

# Report Attachment 2 – Climate Supplement

## DRAFT Technical Memorandum

August 10, 2020

TO: File

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**Subject: Analyses of Long-term Temperatures and Cold Events in DPWUCA**

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### Introduction

Periodic freezing temperatures in west-central Florida are a naturally occurring seasonal weather pattern that can cause substantial economic impacts to agriculture and residents (Peterson and Rumbaugh 2012; Aurit et al. 2013). During prolonged freezes, agricultural growers risk losses of certain crops. To lower the likelihood of damage, surface water or groundwater can be used for cold protection of crops, although groundwater is preferred because of its relatively consistent lukewarm temperature and lower potential for pathogens (Peterson and Rumbaugh 2012; Aurit et al. 2013). Cold protection for many crops in this region is typically initiated when temperatures fall at or below 34° F (Peterson and Rumbaugh 2012; Zamora-Re et al. 2016; Borisova et al. 2018).

In 2010, nine nights of freezing or near-freezing temperatures occurred over 11 consecutive days from January 3 to 13 in the Dover/Plant City area of eastern Hillsborough County, Florida (Peterson and Rumbaugh 2012). The event was record-breaking in many parts of central and southern Florida (NOAA 2010). At the beginning of 2010, permitted average annual water use in what is now the Dover/Plant City Water Use Caution Area (DPWUCA; Figure 1) was 157 million gallons per day (mgd). During the 2010 cold event, an estimated 891 mgd was extracted for cold protection in the DPWUCA (Peterson and Rumbaugh 2012). Groundwater modeling showed that drawdown in the Upper Floridan aquifer could have exceeded 80 feet at the cone of depression's center, while drawdown greater than 5 feet extended over an area of about 222 mi<sup>2</sup> (Peterson and Rumbaugh 2012). Approximately 760 dry well complaints and 140 documented sinkholes occurred near the area of maximum drawdown.

This technical memorandum attempts to place the 2010 event in context by analyzing long-term temperature data for the area and estimating a recurrence interval for an event of similar magnitude. Additionally, cold event durations (in hours) and starting groundwater level elevations are assessed.

## Data Sources

Minimum daily temperature data were obtained from the Plant City station (Figure 1) from 1892 to April 2020 through the National Oceanic and Atmospheric Administration<sup>1</sup> (NOAA) and Florida Climate Center<sup>2</sup> (FCC). Gaps were infilled using linear regression with nearby stations from the same data sources, accounting for about 7% of the final dataset (Table 1; Figure 2). Throughout its history, the Plant City station has moved locations several times, with an overall maximum change of less than half a mile for distance and 11 feet for elevation<sup>3</sup>; it is unclear what effects could have resulted from these shifts at various times in the station's period-of-record, but they are not expected to substantially alter the results of the following analyses.

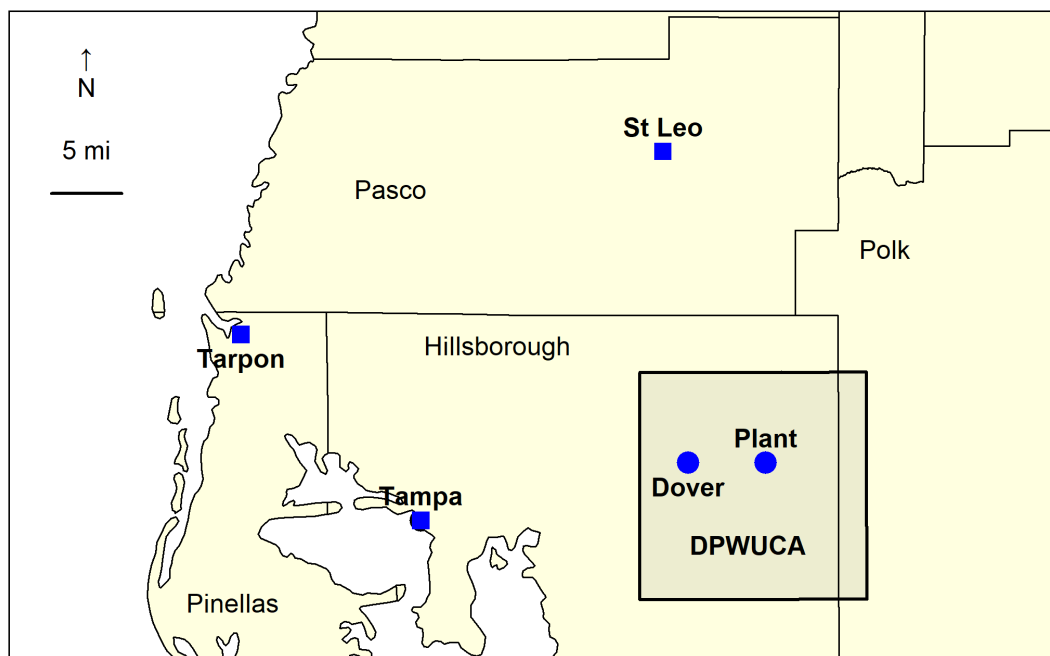


Figure 1. Locations of temperature stations used for analyses (circles), as well as stations used to estimate temperatures at the target stations (squares).

Temperature data for Dover City (Figure 1) are available from the Florida Automated Weather Network<sup>4</sup> (FAWN) at heights of 10 cm, 60 cm, and 2 m (with respect to ground surface). Additionally, wet bulb temperature data is calculated for the 2-meter temperature data, which most closely replicates the temperature data that agricultural growers use to assess the need to implement cold protection (Borisova et al. 2018). Wet bulb temperature, which can be measured using a thermometer covered in a wet cloth, accounts for the effects of evaporative cooling; it can also be calculated using air temperature, dew point temperature, saturated vapor pressure, and air pressure, as FAWN does using the Newton-Raphson algorithm.<sup>5</sup> Fifteen-minute wet bulb temperature

<sup>1</sup> <https://www.ncdc.noaa.gov/cdo-web/>

<sup>2</sup> <https://climatecenter.fsu.edu/climate-data-access-tools/downloadable-data>

<sup>3</sup> <https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USC00087205/detail>

<sup>4</sup> <https://fawn.ifas.ufl.edu/data/>

<sup>5</sup> [https://fawn.ifas.ufl.edu/tour/fawn\\_info/](https://fawn.ifas.ufl.edu/tour/fawn_info/)

data were obtained from FAWN from 1998 to April 2020 and interpolated with a 4 step (i.e. 1 hour) maximum gap allowed for interpolation. Approximately 3,000 data points were interpolated, equivalent to roughly 31 days. This 15-minute dataset was then aggregated into daily minimums (

Figure 3). As no data are available for the year 2000, July to December 2003, and January to July 2013, substantial periods which include months of the year during which cold events have been known to occur (Table 2), linear regression with the Plant City station (based on using overlapping 1998 to 2019 data) was used to estimate minimum daily temperature for these and various other smaller data gaps. Modeled data comprise a total of 15% of the final 1998 to April 2020 dataset for Dover City. The linear model used was  $DC = 1.02*PC - 3.31$ , where DC and PC represent daily minimum temperature ( $^{\circ}$  F) at Dover City and Plant City, respectively ( $R^2 = 0.92$ ; mean absolute error =  $2.0^{\circ}$ ; degrees of freedom = 6,852).

Table 1. Data used in the final Plant City daily minimum temperature time series (1892–April 2020). Regression used overlapping data through 2017. MAE, Slope, and Int. in units of  $^{\circ}$  F. MAE = mean absolute error. DF = degrees of freedom. N = number of times that station was used in the final series. GHCND ID = Global Historical Climatology Network Daily ID.

Station	R <sup>2</sup>	MAE	Slope	Intercept	DF	N	GHCND ID
Plant City	1.00	0.0	1.00	0.00	-	43,373	USC00087205
Tampa	0.90	2.4	0.97	-0.59	30,272	787	USW00012842
Tarpon Spgs.	0.89	2.6	0.96	1.14	41,738	2,710	USC00088824
Saint Leo	0.92	2.3	1.00	-0.67	41,202	2	USC00087851
Brooksville	0.87	2.9	0.95	2.86	38,808	0	USC00081046

Table 2. Percentage of cold events occurring each month of the year in the station’s dataset. Similar percentages result when using days instead of events (which can include multiple days).

Month	Plant City (1892–4/2020)	Dover City (1998–4/2020)
1		32%
2		23%
3		9%
4		1%
11		8%
12		26%

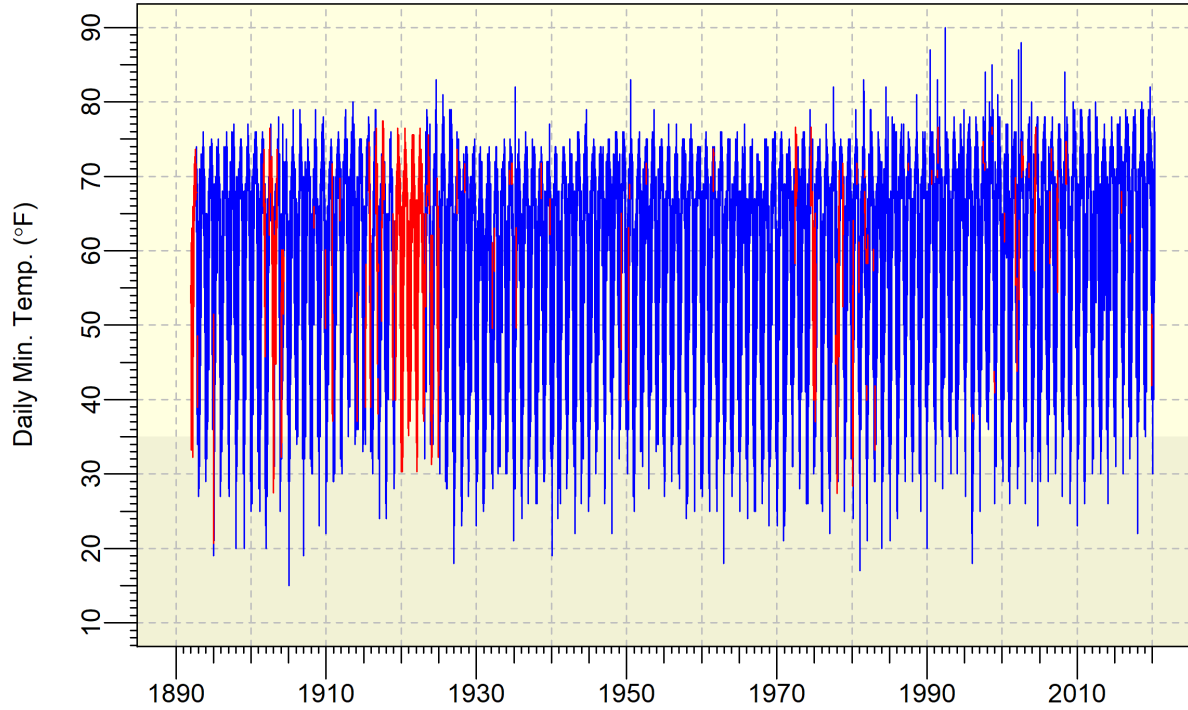


Figure 2. Time series of daily minimum temperatures at Plant City (1892–April 2020). Red indicates temperatures modeled based on linear regression with other stations.

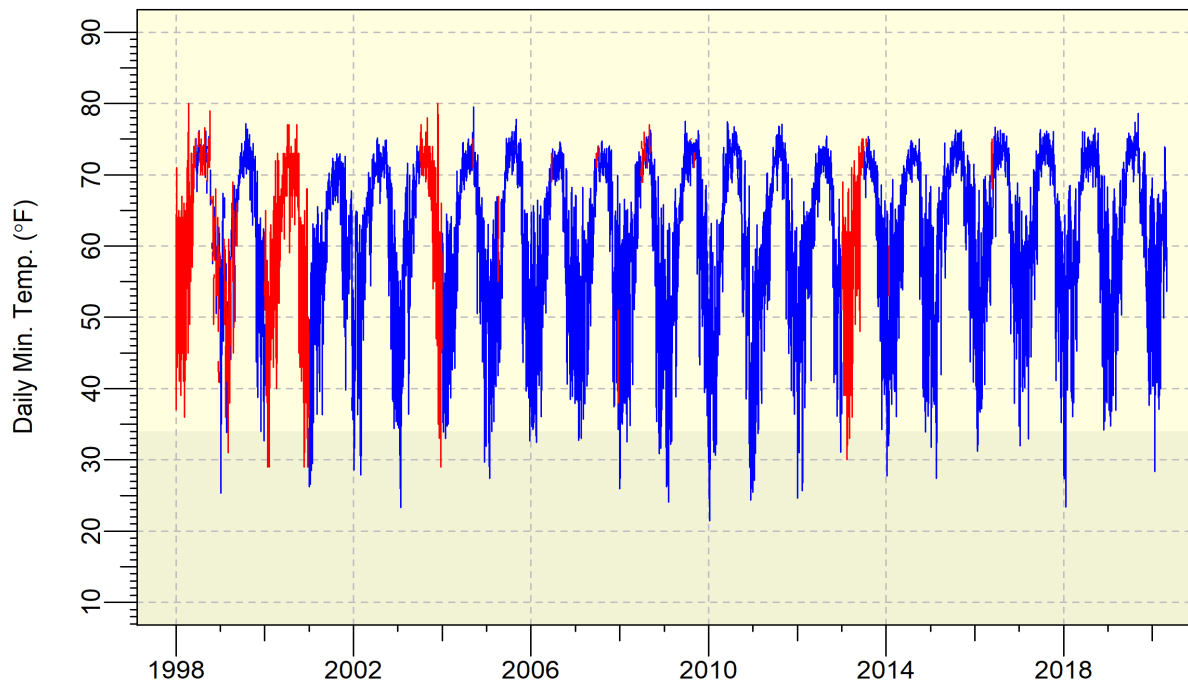


Figure 3. Time series of daily minimum temperatures at Dover City (1998–April 2020). Red indicates temperatures modeled based on linear regression with the Plant City station.

## **Cold Event Thresholds**

A 34° F threshold is used for the Dover City station as the threshold at which agricultural growers typically initiate cold protection withdrawals (Peterson and Rumbaugh 2012, Zamora-Re et al. 2016, Borisova et al. 2018). The Plant City station averages about one to two degrees warmer than Dover City, making a 35° F threshold for the Plant City station reasonably comparable to the 34° F threshold at Dover City that triggers cold protection. The following analyses consider “cold events” as when minimum daily temperature falls at or below the threshold temperature. Cold event magnitude or length is defined here as the consecutive number of days that the minimum daily temperature fell at or below the threshold temperature. While temperatures during any given cold event likely rise above the threshold for some part of one or more days in the event, as discussed later, event duration (hours) and magnitude (days) were found to be strongly correlated, indicating minimum daily temperatures can serve as suitable proxies for event duration.

With one exception, the analyses do not consider linked events (for example, two 3-day events separated by one day of warmer temperatures) that could result in groundwater withdrawals like larger single events. Although the minimum daily 2-meter wet bulb temperature at Dover City on January 8, 2010 is 34.11° F, which would break the observed 11-day cold event into two 5-day events, based on temperature data from Plant City and other stations which indicate cold event temperatures, and to account for the effective magnitude of the event, this number is rounded down to 34° F for the purposes of this analysis.

## **Cold Events in the Observed Record**

Over the 128-year Plant City dataset, the 11-day 2010 event was unprecedented at the 35° F threshold, with the next largest magnitude events of 7 days in length occurring in January of 1893 and 2002 (Figure 4). The 2010 event was similarly unprecedented in the 22-year Dover dataset at the 34° F threshold, with the next largest event of 5 days in length occurring in January 2001 (Figure 5). Thus, the 2010 event was 1.6 to 2.2 times as long as the next-longest event in the daily minimum temperature records.

The data show that cold events are common, but they rarely exceed 3 days in length (Table 3). In the Plant City and Dover City records, respectively, 98% and 95% of years had at least one cold event of any length. For Plant City, of 806 unique cold events, 95% were 3 days or smaller, 84% 2 days or smaller, and 52% were only 1 day. For Dover City, of 89 unique cold events, 96% were 3 days or smaller, 85% were 2 days or smaller, and 58% were only 1 day.

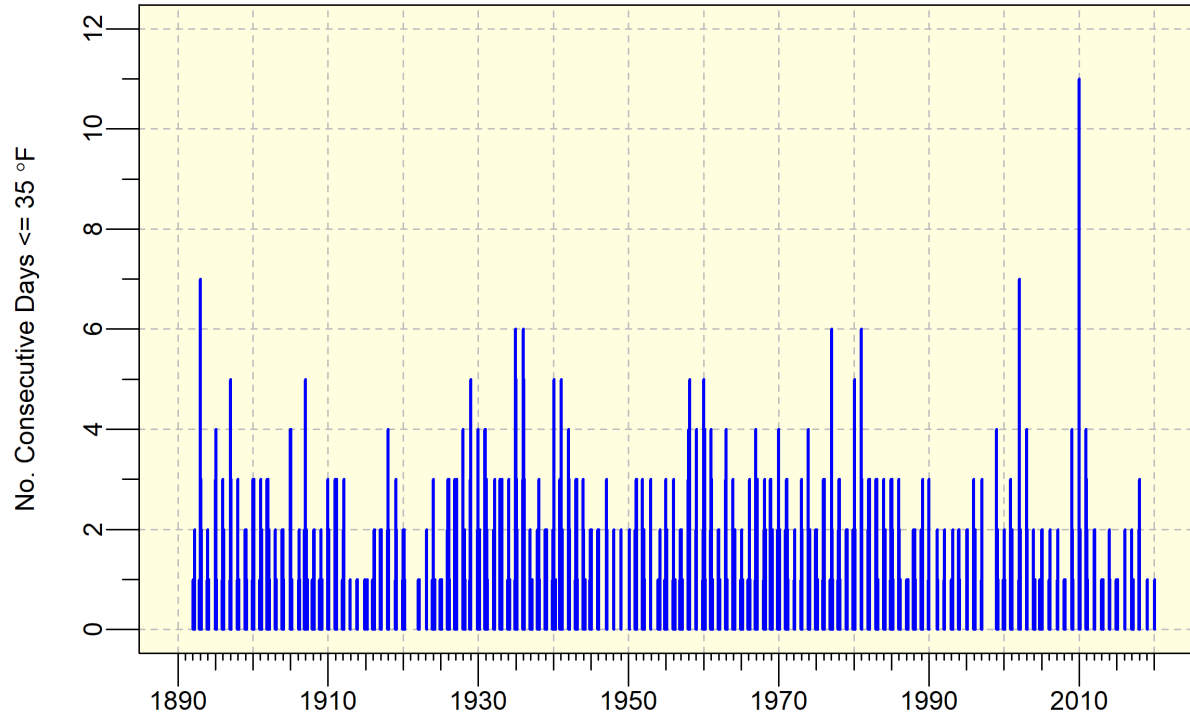


Figure 4. Dates and magnitudes of cold events at Plant City (1892–April 2020).

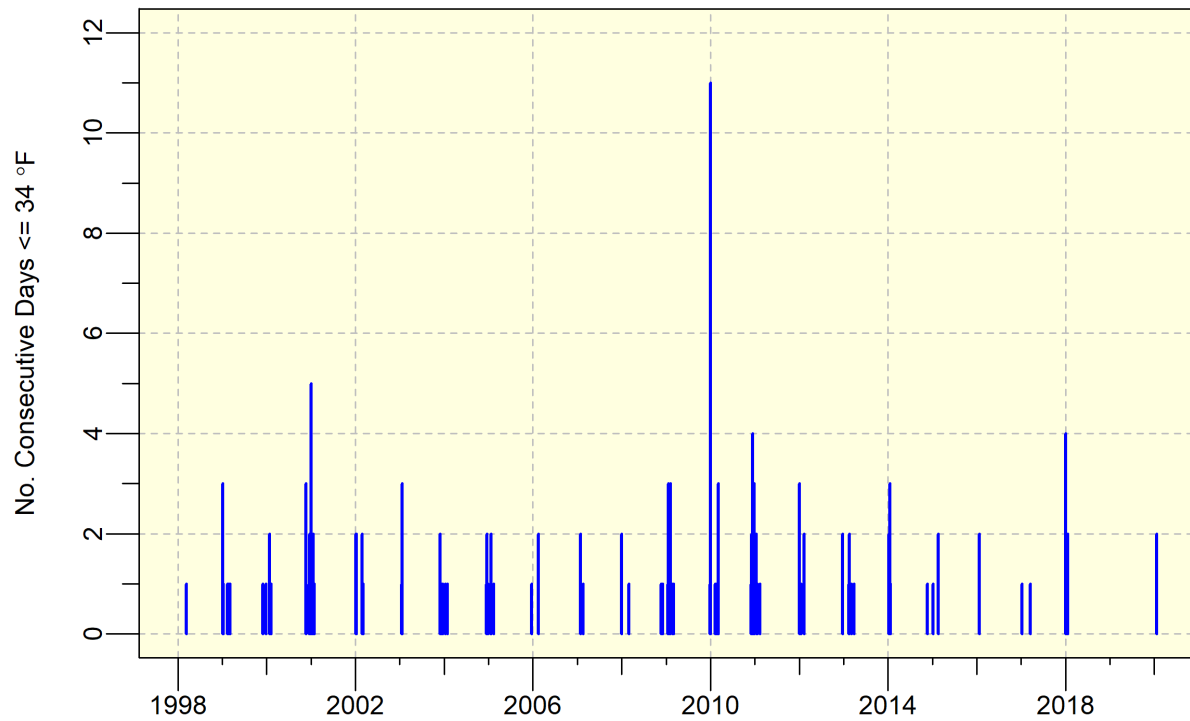


Figure 5. Dates and magnitudes of cold events at Dover City (1998–April 2020).

Table 3. Number of cold events by days-durations, using 35° F threshold for Plant City (1892–April 2020) and 34° F threshold for Dover City (1998–April 2020) daily minimum temperature data.

Days	Plant City	Dover City
1	422	52
2	253	24
3	91	9
4	23	2
5	10	1
6	4	0
7	2	0
8	0	0
9	0	0
10	0	0
11	1	1

## Estimating Cold Event Recurrence Intervals

Relating event magnitude to average recurrence interval (or equivalent annual exceedance probability) on a logarithmic or semilogarithmic scale is commonly used to analyze the frequency of precipitation, streamflow, or seismic events (Dalrymple 1960; Bonnin et al. 2011; England 2005; Gibson and Dimas 2014), which is a type of cumulative frequency analysis. However, caution must be employed in extrapolating these curves, since selected models typically poorly represent underlying physical phenomena and therefore result in unreliable predictions (Dalrymple 1960). For example, for streamflow frequency analyses, it is generally recommended to extrapolate no more than twice the length of the data record (Swain et al. 2004).

If these limitations are kept in mind, cumulative frequency analysis can provide an estimate of the recurrence interval, with the number of consecutive freeze days as magnitude against the logarithmic annual exceedance probability. To do this, the 2010 event is censored from the distribution as a “black swan” event for which a prediction is desired in the absence of a known occurrence (i.e. it is assumed that the data record is not sufficiently long to characterize the recurrence interval of the target event). To avoid biasing the recurrence interval too high, the event is instead replaced with an event equal to the magnitude of next-largest event in the record (7 days for Plant City and 5 days for Dover City). The annual exceedance probability for each magnitude is calculated as the number of winters (years) in which at least one event equal to or greater than that magnitude occurred, divided by the sum of one and the total number of years of data; the inverse of this value is the recurrence interval in years (Table 4). For this analysis, years begin in May and end in April, so that winters are not split (no cold events were recorded between May and August in either dataset). By using the annual maximum series, some of the effects of serial dependence are removed. Thus, as used in this work, the annual exceedance probability is the probability associated with equaling or exceeding a given

magnitude in any given year at least once, while its inverse (the recurrence interval) provides the average time between years (not events) that the magnitude is equaled or exceeded at least once (e.g. Bonnín et al. 2011).

Assuming a linear model satisfactorily describes the annual exceedance probability curve, a recurrence interval for the 2010 event is estimated at approximately 560 years for the Plant City dataset (95% prediction interval: 160 to 2,570 years; Figure 6 and Table 4) and 590 years for the Dover City dataset (95% prediction interval: 100 to >>10,000 years; Figure 7 and Table 5).

The 95% prediction intervals demonstrate the enormous uncertainty involved with the estimates for the 2010 event, ranging as low as 100 years spanning upwards into the thousands, a range that could be further widened by considering factors such as different temperature thresholds and data subsets. Due to the use of a logarithmic scale for annual exceedance probability, and the extensive extrapolation to 11 days, small changes in the dataset and the resulting slope and intercept can result in large changes in the estimated recurrence interval. For example, the estimated slope and intercept for the Plant City dataset is -3.382 and 1.712, respectively, which results in the 540-year recurrence interval estimate. Changing the slope by just one tenth of a point, to -3.482 or -3.582, changes the estimated recurrence interval to 470 and 670 years, respectively.

Table 4. Observed recurrence intervals (years) of cold events by days-durations, using 35° F threshold for Plant City (1892–2019) and 34° F threshold for Dover City (1998–2019) daily minimum temperature data (Years run from May to April).

Days	Plant City	Dover City
1	1.0	1.1
2	1.1	1.2
3	1.7	2.6
4	4.0	5.8
5	8.6	11.5
6	18.4	*23.0
7	43.0	*23.0
8	*129.0	*23.0
9	*129.0	*23.0
10	*129.0	*23.0
11	*129.0	*23.0

\* Value is associated with the 11-day event (and is roughly equal to the number of years of data) and was censored from the recurrence interval estimates.

Table 5. Estimated recurrence intervals (years) of cold events by magnitude (days), using 35° F threshold for Plant City and 34° F threshold for Dover City daily minimum temperature data.

Days	Plant City	Dover City
1	0.6	0.8
2	1.2	1.5
3	2.4	2.9
4	4.7	5.7
5	9.4	11.0
6	18.5	21.4
7	36.6	41.5
8	72.3	80.5
9	142.9	156.3
10	282.2	303.3
11	557.6	588.7

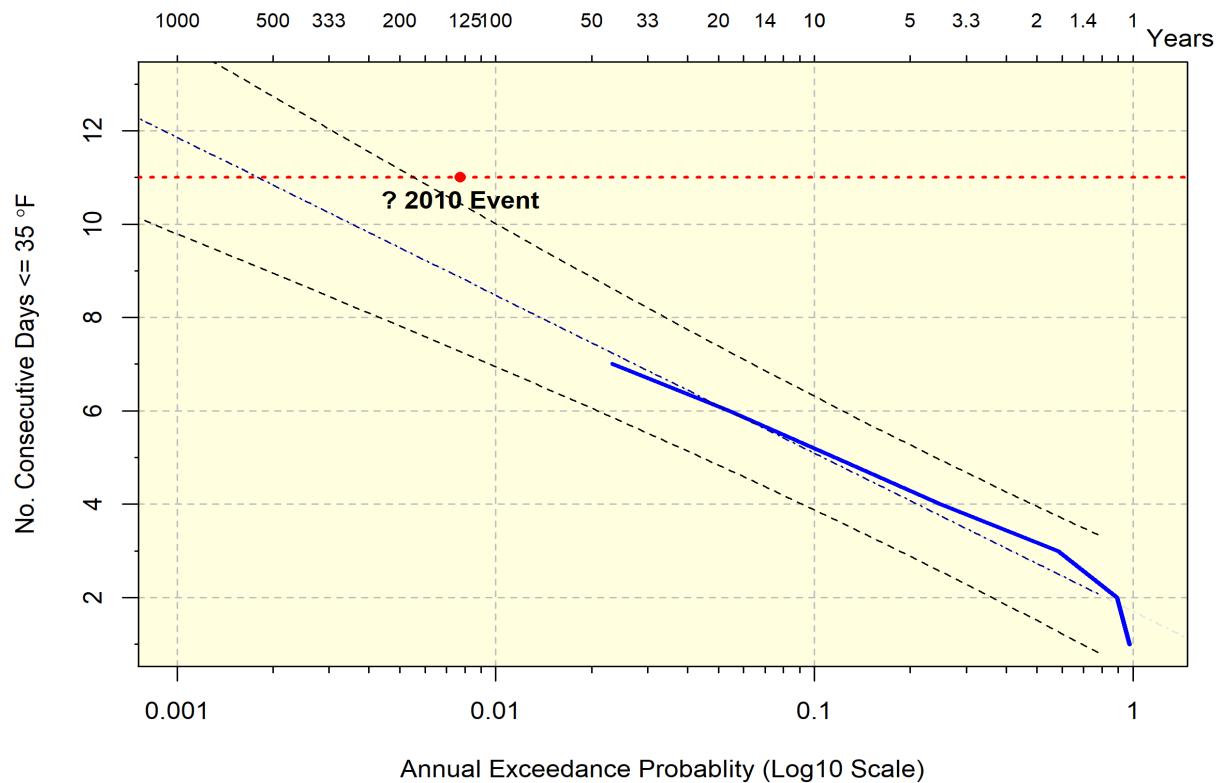


Figure 6. Observed (thick blue line) and extrapolated annual exceedance probability (recurrence interval) curve (diagonal dash-dot blue line) estimated from the Plant City dataset (May 1892 – April 2020). Outer bounds (black dashed lines) represent the 95% prediction interval. Thick horizontal red dashed line marks the 11-day event, while the red point reflects the recurrence interval based strictly on the dataset (which approximately equals the number of years of data, as the event only occurred once in record). The

recurrence interval of the 11-day event is estimated to be where the curve crosses the horizontal 11-day line.

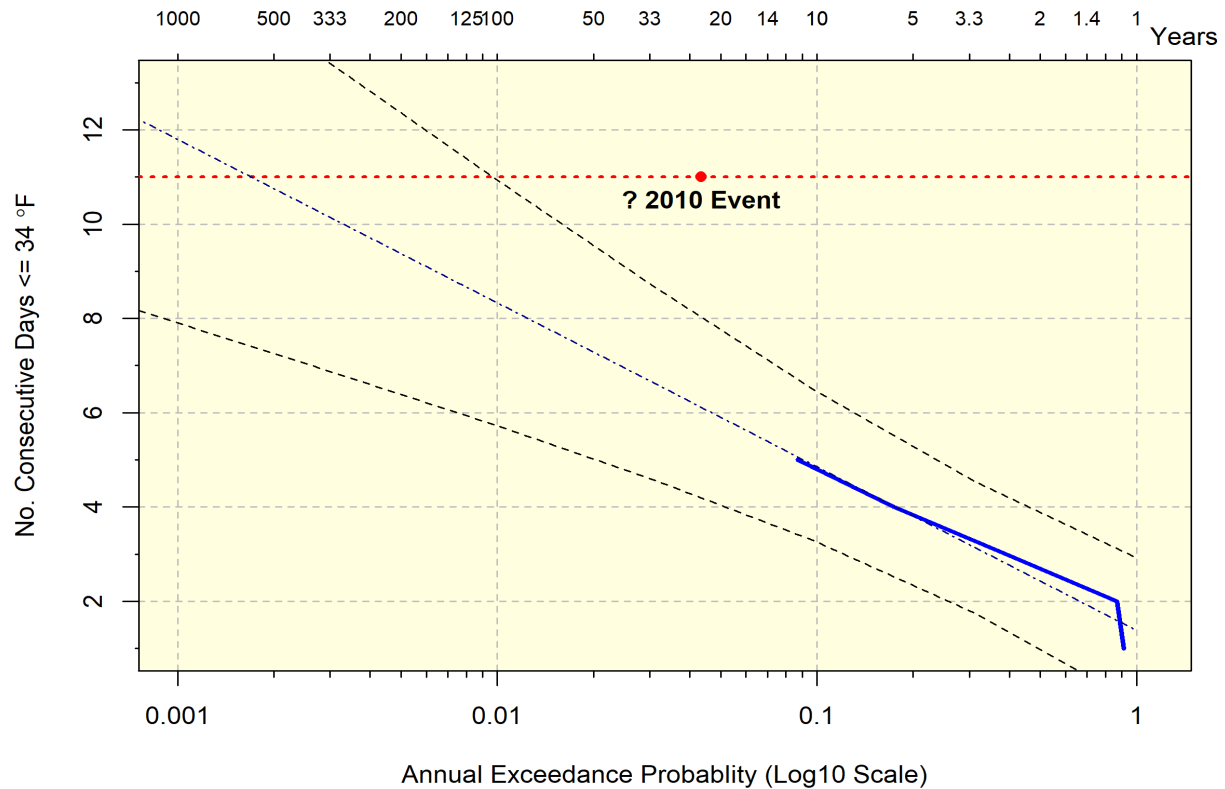


Figure 7. Observed (thick blue line) and extrapolated annual exceedance probability (recurrence interval) curve (diagonal dash-dot blue line) estimated from the Dover City dataset (May 1998 – April 2020). Outer bounds (black dashed lines) represent the 95% prediction interval. Thick horizontal red dashed line marks the 11-day event, while the red point reflects the recurrence interval based strictly on the dataset (which approximately equals the number of years of data, as the event only occurred once in record). The recurrence interval of the 11-day event is estimated to be where the curve crosses the horizontal 11-day line.

As one measure of assessing the sensitivity of the recurrence interval estimated from the two datasets, 1,000 randomly selected unique combinations of 60-year (for Plant City) and 10-year (for Dover City) data subsets were tested (the subset years did not have to be consecutive). For Plant City, 166 combinations did not result in a valid regression; of the remaining 834 combinations, the median recurrence interval for the 2010 event is 610 years while the mean is 650 years, with a range of 130 to 3,390 years. For Dover City, of 967 valid regressions, the median recurrence interval is 550 years while the mean is 3,160 years, with a range of 20 to  $\gg 10,000$  years.

Using a higher threshold for Plant City (36°F) serves to decrease the estimated recurrence interval for the 2010 event to 300 years, approximately half of the interval estimated using the 35° F threshold.

Based on the prediction intervals and subset tests for Plant City and Dover City data, a recurrence interval between 300 and 2,500 years seems reasonable for the 2010 event, with a best estimate of 570 years from the means of the recurrence intervals of the two full datasets, which also roughly corresponds to the sensitivity test means and medians.

## **Long-term Trends in Daily Minimum Temperatures**

Long-term trends in temperatures could shift the likelihood of cold event occurrences in the future. From 1892 to April 2020 at Plant City, daily minimum temperature has increased by about 0.02° F per year ( $p < 0.01$ ). The mean decadal temperatures of winter months (December, January and February, wherein over 80% of cold events occur; Table 2) also suggest an increasing trend in daily minimum temperatures by about 0.02° F per year ( $p = 0.05$ ). Similarly, averaging the number of days at or below the 35° threshold per year by decade suggests a decrease (albeit statistically insignificant) in the annual number of cold event days, corresponding to a decrease of about 0.03 days per year from 1892 to 2019, or a loss of approximately 3.5 days per year over the period-of-record (Figure 9). At Dover City, from 1998 to April 2020, daily minimum temperature at Plant City increased by about 0.13° F per year ( $p < 0.01$ ), 0.20° F per year just winter months ( $p < 0.01$ ), but the limited number of decades makes decadal-level analyses infeasible.

At Plant City, the cumulative number of days at or below the 35° F threshold suggests a break in the number of freeze days occurring per year around 1985, where the rate of about 12 freeze days per year drops to about 7 days per year (via linear slopes, both  $p < 0.01$ , and period annual averages; Figure 10). This shift does not appear to coincide with movements of the station, and while changes in equipment have occurred multiple times since 1980, previous work has identified a global “regime shift” toward warmer temperatures that occurred in the 1980s (Reid et al. 2016). To account for this possible shift, recurrence intervals for the 2010 event were estimated using Plant City data from 1985 to 2019. This increased the recurrence interval estimated from Plant City to approximately 1,400 years, which falls within the estimated range of 300 to 2,500 years. If only 1985 to 2019 is considered, the warming rate at Plant City increases to about 0.06° F per year ( $p < 0.01$ ), with a rate of 0.08° F per year ( $p < 0.01$ ) for winter months.

## **Climate Cycles and Temperatures in Florida**

Superimposed on long-term temperature trends, climate cycles can also influence temperatures in Florida. Several climate cycles act upon Florida, including the Atlantic Multidecadal Oscillation (AMO), El Niño Southern Oscillation (ENSO), and Pacific Decadal Oscillation (PDO) (Kirtman et al. 2017). The periodicity of the AMO is on the order of 20 to 50 years, ENSO on the order of 2 to 10 years, and PDO on the order of 5 to 30 years (Kirtman et al. 2017; Cameron et al. 2018).

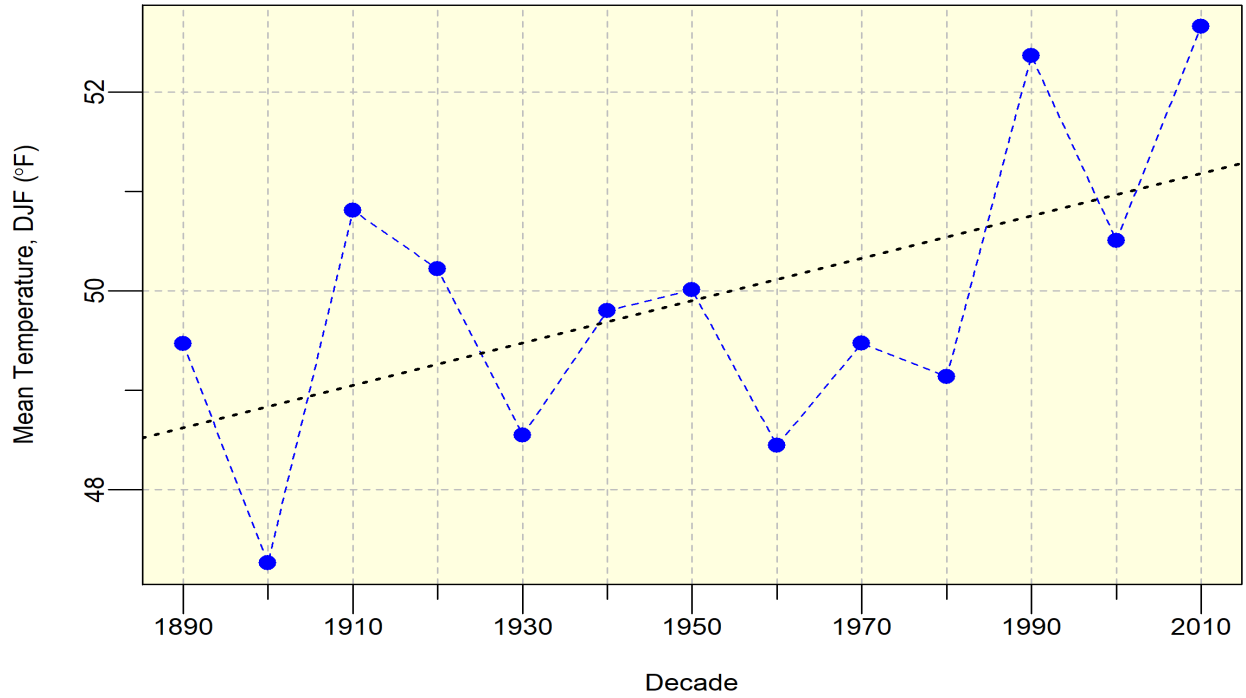


Figure 8. Mean decadal temperatures of selected winter months (December, January, and February) at Plant City.

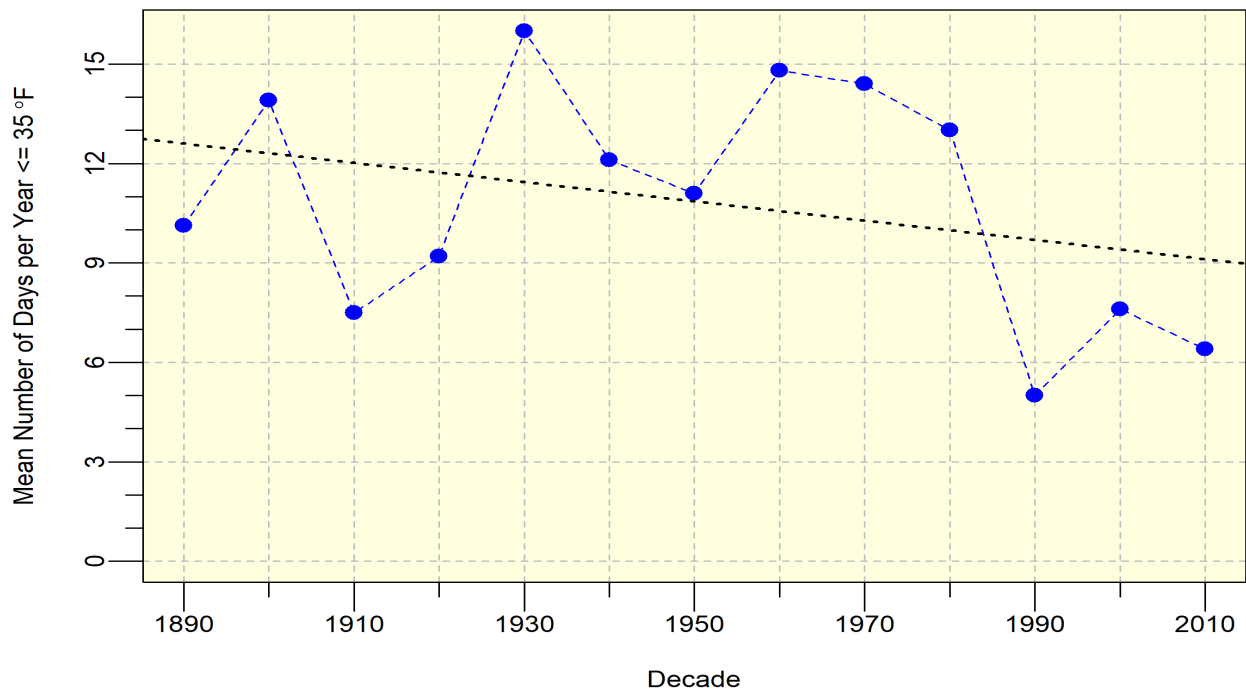


Figure 9. Average number of total days per year, by decade, at or below the 35° F threshold at Plant City.

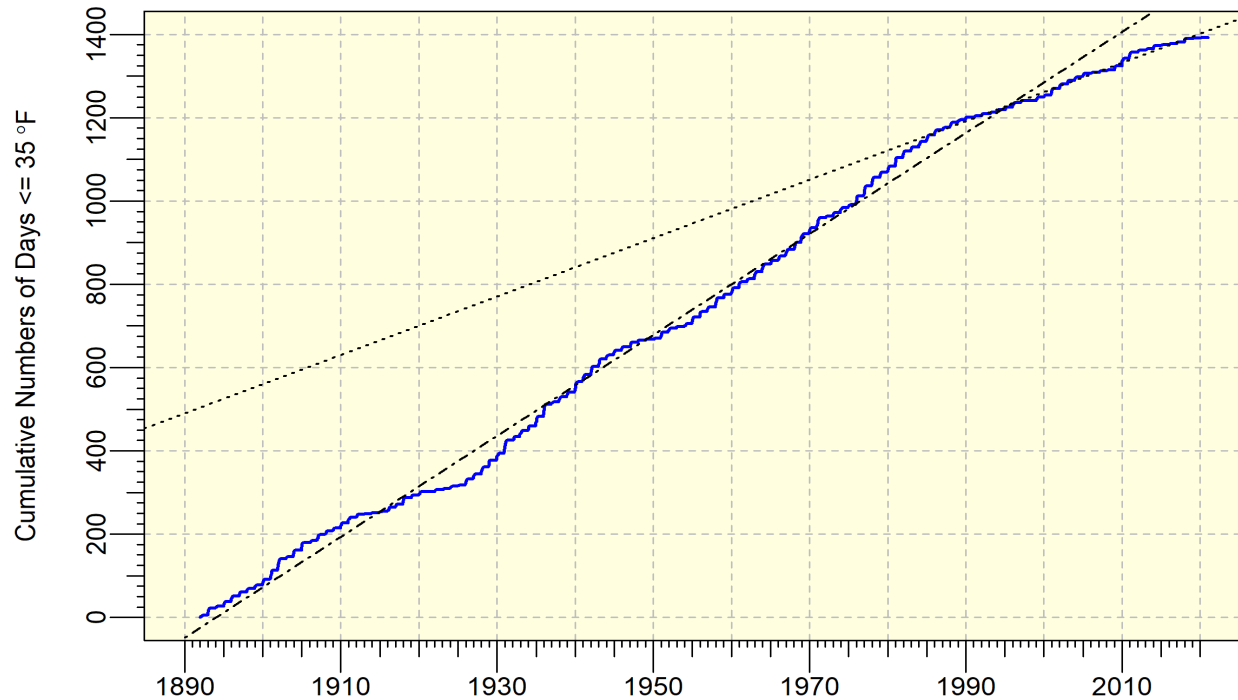


Figure 10. Cumulative number of days at or below the 35° F threshold at Plant City. Dash-dot line shows trend of 1892 to 1985; dashed line shows trend of 1985 to April 2020.

In the Panhandle of Florida, the positive phase of the AMO correlates with less rainfall and higher temperatures (Maleski and Martinez 2018). In southern Florida, no relationship was found between AMO phase and winter temperatures, but the positive phase was associated with higher summer temperatures (Moses and Anderson 2013). However, in peninsular Florida, while the positive AMO phase is associated with wetter summers, the AMO's relationship (if any) to temperatures is unclear. In most of peninsular Florida, El Niño phases of ENSO are associated with cooler and wetter (higher rainfall) winters, while La Niña phases are associated with warmer and dryer winters (Kirtman et al. 2017). For the PDO, the effect in Florida is similar to ENSO but with weaker relationships with temperature and rainfall; the positive phase is associated with lower temperature and higher rainfall (Kirtman et al. 2017). Work by Cameron et al. (2018), which aggregated ENSO phases for the three most recent AMO phases, suggests that El Niño events may be occurring less frequently and La Niña events more frequently, which could potentially be associated with warmer winters.

## Cold Event Hour Durations

So far, analyses have focused on daily minimum temperatures and the numbers of consecutive days that reached a specific threshold for daily minimum temperature, without considering the amount of time (e.g. hours) that temperatures fell at or below the threshold. Using the original 15-minute Dover City temperature data from 1998 to April 2020, it is possible to examine the time durations associated with cold events.

For the hour duration analyses, while data gaps for daily minimum temperature were estimated using the Plant City station, 15-minute data could not be found for Plant City or other appropriate surrogate stations, so gaps were not infilled. Therefore, large data gaps remain in the 15-minute temperature data for Dover City for the year 2000, July to December 2003, and January to July 2013.

In the 15-minute dataset for Dover City from 1998 to April 2020, 73 cold events were characterized, including three 5-day events, two 4-day events, eight 3-day events, twenty 2-day events, and forty 1-day events (Table 6). While the number of days in the events positively correlated with the duration ( $R^2 = 0.78$ ;  $p < 0.01$ ), in some instances, events occurring over fewer days recorded more hours at or below the 34° F threshold compared to days occurring over more days. For example, a 4-day event occurring over January 3 to 6, 2018 recorded 24.5 hours at or below the threshold, while eighteen 3-day events and one 2-day event matched or surpassed this duration.

The longest event occurred between January 3 and 13, 2010, when temperatures fell at or below 34° F for approximately 126 hours; this run was split across two 5-day segments by January 8, for which the lowest temperature was 34.11° F, as previously discussed (Table 6). The 90<sup>th</sup> percentile event lasted approximately 29 hours. The shortest events lasted only 15 minutes over one day.

Considering only the eight 3-day events (recall that events lasting 3 or fewer days represent 95% of all cold events; Table 3), the 90<sup>th</sup> and 95<sup>th</sup> percentiles were approximately 33 and 33.5 hours, respectively (Table 7). The longest event was approximately 34 hours. On average, the first event day comprised 25% of total event duration, the second day 42%, and the third day 33% (Table 8).

Including all subsets of higher events (i.e. a 4-day event includes two 2-day events, and a 5-day event includes three 3-day events), the 90<sup>th</sup> and 95<sup>th</sup> percentiles were approximately 40.5 and 44 hours, respectively, while the longest event was approximately 55 hours (Table 7). On average, when including subsets, the first event day comprised 31% of total event duration, the second day 39%, and the third day 31% (Table 8). However, this approach, which resamples the higher events, biases the statistics toward those more severe events.

Including only the first subset of higher events, the 90<sup>th</sup> and 95<sup>th</sup> percentiles were approximately 34 and 43 hours, respectively, while the longest event was approximately 55 hours (Table 7). On average, when including the first subset, the first event day comprised 23% of total event duration, the second day 44%, and the third day 34% (Table 8).

Table 6. Durations, in hours, that temperatures fell at or below 34° F for three-day cold events in the 1998 to 4/2020 15-minute Dover City temperature dataset, including 3-day subsets of higher (i.e. 4-day and 5-day) events.

# of Days in Original Event	Date	Day 1	Day 2	Day 3	Total
3	1/4/1999	0.3	15.0	9.5	24.8
3	1/23/2003	3.8	21.3	8.8	33.8
3	1/21/2009	14.8	10.0	8.3	33.0
3	2/4/2009	3.3	17.0	8.8	29.0
3	3/5/2010	0.8	1.0	2.8	4.5
3	12/27/2010	7.3	12.5	9.0	28.8
3	1/3/2012	10.0	13.8	8.5	32.3
3	1/17/2014	6.8	2.0	3.5	12.3
4	12/13/2010	1.5	20.3	12.5	34.3
4	12/14/2010	20.3	12.5	7.8	40.5
4	1/3/2018	0.8	9.8	8.8	19.3
4	1/4/2018	9.8	8.8	5.3	23.8
5	1/3/2001	7.0	13.8	8.8	29.5
5	1/4/2001	13.8	8.8	0.3	22.8
5	1/5/2001	8.8	0.3	8.3	17.3
5	1/3/2010	7.5	11.3	9.8	28.5
5	1/4/2010	11.3	9.8	17.3	38.3
5	1/5/2010	9.8	17.3	8.8	35.8
5	1/9/2010	19.5	20.0	15.8	55.3
5	1/10/2010	20.0	15.8	8.5	44.3
5	1/11/2010	15.8	8.5	8.0	32.3

For three-day events, the average and modal distribution of duration across the three days is that the first day has the lowest percentage of the total for the event, the second day has the highest, and third day is intermediate (Table 9).

## Groundwater Level Elevations

To assess typical groundwater elevations before the start of cold events, the 15-minute Dover City temperature dataset was collated by datetime with water level elevation data for DV-1 Upper Floridan aquifer (Suwannee) monitor well (SID 18797) from 1998 to April 2020. Data collection occurred hourly at the well from 1998 until December 2010, at which point 15-minute data become available (data for the well also exist from 1990 to 1997, with collection intervals varying from weekly to hourly over that time period). This well was selected due to its usage in the Minimum Aquifer Level (Peterson and Rumbaugh 2012).

Table 7. Selected summary statistics of cold event durations in hours. P90 = 90<sup>th</sup> percentile. P95 = 95<sup>th</sup> percentile.

Events Sampled	N	P90	P95	Max
3-Day Events	8	33.2	33.5	33.8
3-Day + 1 <sup>st</sup> Subset of Higher Events	13	34.2	42.7	55.3
3-Day + All Subsets of Higher Events	21	40.5	44.3	55.3
All Events	73	29.0	35.5	71.8

Table 8. Average percentage of total event duration that each day comprised. Numbers may not sum to 100% due to rounding.

Events Sampled	N	Day 1	Day 2	Day 3
3-Day Events	8	25%	42%	33%
3-Day + 1 <sup>st</sup> Subset of Higher Events	13	23%	44%	34%
3-Day + All Subsets of Higher Events	21	31%	39%	31%

Table 9. The percentage of events falling within various 3-day duration combinations, including only pure 3-day events, 3-day events plus the first subset of higher (i.e. 4- and 5-day) events, and 3-day events plus all subsets of higher events. L is the lowest percentage of the total for the event for the day, I am intermediate, and H is highest. For example, L-H-I indicates the first day had the least amount of time, the second day had the highest, and the third day was in between. Numbers may not sum to 100% due to rounding.

Combinations	3-Day	3-Day + 1 <sup>st</sup> Subset of Higher	3-Day + All Subsets of Higher
L-H-I	50%	62%	38%
H-I-L	13%	8%	29%
I-H-L	13%	15%	14%
H-L-I	13%	8%	10%
L-I-H	13%	8%	5%
I-L-H	0%	0%	5%

For each of the 73 cold events in this dataset, the first groundwater elevation reading of the first day of the cold event was obtained. This method was found to result in very similar results to using the water level reading occurring just before the first temperature reading at or below 34° F (mean difference of 0.10 feet for cold events 3 days or more in length). For example, for the January 4, 1999 3-day cold event, the midnight reading of 56.81 feet NGVD closely approximates the 57.04 feet NGVD reading that occurred at 9:00 AM just before the first cold event reading of 33.78° F at 9:15 AM.

In considering event starting water level elevations, it is important to assess the influence of potentially linked events, since preceding events can depress groundwater levels and result in an already-lowered groundwater levels by the start of the next cold event. An example is shown in Figure 11, where the 1-day cold event occurring on February 19, 2007 was preceded by a 1-day cold event on February 17, 2007. For each of the 73 cold events, graphs displaying water level data and temperature data were manually reviewed;

events were flagged as potentially linked if they followed a preceding cold event and water level had not yet recovered from the preceding event when a new cold event started. As an additional piece of information, water levels were compared to their period-of-record daily means, although natural factors (such as drought) can also lower water levels relative to this normal, so variation from the normal was not considered indicative of a linked event without additional corroborating evidence. Thirteen events were identified as potentially linked and were therefore excluded from starting elevation analyses. The results are shown in Table 10, which indicates that the typical groundwater elevation before cold events is around 53 feet NGVD. This value closely matches the starting elevation before the 2010 11-day event and also roughly corresponds to the January (which month encompasses a plurality of cold events; Table 2) normal level of about 54 feet NGVD.

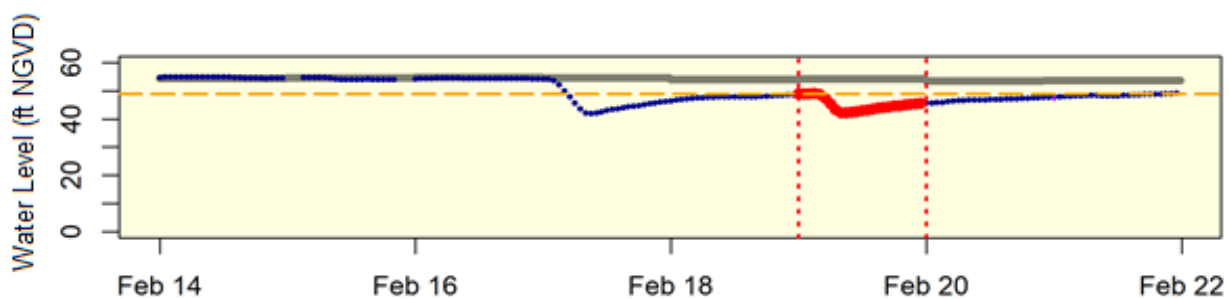


Figure 11. Groundwater level elevation at DV-1 for the February 19, 2007 1-day cold event (red points bracketed by vertical red dotted lines). The horizontal gray line shows the “normal” daily water level (based on daily period-of-record means), while the horizontal orange dashed line shows the water level at the beginning of the flagged cold event. Water levels for this event were already lowered by the 1-day cold event that occurred on February 17, 2019.

Table 10. Selected summary statistics of groundwater level elevations (ft NGVD) at DV-1 before cold events. P05 = 5<sup>th</sup> percentile. P10 = 10<sup>th</sup> percentile.

Magnitude	N	Min	P05	P10	Avg	Max
3-Day	7	45.3	45.8	46.4	52.3	57.1
≥3-Day	9	45.3	46.0	46.7	52.7	57.1
≥1-Day	60	44.2	44.5	46.0	53.1	61.1

## Conclusion

The 2010 11-day event was an unprecedented cold spell in the reviewed 128-year temperature record and estimates of its recurrence interval suggest it could occur much less frequently than that (with an estimated recurrence interval between 300 and 2,500 years, with a current best estimate of 570 years). Additionally, trends of increasing daily minimum temperature and correspondingly decreasing frequency of freezing days are expected to further reduce the frequency at which an event of the 2010 magnitude would occur in the future. For a more representative cold event, 95% of observed cold events

are 3 days or less in length, making a 3-day event, which has an estimated recurrence interval of 2 to 3 years, a reasonably conservative cold event to use for most modeling scenarios. The typical groundwater elevation at DV-1 before cold events was found to be about 53 feet NGVD.

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