ERDC/TN WRAP-23-2
June 2023

Antecedent Precipitation Tool (APT) Version 2.0: Technical and User Guide

by Joseph L. Gutenson, Chase O. Hamilton, and Jason C. Deters

PURPOSE: This document provides an overview of the technical components of the Antecedent Precipitation Tool (APT) and a user's guide for the APT. The APT is an automation tool that the US Army Corps of Engineers (USACE) developed to facilitate the comparison of antecedent or recent precipitation conditions for a given location to the range of normal precipitation conditions that occurred during the preceding 30 yr.* In addition to providing a standardized methodology to evaluate normal precipitation conditions (precipitation normalcy), the APT queries additional datasets to assess the presence of drought conditions and the approximate dates of the wet and dry seasons for a given location. This document constitutes an update to *Antecedent Precipitation Tool (APT) Version 1.0: Technical and User Guide* (Gutenson and Deters 2022).

BACKGROUND: The APT automates an existing methodology in which a method of evaluating 30-day rolling totals of precipitation is combined with the Natural Resources Conservation Service (NRCS) Engineering Field Handbook weighting factors (combined method) (NRCS 1997), providing utility in evaluating precipitation normalcy for individual dates at an individual site (Sprecher and Warne 2000). In addition to providing a standardized methodology to evaluate precipitation normalcy, the APT also provides two additional indices of longer-term hydrologic input:

1. The presence of drought conditions using the monthly National Oceanic and Atmospheric Administration (NOAA) US Climate Divisional Database (nClimDiv) Palmer Drought Severity Index (PDSI) (Palmer 1965)
2. The approximate dates of the wet and dry seasons for a given location using the Web-Based, Water-Budget, Interactive, Modeling Program (WebWIMP) (University of Delaware 2009)

USACE originally developed the APT to streamline and automate the evaluation of precipitation normalcy and other climatic variables to complete wetland delineations whenever an assessment of the following site-specific conditions is necessary: dry season, drought conditions, lower than normal antecedent precipitation, or greater than normal antecedent precipitation (USACE 2008). The methodology underlying the APT precipitation normalcy calculation has demonstrated success in determining precipitation normalcy for hydric soil and wetland determinations (Vepraskas et al. 2019).

An APT analysis can be conducted to determine the normal periodic range of precipitation for any geographic location in the United States where adequate precipitation data are available and can determine whether observed precipitation prior to a given observation date falls within that normal periodic range. An APT analysis can be completed for any date of interest within the available precipitation record and therefore can be useful for evaluating antecedent precipitation

* For a full list of the spelled-out forms of the units of measure and unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248–52 and 345–7, respectively. https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

conditions for any point-in-time or indirect hydrologic observation (e.g., aerial photographs or data collected during a site visit).

ANTECEDENT PRECIPITATION TOOL (APT) TECHNICAL DETAILS: The APT calculates an Antecedent Precipitation Score for a given observation point and observation date using historic precipitation data. The Antecedent Precipitation Score serves as a measurement of precipitation normalcy that is described by the Antecedent Precipitation Condition (e.g., normal, wet, or dry conditions) for the observation point and observation date. All precipitation data the APT uses to calculate the Antecedent Precipitation Score come from either station data in the NOAA Global Historic Climatology Network (GHCN)–Daily precipitation dataset (Menne et al. 2012; NOAA 2022b) or the US Climate Gridded Dataset–Daily (nClimGrid-Daily) gridded precipitation dataset (Durre et al. 2022; NOAA 2022a; 2022c). An observation point designates the user-defined location of interest for running the APT. The user of the APT identifies an observation point using a single latitude and longitude. The user also identifies an observation date using a month, day, and year. The APT calculates an Antecedent Precipitation Score by one of two general means, as specified by the user: single-point or watershed analysis.

SINGLE-POINT ANALYSIS

Station-based APT analysis. When the user runs a single-point analysis, the APT builds one 30 yr precipitation climatology and compares the antecedent 90-day period to this precipitation climatology for the observation point using the combined method described above, as recommended by Sprecher and Warne (2000). When performing a station-based APT analysis, the first step in this single-point analysis is for the APT to identify the primary station or the weather station within the GHCN where the APT primarily derives the precipitation climatology. The primary station selection process must overcome a lack of GHCN stations with complete historical records. Thus, the primary station selection process includes a dual-layered determination: (1) a weighted distance ranking and (2) assessment of record completeness. Weighted distance ranking occurs by assessing the distance and elevation differences from the observation point to GHCN stations using the formula:

$$\delta_i = \varphi_i \left(\frac{\rho_i}{1{,}000} + 0.45 \right) \tag{1}$$

In Equation 1, δ_i is the weighted distance from the GHCN station i to the observation point in units of mi*ft, φ_i is the great circle distance (GeoPy 2018) from the *i*th GHCN station to the observation point in units of miles, and ρ_i is the difference in elevation between the *i*th GHCN station and the observation point in units of feet. By working with experienced USACE project managers from across the United States and ascertaining their best professional judgement, the developers arrived at the formulation of Equation 1. The APT assesses the weighted distance for all stations within a φ_i = 48 km (30 mi) radius using this weighted distance formula. If additional station data are necessary due to data gaps at GHCN stations within the 48 km (30 mi) radius, the APT will sequentially increase the radius until either completing a 30 yr time series, reaching the maximum search radius, or using the maximum number of stations (15 GHCN stations). If the latitude of the observation point is less than 50° latitude (i.e., in the Contiguous United States [CONUS]), the radius of the search distance will incrementally increase by 16 km (10 mi) and extend to a maximum of 97 km (60 mi). If the latitude of the observation point is greater than or equal to 50° latitude (e.g., in Alaska), the search distance will incrementally increase by 48 km (30 mi) and extend to a maximum of 805 km (500 mi). A ranked list of GHCN stations is determined by ordering GHCN stations based upon δ_i values. The APT acquires an approximate elevation value for the observation point from the US Geological Survey (USGS), Elevation Point Query Service (EPQS) (USGS 2023c). The EPQS determines elevation values by interpolating from data within the USGS 3D Elevation Program (3DEP) dynamic elevation service for the observation point or GHCN station. 3DEP data consists of multiple resolutions of digital elevation model (DEM) data, including 1 m resolution lidar-based DEM data, where available, and 1/3 arc-second (approximately 9 m) seamless DEM data. 3DEP data currently possesses an overall vertical root mean square error of 0.53 m (USGS 2023a; Stoker and Miller 2022).

In determining the APT primary station, the APT also assesses the completeness of the precipitation records for each GHCN station in the ranked list of GHCN stations. Many GHCN stations lack complete precipitation records for the necessary time span. A nationwide assessment of the APT found that at least 68 daily records for the APT within the 90-day antecedent period (>75%) and greater than 6,000 daily records in the 30 yr normal period best reflected the primary station determinations made by USACE project managers when using incomplete precipitation records. The APT gives ranking preference to any GHCN stations with at least 8,000 daily records within the normal period and gives further ranking preference to stations with greater than 10,000 daily records within the normal period. The APT iterates through the ranked list of GHCN stations. If a GHCN station meets the minimum record length specifications, the APT assesses the number of records and the δ_i value for the station. The GHCN station that has the lowest weighted difference (δ_{min}) for the GHCN stations in the ranked list and meets the minimum records specifications will be the chosen primary station, unless a GHCN station with $\delta_i > \delta_{min}$ has greater than 8,000 daily records and meets the following criteria:

$$\delta_{8000} < 2\tau\delta_{min} \quad (2)$$

In Equation 2, δ_{8000} is the lowest weighted difference of the GHCN station with greater than 8,000 daily records within the normal period, and τ is a distance toleration factor, which is currently set to 0.75 based upon evaluation by the APT development team.

Similarly, if a GHCN station in the ranked list of GHCN stations has $\delta_i > \delta_{min}$ and greater than 10,000 records in the normal period, this GHCN station becomes the primary station if meeting the following criteria:

$$\delta_{10000} < 4\tau\delta_{min} \quad (3)$$

In Equation 3, δ_{10000} is the lowest weighed difference of the GHCN station with greater than 10,000 daily records in the normal period.

If GHCN stations meet the δ_{8000} and δ_{10000} criteria specified above, the APT selects the δ_{10000} if the following criteria are met in Equation 4:

$$\delta_{10000} < 2\tau\delta_{8000} \quad (4)$$

Otherwise, the GHCN station meeting the δ_{8000} criterion is the primary station.

Once the APT selects a primary station from the ranked list, the APT determines where values are missing in the primary station records and which GHCN stations fill those values. The APT determines which GHCN station fills the data gaps in the primary station records by calculating δ_i between the primary station and other GHCN stations. The APT reorders GHCN stations based upon the recalculated δ_i values, and those stations are sequentially used to backfill data gaps in the primary station records. There are no minimum record-completeness requirements for selecting GHCN stations that fill primary station data gaps. As data filling occurs within each search radius, if greater than 1 day of data gap remain in the record, the primary station selection process and subsequent data filling will repeat at the increased search radius. If gaps in the primary station records persist after 15 GHCN stations are used or the APT reaches the maximum search radius to backfill the primary station records, the APT performs a linear interpolation between the first observation before the data gap and when observations in the primary station record return. The number of continuous days within a data gap cannot be greater than 1 day for linear interpolation to fill the gap.

Grid-based APT analysis. Alternative to the station-based APT analysis, the user may derive the precipitation climatology of their observation point using the GHCN daily gridded precipitation product, from the nClimGrid-Daily dataset. The NOAA National Centers for Environmental Information (NCEI) develop and publish the nClimGrid-Daily precipitation product. The nClimGrid-Daily precipitation product has a 0.0417° horizontal resolution (approximately 5 km or 3.1 mi) and covers the CONUS from 1 January 1951 to approximately 2 to 3 days after the current date. NCEI produces the nClimGrid-Daily precipitation dataset using a quality-controlled version of the same GHCN station data that the APT collects. The quality-controlled GHCN station data are an input into an interpolation algorithm that creates an initial gridded precipitation dataset. Initial postprocessing of the initial gridded precipitation dataset removes spurious nonzero precipitation totals from the initial CONUS precipitation grid. nClimGrid-Daily precipitation data are preliminary until the fourth day of the subsequent month when they are adjusted to ensure consistency with the NCEI nClimGrid-Monthly dataset. When alignment with the nClimGrid-Monthly dataset occurs, the previous 2 months of nClimGrid-Daily precipitation also reprocess to include any additional observations. Therefore, nClimGrid-Daily data for the current month and previous 2 months are subject to change. Visiting the nClimGrid-Daily data dissemination platform (*https://www.ncei.noaa.gov/thredds/catalog/nclimgrid-daily/catalog.html*) will assist the user in ascertaining the current status of near real-time nClimGrid-Daily data. Monthly data marked as preliminary (e.g., ncdd-202304-grd-prelim.nc) are subject to change. Although several gridded precipitation products exist, nClimGrid-Daily exists to overcome limitations in the methodologies, length of records, update frequency, and spatial resolution of other existing gridded temperature and precipitation products (Durre et al. 2022). Thus, the APT currently utilizes the nClimGrid-Daily dataset instead of alternative gridded precipitation products.

To produce a climatology using the nClimGrid-Daily precipitation product, the APT uses the location of the observation point to find the nearest nClimGrid-Daily grid cell centroid. The APT calculates the distance between the observation point and all grid cell centroids using the Haversine Formula (Kettle 2017). The APT selects the nClimGrid-Daily grid cell centroid that minimizes the distance calculated by the Haversine Formula. The Haversine Formula calculates distance using the following expression:

$$a = \sin\left(\frac{\frac{\pi}{180}(lat_g - lat_o)}{2}\right)^2 + \cos\left(\frac{\pi}{180}lat_o\right)\cos\left(\frac{\pi}{180}lat_g\right)\sin\left(\frac{\frac{\pi}{180}(lon_g - lon_o)}{2}\right)^2 \quad (5)$$

Where π is the mathematical constant expressing the ratio of a circle's radius to the circle's circumference, lat_g is the latitude of each grid cell centroid in decimal degrees, lat_o is the latitude of the observation point in decimal degrees, lon_g is the longitude of each grid cell centroid in decimal degrees, and lon_o is the longitude of the observation point in decimal degrees. The value a is then used to calculate c, using the following expression:

$$c = \arctan\left(\frac{\sqrt{a}}{\sqrt{1-a}}\right) \quad (6)$$

The value of c then passes to the following equation to calculate the distance between the observation point and grid cell centroid:

$$d = cr \quad (7)$$

Where r is the radius of earth, which is approximately 6,371 km. The value d is in units of length (kilometers). The grid cell centroid that minimizes d is the nearest grid cell to the observation point, and the APT uses this grid cell's precipitation values.

Antecedent Precipitation Score. When the user runs a single-point analysis, the APT builds one 30 yr precipitation climatology and compares the antecedent 90-day period to this precipitation climatology for the observation point and observation date using the combined method described above. The APT will build the precipitation climatology dataset using the station or grid-based approaches described above. The APT compares rolling 30-day totals for three annotation points to the proceeding 30-yr climatology: the observation date (including precipitation on the observation date), the date that falls 30 days prior to the observation date, and the date that falls 60 days prior to the observation date.[†] This methodology derives from Sprecher and Warne (2000) and NRCS (1997) and is summarized as the following expression:

$$\alpha = \sum_{j=1}^{n} \gamma_j \omega_j \quad (8)$$

In Equation 8, α is the Antecedent Precipitation Score, γ_j is the condition value assigned for the *j*th 30-day annotation point, ω_j is the weighing value assigned to the *j*th 30-day annotation point, and n is the number of annotation points or rolling periods. If the 30-day rolling total for the *j*th annotation point falls below the 30th percentile in the 30-yr climatology, $\gamma_j = 1$. If the 30-day rolling total for the *j*th annotation point falls between the 30th and 70th percentile in the 30-yr climatology, $\gamma_j = 2$. If the 30-day rolling total for the *j*th annotation point falls above the 70th

[†] If the water year of the observation date falls on a leap year, the APT does not calculate February 29 percentiles. Instead, the APT averages the February 28 and March 1 percentiles.

percentile in the 30-yr climatology, $\gamma_j = 3$. There are currently three annotation points for three rolling periods (n = 3). If the jth 30-day annotation point is the observation date, ω_j = 3 for jth 30-day annotation point. If the jth 30 day annotation point is the 30 days before the observation date, ω_j = 2 for jth 30-day annotation point. If the jth 30-day annotation point is 60 days before the observation date, ω_j = 1 for jth 30-day annotation point. The APT assigns categorical summaries, termed the Antecedent Precipitation Conditions, for each Antecedent Precipitation Score. Table 1 summarizes the Antecedent Precipitation Score categories.

Table 1. Antecedent Precipitation Score categories derived from NRCS (1997).

Antecedent Precipitation Score (α) Range, where *n* = 3	**Antecedent Precipitation Condition**
Antecedent Precipitation Score < 10	Drier than Normal
10 ≤ Antecedent Precipitation Score < 15	Normal Conditions
15 ≥ Antecedent Precipitation Score	Wetter than Normal

Web-Based, Water-Budget, Interactive, Modeling Program (WebWIMP) and Palmer Drought Severity Index (PDSI). The APT calculates the Antecedent Precipitation Score independent of the WebWIMP and PDSI calculations. However, for each observation point, the APT provides the user with wet season and dry season and drought conditions by querying the WebWIMP and nClimDiv PDSI datasets, respectively.

USACE (2008) advises the use of the WebWIMP in approximating wet or dry season context for the purposes of wetland delineation. WebWIMP is a web application developed and maintained by the University of Delaware (University of Delaware 2009). WebWIMP provides an interface to global monthly water-balance estimates that are a gridded raster product with a 0.5° horizontal resolution. The methodology powering WebWIMP calculates the monthly water-balance estimates based upon a global network of over 13,000 weather observation stations (Wilmott et al. 1981a, b). A modified form of the Thornthwaite scheme (Thornthwaite 1948) calculates estimates of monthly average potential evapotranspiration (PET) using average monthly surface air temperature. PET is a measurement of the amount of moisture that, if available, would be consumed by evapotranspiration (AMS 2012). PET is important because it quantifies the removal of water from the land surface and insertion back into the atmosphere when sufficient water is available on the land surface (Singer et al. 2021; Milly and Dunne 2016). WebWIMP presents these resulting differences for the weather observation stations as an interpolated, spatially continuous raster (Willmott et al. 1985). Because PET estimates the amount of atmospheric demand for water and precipitation is an estimate of the supply of atmospheric water, the difference between average monthly precipitation and an estimate of monthly average PET can indicate when the wet or dry season occurs on the land surface. A negative difference between monthly precipitation and PET indicates the dry season. A positive difference indicates the wet season (USACE 2008).

One limitation of WebWIMP data is that the Thornthwaite (1948) methodology estimates PET. Penman-Montheith, or other radiation-based means of estimating PET, are generally preferred over temperature-based approaches, such as Thornthwaite. However, temperature-based approaches rely upon readily available meteorological inputs like temperature while radiation-based approaches require meteorological data that are available less frequently (van der Schrier et al. 2011; Lang et al. 2017). Further, the spatial and temporal resolution of WebWIMP is relatively coarse and may limit WebWIMP effectiveness during transitional periods between the wet season and dry season. The APT uses the observation point's geographic location to determine which WebWIMP grid cell into which the observation point falls. The APT then assigns wet or dry season to the APT analysis using the WebWIMP difference between monthly precipitation and PET for the month of the observation date within that grid cell. Table 2 lists the categorical summaries of WebWIMP wet season and dry season categorical assignment (USACE 2008).

Table 2. Web-Based, Water-Budget, Interactive, Modeling Program (WebWIMP) values and associated seasonal categories derived from USACE (2008).

(monthly average precipitation)–PET	Range Descriptor
≥0	Wet Season
<0	Dry Season

The APT queries the NOAA monthly CONUS PDSI calculations within nClimDiv to determine whether drought conditions are present for a given observation point (NOAA 2014; Vose et al. 2014). The PDSI is a cumulative index estimated by calculating a water balance using observed precipitation and calculated PET (Palmer et al. 1965). Like the WebWIMP, the PDSI uses the Thornthwaite (1948) approach to calculate PET while Penman-Montheith or other radiation-based approaches to PET calculation are generally preferred (Lang et al. 2017). The PDSI also treats all precipitation, including snowfall, as liquid precipitation and does not account for vegetative or soil conditions in evaporation calculations. Further, because of the monthly time-step, the nClimDiv PDSI does not reflect short-term hydrologic conditions. However, previous research has shown that monthly, basin-averaged PDSI values can correlate well with observed monthly average soil moisture and yearly average streamflow measurements (Dai et al. 2004; Dai 2011, 2012). The APT uses the latitude and longitude of the observation point to determine into which climate division the observation point falls. The APT assigns that climate region's PDSI value during the period of interest to the observation point. Categorical summaries are determined for each PDSI range. Table 3 summarizes the PDSI categories provided by the APT and adapted from Palmer (1965).

Table 3. Palmer Drought Severity Index (PDSI) values and associated categories (adapted from Palmer [1965]).

PDSI Range	Range Descriptor
PDSI = −99.99	Not available
4 < PDSI	Extreme wetness
2.99 < PDSI ≤ 4	Severe wetness
1.99 < PDSI ≤ 2.99	Moderate wetness
0.99 < PDSI ≤ 1.99	Mild wetness
0.49 < PDSI ≤ 0.99	Incipient wetness
−0.51 < PDSI ≤ 0.49	Normal
−1.01 < PDSI ≤ −0.51	Incipient drought
−2.01 < PDSI ≤ −1.01	Mild drought
−3.01 < PDSI ≤ −2.01	Moderate drought
−4.01 < PDSI ≤ −3.01	Severe drought
PDSI ≤ −4.01	Extreme drought

Watershed Analysis. An APT watershed analysis undergoes the same processes as those described above for the single-point analysis. However, the assessment process occurs at randomly assigned sampling points within a specified watershed assigned to the observation point. An observation point's watershed area can be designated using the USGS National Water Boundary Database (WBD) hydrologic unit code (HUC) 8, 10, and 12 boundaries or through a custom watershed polygon. WBD HUCs are nested hydrographic features that hierarchically organize, classify, and map surface-water features in the United States. The hierarchy assigns two digits at each level of the hierarchy, as the geographic range of an area narrows from a regional 2-digit level (HUC 2) to an 8-digit subbasins (HUC 8), 10-digit watersheds (HUC 10), 12-digit subwatersheds (HUC 12), and so forth (Seaber et al. 1987; Jones et al. 2022). Using a HUC 8, 10, or 12 in the APT watershed analysis will not account for any upstream HUCs and will utilize the entire HUC area in which the observation point falls. A custom watershed analysis can overcome the limitations associated with the use of a HUC 8, 10, or 12. The user must generate the custom watershed using a third-party tool such as the EPA Watershed Assessment, Tracking & Environmental Results System Web Services (EPA 2022), USGS StreamStats (USGS 2023b), or the ArcGIS Pro Watershed tool (Esri 2022). The user may select which type of watershed analysis to run. The observation point must fall within the chosen watershed polygon boundary.

The APT randomly assigns sampling points within the designated watershed area. The APT randomly generates points within the minimum and maximum latitude and longitude values for the watershed and tests them against two sampling conditions. First, the APT will test whether the point falls within the watershed. Second, the APT will test whether the point is closer to any of the previously selected sampling points than the default sampling point spacing distance. To ensure the best reflection of point dispersion on all watersheds, the default point spacing was lowered during the development of the APT watershed analysis until reaching a value of 6 km (3.75 mi). In the case of each HUC, the sampling process repeats until 1,500 consecutive sampling points fail one of the two tests above or, in the case of the custom watershed, when 3,000 consecutive sampling points fail one of the two sampling tests above.

Once the APT develops a list of sampling points, the APT calculates the Antecedent Precipitation Score for each sampling point, determines the seasonality using WebWIMP, and assesses drought conditions using the NOAA nClimDiv monthly PDSI for each sampling point. The APT then averages all the sampling point Antecedent Precipitation Scores to represent Antecedent Precipitation Score for the observation point.

APT USER GUIDE

Installation Instructions. The following steps are required to install the APT on a user's Windows machine:

1. The user can access the latest version of the APT by navigating to the APT GitHub release page at *https://github.com/erdc/Antecedent-Precipitation-Tool/releases/latest* and downloading the Antecedent.Precipitation.Calculator.7z folder. Please note that this version of the APT functions only on Windows machines.

2. The user must extract the operational code by using the 7-zip file manager software, available for download at https://www.7-zip.org/.
3. Once extracted, the user will then have access to the Antecedent Precipitation Tool directory. To access the tool's functionality, the user should navigate into the Antecedent Precipitation Tool directory to find the main_ex.exe file. The Antecedent Precipitation Tool directory contains all the files necessary to operate the APT and the APT's outputs.
4. Double-clicking the main_ex.exe file will open the APT Microsoft Disk Operating System (MS-DOS) window. This window will provide the user with feedback when the tool is operating that will be useful in diagnosing issues that the user might encounter.
5. If the user is operating the APT for the first time, the APT will create the Antecedent Precipitation Tool.lnk file on the user's desktop for easy access.
6. To ensure the inputs utilized by the APT are up to date, the system will automatically check for and install updates to APT datasets.
7. The APT MS-DOS window will launch the APT graphical user interface (GUI). Figure 1 illustrates the current GUI.

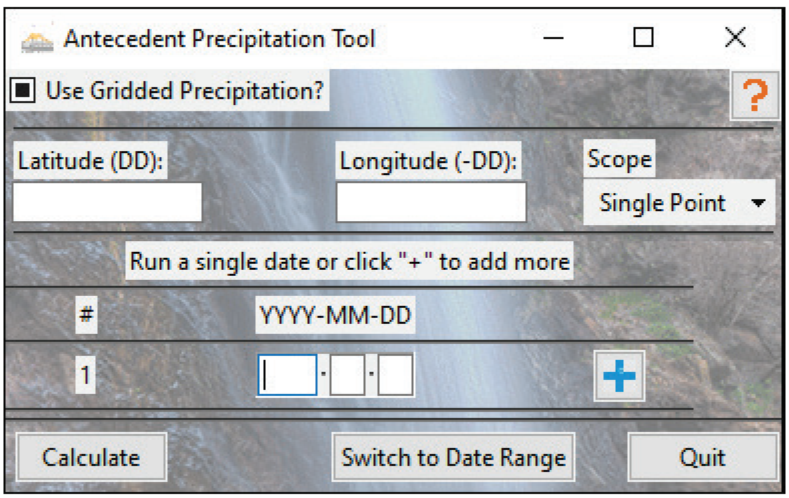


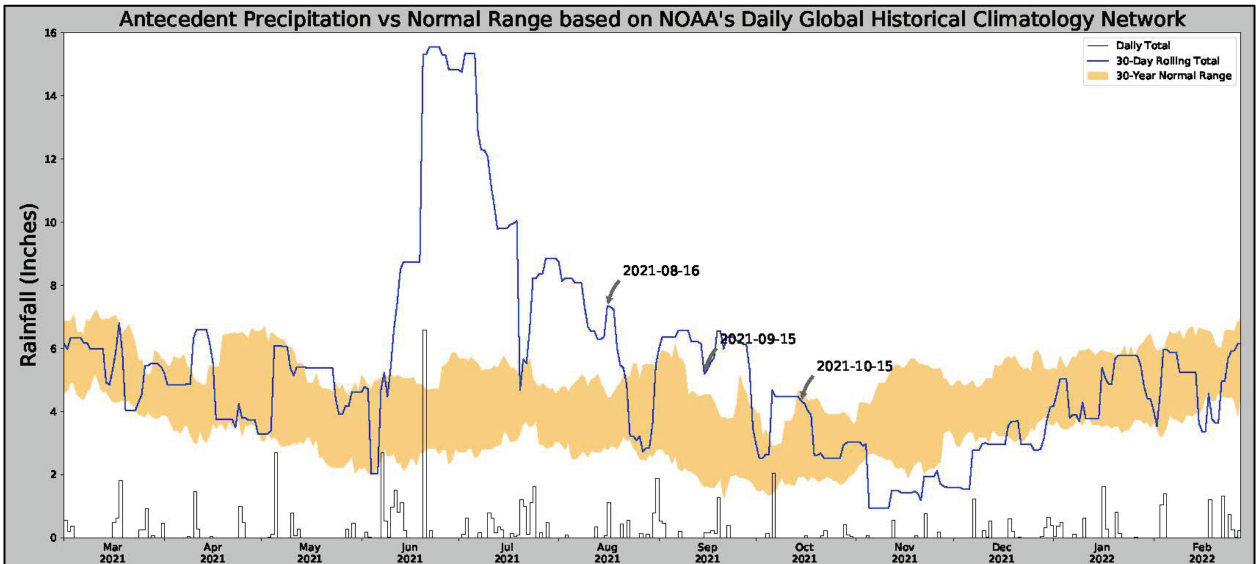
Figure 1. The Antecedent Precipitation Tool (APT) Version 2.0 graphical user interface (GUI).

User interactions with the APT primarily take place within the GUI. A series of walkthroughs on how to access APT functionality using the GUI accompany this user and technical guide and can be accessed by clicking the *?* mark in the *top-right corner* of the GUI (Figure 1). Each walkthrough illustrates the specific process undertaken for each permutation of APT usage. Therefore, this technical and user guide will not cover specific operational steps within the APT.

Operational Extents. The APT will conduct an analysis for nearly any point in the United States and its territories. The US Census Bureau's 2021 national cartographic boundary shapefile (1:5,000,000 resolution) defines the operational extent of the APT (US Census Bureau 2022). A user's designated observation point must fall within the national cartographic boundary to conduct an APT analysis for that point.

Output Description. After completion of each APT run, the APT will provide several outputs. The folder containing these outputs will automatically open on the user's machine following completion of each APT analysis. This folder will be present in the Outputs directory within the Antecedent Precipitation Tool directory. The Outputs directory will organize APT output according to the APT version that conducted the analysis. For example, APT Version 2.0.0 output will be within Outputs/v2_0_0 directory.

The contents of the folder will vary depending upon the analysis undertaken. In general, the APT output consists of three output types. The first is a PDF summarizing the APT results, including the Antecedent Precipitation Score, WebWIMP seasonal determination, and PDSI drought determination at both single-point and watershed scales. Figure 2 depicts an example of the single-point summary output provided by the APT when utilizing the GHCN station data. Detailed walkthroughs of each PDF summary accompany this document. The second component of the APT output will be GHCN station or GHCN gridded data collected and analyzed by the APT and saved as comma-separated value (CSV) files. The third component will be a summary PDF and CSV files, created if the user runs a watershed analysis or multiple dates.



Coordinates	33.2098, -87.5692
Observation Date	2021-10-15
Elevation (ft)	225.39
Drought Index (PDSI)	Extreme wetness
WebWIMP H_2O Balance	Wet Season

30 Days Ending	30th %ile (in)	70th %ile (in)	Observed (in)	Wetness Condition	Condition Value	Month Weight	Product
2021-10-15	1.928347	4.642126	4.322835	Normal	2	3	6
2021-09-15	1.629921	4.52441	5.188977	Wet	3	2	6
2021-08-16	2.787008	4.427559	7.34252	Wet	3	1	3
Result							Wetter than Normal - 15

US Army Corps of Engineers

ERDC

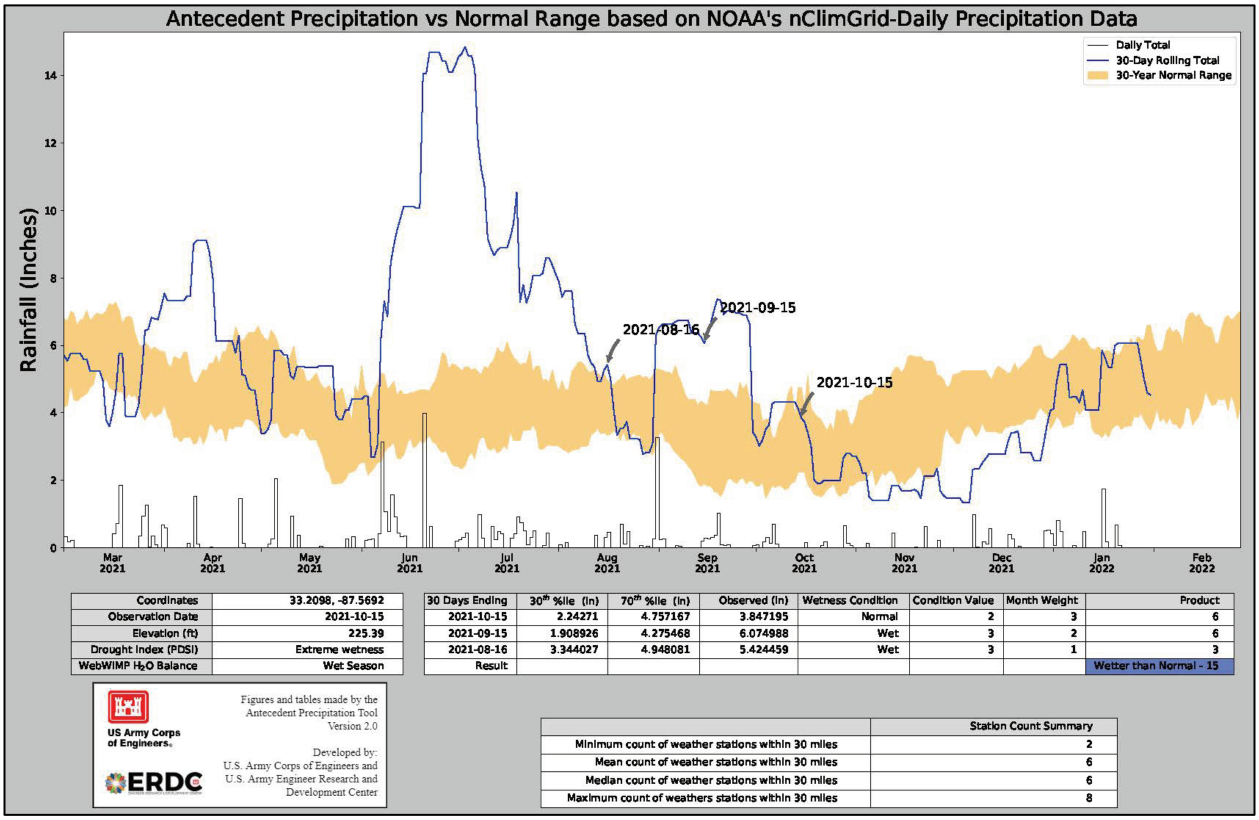
Figures and tables made by the Antecedent Precipitation Tool Version 2.0

Developed by: U.S. Army Corps of Engineers and U.S. Army Engineer Research and Development Center

Weather Station Name	Coordinates	Elevation (ft)	Distance (mi)	Elevation Δ	Weighted Δ	Days Normal	Days Antecedent
TUSCALOOSA OLIVER DAM	33.2097, -87.5936	151.903	1.411	73.487	0.738	11106	90
NORTHPORT 2 S	33.2125, -87.5914	149.934	0.232	1.969	0.105	124	0
TUSCALOOSA MUNI AP	33.2119, -87.6161	149.934	1.31	1.969	0.592	92	0
TUSCALOOSA ACFD	33.2119, -87.6161	168.963	1.31	17.06	0.612	1	0
HOLT L&D	33.2533, -87.45	194.882	8.829	42.979	4.353	30	0

Figure 2. An example of the PDF output provided to the user after an APT single-point analysis with Global Historic Climatology Network (GHCN) station data.

APT single-point analysis outputs. For a single point analysis, the APT output will be stored within a directory named according to the latitude and longitude of the observation point (e.g., 33.2098, −87.5692). Within this directory, the APT will provide the user with the two APT outputs. The first output will be a PDF summary that resembles Figure 2 or Figure 3, depending upon whether the APT analysis undertaken is based upon GHCN station or gridded precipitation data. The differences between Figure 2 and Figure 3 are the titles of the images at the *top* of the PDF and the tables in the *bottom-right corners* of each figure. The *bottom-right table* in Figure 2 expresses information on the weather station data utilized in the APT station-based analysis. The *bottom-right table* in Figure 3 summarizes the counts of weather stations that are within approximately 48.2 km (30 mi) of the grid cell used by the APT to extract precipitation data.



Coordinates	33.2098, -87.5692
Observation Date	2021-10-15
Elevation (ft)	225.39
Drought Index (PDSI)	Extreme wetness
WebWIMP H_2O Balance	Wet Season

30 Days Ending	30^{th} %ile (in)	70^{th} %ile (in)	Observed (in)	Wetness Condition	Condition Value	Month Weight	Product
2021-10-15	2.24271	4.757167	3.847195	Normal	2	3	6
2021-09-15	1.908926	4.275468	6.074988	Wet	3	2	6
2021-08-16	3.344027	4.948081	5.424459	Wet	3	1	3
Result							Wetter than Normal - 15

	Station Count Summary
Minimum count of weather stations within 30 miles	2
Mean count of weather stations within 30 miles	6
Median count of weather stations within 30 miles	6
Maximum count of weathers stations within 30 miles	8

Figure 3. An example of the PDF output provided to the user after an APT single-point analysis with US Climate Gridded Dataset-Daily (nClimGrid-Daily) gridded precipitation data.

The second component of APT output, the precipitation data, will be in a directory titled Station Data or Gridded Data, based upon the user's choice of GHCN station or gridded data for the analysis, and will be stored as CSV files.

Within the Station Data directory, all data from each of the GHCN stations listed in the weather station table in Figure 2 will be output as CSV data and will be titled <name of the GHCN station>_<year of observation date>-<month of observation date>-<day of observation date>.csv (e.g., HOLT L&D_2011-01-01.csv). Two of the CSV files contain the merged GHCN data that the APT uses to determine the Antecedent Precipitation Score for the observation point and observation date. The titles of these merged data files will be merged_stations_<year of observation date>-<month of observation date>-<day of observation date>.csv (e.g., merged_stations_2011-01-01.csv) and merged_stations_converted_to_in_<year of observation date>-<month of observation date>-<day of observation date>.csv (e.g., merged_stations_converted_to_in_2011-01-01.csv). Table 4 is a data dictionary for each of these CSV files that are output by the APT within the Station Data directory.

Table 4. Data dictionary for the APT merged_stations_<observation date>.csv and merged_stations_converted_to_in_<observation date>.csv files.	
Column	**Description**
Column 1	Date of each precipitation observation expressed in YYYY-MM-DD format
Column 2	Depth of each daily precipitation observation. Units of 10*millimeters for <name of the GHCN station>_<year of observation date>-<month of observation date>-<day of observation date>.csv and merged_stations_<year of observation date>-<month of observation date>-<day of observation date>.csv. Units of inches for merged_stations_converted_to_in_<year of observation date>-<month of observation date>-<day of observation date>.csv

Within the Gridded Data directory, the GHCN gridded data used to generate Figure 3 will be output as CSV data. There will be one CSV file present in the directory. The CSV file contains the daily GHCN data with precipitation depth in units of millimeters and a daily count of precipitation observations that are within 30 mi of the chosen grid cell. The APT uses the precipitation depth data to determine the Antecedent Precipitation Score for the observation point and observation date. The title of these data files will be gridded_data_<year of observation date>-<month of observation date>-<day of observation date>.csv (e.g., gridded_data_2011-01-01.csv). Table 5 is a data dictionary for these CSV files that are output by the APT within the Gridded Data directory.

Table 5. Data dictionary for the APT gridded_data_<observation date>.csv file.	
Column	**Description**
Column 1	Date of each precipitation observation expressed in YYYY-MM-DD format
Column 2	Depth of each daily precipitation observation. Units of millimeters for gridded_data_<year of observation date>-<month of observation date>-<day of observation date>.csv
Column 3	Number of input observations from GHCN weather stations that are within 48.2 km (30 mi) of the selected grid cell

Running an APT single-point analysis for multiple observation dates, as a batch process, will yield the same data provided by the single-point analysis for each observation point, observation date, and chosen precipitation dataset. This output will reside in the same directory as a single-point, single observation date analysis. In addition, the APT will provide the user with a summary PDF and CSV file. The PDF will be a compilation of summary plots for each observation date and will be named (<latitude of the observation point>, <longitude of the observation point>) Batch Result.pdf (e.g., (33.2098, −87.5692) Batch Result.pdf). The CSV file will summarize each observation date for the observation point and will be named (<latitude of the observation point>, <longitude of the observation point>) Batch Result.csv (e.g., (33.2098, −87.5692) Batch Result.csv). Table 6 is a data dictionary of the CSV summary file.

Table 6. Data dictionary for the APT merged_stations_<observation date>.csv file.	
Column	**Description**
Latitude	Latitude of the observation point, in degrees
Longitude	Longitude of the observation point, in degrees
Date	Date of the observation date, expressed as YYYY-MM-DD
PDSI Class	PDSI drought determination for the observation point and observation date. Expressed as one of 12 different categories: Not available, Extreme wetness, Severe wetness, Moderate wetness, Mild wetness, Incipient wetness, Normal, Incipient drought, Mild drought, Moderate drought, Severe drought, Extreme drought (Table 3)
Season	WebWIMP seasonal determination for the observation point and observation date. Expressed as one of two different categories: Wet Season, Dry Season (Table 2)
Antecedent Precipitation Score	Antecedent Precipitation Score determination for the observation point and observation date. Integer value that will range between 6 and 18
Antecedent Precipitation Condition	Descriptive summary for the Antecedent Precipitation Score. Expressed as one of three different categories: Normal Conditions, Wet Conditions, or Dry Conditions (Table 1)

APT watershed analysis outputs. For watershed analyses, the APT creates a separate subdirectory within the Outputs directory named ~Watershed. Within this directory, the watershed scale will separate different watershed runs. 12-digit HUC outputs will fall within the HUC12 directory. Ten-digit HUC outputs will fall within the HUC10 directory. Eight-digit HUC outputs will fall within the HUC8 directory. Custom polygon outputs will fall under the Custom Polygon directory. Below the watershed scale directory, the unique identifier for the HUC or the custom polygon will define the subdirectory name. For example, if a HUC12 analysis is undertaken at observation point with a latitude of 33.2098 and longitude of −87.5692, the directory containing this watershed analysis will be Outputs\v2_0_0\~Watershed\HUC12\031601120505.

Within each watershed analysis directory, two general types of files will be present. The first is a PDF summary that contains a summary of the watershed analysis on the first page (Figure 4) and an APT single-point summary for each sampling point used in the watershed analysis on subsequent pages (Figure 2). The APT watershed summary will be named <year of observation date>-<month of observation date>-<day of observation date> - <watershed name> - Batch Result.pdf (e.g., 2011-01-01 - 031601120505 - Batch Result.pdf). The second output of the APT watershed analysis is a CSV file containing a summary of each sampling point used in the watershed analysis. Table 7 is the data dictionary for the watershed analysis summary CSV file. The CSV file will be named <year of observation date>-<month of observation date>-<day of observation date> - <watershed name> - Sampling Results.csv (e.g., 2011-01-01 - 031601120505 - Sampling Results.csv). The APT watershed analysis will also generate single-point analysis outputs for each sampling point used in the watershed analysis. The APT stores these single-point results within the same directory as all other APT single-point analysis outputs.

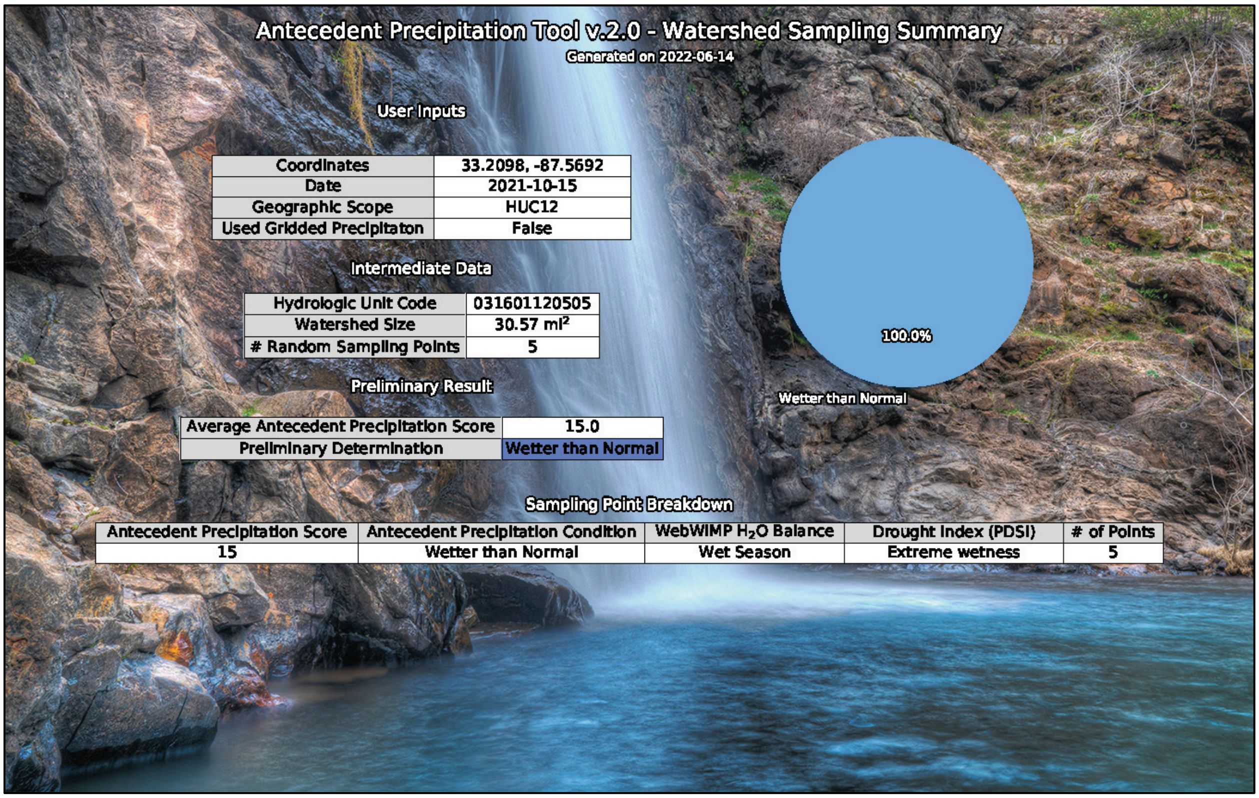


Figure 4. Example of an APT watershed summary.

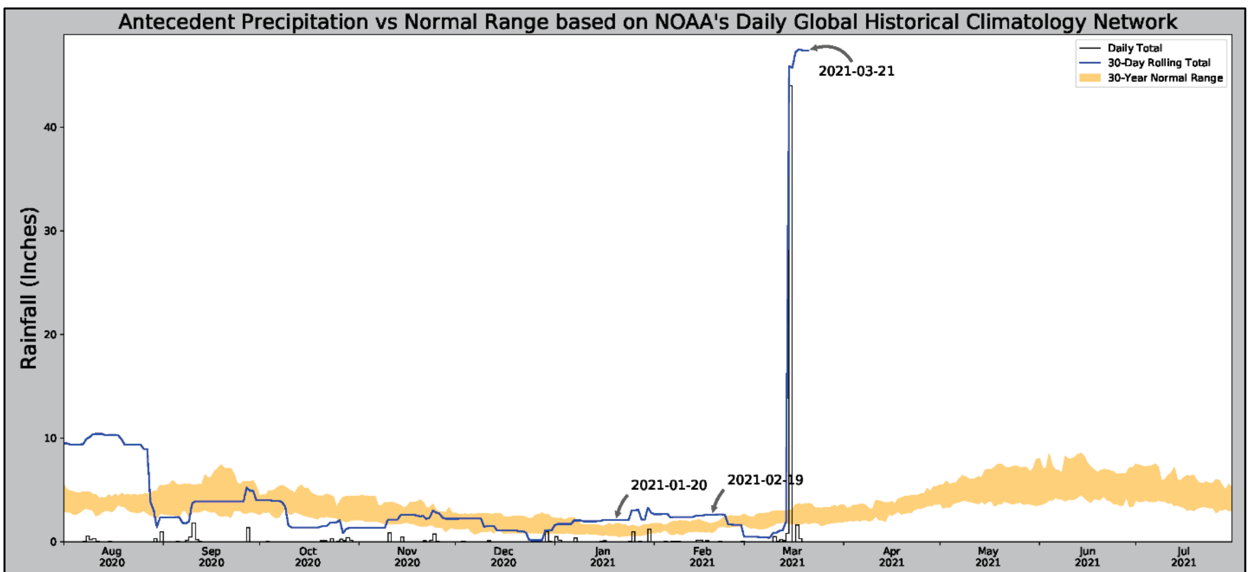
Table 7. Data Dictionary for the APT <year of observation date>-<month of observation date>-<day of observation date>-<watershed name>-Sampling Results.csv file.

Column	Description
Latitude	Latitude of the sampling point, in degrees
Longitude	Longitude of the sampling point, in degrees
Date	Date of the observation date, expressed as YYYY-MM-DD
PDSI Value	PDSI value for the sampling point on the observation date. Decimal value that typically ranges from −6 to 6. Negative values indicate dry conditions, and positive values indicate wet conditions
PDSI Class	PDSI drought determination for the sampling point and observation date. Expressed as one of 12 different categories: Not available, Extreme wetness, Severe wetness, Moderate wetness, Mild wetness, Incipient wetness, Normal, Incipient drought, Mild drought, Moderate drought, Severe drought, Extreme drought (Table 3)
Season	WebWIMP seasonal determination for the sampling point and observation date. Expressed as one of two different categories: Wet Season, Dry Season (Table 2)
Antecedent Precipitation Score	Antecedent Precipitation Score determination for the sampling point and observation date. Integer value that will range between 6 and 18
Antecedent Precipitation Condition	Descriptive summary for the Antecedent Precipitation Score at the sampling point and observation date. Expressed as one of three different categories: Normal Conditions, Wet Conditions, or Dry Conditions (Table 1)

Diagnosing and Addressing APT Errors. The following sections highlight common issues encountered while using the APT and ways to address these issues. At any time, the user may contact USACE directly for questions regarding the APT at *APT-Report-Issue@usace.army.mil*.

Network security errors. The APT is sensitive to each user's network security settings due to the number of requests that the APT makes to external web services and servers. If a network security error occurs, the symptom that typically appears is the APT MS-DOS window initially opening and abruptly closing, without loading the GUI. If this error occurs, the user is encouraged to contact their network administrator to determine how the APT can be allowed to make calls to external servers.

National Oceanic and Atmospheric Administration (NOAA) Global Historic Climatology Network (GHCN) errors. In a station based APT analysis, the APT calculates the Antecedent Precipitation Score using the NOAA GHCN network of weather stations. GHCN data reside on the NOAA servers, and the APT accesses the data on demand. If the GHCN data service is down, the APT-DOS window will inform the user that the data service appears to be offline. Further, the user may note erroneous data such as the Antecedent Precipitation Score calculations in Figure 5. If the user experiences GHCN downtime or finds erroneous precipitation values, the user should communicate these errors to the NOAA GHCN-Daily team at *ncdc.ghcnd@noaa.gov*.



Coordinates	38.814622, -94.44128
Observation Date	2021-03-21
Elevation (ft)	1025.44
Drought Index (PDSI)	Mild wetness (2021-02)
WebWIMP H_2O Balance	Wet Season

30 Days Ending	30th %ile (in)	70th %ile (in)	Observed (in)	Wetness Condition	Condition Value	Month Weight	Product
2021-03-21	1.736221	3.672835	47.40945	Wet	3	3	9
2021-02-19	0.877559	1.757087	2.582677	Wet	3	2	6
2021-01-20	0.555906	1.727559	2.062992	Wet	3	1	3
Result							Wetter than Normal - 18

Weather Station Name	Coordinates	Elevation (ft)	Distance (mi)	Elevation Δ	Weighted Δ	Days (Normal)	Days (Antecedent)
PLEASANT HILL WFO	38.81, -94.2647	1000.0	9.512	25.44	4.522	9224	69
LEE'S SUMMIT 1.4 WSW	38.9072, -94.4057	969.16	6.677	56.28	3.38	0	21
LEES SUMMIT REED WR	38.8803, -94.3358	1000.0	7.267	25.44	3.455	2107	0
UNITY VILLAGE	38.9483, -94.3969	941.929	9.54	83.511	5.09	22	0

Figure 5. Erroneously high daily precipitation value reported on the GHCN servers that caused a significant skew in the APT Antecedent Precipitation Score results.

NOAA nClimGrid-Daily errors. In a gridded APT analysis, the APT calculates the Antecedent Precipitation Score using NOAA's nClimGrid-Daily dataset. The nClimGrid-Daily dataset resides on a Thematic Real-time Environmental Distributed Data Services Data Server (Unidata 2018) that allows the APT to access the data remotely (NOAA 2022a; 2022c). If a user has trouble accessing the nClimGrid-Daily dataset using the APT or if the user has specific technical questions about the nClimGrid-Daily dataset, please email the nClimGrid-Daily team at *ncei.grids@noaa.gov*.

US Geological Survey (USGS), Elevation Point Query Service (EPQS) errors. The APT also queries the USGS EPQS web services on demand to acquire an elevation estimate at the observation point. The user may experience intermittent downtime with the USGS EPQS services. If the APT is unable to use USGS EPQS services, the APT will report this in the APT-DOS window. If the user encounters downtime with the USGS EPQS services, the user is encouraged to monitor the EPQS using these web viewers: *https://stats.uptimerobot.com/gxzRZFARLZ/793824472* and *https://stats.uptimerobot.com/gxzRZFARLZ/783928734*. The status of these services must be operational for the EPQS to work. If an EPQS outage is extended, report the issue directly to the USGS National Map team at *tnm_help@usgs.gov*.

PDSI and Web-based, Water-Budget, Interactive, Modeling Program (WebWIMP) errors. Occasionally, the APT will determine that the PDSI is "Not available" and will provide a PDSI value of −99.99 in summary CSV files. This occurs when the PDSI data for a particular observation point are unavailable within the NOAA nClimDiv dataset or if the observation point does not fall within one of the NOAA climate divisions. Also, the APT will omit WebWIMP seasonal determinations in the summary PDF and CSV files if an observation point does not fall within the WebWIMP domain. Although the WebWIMP domain covers all the land surface of Earth, observation points near the coastal areas may erroneously be determined to be within the local waterbody and not within the WebWIMP domain.

Primary station determination errors. After each APT run, the user should monitor the MS-DOS window. In instances where the APT operates in remote environments and the user is undertaking a station-based APT analysis, the APT may be unable to designate a primary station because of faulty data or a lack of stations that meet the minimum station record specifications. In such instances, the MS-DOS window will prompt the user to restart the program and will print the specific error encountered. Figure 6 illustrates one instance where data issues appear to have made the APT unable to select a primary station. Under such circumstances, the user can attempt a gridded APT analysis since it does not require a primary station determination. The user should make sure to close and reopen the APT under such circumstances before continuing operation.

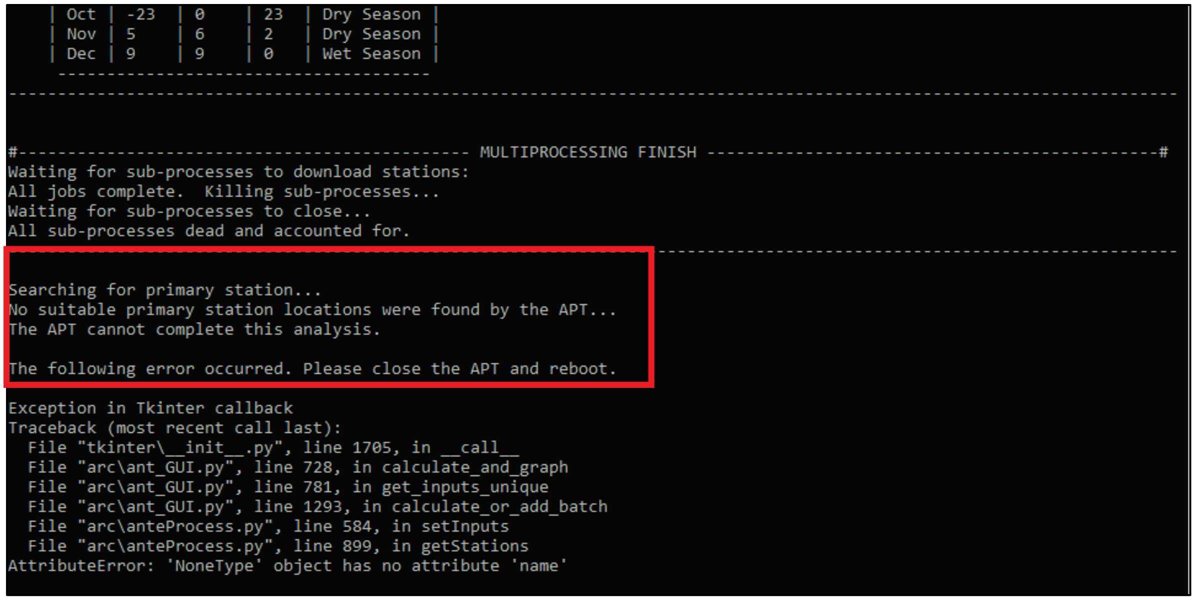


Figure 6. An example of an error report in the APT Microsoft Disk Operating System (MS-DOS) window encountered when selecting the primary station with the error outlined in *red*. These issues typically occur in remote locations. Remember to restart the APT after encountering such issues.

When to use station-based or grid-based APT. In the current version of the APT, no hybrid blending of station-based or gridded GHCN data occurs. The user must select whether to conduct an APT station-based or gridded analysis. The analysis producing the most appropriate results will vary by situation. The APT provides data to support which analysis is most appropriate.

The gridded APT analysis will be useful when the station-based APT analysis fails to complete an analysis. A failed, station-based APT analysis can occur because the APT cannot locate a suitable primary station, the APT fails to fill in data gaps with secondary stations, or one or more data services the APT utilizes are experiencing downtime. In some of these instances of APT station-based run failures, the APT gridded analysis may offer a viable analysis. These situations typically arise in limited portions of the United States with poor weather station coverage but can also occur in locations with plentiful weather stations in the immediate vicinity of the observation point. For example, in situations where plentiful weather stations are available, there have been instances reported by APT users where a large portion of weather stations in a region are missing the same period of precipitation data.

There are also instances where the APT station-based analysis successfully completes an analysis, but the results are questionable for your observation point. For instance, the APT sometimes reports an erroneous precipitation value, like Figure 5 illustrates. Furthermore, the primary station can be up to approximately 96.6 km (60 mi) away from the observation point at locations below 50° latitude and 805 km (500 mi) away from at locations above 50° latitude. Primary stations that are greater than approximately 5–7 km (3.1–4.5 mi) away from the observation point are at a distance that is greater than the approximate dimensions of each grid cell in the gridded dataset. Likewise, elevation differences between the observation point and primary station can be large.

The APT may also select precipitation data from a GHCN station outside of the observation point's drainage area. Selecting a GHCN station outside of the observation point's watershed will be an important consideration when interpreting the results of the antecedent period in regions where extreme precipitation events can be highly localized (e.g., recent storm events that have occurred in one adjacent watershed but not another). When the APT reports erroneous precipitation in the APT station-based analysis, distances or elevation differences between a primary station and observation point are large, or when the APT utilizes a high volume of station-based precipitation data that are outside the observation point's drainage area, the APT gridded analysis may provide better results in the user's analysis.

The APT gridded analysis provides a summary of the number of weather stations that are used to compute the nClimGrid-Daily gridded precipitation and are within approximately 48.2 km (30 mi) of the nClimGrid-Daily grid cell used by the APT to extract precipitation data. A low number of stations that are near the grid cell may weaken the accuracy of the APT gridded results. The user should use the summary of station counts present in Figure 3 as a proxy measurement of reliability of the APT gridded analysis. Figure 7 summarizes monthly minimum, median, mean, and maximum counts of all weather stations that were used to compute the nClimGrid-Daily precipitation and are within 48.2 km (30 mi) of each nClimGrid-Daily grid cells for all of CONUS from January 1989 to January 2022. Figure 7 can help the user understand the relative station count density of their observation point's grid cell as compared to the averages for all of CONUS. For instance, if the grid cell assigned to your observation point averages fewer than five stations within 48.2 km (30 mi) of its location, the cell contains a relatively low number of nearby observations and could be indicative of a lower accuracy at the grid cell.

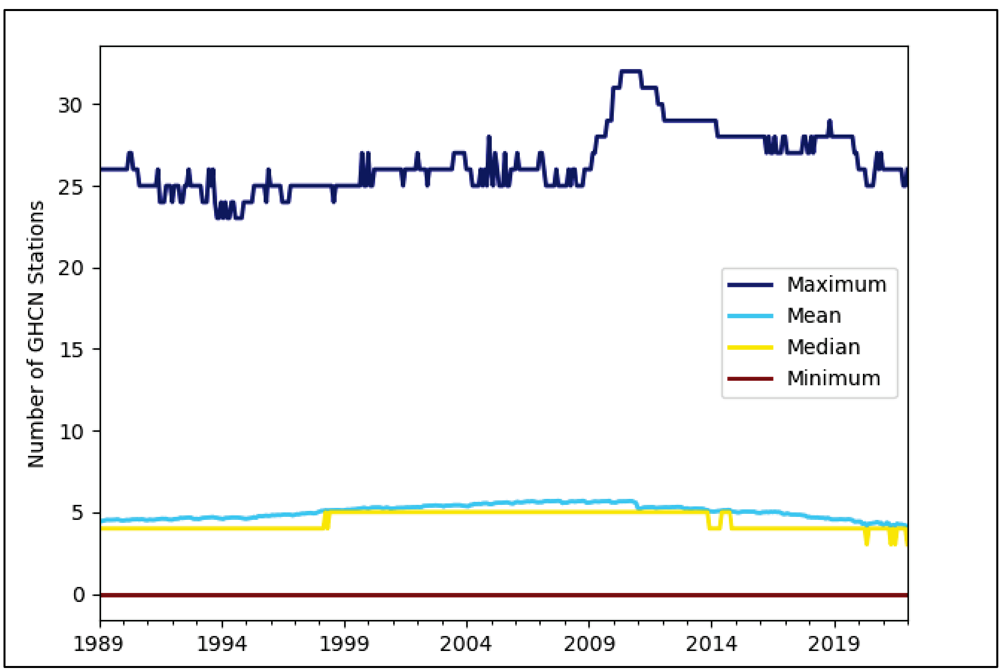


Figure 7. The minimum, median, mean, and maximum average monthly count of all stations within 48.2 km (30 mi) for all nClimGrid-Daily grid cells from January 1989 to January 2022.

The authors advise that the user perform both the station-based and gridded APT analyses. Running both analyses should provide additional lines of evidence to support the user's best professional judgement. If differences between both analyses occur and none of the situations above are encountered by the user, the user should interrogate the hydrologic setting of their observation point and relate this to both the APT station-based and gridded results. Precipitation is only one part of the water budget, and the impact of antecedent precipitation on local hydrologic conditions may vary with place and time. The impact of precipitation on local hydrologic conditions can vary depending on a combination of additional factors such as precipitation type, precipitation distribution, temperature, anthropogenic influences, and the physical composition of a watershed (Sprecher and Warne 2000; Slater and Villarini 2017). Other data sources such as drought monitors and hydrologic models incorporate multiple hydrologic inputs and may better capture the impact of precipitation and other meteorological variables on terrestrial hydrologic systems (Haslinger et al. 2014; Tijdeman et al. 2018). The user should consult multiple lines of evidence, in combination with APT, when analyzing the hydroclimatology of their observation point. Additional lines of evidence are cataloged and described by Sparrow et. al (2022). There may also be additional lines of evidence available at the local, state, and regional level. For instance, the State of Arizona provides an evaluation of flow regime for streams in Arizona (ADEQ, n.d.).

CONCLUSION: The APT is an automation tool that facilitates the comparison of antecedent or recent precipitation conditions for a given location to the range of normal precipitation conditions that occurred during the preceding 30 yr. The primary difference between Version 1.0 and Version 2.0 of the APT is that Version 2.0 of the APT provides the user the ability to access two different precipitation datasets, GHCN station data and nClimGrid-Daily gridded data, in each APT analysis they run. This document details the technical aspects of each APT analysis and provides initial guidance to the user of the APT on how to download, install, and troubleshoot the APT.

ACKNOWLEDGEMENTS: The USACE Wetlands Regulatory Assistance Program (WRAP) provided funding to support this research. Mr. Kent H. Sparrow II and Mr. Stephen W. Brown of the US Army Engineer Research and Development Center (ERDC) provided technical review of this document.

Portions of this report have been modified and reprinted from J. L. Gutenson and J. C. Deters, *Antecedent Precipitation Tool (APT) Version 1.0: Technical and User Guide*, ERDC/TN WRAP-22-1 (Vicksburg, MS: US Army Engineer Research and Development Center, 2022), http://dx.doi.org/10.21079/11681/43160. Public domain.

POINTS OF CONTACT: For additional information, contact Dr. Joseph L. Gutenson, ERDC, Vicksburg, MS (601-287-1436; Joseph.L.Gutenson@erdc.dren.mil), or the program manager of WRAP, Mr. Kyle B. Gordon (601-634-3717; Kyle.B.Gordon@usace.army.mil). This technical note should be cited as follows:

Gutenson, J. L., C. O. Hamilton, and J. C. Deters. 2023. *Antecedent Precipitation Tool (APT) Version 2.0: Technical and User Guide.* ERDC/TN WRAP-23-2. Vicksburg, MS: US Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/47189.

REFERENCES

ADEQ (Arizona Department of Environmental Quality). n.d. "eMaps." *https://adeq.maps.arcgis.com/apps/webappviewer/index.html?id=e224fc0a96de4bcda4b0e37af3a4daec&showLayers=Counties;Flow%20Regimes%20-%20Perennial%20Intermittent%20Ephemeral%20Streams*.

AMS (American Meteorological Society). 2012. "Potential Evapotranspiration." *https://glossary.ametsoc.org/wiki/Potential_evapotranspiration*.

Dai, A. 2011. "Characteristics and Trends in Various Forms of the Palmer Drought Severity Index during 1900–2008." *Journal of Geophysical Research Atmospheres* 116 (D12). *https://doi.org/10.1029/2010JD015541*.

Dai, A. 2012. "Palmer Drought Severity Index (PDSI)." *https://climatedataguide.ucar.edu/climate-data/palmer-drought-severity-index-pdsi*.

Dai, A., K. E. Trenberth, and T. Qian. 2004. "A Global Dataset of Palmer Drought Severity Index for 1870–2002 : Relationship with Soil Moisture and Effects of Surface Warming." *Journal of Hydrometeorology* 5 (6): 1117–1130. *https://doi.org/https://doi.org/10.1175/JHM-386.1*.

Durre, Imke, Anthony Arguez, Carl J. Schreck, Michael F. Squires, and Russell S. Vose. 2022. "Daily High-Resolution Temperature and Precipitation Fields for the Contiguous United States from 1951 to Present." *Journal of Atmospheric and Oceanic Technology* 39 (12): 1837–55. *https://doi.org/10.1175/JTECH-D-22-0024.1*.

EPA (US Environmental Protection Agency). 2022. "WATERS (Watershed Assessment, Tracking & Environmental Results System)." *https://www.epa.gov/waterdata/waters-watershed-assessment-tracking-environmental-results-system.*

Esri. 2022. "Watershed (Ready to Use)." *https://pro.arcgis.com/en/pro-app/latest/tool-reference/ready-to-use/watershed.htm*.

GeoPy. 2018. "Calculating Distance" *https://geopy.readthedocs.io/en/stable/#module-geopy.distance*.

Gutenson, J. L., and J. C. Deters. 2022. *Antecedent Precipitation Tool (APT) Version 1.0: Technical and User Guide*. ERDC-TN WRAP-22-1. Vicksburg, MS: US Army Engineer Research and Development Center. *http://dx.doi.org/10.21079/11681/43160*.

Haslinger, K., D. Koffler, W. Schoner, and G. Laaha. 2014. "Exploring the Link between Meteorological Drought and Streamflow: Effects of Climate-Catchment Interaction." *Water Resources Research* 50 (3): 2468–2487. *https://doi.org/10.1002/2013WR015051*.

Jones, K. A., L. S. Niknami, S. G. Buto, and D. Decker. 2022. *Federal Standards and Procedures for the National Watershed Boundary Dataset (WBD),* 5th ed. US Geological Survey Techniques and Methods 11-A3. Reston, VA: US Geological Survey. *https://doi.org/10.3133/tm11A3*.

Kettle, S. 2017. *Distance on a Sphere: The Haversine Formula*. *https://community.esri.com/t5/coordinate-reference-systems-blog/distance-on-a-sphere-the-haversine-formula/ba-p/902128#:~:text=For%20example%2C%20haversine(%CE%B8),longitude%20of%20the%20two%20points*.

Lang, D., J. Zheng, J. Shi, F. Liao, X. Ma, W. Wang, X. Chen, and M. Zhang. 2017. "A Comparative Study of Potential Evapotranspiration Estimation by Eight Methods with FAO Penman–Monteith Method in Southwestern China." *Water* 9 (10): 734. *https://doi.org/10.3390/w9100734*.

Menne, M. J., I. Durre, R. S. Vose, B. E. Gleason, and T. G. Houston. 2012a. "An Overview of the Global Historical Climatology Network-Daily Database." *Journal of Atmospheric and Oceanic Technology* 29 (7): 897–910. https://doi.org/10.1175/JTECH-D-11-00103.1.

Milly, P. C. D., and K. A. Dunne. 2016. "Potential Evapotranspiration and Continental Drying." *Nature Climate Change* 6 (10): 946–949. https://doi.org/10.1038/NCLIMATE3046.

NOAA (National Oceanic and Atmospheric Administration). 2005. "Drought Indices: Explanation." https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/palmer_drought/wpdanote.shtml.

NOAA. 2014. "nClimDiv: Statewide-Regional-National Drought." https://www1.ncdc.noaa.gov/pub/data/cirs/climdiv/drought-readme.txt.

NOAA. 2022a. "Auxiliary Observation Counts for US Daily Gridded Fields (nClimGrid-Daily Auxiliary)." https://www.ncei.noaa.gov/thredds/catalog/nclimgrid-daily-auxiliary/catalog.html.

NOAA. 2022b. "Global Historical Climate Network daily (GHCNd)." https://www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily.

NOAA. 2022c. "US Daily Gridded Fields (nClimGrid-Daily)." https://www.ncei.noaa.gov/thredds/catalog/nclimgrid-daily/catalog.html.

NRCS (Natural Resources Conservation Service). 1997. "Hydrology Tools for Wetland Determination." In *Part 650 Engineering Field Handbook* (August). Washington, DC: US Department of Agriculture. https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17556.wba.

Palmer, W. C. 1965. "Meteorological Drought." *US Weather Bureau, Research Paper No. 45*. https://www.ncei.noaa.gov/monitoring-content/temp-and-precip/drought/docs/palmer.pdf.

Schrier, G. van der, P. D. Jones, and K. R. Briffa. 2011. "The Sensitivity of the PDSI to the Thornthwaite and Penman-Monteith Parameterizations for Potential Evapotranspiration." *Journal of Geophysical Research* 116 (D3). https://doi.org/10.1029/2010jd015001.

Seaber, P. R., F. P. Kapinos, and G. L. Knapp. 1987. "Hydrologic Unit Maps." *US Geological Survey Water-Supply Paper 2294*. https://doi.org/10.3133/wsp2294.

Singer, M. B., D. T. Asfaw, R. Rosolem, M. O. Cuthbert, D. G. Miralles, D. MacLeod, E. A. Quichimbo, and K. Michaelides. 2021. "Hourly Potential Evapotranspiration at 0.1° Resolution for the Global Land Surface from 1981-Present." *Scientific Data* 8 (1): 1–13. https://doi.org/10.1038/s41597-021-01003-9.

Slater, L. J., and G. Villarini. 2017. "Evaluating the Drivers of Seasonal Streamflow in the US Midwest." *Water (Switzerland)* 9 (9): 1–22. https://doi.org/10.3390/w9090695.

Sparrow, K. H., J. L. Gutenson, M. D. Wahl, and K. A. Cotterman. 2022. *Evaluation of Climatic and Hydroclimatic Resources to Support the US Army Corps of Engineers Regulatory Program*. ERDC/CHL TR-22-19. Vicksburg, MS: US Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/45484.

Sprecher, S. W., and A. G. Warne. 2000. *Accessing and Using Meteorological Data to Evaluate Wetland Hydrology*. ERDC/EL TR-WRAP-00-1. Vicksburg, MS: US Army Engineer Research and Development Center. https://apps.dtic.mil/dtic/tr/fulltext/u2/a378910.pdf.

Stoker, J., and B. Miller. 2022. "The Accuracy and Consistency of 3D Elevation Program Data: A Systematic Analysis." *Remote Sensing* 14 (4): 940. https://doi.org/10.3390/rs14040940.

Thornthwaite, C. W. 1948. "An Approach toward a Rational Classification of Climate." *Geographical Review* 38 (1): 55–94. https://doi.org/10.2307/210739.

Tijdeman, E., L. J. Barker, M. D. Svoboda, and K. Stahl. 2018. "Natural and Human Influences on the Link Between Meteorological and Hydrological Drought Indices for a Large Set of Catchments in the Contiguous United States." *Water Resources Research* 54 (9): 6005–6023. https://doi.org/10.1029/2017WR022412.

Unidata. 2018. "THREDDS Data Server 5.4." https://www.unidata.ucar.edu/software/tds/current/.

University of Delaware. 2009. "WebWIMP: The Web-Based, Water-Budget, Interactive, Modeling Program." http://cyclops.deos.udel.edu/wimp/public_html/index.html.

USACE (US Army Corps of Engineers). 2008. *Regional Supplement to the Corps of Engineers Wetland Delineation Manual: Arid West Region (Version 2.0)*. ERDC/EL TR-08-28. Vicksburg, MS: US Army Engineer Research and Development Center. https://usace.contentdm.oclc.org/utils/getfile/collection/p266001coll1/id/7627.

US Census Bureau. 2022. "Cartographic Boundary Files." https://www.census.gov/geographies/mapping-files/time-series/geo/cartographic-boundary.html.

USGS (US Geological Survey). 2023a. "How Accurate are Elevations Generated by the Elevation Point Query Service in The National Map?" https://www.usgs.gov/faqs/how-accurate-are-elevations-generated-elevation-point-query-service-national-map.

USGS (US Geological Survey). 2023b. "StreamStats." https://www.usgs.gov/streamstats.

USGS (US Geological Survey). 2023c. "The National Map–Elevation Point Query Service." https://apps.nationalmap.gov/epqs/.

van der Schrier, G., P. D. Jones, and K. R. Briffa. 2011. "The Sensitivity of the PDSI to the Thornthwaite and Penman-Monteith Parameterizations for Potential Evapotranspiration." *Journal of Geophysical Research Atmospheres* 116 (3): 1–16. https://doi.org/10.1029/2010JD015001.

Vepraskas, M. J., J. F. Berkowitz, and C. Arellano. 2019. "Determining Normal Precipitation Ranges for Hydric Soil Assessments." *Soil Science Society of America Journal* 83 (2): 503–510. https://doi.org/10.2136/sssaj2018.09.0333.

Vose, R. S., S. Applequist, M. Squires, I. Durre, C. J. Menne, C. N. Williams, C. Fenimore, K. Gleason, and D. Arndt. 2014. "Improved Historical Temperature and Precipitation Time Series for US Climate Divisions." *Journal of Applied Meteorology and Climatology* 53 (5): 1232–1251. https://doi.org/10.1175/JAMC-D-13-0248.1.

Willmott, C. J., C. M. Rowe, and Y. Mintz. 1985. "Climatology of the Terrestrial Seasonal Water Cycle." *Journal of Climatology* 5: 589–606. https://doi.org/10.1002/joc.3370050602.