that sat over the Yucatan
336 peninsula for 3 to 5 days prior to moving east and making landfall in south Florida as a category
337 2 storm on October 24, 2005. Although precipitation was not collected during the landfall of this
338 storm (as all of the precipitation collectors were moved inside at least 1 week prior as part of
339 hurricane preparations in the region), the extremely low stable isotopic values collected 2 weeks
340 prior to the storm are indicative of the storm's influence on the region despite its location over
341 the Yucatan Peninsula, approximately 1000 km to the southwest (Fig. 2). Similar observations
342 of low isotope values in precipitation in Houston, Texas were reported from a squall line
343 associated with Hurricane Opal (Sept. 1995) despite the hurricane not passing over Houston
344 (Lawrence et al., 1998). In addition, low isotope values ($\delta^{18}\text{O}=-16\text{‰}$) were reported in
345 precipitation of the lower Florida Keys during Tropical Storm Gilbert (Sept. 2001) although the
346 storm did not cross the Keys (Lawrence et al., 2004). These events combined with that of the
347 large negative producing events observed in this study, suggests that storms that cross over south
348 Florida from the west tend to bring lower isotope values. Other precipitation events monitored in
349 this study that produced isotopically low values happened in December (1999; 2000) at the
350 Redlands station. The cold-fronts originate from middle latitude North America, and it is
351 common for interior portions of the Florida peninsula to experience colder temperatures than the
352 coastal locations during their winter-time passage.

353 During the 10-year period of study, there were one strong (1997-1998), and two moderate
354 (2002-2003 and 2006) El Niño-Southern Oscillation (ENSO) events (Childers et al., 2006).
355 ENSO events are known to suppress tropical cyclone activity in the western Atlantic and so was
356 the case in those years. A summary of hurricane activity during the decade long study revealed
357 that the average number of tropical cyclones in the Atlantic Ocean was 12. The highest number

358 was recorded in 2005, when 3 cyclones crossed over Florida including Katrina and Wilma. The
359 lowest number of tropical cyclones was recorded during the ENSO years of 1997 and 2006.
360 Although ENSO events tend to reduce tropical cyclone activity they tend not to reduce the
361 amount of annual precipitation in south Florida (Childers et al., 2006). What results is a shift in
362 the precipitation pattern toward more precipitation during the beginning of the dry season
363 (December through February) and even less precipitation than normal at the end of the dry
364 season (March through May). The limited data collected in this investigation precludes a
365 comprehensive analysis of isotopic values in south Florida precipitation with ENSO events.
366 However, low isotope values observed prior to passage of hurricanes, along with the lowest
367 annual average isotopic values observed at RSMAS and BNP during 2005 (Table 8), the year
368 with the most hurricanes, suggests a relationship of lower isotopic values with increased
369 hurricane frequency.

370 Due to the data being composited on weekly and monthly time intervals, it is difficult to
371 reconstruct the isotopic signature of particular cyclones. Often there is extreme variability in the
372 isotopic composition of precipitation throughout a single rain event (Gambell and Frieman,
373 1965; Miyake et al., 1968; Rindsberger et al., 1983) and even spatially within a tropical cyclone
374 (Gedzelman et al., 2003). However, hydrological and paleo-climatological data such as obtained
375 from the isotopic composition of groundwater from wells, often represent smoothed or average
376 precipitation values, therefore weekly or monthly data collection is justified. Price and Swart
377 (2006) illustrate from the monthly collection of surface water and groundwater from the
378 Everglades, there is a seasonal signal in isotopes with lower isotope values observed in the wet-
379 season as compared to the dry-season, corroborating the precipitation isotope patterns found in
380 this study. Inspection of the stable isotopic signature of tree rings, freshwater ostracods or

381 benthic foraminifera in the Everglades may provide a paleoclimate signal for seasonal variation
382 in the isotopic composition of precipitation in south Florida. The Everglades and south Florida
383 has been recognized as a litmus for climate change in a recent NAS report. Sealevel rise,
384 seawater intrusion, and flooding along with the potential loss of freshwater Everglades habitat
385 and its ecosystem species are all concerns. Continued observation of the isotopic composition of
386 precipitation can be used to as an indicator of climate change and its effect on the hydrology of
387 south Florida and the Everglades.

388

389 **5.0 Conclusion**

390 The results of this study indicate a spatial and seasonal variation in the δD and $\delta^{18}O$ of
391 precipitation in south Florida. Spatially, the weighted-mean δD and $\delta^{18}O$ values of precipitation
392 tends to be more positive along the coastal Atlantic regions. Inland sites tend to have more
393 positive d-excess values due to recycling of Everglade surface water. Precipitation from the
394 lower Keys seems to be influenced from a more maritime source, where low cloud condensation
395 nucleus content controls droplet size.

396 The δD and $\delta^{18}O$ signature of precipitation in south Florida varies seasonally with lower
397 δD and $\delta^{18}O$ values observed at the start and end of the summer wet season, and slightly higher
398 isotopic values observed in June through August. The lower δD and $\delta^{18}O$ values suggest a more
399 oceanic vapor source, fractionation by upstream rainout, and the effect of greater disequilibrium
400 between larger hydrometeors as they fall through lower tropospheric isotope ratios whereas the
401 higher values indicate influence of evaporated Everglades surface water. Low δD and $\delta^{18}O$
402 values also are observed in tropical cyclones and cold fronts that come from the west and
403 northwest.

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571

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578

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582

583 **Figure 6.** Results of spectral analysis of the RSMAS data.

584

585 **Figure 7.** Annual precipitation as a departure from the 30-year mean (1976-2005) at Miami
586 International Airport.

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591

1 **Table 1.** Summary of precipitation collection dates, latitude, longitude, number of samples (n), weighted mean $\delta^{18}\text{O}$, δD , and d-excess for each of
 2 the five sites in south Florida.

Site	Latitude	Longitude	Collection Dates	n	Weighted mean $\delta^{18}\text{O}$ (‰)	S.E. $\delta^{18}\text{O}$ (‰)	Weighted mean δD (‰)	S.E. δD (‰)	Weighted mean d-excess (‰)
Redland	25° 31' 08.43" N	80° 29' 28.95" W	8/97-8/01	43	-3.22	0.26	-12.2	2.1	13.4
RSMAS	25° 43' 57.00" N	80° 09' 47.65" W	12/99-8/01, 8/03/12/06	120	-2.80	0.18	-12.3	1.3	10.1
BNP	25° 27' 50.82" N	80° 20' 04.75" W	9/03-1/06	59	-2.82	0.23	-12.9	2.0	9.6
Key Largo	25° 05' 12.03" N	80° 27' 11.14" W	7/01-7/02	14	-2.84	0.37	-12.8	3.3	9.9
Long Key	25° 50' 14.53" N	80° 48' 02.89" W	1/02-12/02	36	-3.64	0.34	-20.2	2.9	8.8

1 **Table 2.** Precipitation amount, $\delta^{18}\text{O}$, and δD for samples collected at Biscayne National Park (BNP).

Date (m/d/yr)	amount ¹ (mm)	$\delta^{18}\text{O}$ ‰	δD ‰	Date (m/d/yr)	amount ¹ (mm)	$\delta^{18}\text{O}$ ‰	δD ‰
9/4/2003	0.25	-0.72	-0.1	1/4/2005	0.51	0.11	10.7
9/26/2003	219.20	-2.63	-8.7	1/20/2005	0.76	-1.33	11.5
10/21/2003	101.60	-3.55	-17.9	6/14/2005	5.59	-4.21	-27.8
10/28/2003	107.19	-1.74	2.9	6/20/2005	404.37	-5.83	-39.4
10/29/2003	2.29	-1.30	-2.6	6/21/2005	94.23	-8.72	-58.4
10/31/2003	7.37	-1.88	-2.8	6/28/2005	112.01	-2.71	-19.8
11/3/2003	8.64	-1.40	2.0	6/30/2005	1.27	-2.57	-12.9
11/5/2003	59.44	-2.67	-6.7	7/5/2005	7.62	-0.57	-0.6
11/7/2003	154.94	-3.29	-12.9	7/12/2005	91.95	-4.33	-30.7
11/12/2003	3.30	-1.54	-1.2	7/19/2005	12.70	-1.37	-3.0
11/20/2003	3.05	-0.85	2.4	7/21/2005	6.60	-1.35	-0.9
11/24/2003	(a)	-0.05	6.4	7/28/2005	10.67	-0.68	-1.7
12/3/2003	(a)	-0.82	8.2	8/2/2005	10.16	-1.16	-5.4
12/11/2003	23.88	-1.45	4.1	8/9/2005	82.30	-4.06	-22.3
1/15/2004	22.35	-1.22	6.9	8/23/2005	21.34	-1.62	-4.9
1/27/2004	20.07	0.40	3.5	9/16/2005	553.97	-3.47	-14.6
2/6/2004	52.58	-1.34	-0.9	10/4/2005	42.42	-3.74	-19.7
2/26/2004	1.27	-2.44	-5.2	10/6/2005	1.78	-3.40	-16.7
3/17/2004	41.15	-0.46	5.4	10/11/2005	43.94	-9.15	-62.0
3/26/2004	1.78	-0.94	11.0	10/18/2005	10.92	(a)	-4.4
5/27/2004	224.54	-0.49	5.7	11/8/2005	8.38	-1.32	-3.3
8/30/2004	330.20	-0.06	8.4	11/10/2005	0.25	-1.41	0.7
9/21/2004	99.57	-0.60	0.4	11/15/2005	18.80	-1.08	8.3
10/12/2004	177.29	-0.66	1.7	11/29/2005	12.45	-0.38	7.9
10/19/2004	188.98	-4.62	-27.0	12/1/2005	10.92	-1.06	-22.3
10/21/2004	55.88	-2.72	-16.9	12/8/2005	1.02	0.20	9.2
10/25/2004	13.46	-1.62	-0.1	1/17/2006	41.91	-0.14	-0.7
11/1/2004	0.76	-0.64	3.0	1/19/2006	0.76	0.25	9.1
11/8/2004	1.02	-1.21	3.2				
11/10/2004	5.08	-1.34	2.5				
11/15/2004	(a)	-0.87	0.0				
11/26/2004	7.87	-0.85	0.1				
12/9/2004	68.07	0.90	11.3				
12/21/2004	0.51	-0.61	14.3				
12/23/2004	2.54	-1.16	5.3				
12/27/2004	(a)	-2.40	-11.9				

1 Rainfall data obtained from Homestead Airforce Base (<http://www4.ncdc.noaa.gov>)

(a) data not available

1 **Table 3.** Precipitation amount, $\delta^{18}\text{O}$, and δD for
2 samples collected at Key Largo.

Date (m/d/yr)	amount (mm)	$\delta^{18}\text{O}$ ‰	δD ‰
7/20/2001	32.26	-2.08	-6.5
8/17/2001	11.18	-1.32	2.7
8/24/2001	6.10	-0.07	7.3
8/31/2001	8.64	-1.54	6.7
9/4/2001	5.33	-0.42	6.1
11/2/2001	20.83	-3.01	-8.3
11/30/2001	20.60	-0.99	9.4
2/15/2002	113.50	-2.40	-2.0
3/4/2002	36.76	-4.00	-26.6
4/12/2002	76.95	-1.01	-0.8
6/6/2002	88.64	-4.18	-26.4
7/1/2002	173.00	-4.36	-28.2
7/8/2002	122.50	-2.63	-12.9
7/17/2002	109.00	-2.02	-4.5

3

1 **Table 4.** Precipitation amount, $\delta^{18}\text{O}$, and δD for
 2 samples collected at Long Key.

Date (m/d/yr)	amount (mm)	$\delta^{18}\text{O}$ ‰	δD ‰
7/23/2001	36.50	-2.67	-6.8
7/30/2001	20.33	-2.36	-6.2
8/6/2001	115.00	-2.98	-15.6
8/27/2001	2.94	-1.42	5.9
9/3/2001	0.24	1.32	14.0
12/11/2001	34.00	-3.60	-18.3
12/17/2001	0.24	-0.67	3.7
12/26/2001	2.45	-1.65	4.5
1/7/2002	55.37	-5.66	-32.4
1/28/2002	1.72	-0.12	10.4
2/11/2002	48.02	-1.11	7.7
2/18/2002	8.33	-3.10	-13.0
2/25/2002	30.38	-2.28	-4.3
3/11/2002	11.27	-2.18	-4.0
3/25/2002	1.96	-2.05	-6.6
5/13/2002	2.94	0.66	11.2
5/20/2002	28.18	-5.10	-36.2
5/28/2002	28.67	-6.15	-48.7
6/3/2002	1.72	-4.39	-29.3
6/10/2002	1.47	-2.23	-8.0
6/17/2002	123.48	-7.95	-59.9
6/24/2002	80.85	-2.15	-8.0
7/1/2002	23.52	-0.22	3.6
7/8/2002	20.83	-2.57	-8.1
7/17/2002	26.95	-3.28	-17.7
7/23/2002	0.25	0.61	13.3
8/26/2002	26.71	-1.97	-0.9
9/3/2002	18.87	-0.22	2.7
9/16/2002	17.60	-2.37	-7.5
9/23/2002	19.60	-5.24	-32.9
9/30/2002	4.65	-4.67	-28.1
10/15/2002	1.72	-0.77	7.5
10/21/2002	56.84	-3.10	-21.7
11/18/2002	13.00	-1.74	-7.5
11/25/2002	4.41	-1.51	6.2
12/2/2002	0.10	-0.27	14.2

1 **Table 5.** Precipitation amount, $\delta^{18}\text{O}$, and δD
 2 for samples collected at Redland.

Date (m/d/yr)	amount (mm)	$\delta^{18}\text{O}$ ‰	δD ‰
8/31/1997	282.10	-1.40	0.3
9/21/1997	224.90	-4.91	-19.1
10/10/1997	59.10	-4.01	-20.8
12/1/1997	81.40	-1.82	-0.7
12/7/1997	75.00	-6.38	-34.0
1/11/1998	91.46	-1.94	-0.9
2/3/1998	119.00	-3.36	-11.2
3/1/1998	136.20	-1.59	2.0
5/11/1998	108.66	-2.94	-8.1
6/1/1998	72.00	-3.44	-21.7
7/19/1998	112.89	-2.88	-10.7
9/24/1998	483.80	-3.81	-18.5
11/17/1998	197.70	-2.96	-11.4
12/31/1998	48.60	-1.88	-1.9
2/12/1999	99.60	-2.42	-5.2
3/22/1999	4.40	-1.37	-6.1
5/21/1999	91.40	-3.10	-12.5
7/3/1999	197.50	-3.39	-15.4
8/1/1999	299.00	-2.18	-5.6
9/1/1999	125.60	-3.43	-15.2
10/1/1999	116.40	-2.98	-3.7
10/31/1999	197.00	-7.57	-50.6
12/1/1999	21.70	-2.68	-18.2
3/1/2000	39.40	-1.19	9.1
5/1/2000	54.72	-1.27	5.0
5/24/2000	6.50	-7.62	-51.5
6/1/2000	79.00	-0.72	2.4
6/6/2000	30.00	-1.87	-2.6
6/13/2000	101.50	-3.79	-17.8
6/30/2000	218.10	-2.77	-7.8
8/2/2000	183.00	-2.53	-6.0
8/31/2000	178.20	-4.22	-19.9
10/1/2000	75.00	-1.94	-2.5
10/10/2000	155.00	-4.02	-15.8
12/31/2000	66.80	-7.43	-42.9
5/27/2001	18.30	-3.94	-16.1

1 **Table 6.** Precipitation amount, $\delta^{18}\text{O}$, and δD for samples collected at the Rosenstiel School of Marine and Atmospheric Sciences (RSMAS).

Date (m/d/yr)	amount (mm)	$\delta^{18}\text{O}$ ‰	δD ‰	Date (m/d/yr)	amount (mm)	$\delta^{18}\text{O}$ ‰	δD ‰	Date (m/d/yr)	amount (mm)	$\delta^{18}\text{O}$ ‰	δD ‰
12/9/1999	35.00	-0.69	8.9	12/10/2003	23.41	-1.48	5.8	10/10/2005	4.55	-3.10	-20.1
12/22/1999	60.00	-0.14	11.7	12/12/2003	11.02	-1.46	2.5	10/17/2005	43.76	-10.31	-77.9
1/21/2000	1.00	0.62	19.0	12/15/2003	18.10	-2.71	-8.7	11/18/2005	18.45	-0.95	-1.5
1/28/2000	9.00	-2.72	-7.6	12/17/2003	4.20	-0.29	9.5	11/22/2005	13.14	-0.28	4.3
2/11/2000	40.00	-0.83	17.2	12/22/2003	9.25	-1.16	14.5	12/29/2005	5.09	-1.67	-5.6
2/25/2000	55.00	-1.09	4.2	12/24/2003	7.03	1.01	7.1	2/6/2006	47.30	-1.99	-6.5
3/3/2000	1.00	1.47	20.6	1/19/2004	38.19	-3.81	-12.3	2/25/2006	34.73	-1.20	3.5
3/22/2000	120.00	-0.74	1.7	1/28/2004	5.21	0.40	6.3	2/27/2006	7.65	-0.08	2.5
6/6/2000	30.00	-1.77	-2.6	2/2/2004	74.74	-1.76	-16.4	3/24/2006	72.08	-1.30	-2.5
6/13/2000	75.00	-3.81	-17.4	2/17/2004	6.24	-2.19	-2.4	4/10/2006	26.95	-2.01	-6.3
7/3/2000	118.00	-2.19	-8.4	2/26/2004	62.70	1.11	10.1	4/12/2006	12.61	0.75	8.6
7/17/2000	114.00	-0.63	6.7	3/22/2004	(a)	-0.58	6.8	5/16/2006	23.58	-2.67	-4.6
8/3/2000	140.00	-1.08	3.3	3/25/2004	(a)	-0.80	-8.5	5/18/2006	55.44	-5.56	-28.6
8/18/2000	30.00	-0.53	5.4	3/25/2004	8.36	-0.19	7.1	5/26/2006	28.89	-5.23	-29.4
8/29/2000	100.00	-2.16	-7.8	4/3/2004	6.24	0.28	8.6	6/1/2006	69.60	-3.33	-10.5
9/8/2000	85.00	-2.59	-7.6	4/12/2004	15.00	-2.24	-4.8	6/5/2006	60.58	-1.86	-6.4
9/22/2000	77.00	-1.36	-0.4	4/24/2004	(a)	-1.67	2.4	7/10/2006	58.81	-2.72	-17.6
10/3/2000	225.00	-9.00	-55.9	5/4/2004	67.30	-3.71	-17.8	7/18/2006	26.41	-0.01	2.8
10/9/2000	163.00	-6.11	-33.9	6/10/2004	6.94	-1.93	-6.6	7/20/2006	23.41	-2.07	-3.5
12/11/2000	145.00	-1.44	1.0	6/27/2004	7.12	-0.68	-5.9	7/21/2006	12.96	-2.23	-1.9
1/2/2001	1.00	0.40	14.4	6/29/2004	4.47	0.12	8.7	7/28/2006	7.48	-0.12	3.6
3/20/2001	28.00	0.25	8.2	7/4/2004	8.71	0.90	21.1	7/31/2006	11.90	0.79	4.5
6/29/2001	9.80	-0.45	4.8	7/14/2004	7.65	-1.15	-1.5	8/7/2006	16.33	-0.66	-2.5
7/6/2001	4.40	-0.25	15.1	7/23/2004	21.64	-4.39	-24.8	8/15/2006	86.68	-3.09	-14.4
7/10/2001	1.20	-0.20	6.3	7/26/2004	6.59	-3.10	-12.0	8/16/2006	10.75	-2.06	-10.1
7/17/2001	51.40	-2.86	-13.0	7/28/2004	44.65	-4.46	-20.4	8/21/2006	20.93	-2.13	-1.7
7/24/2001	38.60	-1.28	-3.2	8/20/2004	(a)	-2.29	-3.2	9/12/2006	15.26	-5.57	-28.2
8/2/2001	13.00	-3.82	-21.7	10/8/2004	17.56	-0.13	1.0	9/29/2006	7.92	0.94	3.8
8/3/2001	(a)	0.24	8.9	12/5/2004	(a)	-0.57	12.2	10/10/2006	10.57	-1.44	-6.6
8/6/2001	32.00	-0.95	-0.3	2/3/2005	23.41	-2.06	6.5	10/13/2006	49.07	-3.88	-16.5
8/1/2003	(a)	-0.55	-14.3	2/28/2005	9.07	0.06	8.4	10/24/2006	6.77	-0.82	1.8
8/15/2003	(a)	-1.24	-4.4	3/4/2005	29.78	-3.25	0.2	10/31/2006	16.33	-0.75	2.0
9/24/2003	91.55	-3.69	-38.5	3/10/2005	42.17	-4.08	-12.5	11/2/2006	16.77	-4.36	-19.1
9/26/2003	21.07	-2.42	-8.9	3/18/2005	44.65	-3.65	-16.0	11/16/2006	17.21	-2.69	-7.3
9/29/2003	20.31	-3.12	-31.3	3/24/2005	26.95	-0.57	-1.4	11/28/2006	(a)	0.61	0.9
9/30/2003	30.49	-3.04	-33.9	4/8/2005	49.78	-2.15	-11.3	12/14/2006	5.97	-0.22	3.7
10/1/2003	13.67	-0.45	2.6	4/18/2005	5.79	-0.93	5.1	12/15/2006	9.42	-1.06	-8.5

10/21/2003	8.36	-2.18	-9.4	5/4/2005	31.02	-2.27	-7.4	12/18/2006	16.33	-2.31	-5.9
10/29/2003	32.26	-3.27	-15.8	5/6/2005	27.12	-2.32	-19.7	12/19/2006	4.91	1.53	7.2
10/31/2003	8.18	-1.45	-1.6	8/5/2005	6.41	-0.07	7.3				
11/2/2003	10.84	-2.17	-9.2	8/11/2005	3.40	0.86	12.2				
11/6/2003	132.26	-6.03	-39.4	8/19/2005	16.33	-1.24	5.8				
11/7/2003	21.19	-4.77	-34.7	8/22/2005	3.53	0.81	8.9				
11/9/2003	11.02	-1.64	-11.8	8/23/2005	17.39	-3.42	-14.0				
11/10/2003	5.88	-0.89	0.1	9/6/2005	40.40	-4.50	-27.7				

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1 **Table 7.** Seasonal weighted-mean values of $\delta^{18}\text{O}$, δD , and d-excess along with the number of precipitation samples (n) and the standard error (s.e.)
 2 for four sites with at least 1 year of data.

Site	Redland		RSMAS		BNP		Long Key	
Season	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
n	24	19	62	58	29	30	20	16
$\delta^{18}\text{O}$ (‰)	-3.36	-2.86	-3.30	-2.13	-3.26	-1.19	-3.68	-3.56
s.e.	0.30	0.45	0.27	0.22	0.40	0.15	0.46	0.48
δD (‰)	-13.44	-9.40	-16.54	-6.65	-16.60	0.25	-21.51	-17.57
s.e.	2.60	3.62	2.14	1.64	2.98	1.34	3.90	4.48
d-excess	13.43	13.51	9.90	10.40	9.50	9.80	7.91	10.89
s.e.	0.66	1.14	0.76	0.86	0.73	1.12	0.90	1.22

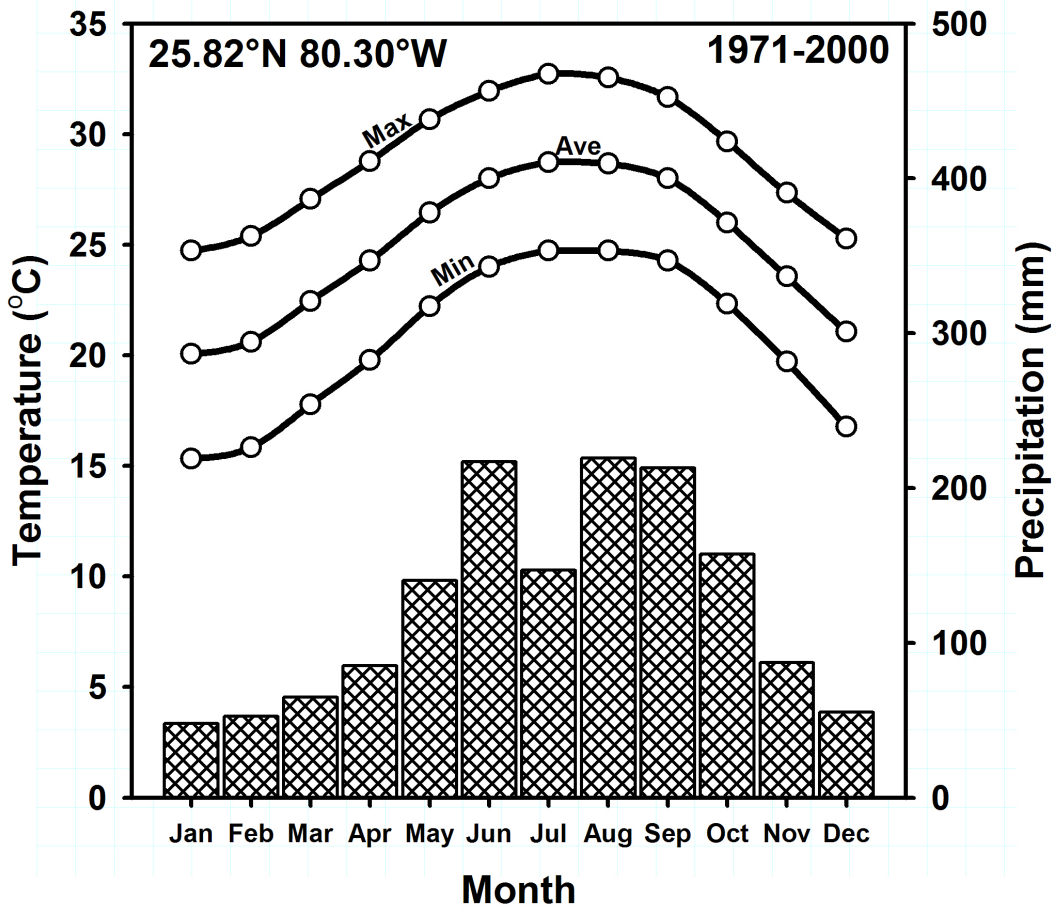
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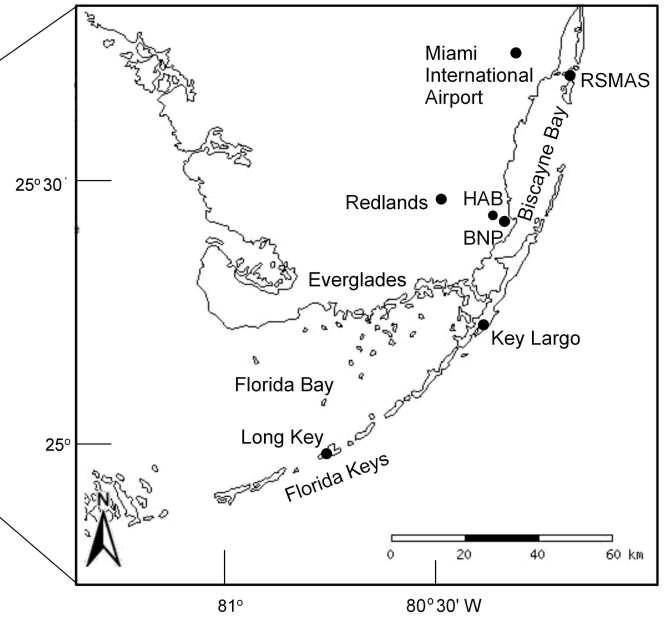
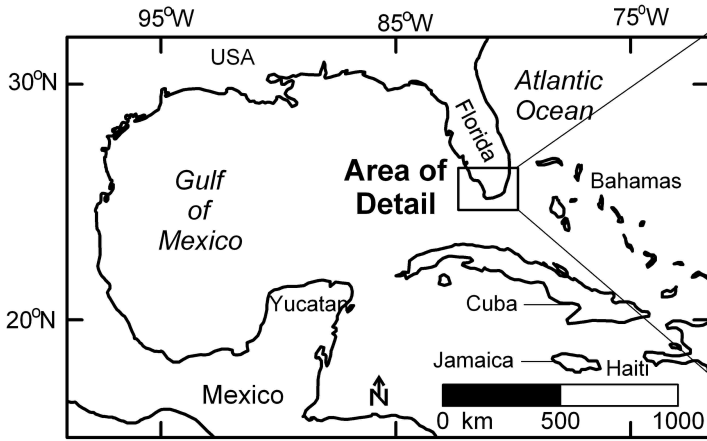
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Table 8. Annual amount-weighted values of $\delta^{18}\text{O}$, δD for sites with over 1 year of data.

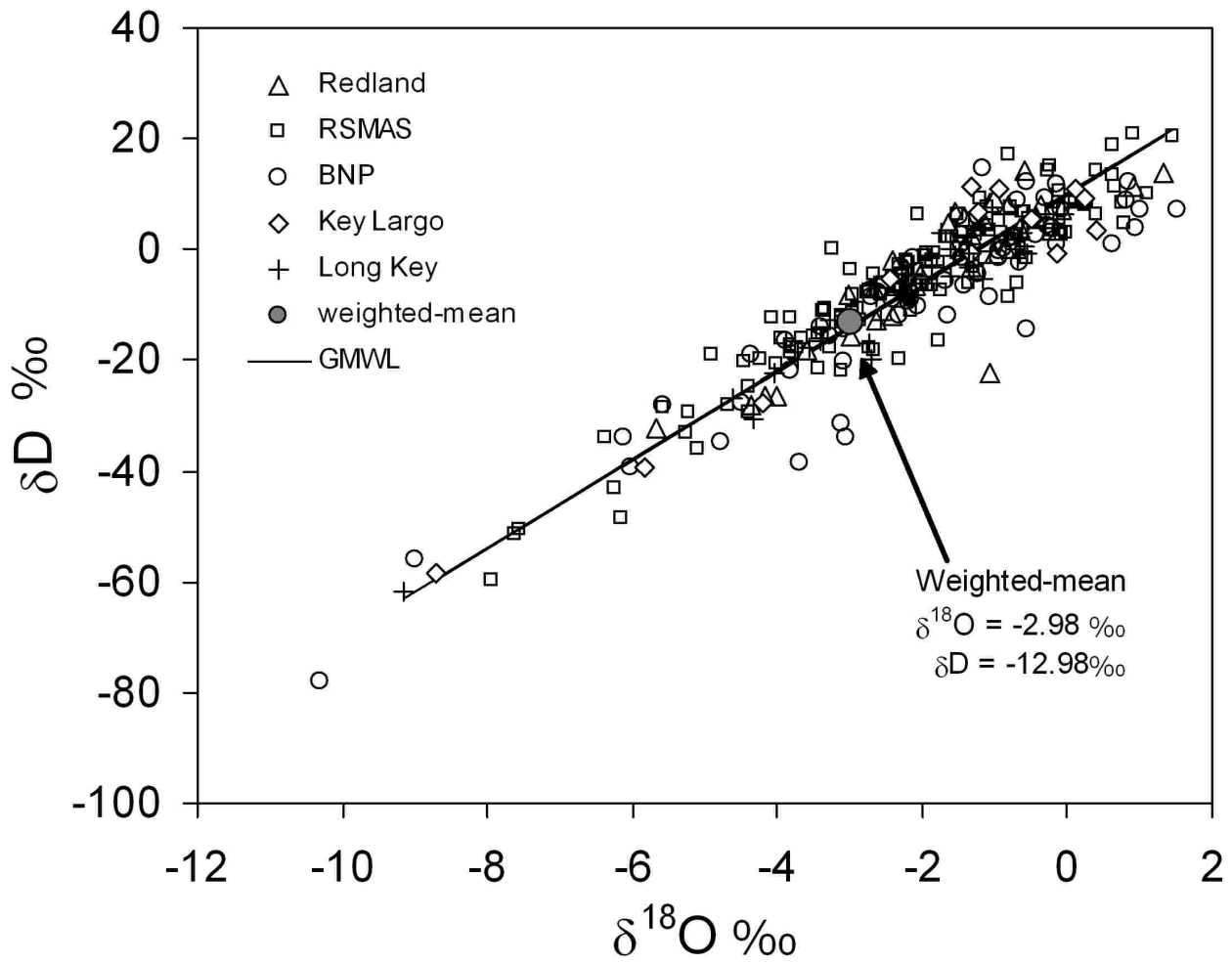
Site	Year	$\delta^{18}\text{O}$ (‰)	δD (‰)
Redland	1998	-3.07	-10.02
	1999	-3.62	-16.58
	2000	-3.16	-11.14
RSMAS	2000	-3.15	-12.63
	2004	-2.02	-8.74
	2005	-3.23	-15.12
	2006	-2.44	-9.29
BNP	2004	-1.08	-0.32
	2005	-4.38	-25.79

Miami International Airport

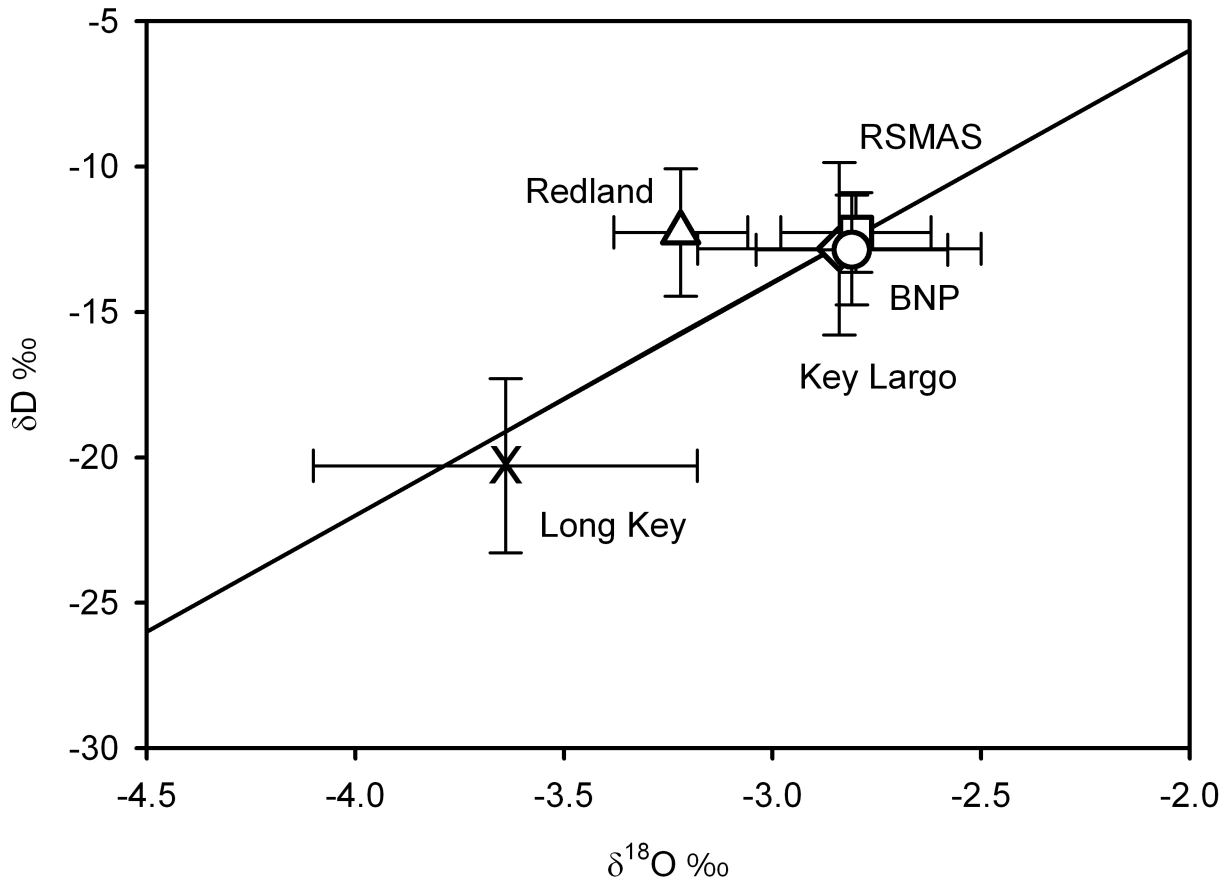




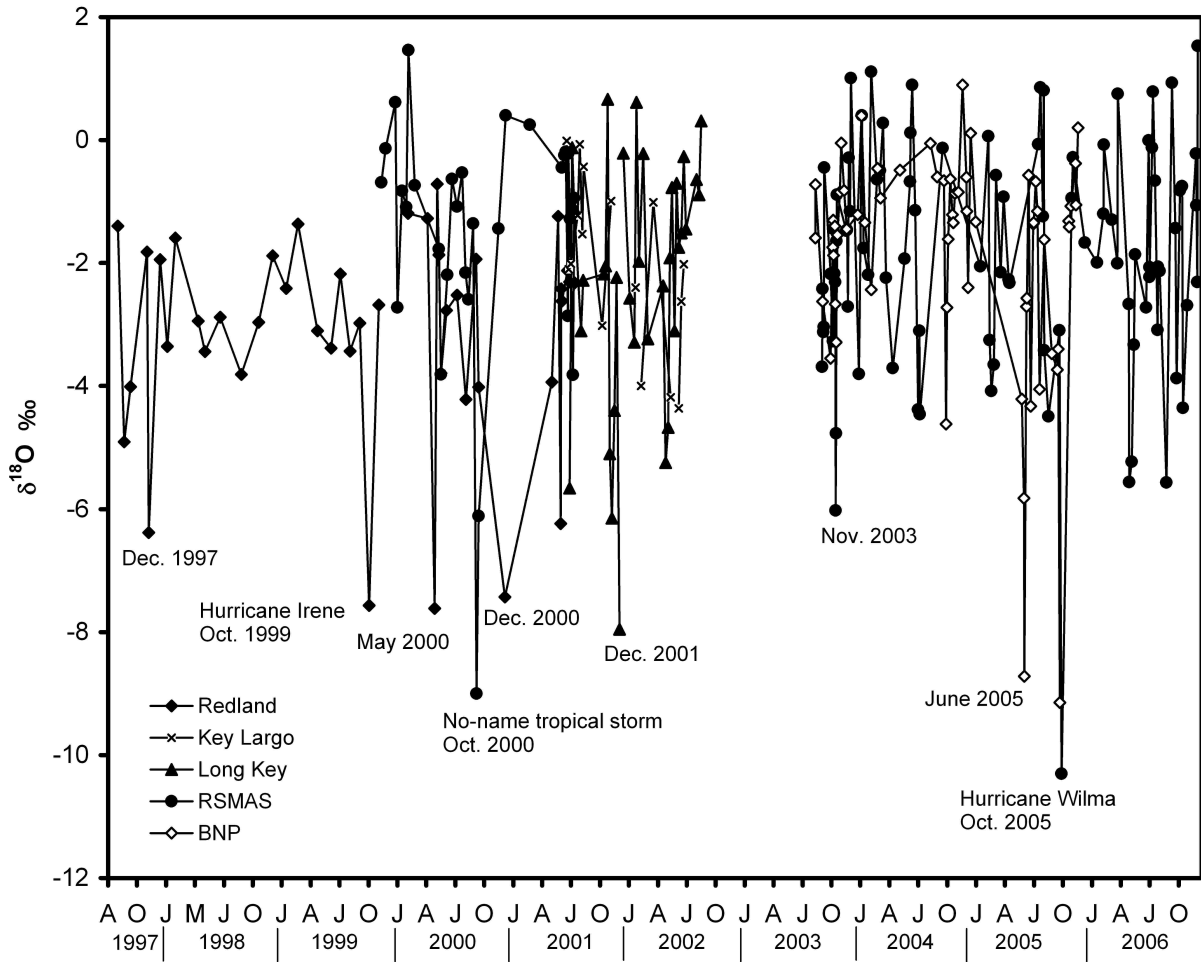
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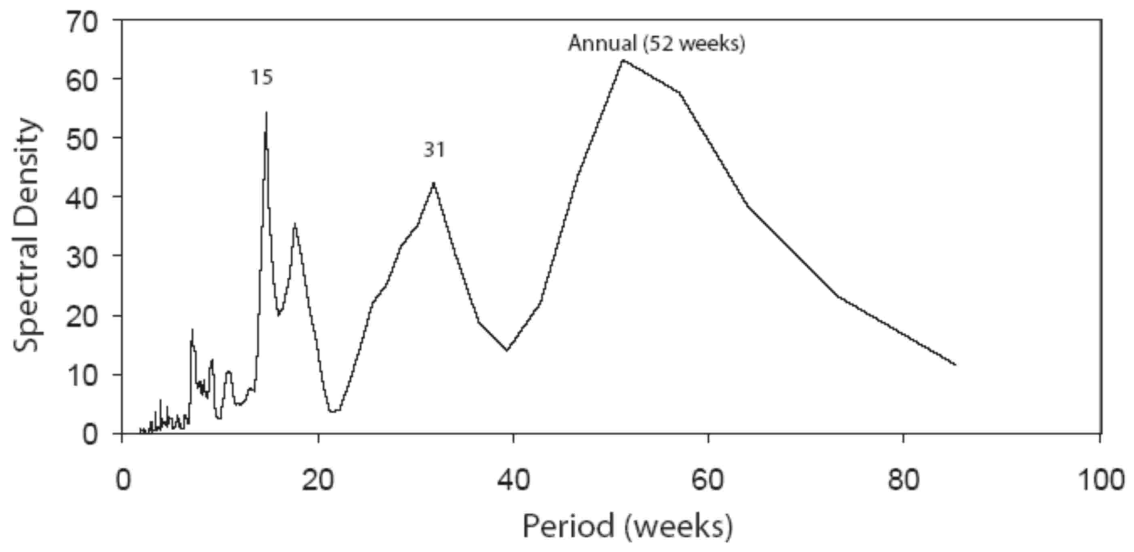


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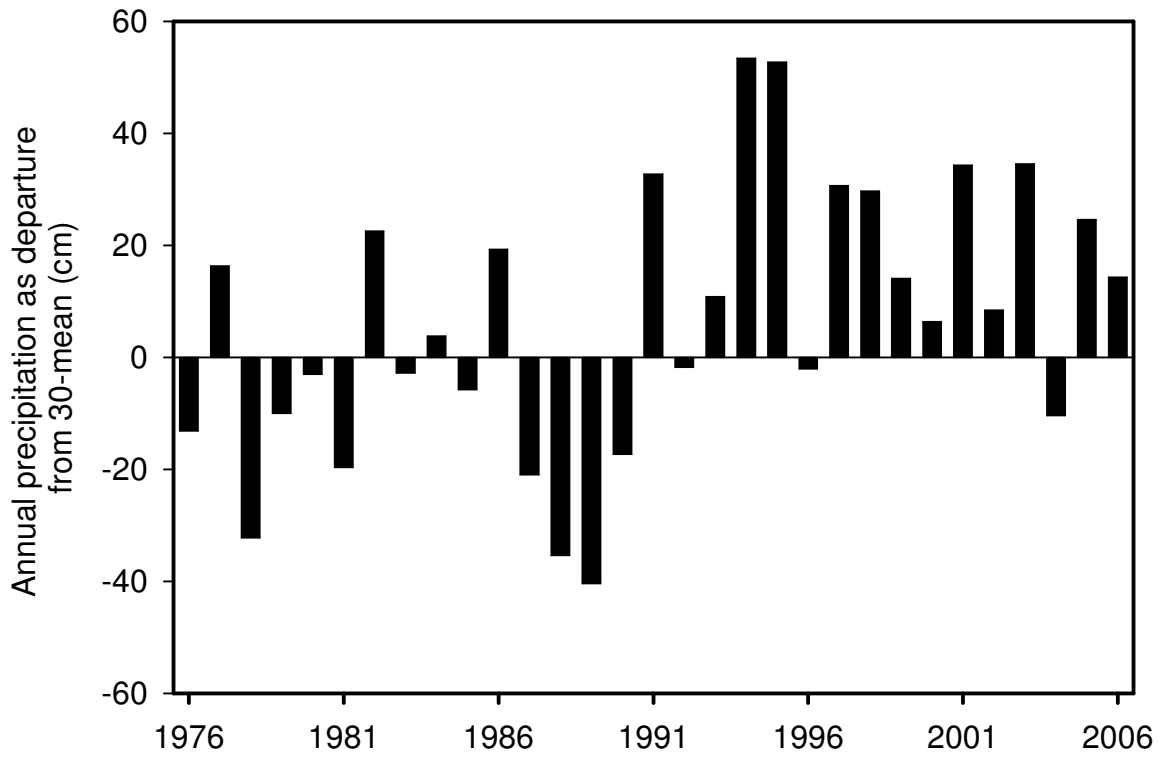


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