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FORECASTING RAIN EVENTS IN THE SOUTHERN GREAT PLAINS USING GPS TOTAL PRECIPITABLE WATER AMOUNTS

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CIRA Cooperative Institute for Research in the Atmosphere

Colorado State University

THESIS

FORECASTING RAIN EVENTS IN THE SOUTHERN GREAT PLAINS USING GPS TOTAL PRECIPITABLE WATER AMOUNTS

Submitted by
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ABSTRACT OF THESIS

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Atmospheric water vapor plays a major role in processes ranging from global climate change to micrometeorology. Because of the large latent heat associated with water's change of phase, the distribution of water vapor affects the vertical stability of the atmosphere and the structure and evolution of storm systems. Atmospheric water vapor is also intimately coupled with the distribution of clouds and rainfall. The most fundamental concept underlying precipitation is that water vapor needs to be transported up into the atmosphere, where it can condense into clouds and grow into droplets large enough to fall to the ground. For this reason, atmospheric water vapor amounts may be an accurate predictor of rainfall. By analyzing water vapor distributions in environments where precipitation is developing or occurring, new knowledge can be formed about rain events that could aid in earlier detection and warnings of storms and of severe weather events such as flash floods.

This study uses Global Positioning System (GPS) satellites and ground stations. GPS satellites, though first developed to provide precise estimates of position, velocity, and time, are also very useful for meteorological purposes.

Using the GPS signal delay caused by the atmosphere, atmospheric temperature and moisture profiles can be determined. Of particular interest to meteorologists is total precipitable water (TPW), which is the amount of water vapor contained in a column over a given area on Earth. GPS networks can estimate precipitable water to an accuracy of within 1.0 mm. The GPS ground station network is particularly dense in the Southern Great Plains region of the United States, allowing for a much better spatial coverage of observations than that given by other instruments such as rawinsondes. GPS sensors also have the ability to measure TPW in all atmospheric conditions at 30-minute intervals. These characteristics make the GPS network in the southern Great Plains region the optimal choice to use for this research.

This thesis explores the relationship between GPS TPW Amounts and Rainfall in the Southern Great Plains region of the United States. It is shown that daily maximum TPW amounts are positively correlated with rainfall amounts in six cities spanning the states of Kansas, Oklahoma, and Texas during different times of year. Using this correlation along with the fact that TPW averages higher on rainy days than on days without rain, daily maximum TPW Amounts are then used to forecast rain events in the same six cities. The forecast accuracies vary between cities and times of year, and some forecasts do not predict significant rain events. Some rain events are accurately predicted only at the cost of high false alarm rates. TPW can be used to give a baseline probability of the occurrence of a rain event throughout the Southern Great

Plains at any time of year, however it is not reliable as a forecast tool without the consideration of other atmospheric variables that contribute to rain formation.

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1. Introduction

Atmospheric water vapor plays a major role in processes ranging from global climate change to cloud microphysics. Because of the large latent heat associated with water's change of phase, the distribution of water vapor affects the vertical stability of the atmosphere and the structure and evolution of storm systems. Atmospheric water vapor is intimately coupled with the distribution of clouds and rainfall. In this study, we intend to explore this relationship between integrated water vapor amounts and rainfall in depth.

There are many factors that influence rainfall, including wind patterns, convection, cloud microphysical processes, and frontal boundary movement. The most fundamental concept underlying precipitation is that water vapor needs to be transported up into the atmosphere, where it can condense into clouds and grow into droplets large enough to fall to the ground. If there is not a significant amount of water vapor or a lifting mechanism to get the water vapor into the upper atmosphere, there is no rain (Doswell et al, 1996).

Due to the importance of water vapor to daily weather events and climate change, atmospheric scientists have developed several means by which to measure the three-dimensional distribution of atmospheric water vapor. Several instruments used to do this are discussed in more detail in the next section.

1.1 Water Vapor Observing Networks

Water vapor is one of the most variable atmospheric constituents, and therefore it is crucial to forecasters that it is measured frequently and accurately. The lack of a dense water vapor observation network that operates accurately in all atmospheric conditions is one of the biggest drawbacks in weather forecasting. This is a current area of research and innovation; to date GPS is the only high frequency, all-weather water vapor observing system available (Holub, 2004). At present, the main instruments used to measure atmospheric water vapor include radiosondes, water vapor radiometers, and satellite instruments. Each instrument has its benefits and its shortcomings, as is discussed in the following sections.

1.1.1 Radiosondes

Radiosondes have been used to measure atmospheric moisture for over 70 years. They give highly accurate depictions of total column water vapor and the vertical distribution of water vapor in the troposphere, however they are not very reliable in the upper atmosphere. Balloons often burst around 25-30 km, making upper atmospheric observations difficult to obtain. High winds and icing of the balloon and instruments also play roles in the inaccuracy of radiosonde data in the upper atmosphere. In the lower troposphere, radiosondes are more reliable. They can be launched in almost any type of weather, however severe thunderstorms and heavy precipitation may cause instrument failure or radio interference.

Another drawback to radiosondes is that they are expendable, and so the cost of the devices restricts the number and frequency of launches. While radiosondes supply an accurate and dependable dataset for real-time weather forecasting, they have very poor spatial and temporal resolution, especially over ocean and underpopulated regions. Due to these limitations, radiosonde measurements are unable to accurately resolve the temporal and spatial variability of water vapor.

1.1.2 Ground-Based Water Vapor Measurements

Ground-based microwave Water Vapor Radiometers (WVRs) measure water vapor radiative brightness temperatures, which are converted into precipitable water using retrieval coefficients calculated from radiosonde data (Hogg et al, 1983). WVRs have high temporal and poor spatial resolution due to the small number of the instruments in use today (Rocken et al, 1993). A drawback of using these instruments to measure water vapor profiles is that they are unreliable during rain events – raindrops on the WVR window introduce unrealistic water vapor measurements.

Microwave WVRs are also flown on satellites. These space-based instruments provide excellent spatial coverage over the oceans, however they do not perform well over land and they provide poor temporal coverage similar to radiosondes.

Another ground-based instrument that is used to measure atmospheric water vapor profiles is the Atmospheric Emitted Radiance Interferometer (AERI). AERI measures downwelling infrared radiation from 3-25 μm every ten minutes

(ARM, 2004). This instrument can give a good description of water vapor in the atmosphere directly above it, however it does not take measurements while any form of precipitation is occurring, and there are very few AERI locations.

1.1.3 Satellite Water Vapor Measurements

Several satellites in use today carry instruments to measure total column water vapor. The GOES Satellites offer the highest temporal resolution available for total column water vapor measurements. The GOES water vapor product is also highly accurate, however the instrument lacks the ability to retrieve water vapor profiles underneath clouds. When conducting research that involves rain or severe weather, it is crucial that measurements be taken under cloudy areas. To overcome the shortcomings of both microwave and infrared (IR) sensors in water vapor measurements, a global, long-term water vapor dataset, NVAP, has been created (Randel et al, 1996). This dataset combines water vapor data from an IR satellite (TOVS), a microwave satellite (SSM/I), and radiosondes. While this is an improvement over only using one instrument to measure water vapor, it still lacks coverage in many areas that the satellites do not cover on a daily basis. Since the microwave sensors do not work well over land, there are still gaps in cloudy areas as well, where the IR sensors do not work and therefore only radiosondes can be used to measure water vapor effectively.

While all of the aforementioned instruments give an accurate TPW measurement, they each have shortcomings in spatial or temporal coverage, or in the ability to make TPW measurements in all atmospheric conditions. In recent years (since 1998), Global Positioning System (GPS) retrieved TPW has become a new source of data (Baltink et al, 2002). GPS sensors have the ability to measure column water vapor in all atmospheric conditions with sub-millimeter accuracy at half-hour intervals (Gutman et al, 2003). The GPS network also provides relatively good spatial resolution over the region studied in this thesis, making it the best option for total column water vapor data. For these reasons, the GPS satellite and ground-station network was chosen for this research. The GPS sensors and network are discussed in more detail in Chapter 2.

The International Water Vapor Project (IHOP, International H_2O Project) was conducted in the summer of 2002 to determine the role of water vapor during convective initiation within the Southern Great Plains region. This experiment lasted six weeks and used every available water vapor observing tool mentioned above, along with aircraft, radar, and lidar observations, to observe the distribution of water vapor throughout the atmosphere and how it interacted with other atmospheric variables. IHOP 2002 was one of the largest North American weather field experiments in history (Weckwerth, 2003), which demonstrates the worldwide importance of studying water vapor in order to improve our understanding of atmospheric processes, especially convective initiation. Other goals of IHOP were the improvement of water vapor observing tools and the assessment of the improvement of model Quantitative Precipitation Forecasting (QPF) due to the assimilation of detailed moisture fields (Weckwerth, 2003). The vast moisture, temperature, and wind datasets from this field experiment are still being used and will be used for many years to come in comprehensive studies.

1.2 Study Motivation and Description

This research attempts to use TPW amounts from GPS satellites and ground stations to forecast rain events in the Southern Great Plains region of the United States. There is a positive correlation between column water vapor amounts in the atmosphere and daily rainfall (which is discussed in detail in Chapter 3), however to our knowledge it has not yet been analyzed in depth in various climatological settings and during different times of year. This study derives its motivation from several issues in forecasting precipitation, described in the following subsections.

1.2.1 Scientific Objectives

There are several questions that this study is intended to answer. The most prominent is, "What is the relationship between GPS TPW amounts and rainfall amounts in the Southern Great Plains?" The follow-up questions are then, "Can this relationship be used to make a valid rain forecast?", and "What are the false alarm rates of these rain forecasts?" Finally, we ask, "What does this study teach us about the regional climatology of the Southern Great Plains region?"

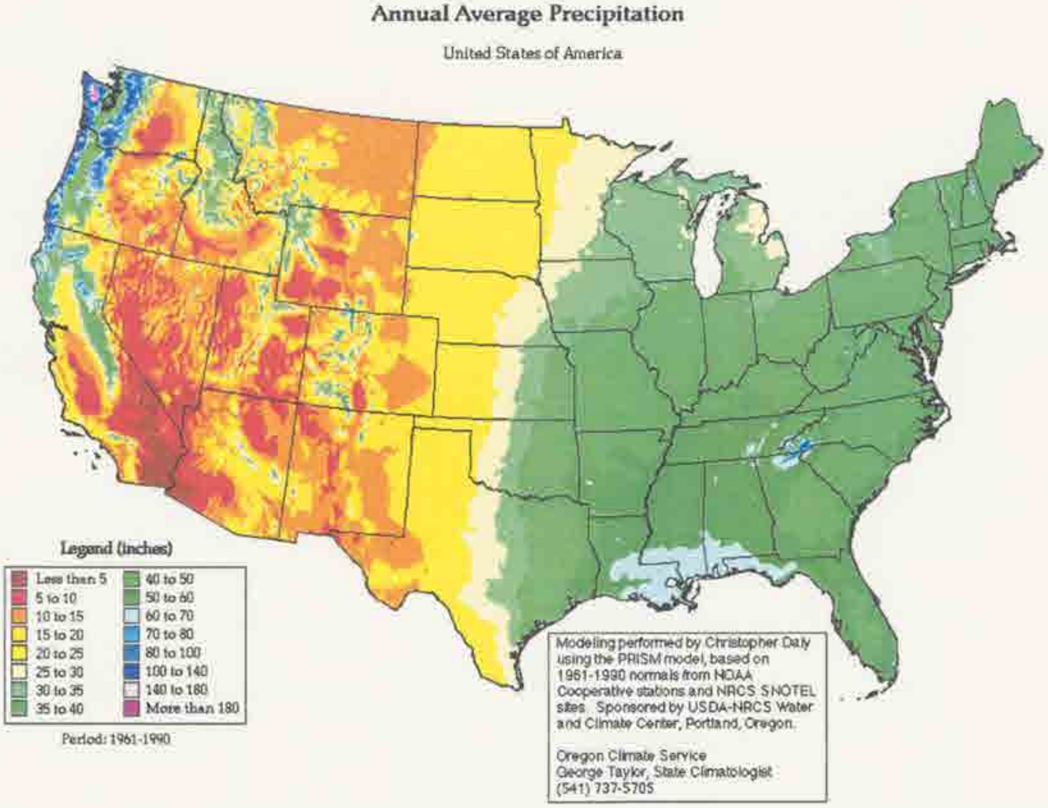
To answer these questions, six cities were chosen to be analyzed in Kansas, Oklahoma, and Texas. These cities span the climatological diversity of the region discussed in section 1.2.2, and are shown in detail in Chapter 2 of this thesis. For each of these cities, GPS and daily rainfall data were acquired and then compared over 12-14 months in several ways to establish their relationship. The validity of forecasts made using this relationship is then explored for different times of year in each city. Finally, each city is compared with the other cities to determine where and when the best forecast can be made.

This thesis is organized as follows. Chapter 2 describes the datasets that were used in this study along with the instrumentation and algorithms used to retrieve the data and the associated errors. Chapter 3 analyzes the relationship between TPW and rain amounts from each of the six cities studied for various times of year. The results from each city and time of year are then compared with the results from the other cities and times of year to determine where and when the best rain forecast might be made. In Chapter 4, actual forecasts and false alarm rates for specific months from each city are looked at and compared to determine how well GPS-TPW acts as a forecast tool. This study of the Southern Great Plains water vapor and rainfall patterns provides new insight into regional climatology, which is discussed in Chapter 5. A review of the results and conclusions drawn from this work is also presented in Chapter 5 along with suggestions for future research.

1.2.2 Climatology of Precipitation in the United States

Precipitation varies greatly throughout the United States both spatially and temporally. There are years of drought in certain regions while other regions receive severe flooding. Generally periods of thirty years of precipitation amounts are collected and averaged to create a yearly precipitation map like the one in Figure 1.1. Whether precipitation for a given location and year is above or below average is based on its deviation from these "normal" amounts. The normal amounts used for this study were based on rainfall totals for the years 1971-2000.

As can be seen in Figure 1.1, there is a large East-West gradient in precipitation totals over Kansas, Oklahoma, and Texas. In Western Oklahoma, annual totals only reach 20 inches on average, whereas in Eastern Oklahoma yearly rainfall totals can reach 60 inches. These different regimes create several distinct climates over a relatively small spatial extent. By sampling TPW amounts over this gradient and applying them to local rain events, there may be applications found for many areas in the world with similar climates.



Annual Average Precipitation

United States of America

Modeling performed by Christopher Daly using the PRISM model, based on 1961-1990 normals from NOAA Cooperative stations and NRCS SNOTEL sites. Sponsored by USDA-NRCS Water and Climate Center, Portland, Oregon.

Oregon Climate Service
George Taylor, State Climatologist
(541) 737-5705

Figure 1.1. Map of average annual precipitation in the United States from the years 1961-1990.

This gradient can also help visualize whether a forecast based on TPW is more valid in a city that gets large amounts of rainfall or in a city that gets less rainfall. There are many meteorological variables that come into play in this region of the United States to make its climate so diverse, such as the dryline, hurricanes, and moisture from the Eastern Pacific and Gulf of Mexico. These factors contribute to the uniqueness of and diversity within the chosen area, and they make it not only interesting to study, but also necessary to study in order to fully understand all of the processes occurring and their effects on rainfall patterns.

1.2.3 Improved Forecast Validity

Limitations in the analysis of water vapor are the major source of error in short-term (0-24 hours) precipitation forecasts (Bevis et al, 1992). With the advent of the fairly dense network of GPS ground stations throughout the United States comes new hope for improving precipitation forecasts. The high accuracy along with temporal and spatial resolution of water vapor amounts provided by GPS instruments may, with more research, lead to more detailed forecasts. GPS TPW amounts have been experimentally assimilated into the 60-km RUC2 model at the Forecast Systems Lab (FSL) in Boulder, CO. With GPS TPW, the precipitation forecasts at levels greater than one inch have been improved (Gutman et al, 2003). The improvement of precipitation forecasts is a major goal of the United States Weather Research Program (USWRP). The USWRP recognizes that precipitation forecast lead-times are crucial in minimizing both human and economic loss, and so it is working to increase the accuracy and warning time of its forecasts (USWRP, 2004). Assimilating GPS water vapor data into models appears to be a positive step towards reaching this goal. With more reliable Quantitative Precipitation Forecasts (QPFs), there would be implications for huge improvements in forecasts for large rain events including flash floods.

Improved rain forecasts are crucial to almost everybody in the world. Farmers rely on rain for their crops; if they receive a false rain forecast (or several false rain forecasts) it could mean the death of their crops – and possibly less food globally. The military also relies on accurate weather forecasts for their daily operations. Atmospheric changes due to heavy rain or storm systems affect signal propagation. Accurate and timely flood forecasts would prevent deaths and the loss of personal property globally.

There is promise that the GPS network will improve precipitation forecasts. The new GPS network provides good spatial coverage of accurate TPW estimates that can be assimilated into forecast models. This can greatly improve the spatial resolution and reliability of rainfall events as well as the overall forecast validity, especially in the tropics where uncertainties in the moisture field have their greatest impact on forecast model initialization. In this research, the relationship between GPS TPW amounts and rainfall events is analyzed in depth and its implications for forecast improvements are discussed.

2. Datasets

This section discusses the area and time period examined in this study as well as the datasets used. The area and time period are detailed in section 2.1. Three main datasets were used to determine the relationship between TPW and daily rainfall amounts – GPS TPW amounts, National Climatic Data Center 24-hour rainfall totals, and Oklahoma Mesonet 24-hour rainfall totals. The TPW data is derived using GPS satellites and ground stations, and it is collected and distributed on the web by the NOAA/FSL GPS-MET Observing Systems Branch. This is discussed in section 2.2. Also used in this study were daily rainfall totals (also archived online by the NCDC and Oklahoma Mesonet), which are discussed in section 2.3.

2.1 Study Area and Time Period

The spatial focus of this study is on the Southern Great Plains region of the United States, which extends throughout the states of Kansas, Oklahoma, and Texas. TPW and rainfall data were obtained for six cities for this study – Amarillo, TX, Vici, OK, Purcell, OK, Haskell, OK, Hillsboro, KS, and Houston, TX. These cities span a longitude of 95.43° W to 101.88° W and latitude of 29.78° N to 38.3° N.

The temporal focus of this study is from September 2002 through January 2004. Each city is analyzed over a different time frame due to the limitations of the rainfall data and GPS network. The GPS network has only been fully operational since mid-2002 in most cases, and this severely limits the temporal extent of this research. The daily rainfall data, in some cases, was missing for several consecutive months during 2002-2003, and in other cases it did not extend past November 2003. For each city, at least a full year's worth of data was obtained between 2002-2004, and where the data was available as many consecutive months were collected as was possible given the GPS time constraint. These data limitations are further described in the following sections.

2.2 The Global Positioning System

The Global Positioning System was developed by the Department of Defense (DoD) primarily for the U.S. Military to provide precise estimates of position, velocity, and time. The system consists of 24 satellites flying in six orbital planes 20,000 km above the earth. Each satellite transmits L-band radio signals at 1.575 and 1.228 GHz (corresponding to wavelengths of 190 and 244 mm, respectively) which travel to users on the ground equipped with GPS receivers. Many civil applications of GPS in areas such as land transportation, civil aviation, maritime commerce, construction, and agriculture have been discovered since the establishment of GPS. The use of GPS to measure atmospheric water vapor was thought possible as early as 1990, and was proven to have millimeter accuracy and subhourly temporal resolution by the time the GPS ground network was fully operational in 1994 (Wolfe et al, 1999).

2.2.1 The Measurement of Total Precipitable Water (TPW)

GPS signals are refracted and delayed in the Earth's atmosphere – the ionosphere and the neutral atmosphere – as they propagate from the GPS satellites to Earth-based receivers. The time of the signal delay can be measured well due to the high accuracy of the atomic clocks on board the GPS satellites, and TPW can then be calculated from this time delay.

Ionospheric propagation effects are frequency dependent and therefore can be estimated and eliminated using dual frequency receivers. The free electrons in the ionosphere cause dispersion of radio waves at frequencies above 30 MHz. The total electron content (TEC) in the ionosphere along the path from the satellite to the receiver is roughly proportional to the magnitude of the delay of the group velocity of the radio waves, which is inversely proportional to the square of the carrier frequency. By making measurements at both frequencies of radio waves emitted by the GPS satellite, the ionospheric effect can be modeled and removed from the observations. A typical daily average zenith delay due to the ionosphere is 10 meters (Bevis et al, 1992).

The signal propagation in the neutral atmosphere depends on the refractive index associated with temperature, pressure, and water vapor. Water vapor introduces a unique delay due to its dipole moment, which is caused by the asymmetric distribution of charge in the water molecule. The delay in the neutral atmosphere is divided into a delay due to the dipole component of water vapor refractivity (named the wet delay) and the delay due to the nondipole components of the refractivity of water vapor and the other atmospheric constituents (the hydrostatic delay). Both of these delays are smallest for paths oriented along the zenith direction and increase approximately inversely with the sine of the elevation angle (Bevis et al, 1992).

The zenith hydrostatic delay (ZHD) can be estimated by obtaining a surface pressure measurement and applying a mapping function:

$$\mathrm{ZHD} = (2.2779 \pm 0.0024) * P / f(\lambda, H), \tag{2.1}$$

where P is the pressure in millibars at the Earth's surface, and

$$f(\lambda, H) = (1 - 0.00266 * \cos 2\lambda - 0.00028 * H) \tag{2.2}$$

accounts for the variation in gravitational acceleration with latitude λ and height H (Bevis et al, 1992). Since the acceleration of gravity is dependent on height and latitude (due to the slightly oblate shape of the earth), particles and molecules higher in the atmosphere and closer to the equator experience less downward acceleration and therefore stay in the atmosphere longer, creating a greater effect on the delay of GPS signals than constituents located further pole ward and closer to the surface of the earth.

Once the ZHD is known, the zenith wet delay (ZWD) can be calculated by simply subtracting the ZHD from the zenith tropospheric delay (ZTD). The ZTD is estimated by constraining the positions of many widely spaced GPS receivers and measuring the apparent error in position. When all system-related errors are accounted for, the remaining error is assumed to come from the neutral atmosphere.

The ZWD, once calculated, is nearly proportional to the total quantity of integrated water vapor (IWV) in the atmosphere directly above the GPS site. The relation is simply:

$$\mathrm{IWV} = \Pi^{*}\mathrm{ZWD}, \text{ where} \tag{2.3}$$

$$\Pi = 10^{6} / (\rho^{*}R_{v}^{*}[(k_{3}/T_{m}) + k_{2}']), \text{ with} \tag{2.4}$$

$$k_{2}' = k_{2} - m^{*}k_{1}, \text{ and} \tag{2.5}$$

$$T_{m} = 0.72^{*}T_{s} + 70.2 \tag{2.6}$$

where ρ is the density of liquid water, R_v is the gas constant for water vapor, T_m is the weighted mean temperature of the atmosphere, m is the ratio of the molar mass of water vapor to the molar mass of dry air, T_s is the surface temperature, and the physical constants k_1, k_2, and k_3 are from the formula for atmospheric refractivity N:

$$N = k_{1}(P_{d}/T) + k_{2}(P_{v}/T) + k_{3}(P_{v}/T^{2}). \tag{2.7}$$

In equation 2.7 for N, P_d and P_v are the partial pressures of dry air and water vapor, respectively, and T is absolute temperature (Bevis et al, 1993). The formula for T_m is valid in the United States within a latitude range of 27° to 65° N and a height range of 0 km to 1.6 km (Bevis et al, 1992). The formula is a linear regression derived from 8718 radiosonde profiles spanning a two-year interval in the United States, with an rms deviation of 4.7 K (Bevis et al, 1993).

The values of the constants ρ, R_v, and m are well known and have very small uncertainties; therefore they have little impact on Π (Bevis et al, 1993). The uncertainties in Π are derived mainly from T_m, k_1, k_2, and k_3. Since k_1, k_2, and k_3 have all been measured with high certainty, the error in Π is to a good approximation the error in T_m (Bevis et al, 1993). T_m is almost impossible to measure within an accuracy of 1% (Bevis et al, 1993).

To finally calculate TPW from IWV, the relation is simply:

$$IWV = \rho^{*}TPW. \tag{2.8}$$

These terms are often used interchangeably due to the fact that they only differ by a constant factor. TPW in millimeters is equivalent to IWV in kg/m^2.

For more information on the calculation of TPW from the GPS signal delay, refer to Bevis et al, 1992 and Bevis et al, 1993.

2.2.2 Sources of Error

GPS gives a highly accurate measurement of TPW mainly because four to ten satellites are used for each measurement (see Figure 2.1 for depiction), so TPW is essentially over determined. The delay of each satellite signal is calculated and mapped onto zenith using functions that are dependent on the sine of the elevation angle of each satellite, which is a minimum of seven degrees above the horizon. Once all of the delays are mapped onto zenith and the TPW is calculated from each one of them, they are all averaged to get the final TPW product. GPS-TPW is a volume average, taken over a cone-shaped volume of almost 580 km^3. This volume is essentially a cone, apex down, with a height of 5.0 km and a base of 21 km.

While GPS-TPW is highly accurate, there are still various sources of error in the estimation of TPW from GPS satellite radio signals. Pressure sensors located at GPS ground stations have an accuracy of 0.1 hPa. The pressure measurement taken at GPS antenna height is converted to sea-level pressure. In this conversion, the total pressure error amounts to less than 0.3 hPa, which corresponds to an error in IWV of less than 0.1 kg/m^2 (= 1mm TPW). In general, a 1.0 hPa error in surface pressure equates to a 0.3 mm error in TPW. The surface pressure measurement is the primary error source in estimating TPW (Gutman et al, 2003).

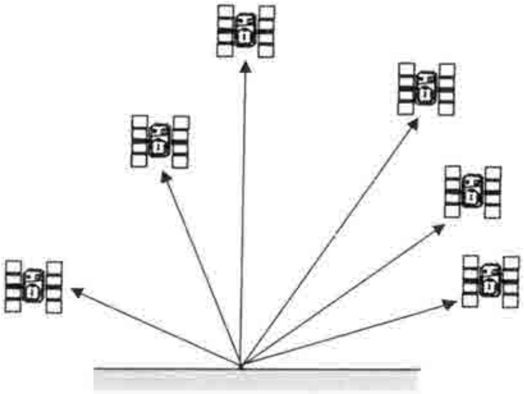


Figure 2.1. Depiction of GPS satellites located above a ground station location.

The secondary error source in the estimation of TPW is in the calculation of T_m. In this calculation, an equation is used that is valid for the entire United States. T_m, however, varies with season and location, so there is an error associated with using one equation for hundreds of locations. Using this equation gives an error of less than 2% in T_m, which corresponds to an error of less than 4% in the recovery of TPW from the ZWD (Bevis et al, 1992). This introduces an average error in the TPW retrieval of 0.16 mm (Gutman et al, 2003). This error represents an upper bound; recent results indicate that T_m can also be predicted using 12-hour operational forecasts with an rms error of 2.4 K (Yuan et al, 1993), which cuts the error in half compared to the linear regression.

Overall, TPW is currently measured from GPS satellites with an average error of less than 1.0 mm (Gutman et al, 2003).

2.2.3 The GPS Ground Station Network

Since the early 1990's, hundreds of GPS ground stations have been erected and used to measure TPW in the United States – several thousand worldwide (Seth Gutman, personal communication). There are currently over 300 ground stations in use in the United States and Canada.

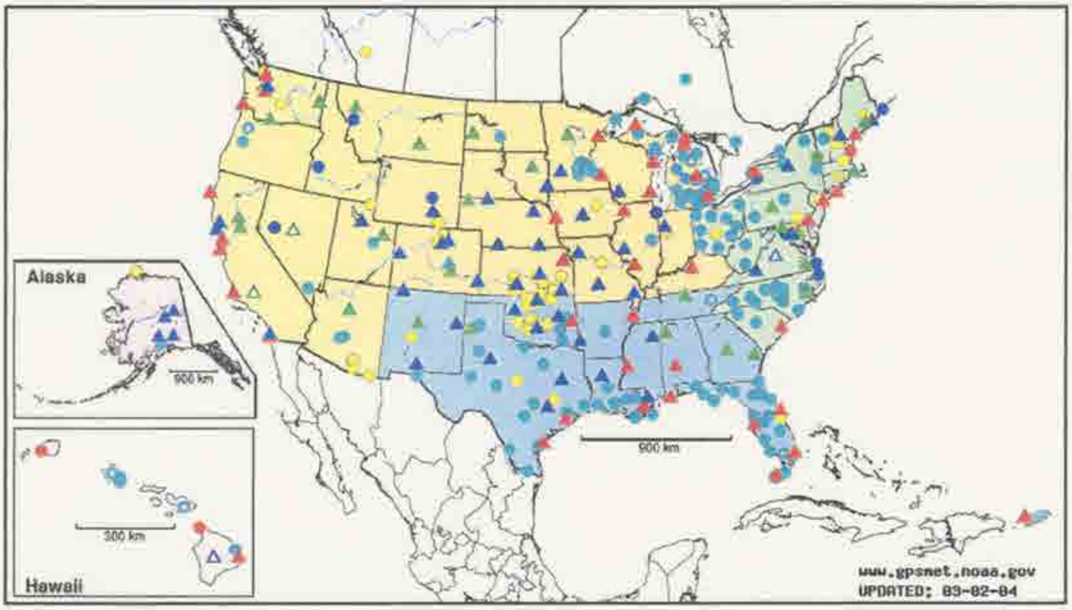


Figure 2.2. GPS ground station locations in the United States. Symbols are detailed in explanation box (left).

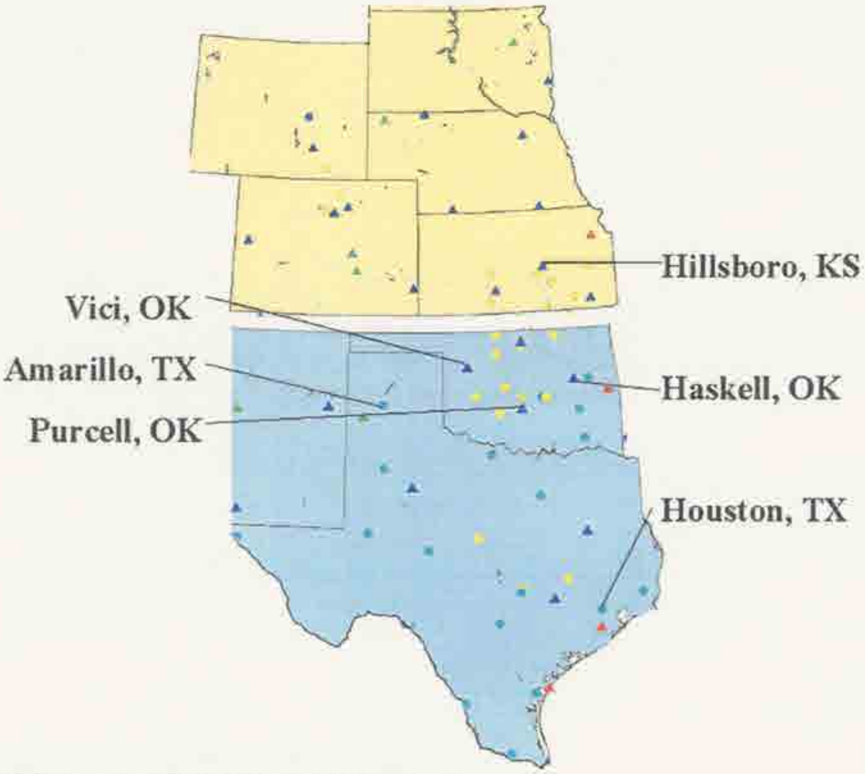


Figure 2.3. Six GPS ground stations used in this study.

There are four major affiliations that run ground station networks: NOAA, Suominet (University-run), the United States Department of Transportation (DOT), and the United States Coast Guard. Figure 2.2 shows GPS ground station locations throughout the United States. More information on the Suominet network can be found in Ware et al., 2000. This research primarily uses six stations run by NOAA or Universities participating in Suominet located in Oklahoma, Kansas, and Texas. These stations are shown in Figure 2.3. The TPW data used in this study were obtained from the NOAA Forecast Systems Laboratory GPS-Meteorology Observing Systems Branch online at http://gpsmet.fsl.noaa.gov/jsp/index.jsp.

2.3 Daily Rainfall Data

Daily rainfall data during the years of 2002-04 were obtained from the National Climatic Data Center's (NCDC's) online Record of Climatological Observations (http://hurricane.ncdc.noaa.gov/dly/DLY) and also from the Oklahoma Mesonet's Public Products Site (http://www.mesonet.ou.edu/public/).

2.3.1 The NCDC

The NCDC collects and archives weather data obtained by the NWS, the Coast Guard, Military, Federal Aviation Administration, and cooperative observers. The Climatological Data containing daily precipitation data by city was used in this research. Data were collected for the cities of Vici, OK, Haskell, OK, Hillsboro, KS, Amarillo, TX, and Houston, TX for the years of 2002-2003. Several months were missing for a few of the cities in Oklahoma, and there were no data for Purcell, OK; to allow for this the second daily rainfall dataset, described below, was chosen. NCDC daily precipitation data consists of a 24-hour total accumulation of precipitation observed at 0700 CST.

2.3.2 The Oklahoma Mesonet

The Oklahoma Mesonet was created by scientists at the University of Oklahoma (OU) and Oklahoma State University (OSU). The network consists of over 110 stations throughout the state of Oklahoma, with at least one station located in each county. At each location temperature, relative humidity, rainfall, barometric pressure, wind speed, soil temperature, incoming solar radiation, and several secondary variables are measured. Each measurement is averaged over five-minute intervals.

The Oklahoma Climatological Survey (OCS) receives the Oklahoma Mesonet data at OU and provides it to Mesonet customers and universities. The data used in this research spans February 2003 through January 2004, and consists of daily rainfall totals observed at midnight CST for the cities of Camargo, Washington, and Haskell. The rainfall observations in Camargo are taken approximately 11.4 km South of the GPS ground station in Vici and the rain observations in Washington are collocated with the GPS ground station in Purcell.

2.3.3 Sources of Error

For cities in Oklahoma, the Mesonet data were taken as truth and the NCDC data, which were not always complete, were used to back up the Mesonet data. This was done to create a continuous record of rainfall measured in the same manner. Often the Oklahoma Mesonet data would conflict with the NCDC data on a given city and day. When this occurred, the Mesonet rainfall amount was used. Due to the fact that two of the Mesonet stations in Oklahoma are not collocated with their corresponding GPS stations (see Table 2.1), on days when one of these Mesonet stations did not record any rain and the corresponding NCDC station did, the NCDC data was used. These days usually had spotty rain showers that may have produced rainfall over the city in question but not over the mesonet site.

Due to the locations of two of the mesonet sites being several kilometers away from the GPS ground stations that were used, this research focuses on rain events within a 22-km radius of the GPS station that is being considered. Some of the cities where NCDC observations were used have the same issue - the sensors are not collocated and consequentially the two measurements are taken up to 22.21 km apart. The distances are summarized in Table 2.1 below (N/A is entered where the rainfall data was not available).

Table 2.1 Distances between GPS ground station sites and rainfall observation sites.

City	Distance of OK Mesonet site from GPS site	Distance of NCDC site from GPS site
Vici, OK	11.43 km	12.44 km
Purcell, OK	0.00 km	N/A
Haskell, OK	21.32 km	22.21 km
Amarillo, TX	N/A	17.73 km
Houston, TX	N/A	0.00 km
Hillsboro, KS	N/A	9.59 km

Due to the highly localized nature of precipitation, there are many sources of error in the daily rainfall data. In cities where the GPS and rainfall measurements are not collocated, there could be heavy rainfall over the GPS site that would not be captured in the rainfall data, or heavy rainfall occurring over the rain gauge with a slot of dry air passing over the GPS sensor. While there is no way to determine a number value for this source of error due to the limited networks of rain gauges and GPS ground stations, it is known that there are at least a few cases where one of these situations may have occurred. This is inferred from looking at maps of radar data from storms that passed over the cities. Several times, precipitation would occur in a neighboring city (15 km away), but not in the specific city being studied. This type of error is most common during the spring and summer months, when convection creates storm cells with highly localized precipitation. In the winter months, when large systems bringing stratiform precipitation to the region are more common, rain is more widespread and uniform. While this spatial problem may have been solved by using linear interpolation to calculate rainfall amounts between cities, this was not done in order to preserve the intermittent nature of rainfall. If rain amounts are linearly interpolated between two cities in which rain is occurring, then it is assumed to be raining everywhere between the two cities, when this may not be true. This study seeks to determine the relationship between GPS TPW and rainfall that occurs in the same area as the GPS sensor, with as little error as possible. To do this, only the rain gauge located the closest to each GPS sensor was used and held as truth, regardless of surrounding rainfall patterns.

Different types of rain events create different sources of error. Thunderstorms tend to have high winds that can blow rain over the rain gauge instead of allowing the rain to fall straight into the gauge. Summer storms can also be short-lived; once they pass and the sun dries out the air or the winds pick up, water from the rain gauge can evaporate before the daily reading is taken. Hail is also a factor during spring and summer storms – not only can it damage the rain gauge but it could also clog it so that other precipitation is not able to land in the rain gauge. On the other hand, heavy stratiform precipitation that lasts for long periods of time can inundate the rain gauge with water and cause water to splash out of the gauge. In the winter months when the temperatures are colder, a large snowstorm could cover the rain gauge and remain there for several days until it melts, giving an inaccurate reading.

Another source of error in the rainfall measurements is the number of sources that they come from. The precision of each rain gauge is within 0.0254 cm, however there is no way to quantify the errors from the different input sources. The Oklahoma Mesonet and the Amarillo National Weather Service station use tipping bucket rain gauges, which are automated and not read manually. During times of heavy rain (over 5 cm per hour) or frozen precipitation, these rain gauges typically measure less than the actual amount of precipitation; either the tipping bucket is unable to keep up with the rain rate or snow is blown over the gauge and not read (Nolan Doesken, personal communication).

The Houston and Hillsboro stations use the standard manual rain gauge, which needs to be read daily by observers. Each rain gauge is read by a different person with his or her own habits and preferences; this introduces error due to human flaws. In Houston, there is very little error from evaporation due to the humid environment, and also most of the precipitation falls as rain so there is also very little error due to snow, hail, or sleet. In Hillsboro, which is much further north, the errors from evaporation, high winds, and frozen precipitation are much larger.

On average, the error introduced into the daily rainfall amounts from all six of these stations should not exceed 5% (Nolan Doesken, personal communication). All of the stations are calibrated yearly and kept in good condition. In the case of the four tipping bucket gauges, the error is uneven due to the fact that the gauges consistently under measure precipitation – it is extremely rare, and usually due to instrument failure, that one of these gauges over measures rainfall (Nolan Doesken, personal communication). Observation taken in the other two cities using the manual rain gauges can vary above or below reality due to human error in reading the gauges.

3. GPS Total Precipitable Water Amounts

The main question to be answered in this thesis is, "Can rain events be forecast using GPS TPW amounts?" By looking at a time series of TPW, a definite pattern can be seen. Figure 3.1 shows a plot for Haskell, OK for the month of December 2003. There are several peaks in the water vapor, lasting for about a day each. Upon examining the daily rainfall data for this month, it was noted that each of the TPW peaks occurred on a day when a rain event also occurred (days with rain events noted by red arrows in Figure 3.1). While from looking at this particular month it looks like TPW is an excellent indicator of rain events, other months do not have such clear plots. Figure 3.2 shows the plot for the month of August in Haskell, OK. In this plot, the TPW peaks are harder to define; TPW is much higher in general in the summer months than in the winter months and therefore summer rain events are not always associated with large peaks in TPW. However rain events still tend to coincide with higher TPW amounts; for instance it rained during the last three days of August in Figure 3.2, when TPW was at its peak for that month. Rain events also occurred on the 2nd, 3rd, 5th, and 14th of the month.

Using maximum TPW values on days with and without rain, it was calculated that the average TPW on rainy days is higher than the TPW on dry days by around 1.0 cm in all of the cities analyzed. This demonstrates that TPW is higher on rainy days than on days without any rainfall. By looking at only the

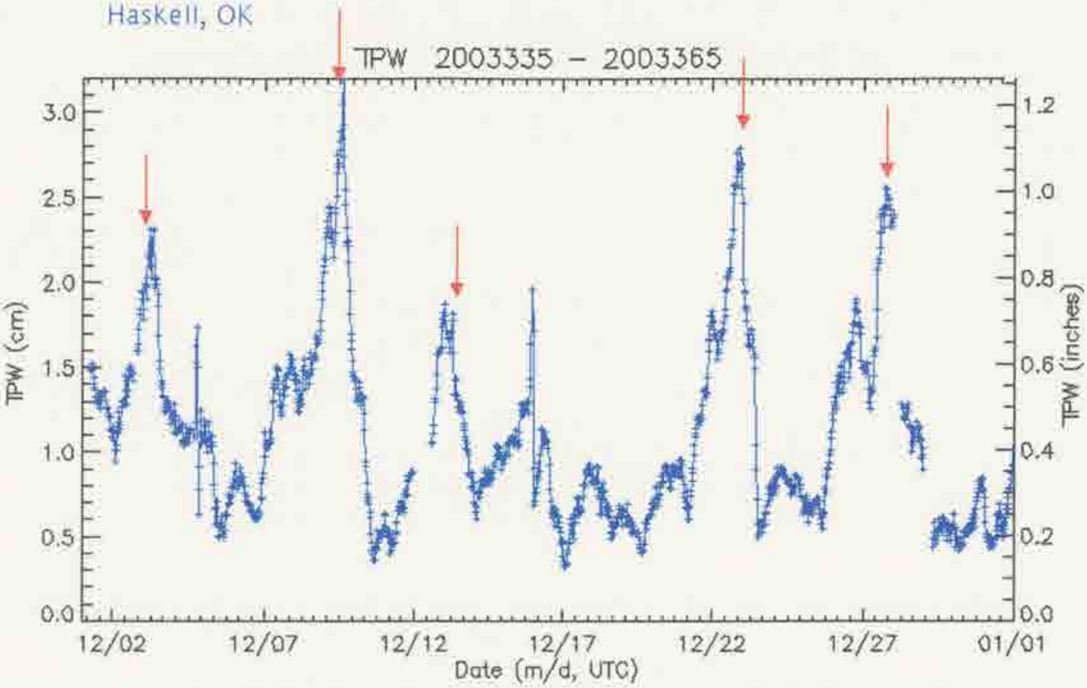


Figure 3.1. Time series of TPW over Haskell, OK for the month of December 2003. (From NOAA-FSL GPS-Met Observing Systems Branch.)

rainy days, a positive correlation was found between 24-hour maximum TPW amounts and 24-hour rainfall totals, which further implies that higher TPW values correspond with larger rainfall amounts. Figure 3.3 shows the relationship between peak TPW amounts and rainfall amounts on rainy days throughout the Southern Great Plains region. A simultaneous correlation was calculated instead of a time lag correlation due to the fact that the exact time between the peak TPW amounts and the beginning or end of rain events was not known, although the maximum amount it could be is 24 hours. The time between TPW maxima and the start of rain varies for every rain event. While Figure 3.3 shows a positive correlation, it cannot be said whether or not TPW could be a new forecast tool for rain events without knowing the forecast lead time that peak

TPW amounts would give before a rain event would occur. This is discussed more in Chapter 4.

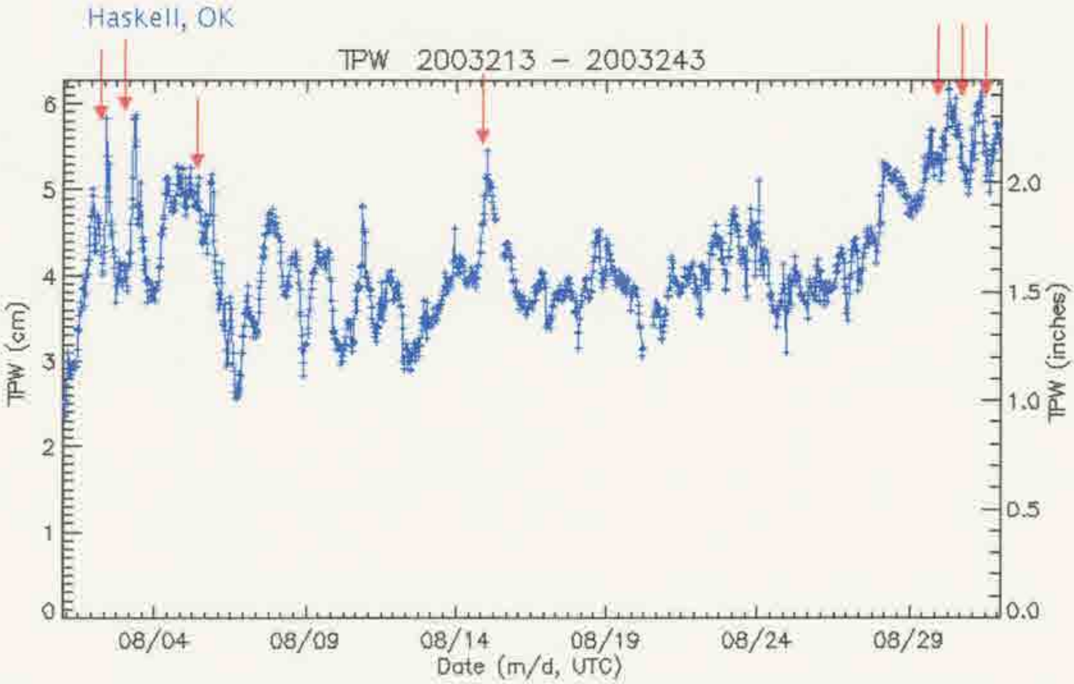


Figure 3.2. Time series of TPW over Haskell, OK during the month of August 2003. (From NOAA-FSL GPS-Met Observing Systems Branch.)

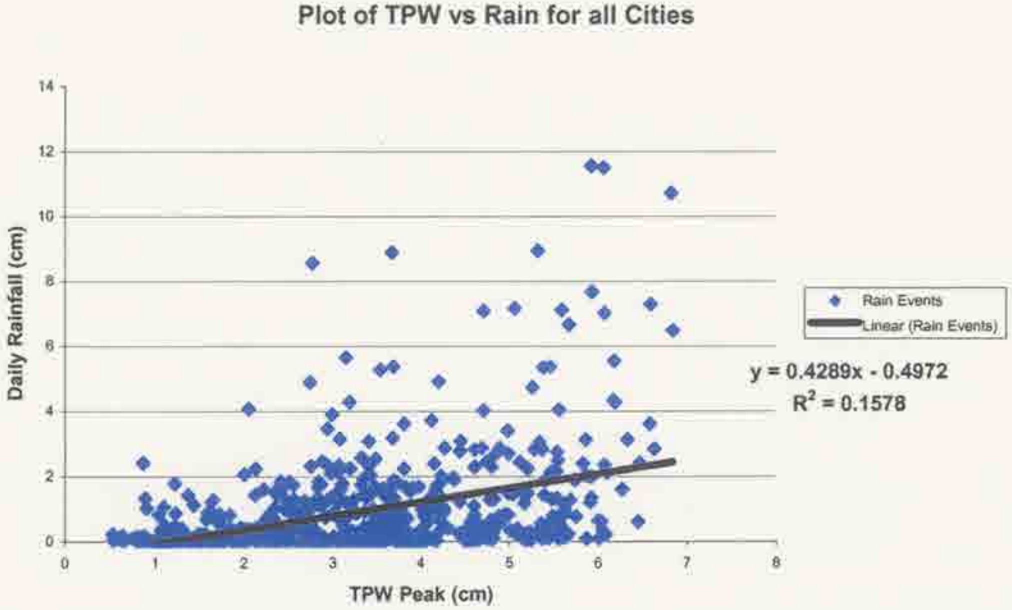


Figure 3.3. Scatter plot of TPW and Rainfall Amounts for all six cities analyzed, over a time period of 9/2002-1/2004. Correlation is .397. Error bars are as shown in Figure 3.4.

In the following sections, the relationship between GPS TPW and rainfall amounts is explored. Each of the six cities is looked at individually. First, the climatological setting is described to outline where dry and wet conditions existed throughout the region studied. This helps detail which cities received below-average rainfall during the time period analyzed, which many affect the results of this study. Once the setting is in place, in section 3.2 the overall relationship between rainfall amounts and peak TPW amounts on rainy days is looked at. The correlation between TPW and rainfall amounts for 6-month periods is also looked at. This is broken up "seasonally", one period contains rain events during the months of October through March and the other consists of events from April through September. Since there are different processes occurring at different times of year in the Southern Great Plains – for example, a large portion of summer rainfall in the great plains is due to convection caused by strong daytime heating – there may be a different relationship between TPW and rainfall amounts in the summer than in the winter.

We also look at the correlation between TPW and rain amounts for heavy rain events to see if there is a higher correlation for heavy rain days than for light rain days. Finally, we look at the correlation for rainy days with TPW greater than 2 cm. In section 3.3 the six cities are compared and the results are discussed.

3.1 Climatological Setting

The years of 2002-2003 tended to be dry in the Southern Great Plains (SGP). While it can be seen in Figure 1.1 (Section 1.2.1) that the eastern SGP is much wetter than the western SGP on average, the years of 2002-2003 did not necessarily follow climatology. The situations are shown in Table 3.1. Only Houston received above average rainfall for the period studied, with Vici receiving the smallest percentage of its annual average rainfall. The percent of normal precipitation was calculated from one year's worth of rainfall data for each city. For cities where more than one year's worth of data was available, the rainfall amounts were calculated for the 12-month period that contained as much of the year 2003 as was available. When calculating the percent of normal rainfall for each city using other 12-month periods (where available), a difference of up to 5% from the values in table 3.1 occurred. Errors are also introduced due to the differences in rainfall measurements between the NCDC and Oklahoma Mesonet in certain cities. At times the monthly precipitation amounts from these two datasets did not agree. The uncertainty in the measurement of rainfall amounts (due to the faulty nature of rain gauges during high winds or to the manner in which a person reads the rain gauge) also causes some error in calculating a yearly rainfall total.

Table 3.1. Percent of normal annual rainfall for each city along with dates used to calculate rainfall amounts. Normal amounts are calculated using rainfall from 1971-2000.

City	Dates	% Of normal annual rainfall (+/- 5%)
Amarillo	12/2002-11/2003	73.2%
Vici	2/2003-1/2004	65%
Purcell	2/2003-1/2004	70.9%
Hillsboro	12/2002-11/2003	100%
Haskell	2/2003-1/2004	80.3%
Houston	1/2003-12/2003	120.1%

While in some cases the percent of normal rainfall seen in table 3.1 enhances the precipitation gradient seen in Figure 1.1 (Section 1.2.1), it also confuses it somewhat. For example Haskell is a wetter city (comparable to Houston) climatologically, however during the study period it was drier than average, which puts it in a similar rainfall category as Hillsboro instead of Houston. While Amarillo received a slightly higher percentage of normal precipitation than Vici, it was still the driest city out of the six, receiving only 35.56 cm of rain in the period December 2002 through November 2003. Houston remains the wettest city, receiving over 144.8 cm of rain during 2003.

3.2 Data Analysis

In this section, rainfall and TPW data from each of the six cities is analyzed to determine if rain forecasts may be more accurate in one city than another. The simultaneous correlation between the maximum TPW amount and rainfall totals on rainy days is explored in several different ways to determine the situation in which the correlation is highest (which might lead to a better forecast).

3.2.1 Amarillo, TX

Amarillo, TX is the driest city in this study. It received only 35.5 cm of rain in the 12-month period 12/2002-11/2003. Due to the dry winds blowing into Amarillo from the mountains and deserts to its west, there is not as much water vapor there as in cities further east. The dryness in Amarillo in the summer is also related to the dryline, which is the boundary between moist and dry air that moves eastward across the SGP region during the day in the summer months.

Amarillo is often west of the dryline, in the drier air. TPW above Amarillo for the time period studied averages 1.58 cm, with a standard deviation of 0.94 cm. The peak in TPW of 2.96 cm occurs in August, with a minimum of 0.63 cm occurring in December. In the time period studied (September 2002 – November 2003), the most variable month was October 2003, with a mean TPW of 1.62 cm and a standard deviation of 0.78 cm. The least variable month was January 2003, with a mean TPW of 0.67 cm and a standard deviation of 0.21 cm.

In the first part of this analysis a scatter plot of peak TPW amounts and Daily Rainfall Amounts for 114 rainy days (all of the rain events during the study period) is made. This is shown in Figure 3.4. TPW and Rainfall Amounts in this plot have a correlation of .27, which is significant above the 99% level. This graph shows a significant positive correlation between TPW and Rain.

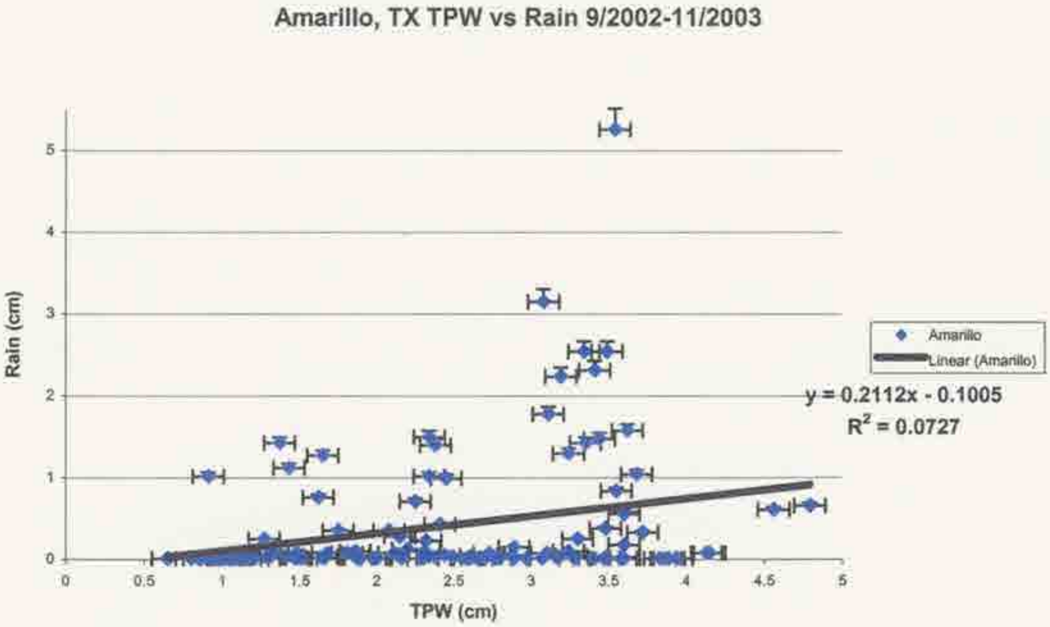


Figure 3.4. Plot of TPW vs. Rainfall Amounts for Rainy Days in Amarillo, TX. Correlation is .27. Abscissa error bars account for 1mm error in GPS TPW; ordinate error bars account for up to 5% under measurement error in daily rainfall amounts.

Next, "summer" and "winter" plots were made. The summer plots only use data from the months of April through September, and the winter plots use data from the months of October through March. These plots were made to determine if there is a higher correlation during one time of year than the other. In the Great Plains, there are different mechanisms that cause rainfall in the summer than in the winter. In the summer, there is a large amount of daytime heating that creates rising motion. If there is a significant amount of water vapor in the air, clouds form and water vapor builds up until it begins to fall to the ground. During the winter the main mechanism is large-scale systems moving into the region from the west – they do not generally form right over the region being studied. Figure 3.5 shows the October-March plot for Amarillo, TX. This plot uses 54 rainy days and has a correlation of .386.

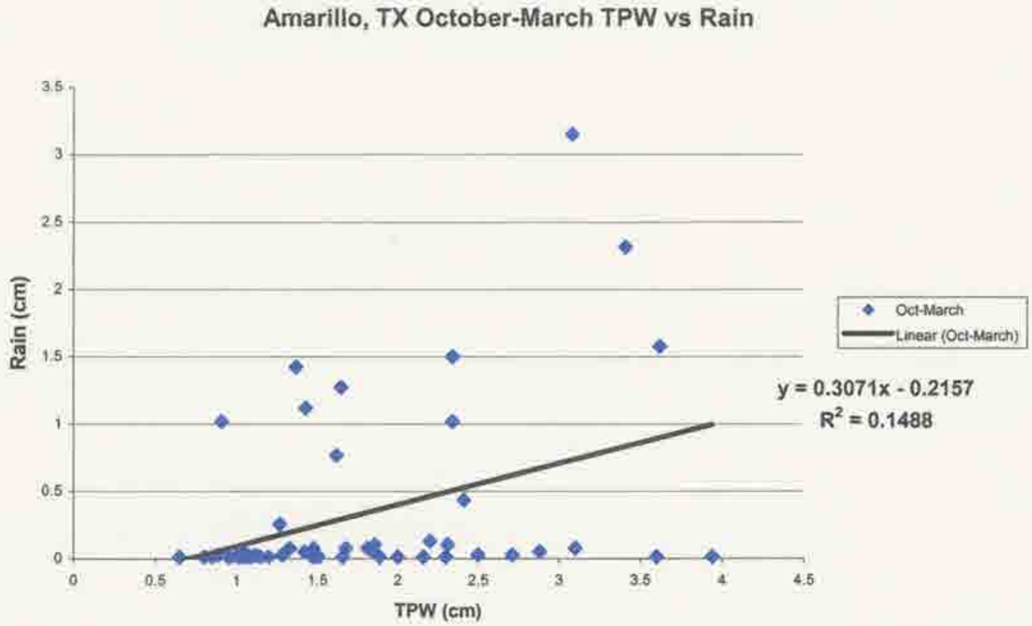


Figure 3.5. Scatter plot of TPW and Rainfall Amounts during the months of October through March in Amarillo, TX. Correlation is .386. Error bars are as shown in Figure 3.4.

As can be seen from comparison of Figure 3.5 to Figure 3.4, the correlation is higher in the winter months than year-round (from the 15 months of data used). The correlation for April-September is .195, using 52 points (plot shown in Appendix). This low correlation during the summer months is most likely what keeps the overall correlation low in Amarillo.

From looking at Figure 3.4, the very light rain events appear to be fairly spread out along the TPW axis. Light rain events seem to occur at almost any TPW value, and therefore may be lowering the correlation. The next plot we look at is for heavy rain events (rainfall greater than .5 cm and 1.0 cm), to determine if heavier rain events are better correlated than all rain events together. This plot is shown in Figure 3.6. The correlation for rain events greater than 0.5 cm is .126; for rain events greater than 1.0 cm it is .44. The correlation for rain events greater than 1.0 cm is clearly larger than the overall correlation of .27, which leads to the conclusion that several small rain events occur at relatively large TPW amounts in Amarillo.

Finally we look at rainy days with TPW greater than 2.0 cm (figure shown in Appendix). The correlation for this plot is .161, using 75 points. From looking at Figure 3.4, it can be seen that the largest rain events occur at relatively large TPW amounts. By isolating the larger TPW amounts, a higher correlation was thought possible than the overall correlation using all TPW amounts. However this did not occur, most likely due to the fact that the correlation is influenced by the many small rain events occurring at higher TPW values.

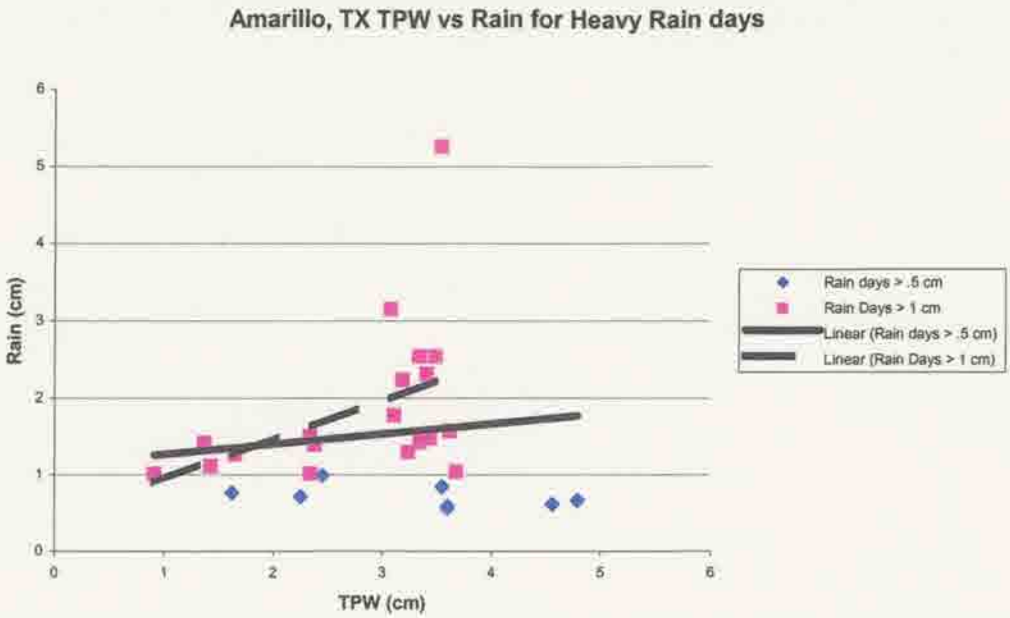


Figure 3.6. Scatter plot of TPW and Rainfall Amounts greater than 0.5 and 1.0 cm for Amarillo, TX. Error bars are as shown in Figure 3.4.

In summary, the highest correlation in Amarillo, TX between TPW and Rain Amounts was .44, found when looking at only heavy rain events over 1.0 cm. The next highest correlation occurred in the winter 6-month period. This suggests that heavy rain events or cold season rain events might be better predicted than all rain events together.

3.2.2 Vici, OK

Vici, OK is the second driest city in this study, having received 45.7 cm of rain from February 2003 – January 2004. While Vici is affected by many of the same meteorological processes as Amarillo, it receives slightly more rainfall on an annual basis. Since Vici is located about 200 km east of Amarillo, it may receive some moisture from the south due to the Low-Level Jet blowing from the Gulf of Mexico at night, which generally does not extend as far west as Amarillo.

Dry desert winds blowing from the west are dry over Amarillo but have more time to pick up moisture before reaching Vici, which may also account for the increased moisture there. Amarillo is also affected by the dryline during the spring and summer months – it is often passed by the dryline as it moves eastward, whereas Vici sometimes is not, causing Vici to remain in more moist air. TPW varies by around 1.0 cm across the dryline; during convection and severe storms it can vary by as much as 3.0 cm (as seen from TPW time series plots during dryline movement).

TPW above Vici averages 1.78 cm with a standard deviation of 1.06 cm. The month with the highest average TPW was August, with 3.54 cm; the driest month was December with 0.83 cm average TPW. In the time period studied (February 2003 – January 2004), the most variable month was October 2003, with a mean TPW of 1.82 cm and a standard deviation of 0.79 cm. The least variable month was January 2003, with a mean TPW of 0.86 cm and a standard deviation of 0.23 cm. These months and numbers are almost identical to those of Amarillo; this suggests that these two cities are affected by the same weather systems, causing the TPW to vary in the same manner over both cities.

Shown in figure 3.7 is the scatter plot of TPW and daily rainfall amounts on rainy days. The correlation is .37 using 119 points (rainy days). This correlation is statistically significant above the 99.9% level.

Following this plot, correlations between TPW and rain were calculated for the months of October through March and April through September for the period studied. The correlation for October-March was .145 using 51 points; for April-

September it was .278 using 62 points. These are both lower than the overall correlation, suggesting that rain forecasts in Vici will not be better at one time of year than another.

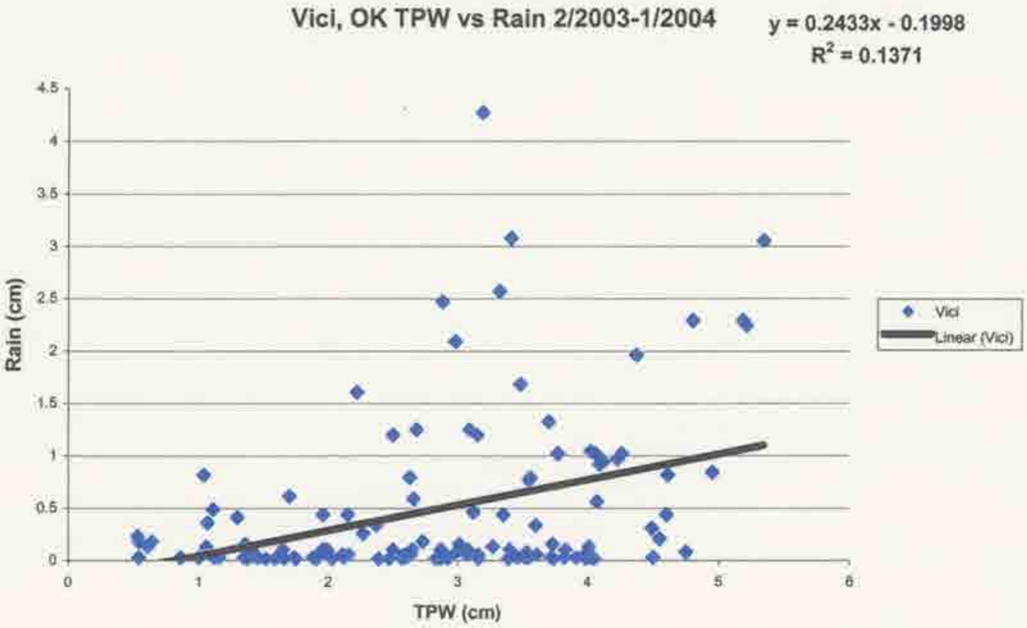


Figure 3.7. Scatter plot of TPW and Rainfall amounts on rainy days in Vici, OK. Correlation is 0.37. Error bars are as shown in Figure 3.4.

The next analysis done was to compute correlations for heavy rain days with rain greater than 1.0 cm and days with rain greater than 0.5 cm. These correlations were .17 and .197, respectively. Heavy rain days in Vici do not show a high positive correlation during this study period. This is most likely due to the large amount of light rain events Vici experienced during 2003. Without a few heavier rain events occurring at high TPW values, the correlation stays low. There is also a cluster of 1-cm rain events corresponding to TPW values of 4 cm or greater, and one large rain event of over 4 cm that occurred around a TPW of 3 cm. In the year of 2003 Vici received below average precipitation; a year that is closer to average will most likely contain a few larger rain events to give a higher correlation for heavy rain days.

Finally, the correlation for days with TPW greater than 2 cm was calculated to be .302. In Vici, the highest correlation was for all rainy days, however using only high-TPW days to make a rain forecast is the next best option.

3.2.3 Purcell, OK

Purcell, OK received 68.8 cm of rain during the period February 2003 – January 2004; the city's average annual rainfall is 97 cm. During this period the average TPW was 2.13 cm, with a standard deviation of 1.22 cm. The month with the highest average TPW was August, with 4.07 cm; the month with the lowest was January with 0.97 cm. The most variable month was November, with an average TPW of 1.80 cm and a standard deviation of 1.0 cm. The least variable month was January, with a standard deviation of 0.27 cm (TPW noted above).

It can be noted that Purcell receives more rainfall and has higher average TPW than Amarillo or Vici. The TPW above Purcell is also slightly more variable. Shown in Figure 3.8 is the correlation plot of TPW and rainfall amounts on rainy days for Purcell, OK. The correlation is .422 using 90 points; it is statistically significant above the 99.98% level. The correlations for the months of October through March and April through September are .179 and .475, respectively. For heavy rain events greater than 0.5 cm and 1.0 cm the correlations are .55 and .55, respectively. For rain events with TPW greater than 2.0 cm the correlation is

.394. These scatter plots are shown in the Appendix. In comparing the correlations for different situations in Purcell, it can be noted that a rain event forecast might be best made for heavy rain events (greater than 0.5 or 1.0 cm).

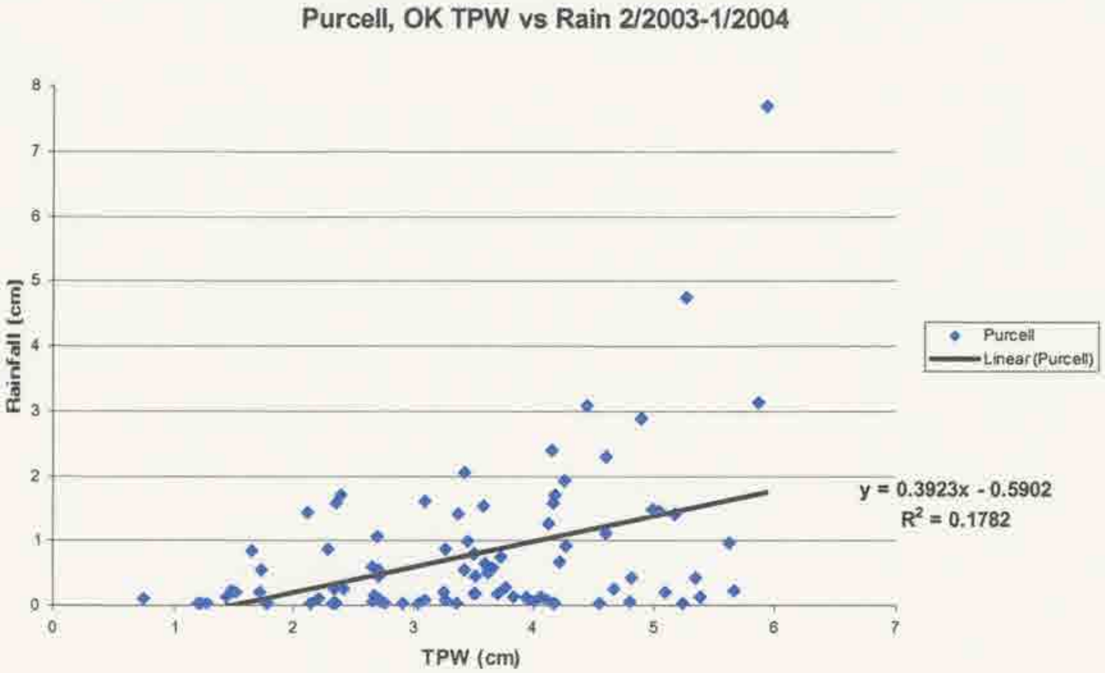


Figure 3.8. Scatter plot of TPW and Rainfall amounts on rainy days in Purcell, OK. Correlation is 0.422. Error bars are as shown in Figure 3.4.

3.2.4 Hillsboro, KS

The city of Hillsboro, KS had the fewest rainy days out of all the cities – 77. However it received 83.8 cm of rainfall during 2003, which is almost exactly its calculated normal amount of rainfall. Since Hillsboro is farther north than any of the other cities, it usually is not affected by the dryline movement across Texas and parts of Oklahoma during the summer months. The state of Kansas experiences spring and summer thunderstorms that originate from the west (over the eastern Rocky Mountains in Colorado) or from the South (from Texas or

Oklahoma, where heating, moisture, and dryline movement are more conducive to storm formation). Often the stream of upper-atmospheric moisture from the eastern Pacific or Gulf of Mexico does not extend as far north as Kansas, and so much of the moisture in Kansas originates from storm systems brought into the area from surrounding regions. In the winter, large frontal systems bring stratiform precipitation to Kansas on a fairly regular basis.

During the period of October 2002 through November 2003, the mean TPW in Hillsboro was 1.75 cm with a standard deviation of 1.08 cm. The month with the highest average TPW was August with 3.72 cm; the lowest average TPW of 0.8 cm occurred in December. The most variable month was October of 2002 with an average TPW of 1.79 cm and a standard deviation of 0.98 cm. The least variable month was January with a TPW of 0.82 cm and a standard deviation of 0.28 cm.

In Figure 3.9 the plot of TPW versus rainfall amounts for rainy days in Hillsboro, KS is shown. This graph covers the period of October 2002 through November of 2003. The correlation is .318 using 77 rainy days; it is statistically significant above the 99% confidence level.

Hillsboro turned out to be a good setting to demonstrate the high variability of the correlations calculated in this thesis. Originally only 27 days were used to create the TPW versus rainfall plot for the months October through March and the correlation was calculated to be .705. When another month of rainfall data was added on and 32 days were used, the correlation dropped to .48. A small addition of five days changed the correlation by 32%. This is an example of the high volatility of the numbers presented in this thesis. Had more years of data been available for analysis, the correlations calculated would be more sustainable – adding or deleting a few days would not change them as drastically as seen above.

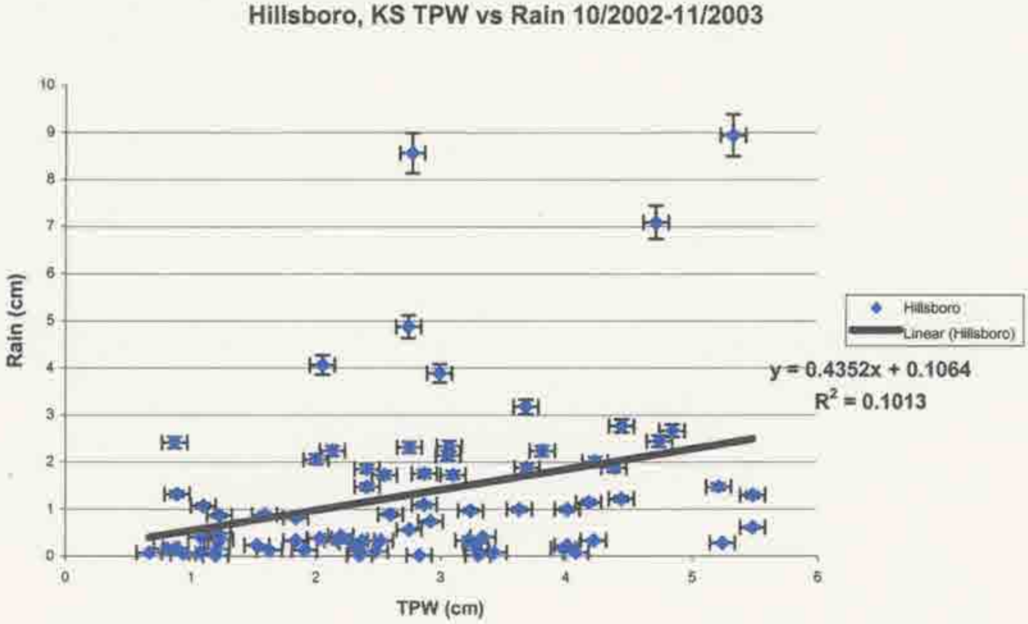


Figure 3.9. Scatter plot of TPW and Rainfall amounts on rainy days in Hillsboro, KS. Correlation is 0.318. Abscissa error bars account for 1mm error in GPS TPW; ordinate error bars account for 5% error in daily rainfall amounts. Ordinate error bars account for over or under measurement in Hillsboro due to human errors in reading the manual rain gauge.

All of the other correlations in Hillsboro were much lower than the .48 calculated for October-March. For the months of April through September, the correlation was .284; for heavy rain events greater than 1.0 and 0.5 cm, the correlations were .19 and .202, respectively. When isolating events with TPW greater than 2.0 cm, the correlation was .183. So it appears that, in Hillsboro, it may be best to forecast rain events during the winter 6-month period, however it should still be done with caution, as adding more months of data is likely to change the correlation even more.

3.2.5 Haskell, OK

Haskell, OK had the most rainy days out of all the cities – 124. However while this city has one of the highest amounts of precipitation in Oklahoma and Texas climatologically, during the time period February 2003 through January 2004, it only received 80% of its normal precipitation. During the aforementioned months, the mean TPW in Haskell was 2.17 cm with a standard deviation of 1.27 cm. The month with the highest average TPW was August with 4.17 cm; the month with the lowest was January with 0.97 cm. The month with the largest standard deviation of 1.11 cm is September, which had a mean TPW of 2.81 cm. The smallest standard deviation of 0.33 cm occurred in January (TPW noted above).

The scatter plot of TPW and rainfall amounts on rainy days in Haskell, OK, along with the other plots for Haskell, are shown in the Appendix. From these plots, the overall correlation between TPW and rainfall amounts on rainy days was calculated to be .285; it is statistically significant above the 99.8% confidence level. When only analyzing the months October through March the correlation was .378; for April through September it was .223. For heavy rain events with rain amounts greater than 1.0 cm and 0.5 cm, the correlations were .133 and .292, respectively. Rain events with TPW greater than 2.0 cm had a correlation of .264. The greatest correlation in Haskell occurs during the 6-month winter period; heavy rain events have the smallest correlation.

average TPW of 4.80 cm and a standard deviation of 0.53 cm. This is drastically different from all of the other cities, which had their smallest variability in January. The TPW over Houston may vary less during the summer months due to the high amounts of TPW present during that time. With a TPW that rarely drops below 4 cm in July or August due to the warm Gulf of Mexico waters close by, there is little room for it to vary leading up to and following rain events.

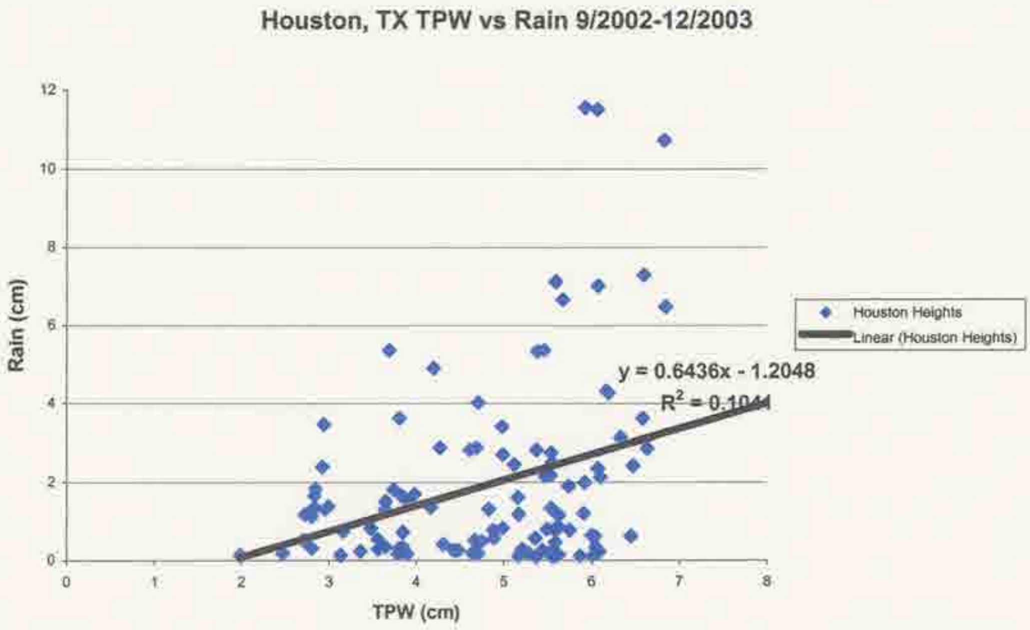


Figure 3.10. Scatter plot of TPW and Rainfall Amounts for Rainy Days in Houston, TX. Correlation is .323. Error bars are as shown in Figure 3.9

Due to the higher TPW throughout the year in Houston, it may be more difficult to discern peaks in water vapor leading up to rain events. Shown in Figure 3.10 is the scatter plot of TPW versus rainfall amounts for rainy days in Houston, TX. The correlation is .323 using 111 rainy days, and it is significant above the 99.9% confidence level. This correlation falls in the middle of the correlations of all of the cities studied.

3.2.6 Houston, TX

Houston, TX is the wettest city in this study. Not only is it the wettest city on average, but it also received above average rainfall during the study period of September 2002 – December 2003. While the other cities in this study are affected by similar weather phenomena such as the dryline and frontal boundaries, Houston has some unique weather features. When considering southeastern Texas, hurricanes, tropical storms, and other disturbances moving north or west from the Gulf of Mexico must also be considered. During the 2002 Hurricane Season, Tropical Storm Fay moved over the Houston area September 6th – 8th, raining almost 7.6 cm. During the 2003 hurricane season, two such disturbances traveled over Houston. The first was Hurricane Claudette, which rained over 5 cm on Houston during July 15th and 16th. The second was Tropical Storm Grace, which dropped another 3.8 cm of rain over the area in late August. These large rain events do not tend to occur further north in the other five cities. This is because the moisture from the Gulf of Mexico gets rained out in southern Texas, where there is not enough moisture to continue to fuel the hurricane over land, causing the hurricane or tropical storm to die out before it gets too far inland.

The average TPW over Houston during the study period was 3.06 cm, with a standard deviation of 1.49 cm. The highest monthly average TPW of 4.86 cm was in August; the lowest of 1.48 cm was in December 2003. The most variable month was September 2003, with an average TPW of 3.73 cm and a standard deviation of 1.31 cm. The least variable month was July, with an

During the months of October through March the correlation between TPW and rainfall amounts was .51; during April through September it was .301. For heavy rain events with rainfall greater than 1.0 cm and 0.5 cm, the correlations were .47 and .38, respectively. For rain events with TPW greater than 2.0 cm, the correlation was .315. All figures are shown in the Appendix. In Houston the correlations are highest for heavy rain events and during the winter months. The lower correlation during the 6-month summer period may come from the abundance of water vapor during the summer months, which causes the peaks in TPW to be less defined leading up to rain events. This phenomenon may be the main factor that lowers the overall correlation in Houston.

3.3 Overview of Cities

3.3.1 Variability of TPW

Upon looking at the variability of TPW for each city above, it can be seen that all the cities have many characteristics in common. Several of the statistics are listed below in table 3.2. The month with the highest average TPW, in every city, is August. The lowest average TPW occurs in the winter months of December and January. This is what was expected, since during the warmer summer months the atmosphere holds more water vapor. TPW is the most variable during the autumn months, and least variable during January in all cities except Houston; possible reasons for this discrepancy were discussed in section 3.2.6. It is interesting to note that the TPW over drier cities such as Amarillo and Vici is not as variable as the TPW over Haskell or Houston. In the dry cities where there is less water vapor available in general, the TPW is not able to vary as greatly as it can in Houston, where large influxes of water vapor from the Gulf occur on a regular basis. Similarly, in January when there is less water vapor in the atmosphere in general, the TPW is less variable for all the cities than during other times of the year. During the autumn months of September, October, and November, the TPW variability is greatest most likely due to the transition from the humid summer months to the drier winter months. The ocean stays warm through the autumn months, creating influxes of water vapor over the cities, where the air has started to become drier. This influx of moist air creates well-defined TPW peaks.

Table 3.2. A summary of the statistics stated in section 3.2.

City	Mean TPW (cm)	Highest TPW (cm) and month	Lowest TPW (cm) and month	Highest SD amount and month	Lowest SD amount and month
Amarillo	1.58	2.96 – August	0.63 – Dec.	0.78 – Oct.	0.21 – Jan.
Vici	1.78	3.54 – August	0.83 – Dec.	0.79 – Oct.	0.23 – Jan.
Purcell	2.13	4.07 – August	0.97 – Jan.	1.0 – Nov.	0.27 – Jan.
Hillsboro	1.75	3.72 – August	0.8 – Dec.	0.98 – Oct.	0.28 – Jan.
Haskell	2.17	4.17 – August	0.97 – Jan.	1.11 – Sept.	0.33 – Jan.
Houston	3.06	4.86 - August	1.48 – Dec.	1.31 – Sept.	0.53 - July

Looking at the mean TPW amounts for each city, it can be noted that the maximum occurs in Houston and the minimum in Amarillo, which agrees well with the precipitation climatology of the area shown in figure 1.1; the areas with more water vapor receive more rainfall. The mean TPW in Hillsboro is slightly lower than that of Vici, however the fact that Hillsboro is farther north than the other cities (and therefore farther away from moisture brought in from the oceans) might be a cause of this. Hillsboro also had the fewest rain events of all the cities, and therefore might have had fewer water vapor peaks to raise its average TPW.

3.3.2 The Relationship Between TPW and Precipitation Amounts

All of the correlations detailed in section 3.2 are summarized below in Table 3.3. A few characteristics of each city can be noted from this table. First, every correlation is positive, which implies that for a given rain event, higher TPW amounts coincide with larger rainfall amounts. This relationship shows promise for forecasting rain events, which we attempt in Chapter 4 of this thesis. The validity of rain forecasts made using TPW amounts is also discussed in Chapter 4.

Another pattern to note is that half of the cities have their highest correlation during the period October through March. This suggests that a rain forecast based on TPW amounts may be more accurate during these months. However by comparing April-September to October-March correlations, it can be seen that two of the cities favor the summer months and the other four favor the winter months. As discussed in section 3.2.1, there are different mechanisms that create rain events in the summer and winter months; however the fact that neither 6-month period consistently shows a higher correlation than the other one implies that all types of rain events (whether the event is caused by convection, stratiform precipitation, hurricanes, etc.) can be forecast equally well.

It was expected that heavy rain events would have a higher correlation than the overall correlation. By removing all of the light rain events that line the bottom edge of the plots, it was thought that the correlation would improve;

however this was only true in half of the cities. These results show that the light rain events, while appearing to occur consistently for all TPW values, are actually more concentrated at low TPW values, which contributes to the positive overall correlation. It is also interesting to note that there is not a noticeable pattern between the correlations for rain events greater than 1.0 cm and rain events greater than 0.5 cm. Half of the cities have a higher correlation for rain events greater than 1.0 cm, and half have a higher correlation for events greater than 0.5 cm. This is most likely due to the rainfall patterns in each city. The cities that did not experience many heavy rain events (greater than 1.0 cm) may have a lower correlation for this category.

In the city of Vici, the correlation for rain events greater than 1.0 cm was relatively small. There are two reasons for this low correlation – 1) During the study period in Vici, there were very few large rain events, and 2) Vici only received 65% of its normal precipitation during 2003. Perhaps in a more normal or even above–average precipitation year this correlation, and perhaps other correlations in Vici, would be higher.

Table 3.3. Summary of correlations between TPW and Rainfall amounts discussed in section 3.2. The highest correlation for each city is highlighted in orange.

City	Overall Correlation	Oct-March correlation	April-Sept correlation	Rain > 1 cm	Rain > 0.5 cm	TPW > 2 cm
Amarillo	.27	.386	.195	.44	.126	.161
Vici	.37	.145	.278	.17	.197	.302
Purcell	.422	.179	.475	.55	.549	.394
Hillsboro	.318	.48	.284	.19	.202	.183
Haskell	.285	.378	.223	.133	.292	.264
Houston	.323	.51	.301	.47	.38	.315

Correlations for rain events with TPW greater than 2.0 cm came out to be fairly close to the April through September correlations. This is most likely due to the higher water vapor amounts during the summer months. In the winter months, TPW does not go above 2 cm as often, and so the majority of the rainy days used to determine this correlation occurred during summer months.

Another interesting feature seen in Table 3.3 is that the cities with the lowest overall correlations are the cities in which the GPS sensor is located the farthest from the rain gauge used in the rainfall measurement (distances were shown in Table 2.1). Purcell and Houston both had GPS sensors collocated with rain gauges, and they have two of the highest correlations in almost every category.

It would be ideal if we could say that the correlations in table 3.3 are definite. In section 3.2.4 it was shown that, by adding or subtracting a mere five points from one of the plots, the correlation changed by 32%. The numbers in Table 3.3 are tentative, at best. Once many more years of TPW and rainfall data have been added to this study, adding or subtracting a few points from a graph will most likely not make a significant difference in the correlation, and the relationship between TPW and rainfall for each city and situation shown above will be known with more confidence.

3.3.3 Error Analysis

There are several sources of error that could affect the results shown in Tables 3.2 and 3.3. The most obvious factor is the uncertainty in GPS TPW and rainfall measurements, portrayed by the error bars in Figures 3.4 and 3.9. TPW measurements are accurate to within 1.0 mm, which is not a significant amount when considering TPW amounts of several centimeters. The error in rain amounts can reach up to 5% during high winds or frozen precipitation events (Nolan Doesken, personal communication). In the cities of Amarillo, Vici, Purcell, and Haskell, an automated tipping bucket gauge is used, which consistently under measures precipitation but rarely over measures it. Houston and Hillsboro use standard manual rain gauges, which are subject to the same errors as the tipping bucket gauges plus additional error due to human errors in reading the gauge. This creates error bars in both directions from these gauges, and only in the plus direction from the other four stations.

In this chapter, all correlations were made using at least 6-month periods. The fact that TPW amounts are different at different times of year was not taken into account when making these plots (for example, the lower overall TPW in January than in August). In some of the scatter plots, there are large rain events that occur at relatively low TPW amounts (around 3 cm), however most of these events occur during the winter months when a TPW amount of 3 cm is considered large and should have a large rain event associated with it. These winter events appear to lower the correlations in this chapter. In Chapter 4, to correct for this and better analyze the TPW-Rainfall relationship, each month will be looked at separately to allow for varying TPW peaks throughout each year.

None of the correlations calculated in this chapter are notably high, or close to 1.0. They average around 0.30. While different research methods (such as using more data points or using linear interpolation between rain gauges) may increase these correlations, they will never approach 1.0. This is mainly due to the fact that there are many other variables that work to create and maintain precipitation other than water vapor. A good discussion of other ingredients that are necessary for precipitation is given by Doswell et al, 1996. The three main ingredients necessary to produce deep convection and buoyancy leading to convective precipitation events, according to Doswell et al, 1996, are sufficient atmospheric moisture, instability (the environmental lapse rate must be conditionally unstable), and a lifting mechanism to transport water vapor into the upper atmosphere so it can condense into rain. While only observing one of these three main ingredients, especially during the summer months when convective precipitation occurs fairly regularly in the southern Great Plains, a high correlation is not expected to be achieved.

4. GPS TPW As a Forecasting Tool

4.1 Contingency Tables

This chapter focuses on forecasting rain events using GPS TPW amounts. Contingency tables were created for individual months in each city; these aid in analyzing peak TPW amounts for rain events along with peak TPW amounts on days without rain. For each 24-hour rainfall observation period, the highest TPW amount was determined. These peak TPW values, along with the rainfall total for each day, were used to create the contingency tables, which show how many days out of each month received rainfall and maximum TPW amounts within the specified ranges. Peak TPW values on rainy days were then used to identify a critical TPW value (also referred to as a cutoff value) above which rain tends to occur for each city and month. Every time TPW increased to this critical value, rain was forecast to occur within 24 hours. Forecasts made in this chapter are relatively simple – rain events are forecast based on a single variable, and actual rainfall amounts are not considered. Precipitation type is also not specified due to the fact that in the SGP region most precipitation falls as rain. The term "rain events" used in this thesis refers to all precipitation types, and all 24-hour precipitation totals used in this research include all forms of precipitation.

By comparing the forecasts in this chapter to rainfall and TPW observations, a false alarm rate can be determined – the false alarm rate is the percentage of rain forecasts that are made that are incorrect (no rain occurs). It can also be seen how often forecasts do not predict rain events that occur. Each contingency table uses 24-hour rainfall totals and the peak TPW amount that occurred during the same period. This creates a forecast time frame of up to 24 hours (meaning that the rainfall occurred within 24 hours of the TPW peak).

It would be fortuitous if a critical TPW value could be defined with a high level of confidence – whenever TPW reaches that certain value or rises over it, rain can be expected within the next 24 hours. If TPW stays below a critical value, rain is not expected. However with only a little over a year's worth of data, this study is unable to declare definite critical values that would give trustworthy rain forecasts. We are only able to propose possible critical values for the few meteorological and climatological situations that were analyzed in the short time period. In the following sections, the tables and forecast accuracy for each city are discussed. Tables were only made for the months which had the most rainy days in each city – each month had at least eight rain events. Only months with more than eight rainy days were used mainly to save time and to limit the number of tables used. With fewer than eight rain events in a month, the tables may not have given a useful or significant result due to the small amount of data. It would be difficult to base a forecast on only a few rain events that may or may not reflect a pattern that would occur if more events were used. For cities in which most months contained over eight rainy days, the months of February and June were chosen to be analyzed so that any seasonal differences in forecast accuracies could be determined.

4.1.1 Amarillo, TX

The contingency table for September 2002 in Amarillo is shown in Table 4.1. Each box in the table contains the number of days on which the rainfall and peak TPW amounts were within the ranges shown. For example, the upper left hand box shows that there was one day in the month of September 2002 when no rainfall occurred (0.0 cm) and during the same 24-hour period the TPW peaked at less than 1.5 cm.

Ideally, to make a good forecast, the days with no rainfall would experience the lowest TPW values. In Table 4.1, however, some dry days occurred at TPW values of up to 3.5 cm, which also correspond to heavier rain events. While there are some outliers in the above chart, there is still a slight tendency for heavier rain events to correspond to higher TPW amounts, as seen in Chapter 3. This pattern can be seen in almost every contingency table in this chapter. To help make sense of Table 4.1 and how it is of use in forecasting, Table 4.2, which shows false alarm rates and forecast accuracy, was made.

Table 4.1. Contingency Table showing the number of days in September 2002 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Amarillo, TX.

9/2002	Peak TPW Amount (cm)						
Daily Rainfall (cm)	0.0 - 1.5	1.51 - 2	2.01 - 2.5	2.51 - 3	3.01 - 3.5	3.51 - 4	Total days
0.0	1	3	10	5	3		22
.01 -.13				2	1	1	4
.14-.26						1	1
.27-.39							0
.40-.64							0
.65-1.02			1				1
1.03-1.28						1	1
2.24					1		1
Total days	1	3	11	7	5	3	30

Table 4.2. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in September 2002 in Amarillo, TX.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
3.5 cm	0%	5 out of 8	2.24 cm
3 cm	37.5%	3	1.02 cm
2.5 cm	53%	1	1.02 cm
2.0 cm	69.2%	0	0.0 cm

Each cutoff value in Table 4.2 signifies a peak TPW value. When TPW values reach this cutoff value or rise above it, a rain event is forecast to occur within the next 24 hours. The false alarm rate is the percentage of days where rain was forecast but it did not rain. To achieve a false alarm rate of 0% (which means it always rains when rain is forecast), not all rain events are predicted. The Largest Rain Amount Missed (column 4 of Table 4.2) is simply the largest 24-hour rainfall that occurred that was not forecast. As the false alarm rate increases, the TPW cutoff decreases, and fewer rain events are missed. Ideally, the last row of each false alarm table will not miss any rain days.

Table 4.2 can be useful to many different people and professions. Not everybody requires a 0% false alarm rate. For example, many military operations rely on accurate and timely forecasts. If there is even the slightest chance of rain, they need to be prepared for it. It is better to call off a mission on a sunny day and be safe than to plan a mission and have it go wrong on an unpredicted rainy day (due to cloud cover or signal attenuation). In this case, having a high false alarm rate could be dealt with as long as all rain events that occurred were forecast. Using the lowest cutoff possible would be the best scenario for these events – it gives a high false alarm rate, but it generally does not miss a single rain event.

Another profession that can benefit from a high false alarm rate is the farming industry. When farmers spray their crops with pesticides, they need to know that it will not rain for the next 24-48 hours so the pesticide will not get washed away before it can take effect. Since spraying crops is a costly and time-consuming process, it is understood that the farmers would rather be safe than sorry and deal with a high false alarm rate as long as it does not rain the day that they spray their crops. By looking at a time series of TPW, farmers could choose days when the TPW is at a minimum value and not likely to rise above even the lowest cutoff value within the next day or so. While this method will have some sort of success rate, it would not be foolproof due to the high variability of TPW from day to day, and the ability for TPW to increase very quickly leading up to a rain event. Using TPW to forecast rain can create a usable 24-hour forecast but is not as reliable for time periods longer than one day. However this does show that TPW could be used to forecast days without rain, as opposed to rain events.

Farmers would also benefit from having a 0% false alarm rate when relying on rain for their crops. If they are given a rain forecast, they expect that rainfall and rely on it for their livelihood. Many fruit and vegetable crops are distributed globally, and if crops die off due to drought it could lead to a worldwide food shortage.

By using tables such as the one shown in 4.2, people can choose what forecast best suits them. Once more years of data have been analyzed and added to these monthly charts, cutoff values will be known with more certainty. On any given day, the chart can be referenced (along with a real-time TPW time series, which is easily accessible on the World Wide Web at http://gpsmet.noaa.gov), and it can be determined what the probability of rainfall is within the next 24 hours. If TPW is less than 2.0 cm (for the month of September in Amarillo), then rain is highly unlikely. If TPW is above 2.0 cm, then there is a 31% chance that it will rain. This information is useful to forecasters. While there are many other factors that contribute to the production of rain, looking at TPW charts and time series provides at least a baseline for rain prediction.

Shown in Table 4.3 is the Contingency table for February 2003 in Amarillo. This month did not have any large rain events, which makes it difficult to draw conclusions from the table. All of the events had similar rainfall amounts but their TPW amounts ranged from 0.51 to 2.5 cm. The false alarm rates are shown in Table 4.4 below. In order to achieve a 0% false alarm rate, only one rain event is predicted.

Table 4.3. Contingency Table showing the number of days in February 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Amarillo, TX.

2/2003	Peak TPW Amount (cm)						
Daily Rainfall (cm)	0.0-0.5	0.51-1.0	1.01-1.25	1.26-1.5	1.51-2.0	2.01-2.5	Total days
0.0	1	9	3	2	1		16
.01 -.13		3	4	1	2	1	11
.14-.26				1			1
.27-.39							0
.40-.64							0
Total days	1	12	7	4	3	1	28

Table 4.4. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in February 2003 in Amarillo, TX.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
2 cm	0%	11 out of 12	.26 cm
1.5 cm	25%	9	.26 cm
1.25 cm	37.5%	7	.13 cm
1.0 cm	40%	3	.13 cm
.5 cm	55.6%	0	0.0 cm

June is a notably wetter month than February, with one day receiving over 5 cm of rain in Amarillo. This month, shown in Tables 4.5 and 4.6, is not able to give a rain forecast with a 0% false alarm rate, and in order to forecast all rain events a cutoff of 2.0 cm is used, which causes rain to be forecast for every day of the month. This suggests that the wetter summer months may not be of much use to forecasters.

As can be seen from the above tables for Amarillo, the highest false alarm rate of 55.6% and the lowest false alarm rate of 25% both occur in February. For forecasts with a 0% false alarm rate, the smallest rain amount missed of 0.26 cm also occurred in February. Other tables for Amarillo are shown in the Appendix.

Table 4.5. Contingency Table showing the number of days in June 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Amarillo, TX.

6/2003	Peak TPW Amount (cm)					
Daily Rainfall (cm)	2.01-2.5	2.51-3.0	3.01-3.5	3.51-4.0	4.01-4.5	Total days
0.0	3	3	3	1	1	11
.01-.13	2	4	4		1	11
.14-.26						0
.27-.39						0
.40-.64						0
.65-1.02				1		1
1.03-1.28						0
1.29-1.91	1		4			5
1.92-2.54			1			1
2.55-3.18						0
3.19-4.45						0
> 5.09				1		1
Total days	6	7	12	3	2	30

Table 4.6. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in June 2003 in Amarillo, TX.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
4.0 cm	50%	18 out of 19	5.09 cm
3.5 cm	40%	16	2.54 cm
3.0 cm	29%	7	1.91 cm
2.5 cm	33.3%	3	1.91 cm
2.0 cm	36.7%	0	0.0 cm

4.1.2 Vici, OK

The Contingency tables in Vici were not extremely useful for forecasting rain events either. In the month of February 2003, shown in Table 4.7, several rain events (including the largest rain event that month) occurred at low TPW amounts. When determining false alarm rates for this month (shown in Table 4.8), even using 1.0 cm TPW as a critical value misses two rain events with a maximum amount of 0.26 cm per event. If a lower cutoff value were chosen, rain would be forecast for every day of the month, which would be inappropriate and unrealistic. The month of June in Vici also had this problem (tables shown in Appendix). This suggests that Vici can get large rain events at relatively small TPW amounts at any time of year – the rain events appear to be less predictable here than in Amarillo. The highest false alarm rate corresponding to a low cutoff TPW in Vici of 57% occurred in September 2003. The lowest false alarm rate was 28.6%, occurring in June 2003.

Table 4.7. Contingency Table showing the number of days in February 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Vici, OK.

2/2003	Peak TPW Amount (cm)						
Daily Rainfall (cm)	0.51-1.0	1.01-1.5	1.51-2.0	2.01-2.5	2.51-3.0	3.01-3.5	Total days
0.0	3	6	4				13
.01-.13	1	5	3	1			10
.14-.26	1	1				1	3
.27-.39		1					1
.40-.64		1					1
Total days	5	14	7	1	0	1	28

Table 4.8. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in February 2003 in Vici, OK.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
2 cm	0%	13 out of 15	.64 cm
1.5 cm	44%	10	.64 cm
1 cm	43%	2	.26 cm

4.1.3 Purcell, OK

Tables 4.9 and 4.10 show the month of June 2003 in Purcell. Forecasts made during this month were able to give a 0% false alarm rate using a high TPW cutoff as well as forecast all rain events that occurred using the lowest TPW cutoff. These two categories are crucial to making a forecast that is useful to the general population. A 0% false alarm rate was also achieved in the month of February (shown in Appendix), but not all rain events were forecast at the lowest cutoff value.

Table 4.9. Contingency Table showing the number of days in June 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Purcell, OK.

6/2003	Peak TPW Amount (cm)								
Daily Rainfall (cm)	2.01-2.5	2.51-3.0	3.01-3.5	3.51-4.0	4.01-4.5	4.51-5.0	5.01-5.5	5.51-6.0	Total days
0.0	1	2	1	5	3	2	1		15
.01-.13			1		2				3
.14-.26				1		1		1	3
.27-.39				1					1
.40-.64									
.65-1.02				1					1
1.03-1.28					1	1			2
1.29-1.91					2	1	1		4
1.92-2.54					1				1
Total days	1	2	2	8	9	5	2	1	30

Table 4.10. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in June 2003 in Purcell, OK.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
5.5 cm	0%	14 out of 15	2.54 cm
5 cm	33%	13	2.54 cm
4.5 cm	37.5%	10	2.54 cm
4 cm	35.3%	4	1.02 cm
3.5 cm	44%	1	0.13 cm
3 cm	44.4%	0	0.0 cm

4.1.4 Hillsboro, KS

Two months contained enough rainy days to be analyzed in Hillsboro – May 2003 and June 2003. Forecasts during these months did not give a 0%

false alarm rate due to one day in each month with high TPW and no rainfall. In May, shown in Tables 4.11 and 4.12, the forecasts all missed at least one rain event. In the month of June, which is shown in the Appendix, false alarm rates reach 75%. This creates the situation of having false alarms far more often than accurate forecasts. Once this occurs, the weather forecast becomes based on chance instead of being based on anything physically or statistically meaningful.

Table 4.11. Contingency Table showing the number of days in May 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Hillsboro, KS.

5/2003	Peak TPW Amount (cm)						
Daily Rainfall (cm)	1.51-2.0	2.01-2.5	2.51-3.0	3.01-3.5	3.51-4.0	4.01-4.5	Total days
0.0	5	4	2	8		2	21
.01-.13	1			1			2
.14-.26							0
.27-.39		1		1			2
.40-.64		1					1
.65-1.02			1	1	1		3
1.03-1.28							0
1.29-1.91							0
1.92-2.54		1					1
2.55-3.18					1		1
Total days	6	7	3	11	2	2	31

Table 4.12. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in May 2003 in Hillsboro, KS.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
3.5 cm	50%	8 out of 10	2.54 cm
3 cm	53.3%	5	2.54 cm
2.5 cm	66.7%	4	2.54 cm
2 cm	64%	1	.13 cm

4.1.5 Haskell, OK

Almost all of the forecasts in the city of Haskell were able to give 0% false alarm rates using a high cutoff value, however most were not able to forecast all rain events using a low TPW cutoff. Shown below in tables 4.13 and 4.14 is the month of February 2003. Along with February, the months of August and

September also were unable to forecast all rain events. Forecasts for all three of these months missed one rain event of .13 cm. From the five months analyzed for Haskell, February gave the lowest false alarm rate of 32%, however this missed one rain event. November gave the lowest false alarm rate of 50% when forecasting all rain events. June was the only month during which forecasts were able to give a 0% false alarm rate using a high cutoff value and to forecast all rain events at a low cutoff value. All tables not shown are in the Appendix.

Looking at the tables for the five months in Haskell, it can be inferred that forecasts vary greatly from month to month. There is no time of year that stands out as having the best forecasts. While June forecasts have a 0% false alarm rate using a cutoff of 5.5 cm, 10 out of 11 rain events are missed. On the other hand, February also gives a 0% false alarm rate at a high cutoff value, and in doing so only misses 12 out of 18 events – while it still misses a significant number of events, this is a much better record than that of June forecasts. September also gives a 0% false alarm rate and only misses 5 out of 12 events, which is the best forecast yet. Which month gives a better forecast also depends on whom the forecast is intended for. As discussed in section 4.1.1, different people and professions prefer different forecast accuracies. While September has the highest forecast accuracy at a 0% false alarm rate, all rain events are not predicted even when using a low cutoff value. And, as also discussed previously, each of these tables reflects only one month of data – many more months will need to be added to these tables before they can give more consistent and reliable cutoff values.

Table 4.13. Contingency Table showing the number of days in February 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Haskell, OK.

2/2003	Peak TPW Amount (cm)							
Daily Rainfall (cm)	0.0-1.0	1.01-1.5	1.51-2.0	2.01-2.5	2.51-3.0	3.01-3.5	3.51-4.0	Total days
0.0	2	6		2				10
.01-.13	1	1	3	1	1			7
.14-.26		1	2					3
.27-.39								0
.40-.64					1			1
.65-1.02			3		1		1	5
1.03-1.28								0
1.29-1.91					1	1		2
Total days	3	8	8	3	4	1	1	28

Table 4.14. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in February 2003 in Haskell, OK.

Cutoff	False Alarm Rate	Rain Days Missed	Largest rain amount missed
2.5 cm	0%	12 out of 18	1.02 cm
2 cm	22%	11	1.02 cm
1.5 cm	11.8%	3	.26 cm
1 cm	32%	1	.13 cm

4.1.6 Houston, TX

In Houston, there were several interesting months. Table 4.15 shows the month of February 2003. One of the largest rain events in this month coincided with the same peak TPW amount as three days without rain. Due to these three days, the false alarm rates for this month are relatively high regardless of which TPW cutoff is used. The errors here suggest that February might not be an ideal month or Houston might not be the ideal city in which to forecast rain events using TPW. Tables 4.17 and 4.18 support the latter part of this argument. These tables are for the month of June 2003; they show that there is a high false alarm rate regardless of the TPW cutoff chosen. Perhaps the high variability of TPW in Houston (discussed in chapter 3) along with the year-round moist atmosphere contribute to the low forecast accuracy. The months of July 2003 and October

2002 were also analyzed and their tables are shown in the Appendix. Forecasts made in October were the most accurate, predicting 10 out of 14 rain events with a 0% false alarm rate and predicting all rain events at the lowest TPW cutoff value with a 39.1% false alarm rate.

Table 4.15. Contingency Table showing the number of days in February 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Houston, TX.

2/2003	Peak TPW Amount (cm)						
Daily Rainfall (cm)	1.01-1.5	1.51-2.0	2.01-2.5	2.51-3.0	3.01-3.5	3.51-4.0	Total days
0.0	4	4	2	2	1	3	16
.01-.13		1					1
.14-.26					1		1
.27-.39						2	2
.40-.64						1	1
.65-1.02					1	1	2
1.03-1.28							
1.29-1.91				2		2	4
3.19-3.82						1	1
Total days	3	6	3	5	2	9	28

Table 4.16. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in February 2003 in Houston, TX.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
3.5 cm	30%	5 out of 12	1.91 cm
3.0 cm	30.8%	3	1.91 cm
2.5 cm	35.3%	1	.13 cm
2.0 cm	42.1%	1	.13 cm
1.5 cm	50%	0	0.0 cm

Table 4.17. Contingency Table showing the number of days in June 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Houston, TX.

6/2003	Peak TPW Amount (cm)									
Daily Rainfall (cm)	2.51 -3.0	3.01 -3.5	3.51 -4.0	4.01 -4.5	4.51 -5.0	5.01 -5.5	5.51 -6.0	6.01 -6.5	6.51 -7.0	Total days
0.0	1		4	2	2	4	3		1	17
.01-.13							1			1
.14-.26						1		1		2
.27-.39								1		1
.4-.64					1		2			3
.65-1.02										
1.03-1.28						1				1
1.29-1.91						1				1
1.92-2.54							1			1
4.0					1					1
5.36						1				1
7.11							1			1
Total days	1		4	2	4	8	8	2	1	30

Table 4.18. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in June 2003 in Houston, TX.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
6.0 cm	33.3%	11 out of 13	7.11 cm
5.5 cm	36.4%	6	5.36 cm
5.0 cm	42.1%	2	4.0 cm
4.5 cm	43.5%	0	0.0 cm

4.2 Summary of Cities

While each city had a different number of months analyzed, the month of June 2003 was common to all of them. This month is summarized in Table 4.19. For each city, this table details whether a 0% false alarm rate (FAR) was achieved, whether all rain events were predicted at a low TPW cutoff (and, if not, what the largest rain event missed was), the highest overall FAR, and the lowest overall FAR.

Table 4.19. Table summarizing forecast accuracies for each city during the month of June 2003.

City	0% FAR?	All rain events predicted?	If not, largest event missed?	Highest FAR	Lowest FAR
Amarillo	no	yes		50%	29%
Vici	no	no	.64 cm	29%	14%
Purcell	yes	yes		44%	0%
Hillsboro	no	no	.13 cm	75%	50%
Haskell	yes	yes		54%	0%
Houston	no	yes		43.5%	33.3%

Table 4.19 shows that two cities were able to have a 0% false alarm rate, while four were not. Four cities had all rain events predicted while two did not. There seems to be no geographical or physical pattern to these forecast accuracies – Amarillo, Hillsboro, and Houston all have high-TPW amounts on days with no rain events (which hinders a 0% FAR); these three cities span the entire region from moist to dry and north to south. TPW in Houston is the most variable out of all of the cities, and in Amarillo it is the least variable. Conclusions

are not easily drawn from this table. This suggests that more years of data may be needed to make the numbers in Table 4.19 believable. Once the numbers are more steady and reliable, it could be said with more certainty that forecasting rain events with GPS TPW in Vici or Houston during the month of June is not very accurate, and that other variables need to be looked at to give a more complete forecast.

Another notable feature of Table 4.19 is that Hillsboro gives a very poor forecast performance. Since the false alarm rates in Hillsboro were the highest of all of the cities in general, perhaps it would not be useful to attempt to predict rain events using GPS TPW in more northern cities or cities that receive snow on a regular basis.

Table 4.20. Table summarizing forecast accuracies for each city during the month of February 2003.

City	0% FAR?	All rain events predicted?	If not, largest event missed?	Highest FAR	Lowest FAR
Amarillo	yes	yes		55.6%	0%
Vici	yes	no	.26 cm	43%	0%
Purcell	yes	no	.13 cm	61%	0%
Haskell	yes	no	.13 cm	32%	0%
Houston	no	yes		50%	30%

The month of February was also common to most of the cities. This month is summarized in Table 4.20 above. It is evident that more cities are able to achieve a 0% false alarm rate during this month, however forecasts in three of the cities were not able to predict all of the rain events. In Vici, two rain events were unpredicted using the lowest cutoff value, both having a maximum value of .26 cm. It looks as though the most accurate forecasts were made in Amarillo in February. This was not the case for the month of June, where Purcell and Haskell had the best forecasts. Since Houston has similar results for both months, it cannot be said that relatively humid cities may give better forecasts during the summer months. Obviously the results shown in tables 4.19 and 4.20 reflect the situation that occurred in each specific month and city, each of which is unique and may not be a "typical" month for any of the cities.

It also does not appear that any one month has higher forecast accuracy than other months in each city. Each city had different forecast results for each month; no pattern is immediately visible. In all of the cities, the false alarm rate never went above 75%; not including Hillsboro the highest was 69% in Amarillo. In most cases, the false alarm rates remained below 60% for all cutoff values. Out of all the months and cities, February 2003 in Houston and September 2003 in Haskell predicted the most rain events at a 0% false alarm rate – 7 out of 12. This shows that a significant amount of rain events are consistently missed in order to achieve a 0% false alarm rate.

One notable conclusion obtained from the contingency and forecast tables shown in this chapter is that GPS TPW might be useful in forecasting days that do not receive any rain. In the months when all rain events can be forecast using the lowest TPW cutoff value, any day where TPW remains below the lowest cutoff value does not receive any rain. This would be very useful to the general public, as well as farmers and the military. People would be able to identify days each month that will not receive any rain. While the forecast accuracies for rain events in this chapter were in many cases too high to make acceptable rain forecasts, they still allow for days without rain to be predicted. Some days that do not receive rain will still be missed using this method, however at least a few dry days will be able to be predicted every month, which to many people is more important than having rain events predicted.

When creating a contingency table for only heavy rain events (greater than 0.4 cm, not shown), the forecast accuracy generally improved. All of the "heavy" rain events were able to be forecast in some months where all rain events could not be forecast. So while the forecast method used throughout this chapter often missed rain events, these rain events were usually small.

One thing that can be inferred with some certainty from the tables in this chapter is the pattern in TPW cutoff values in each city. A yearly time series of TPW for any of the six cities shows a general increase during the spring and summer months, leading to high TPW values during the summer months, and then a decrease during the autumn months leading to lower TPW values during the winter. This pattern is reflected in cutoff values for each month. For example, during the month of August the cutoff values usually reach 5.0 cm or greater (especially in Houston), however in January the cutoff value might be as low as 2.0 cm. It is fairly safe to say that a TPW value of 5 cm will not be seen in the winter months in Amarillo, and it is rarely seen in the summer months.

4.3 Error Analysis

A problem that occurred in Vici in June 2003 is that a day when no rain occurred had the highest TPW value. This issue most likely occurs in other months as well – a peak TPW value is reached one day, in the evening hours, and then it rains early the next morning or during the next day (in a city where the rainfall observation time is midnight). Upon looking at the TPW and rainfall data for that June day in Vici, it was noted that the high TPW value occurred near midnight, with rainfall beginning in the early morning hours of the next day. For this study, the rainfall and TPW on each day were considered to be independent of previous or following days due to the lack of hourly rainfall data to determine which events lasted through observation times. However in reality, a rain event can continue through an observation time or for several days, and a critical TPW amount that is reached right before a rainfall observation is made will still imply rain within the next 24 hours, which includes part of the following day. In the contingency table for June 2003 in Vici, the day with high TPW and no rain should actually be considered as a rainy day, however in this study it is not. This allows for a good amount of error in the forecasts presented in this chapter – the forecasts made using these tables may be more accurate than they seem due to rain events lasting through observation times and TPW values peaking only an hour or two before an observation time (making it seem as though a day with no rain had a high TPW value).

Another error introduced by considering each day independently came from counting a rain event that lasted through an observation time as two separate rain days. This causes two separate TPW peaks to be assigned to these rain events, when in reality there was only one TPW peak leading up to the single rain event. Doing this may lead to lower TPW peak values corresponding to rain events; rain continuing through an observation time is split into two events, and the "second" event is assigned whatever the TPW peak is on the second day, which may be lower than the initial TPW peak that preceded the start of the rain. Had each rain event been considered instead of 24-hour rain totals, the contingency tables shown in this chapter would look more ideal – with the heavy rain events corresponding to higher TPW amounts. In each month considered, there were at least one or two rain events that were assigned TPW values that were too low or a dry day that was assigned a high TPW value.

In this study, the length of rain events is not considered either. Only the daily total rainfall was used – measured every 24 hours. There may or may not be a correlation between TPW and duration of rain events; we do not consider this.

The forecast timing also brings some uncertainty to the results found in this chapter. While each rain forecast uses TPW amounts to determine if it will rain within the next 24 hours or not, rain events generally occur during the peak TPW or within a few hours after it. This was determined from looking at hourly rainfall data in Amarillo and Houston, archived by the NCDC. These data were not fully used in this study due to the fact that hourly rainfall data were only measured at certain stations, most of which are not near GPS sites, however they were still used to back up forecast timing. Since we looked at daily rainfall amounts, the forecasts must allow for the fact that there is a 24-hour range in which the rain and peak TPW can occur; however in the majority of cases this time range is much smaller. It was also noted that, on days when a peak TPW did occur, a full precipitation event rarely occurred before this peak.

From analyzing hourly rainfall data in Amarillo, 30% of rainy days had a peak TPW amount occur before a rain event began, and of these days, only 8% (2 days) had a TPW peak amount occur over 6 hours before the event. Of the 70% of remaining rainy days on which the TPW peak amount was reached after a rain event began, only 18% had the TPW peak occur after the rain event had ended. Therefore, in most cases (87% of all rainy days in Amarillo), TPW reaches a maximum value either before or during a rain event. Only once did a peak TPW amount occur almost 24 hours away from a rain event. Fore cast lead times in Amarillo also tended to be higher during the winter months (December, January, February), which is consistent with the higher correlation during the winter months than the summer months in Amarillo shown in Chapter 3.

Another source of error, though it may be small, is that caused by the grouping of TPW and rainfall amounts into ranges in the contingency tables. Many events that are in the same box are drastically different. This study is likely to benefit from using smaller TPW and rainfall ranges, however there are no two identical events. In order to fully describe each event, there would not be ranges or categories but single numbers, which would make it more difficult to identify cutoff values. Forecasts are kept relatively simple by using cutoff values rounded to the nearest half centimeter. The only way to be sure that each rain event is properly identified, however, is to use smaller ranges or to not group events into ranges at all.

The highly localized and variable nature of rainfall brings in another source of error. During this study, data from two rainfall observation stations in Houston were compared. One was Houston Heights, which is the one described throughout this paper, and the other was the Houston National Weather Service Office (NWSO). The NWSO data were thrown out because the observation station was located over 50 km from the GPS site, however it was still used as a reference on days when Houston Heights did not receive any rain but the TPW was high. On several of these days, there was rain at the NWSO. This situation also occurred at several of the Oklahoma mesonet sites. Some days, generally in the summer, when TPW was high in Purcell, there was no rainfall measured; however from looking at radar maps it was seen that there were spotty showers surrounding Purcell and it was raining as little as 15 km away – which is well within the distance limits of this study defined in Chapter 2. This leads us to conclude that, when TPW is above a cutoff value, it could be raining anywhere within a 22-km radius of the GPS station. However this study did not analyze all rainfall measurements within a 22-km radius of each GPS site, only the closest observation to the GPS site was used. By doing this, the rainfall amounts in the contingency tables for days with high TPW may be too low.

While GPS satellites and ground stations offer a highly accurate real-time TPW product, they are not infallible. GPS TPW amounts are missing for several days each year in each city. While in most cases only one or two measurements are missing per day, at least once a year an entire day would be missing. This is reflected in some of the contingency tables shown in this chapter and the Appendix, where the "Total days" column does not reflect the total number of days in that month. When GPS data were missing for an entire day, it could not be included in a contingency table. If GPS data were missing for a significant portion of a day, the peak TPW value was determined using the available data; however the real peak TPW value may have occurred during the time period that the sensor was not working properly. This source of error may cause the peak TPW values to be biased low in some cases, although these cases were infrequent and occurred only a few times a year in each city.

As has been mentioned several times in this thesis already, more years of data need to be analyzed and added to this analysis before any definite conclusions can be drawn. We can comment on our results and relate them to our study period and region, yet what we have found may not be applicable to future years. Also, TPW is only one variable that contributes to precipitation. Generally, adequate CAPE, weak CIN (Convective Inhibition), and a lifting mechanism are also necessary to produce rainfall. The forecast accuracies calculated in this chapter reflect the use of only one of the three main ingredients crucial to the formation of precipitation. With the addition of other variables such as CAPE and lifting mechanisms, the forecasts would likely be more accurate.

5. Conclusions and Future Work

5.1 Conclusions

Many people and professions rely on accurate and timely rain forecasts. Rainfall affects crop growth and production, military operations, and water supplies, to name a few things. Many variables work to create rain, including atmospheric moisture, daytime heating, wind speed and direction coupled with terrain effects, atmospheric instability, and frontal boundaries (lifting mechanisms). Once forecasters have a better understanding of each variable that affects rain production, rain forecasts will improve in detail and accuracy. Water vapor is one of the most variable atmospheric constituents, and therefore one of the most widely studied. It impacts the earth's climate as well as daily weather such as storm formation and evolution and cloud development. Instruments that measure water vapor and rainfall are constantly being improved in an attempt to better understand the hydrologic cycle and its variability.

In this thesis, the relationship between Total Precipitable Water amounts and daily Rainfall amounts was analyzed. The GPS ground-based network has proven to be an accurate and dependable source of TPW amounts in near real-time. It is also a dense network throughout the southern Great Plains region, and it operates in all atmospheric conditions. Rain gauges, while in a constant state of improvement, are very precise (within 0.025 cm), and rainfall data is quality controlled to allow for any errors introduced by atmospheric variables or the gauge itself (for example evaporation, splash out during heavy rain, or wind speed causing rain to miss the gauge). With these two data sources, water vapor and rainfall were observed with a minimum amount of error in the measurements.

Overall, daily rainfall amounts and daily peak TPW amounts were found to be positively correlated. This means that larger rainfall amounts tended to correspond with larger peak TPW amounts on days that received rain during the study period. To further explore this positive correlation, different situations were analyzed, including six-month seasonal periods, heavy rain days, and rain days with TPW peaks greater than 2.0 cm. A positive correlation was found for each of these subsets in each city as well. There did not appear to be any consistent pattern amongst the different cities; no city had consistently higher correlations than others, and no subset of the data had a higher correlation than others. Four out of six cities showed higher correlations during the months of October through March, but those four cities showed no geographical pattern. Also, having four out of six cities show this trend does not necessarily lead to the definite conclusion that forecasts made during the winter period are more accurate than at other times of year. The forecasts described in Chapter 4 did not show this to be true.

The fact that there is no dependable pattern amongst the cities suggests that the correlations are similar throughout the entire Southern Great Plains area and throughout the entire year. Since this region is often affected by the same storm systems and weather patterns, the water vapor and rain patterns track each other closely from city to city.

Houston is the only city that has a somewhat different weather pattern than the other cities. It is located further south and closer to the ocean. Even with these differences, the correlations for Houston were similar to those of the other cities in all cases. The cities of Houston and Purcell tended to have higher correlations than the other cities in most cases. This is interesting because these are the two cities where the GPS ground station and rain gauge are collocated.

With all of the correlations being similar for every situation considered, it seems that the forecasting of rain would be equally accurate for all forms of precipitation (e.g., convective or stratiform). This was the case, as seen in Chapter 4 where separate months were analyzed to determine forecast accuracy in each city and month. From this analysis it was noted that none of the cities had forecasts that consistently gave both a 0% false alarm rate and were able to predict all rain events year-round. No time of year gave better forecast accuracies than any other time of year. The basic result of this research is that the use of TPW may be able to provide a baseline probability of a rain event at any time of year, but it has not shown much use in predicting rain events without looking at other atmospheric variables. TPW amounts and rain events are somewhat correlated, but they are not so closely linked that rain can be consistently predicted only based on TPW.

Contingency tables and forecasts were made for at least one month in each city. It was determined, using hourly rainfall data from Amarillo, that forecast lead times using TPW range from 0-6 hours, with the majority of the cases being where the TPW peak occurs during a rain event instead of before it. From the rain forecasts in all six cities, 64% of the months analyzed gave a 0% false alarm rate, and for 59% of the months analyzed all rain events were forecast when using a low TPW cutoff value. Depending on his or her needs, an individual can watch a GPS TPW time series be created in near real time on their computer (for their city), and determine when the chance of rain is highest for their particular city. If a person wants a 0% false alarm rate, he or she needs to wait until TPW is at its highest cutoff value. If he or she simply wants to know if there is any chance of rain or not, he or she can look to see if the TPW has surpassed its lowest cutoff value.

The chance of rain can also be calculated based on the current TPW value and the contingency and forecast tables shown in this thesis. If a person glances at the TPW during the month of September in Amarillo and discovers that it is currently at 3.0 cm, he or she can look at the contingency table for September and determine that there is a 28% chance of rain that day. Of course, these statistics are calculated using only one month's worth of data, however many years in the future these numbers may be highly accurate and may act as a dependable source for a rain forecast.

This would aid in simple everyday decisions such as whether or not to wear a raincoat to work; it would also help large businesses and the American economy by allowing farmers, construction workers, and the military to plan their daily operations without worrying about losing money due to unexpected rain.

This is also most useful to forecasters; at the very least it gives them a baseline for rain occurrence. On any given day, a forecaster can reference the contingency table for that month and the current TPW and determine the probability of precipitation. When watching for thunderstorms to develop or a large frontal system to move into the area, a forecaster can use the current TPW to determine if it will rain in the next 24 hours or not, which may aid in determining when the thunderstorms will form or move over the area or when bad weather can be expected. Using the lowest TPW cutoff value for each month to forecast rain, according to our analyses, always gives a false alarm rate of under 73%. In some cases, this may improve forecast accuracy, especially on days when unpredicted rain occurs. At the very least it can be used to give the general public a warning that there is a chance of rain, so that people are prepared for whatever the weather may bring.

In some months, however, one or two rain events occurred at very low TPW values, and were not able to be predicted simply by looking at TPW amounts. There are other factors that work to create rain, and they need to be considered as well in order to get a more complete and detailed forecast.

Another very important prediction that can be obtained using a contingency table is when rain will not occur. When TPW remains below its lowest cutoff value, it can be said that rain is very unlikely to occur. In most months, where all rain events were forecast using a low TPW cutoff value, any day where TPW did not rise above that low cutoff value did not receive rain.

This, to many people, is more useful than knowing when rain events will occur, or what the probability is of a rain event occurring within the next 24 hours.

In summary, more research needs to be done before any definite conclusions can be drawn from these results. The numbers in the tables presented in Chapter 4 and the Appendix reflect only one month of data. Basing a forecast accuracy and reliability on only ten rain events and around 30 days of data does not create a dependable setting for future forecasts. Once several more years of rainfall and GPW-TPW data have been added to this study, the numbers will be able to give a more distinct picture of forecast accuracy.

5.1.1 Regional Climatology

A final question to be answered by this research is, "What do the results outlined in this thesis imply about the climatology of the southern Great Plains region?" We have looked at the climate of the region during the study period, along with patterns in TPW and rainfall. These three variables each contribute to the diversity of this region.

A prominent feature that can be seen across the SGP region is the variability of TPW. It was noted in Chapter 3 that TPW varies the most in moist cities and less in dry cities. TPW is also generally higher in the eastern cities than the western. This shows that, within this region of the United States, water vapor is more prominent in the eastern portions than in the western ones; the eastern portions also receive more influxes of water vapor partly due to the low-level jet at night, partly due to the Pacific Ocean and Gulf of Mexico moisture streams traveling over them, which makes the TPW in those cities more variable.

The cities in the west tend to get dry desert air blown over them; once these winds reach the eastern cities the air is more moist.

Annual plots of both TPW and rainfall in each of the cities shows interesting seasonal patterns throughout the region. Shown in Figure 5.1 is a TPW time series for the year of 2003 in Purcell, OK. It can be seen that TPW is low in the winter months and gradually increases throughout the spring and summer and peaks in August, after which it decreases again. This shows a smooth, gradual seasonal transition. Figure 5.2 shows a plot of annual rainfall in Purcell, OK for the time period February 2003 through January 2004. This plot shows that rainfall amounts are generally higher during the summer months than in the winter months, however from looking at the plot it is obvious that the transition is not very smooth. Many small rain events still occur during the summer months, and large rain events are not limited to the summer months. Plots for the five northernmost cities all looked similar to Figure 5.2, however annual rainfall in Houston followed a slightly different pattern, shown in Figure 5.3. Rainfall in Houston tends to be largest in the autumn months, instead of during the summer months as is seen in the other cities. This is most likely due to the occurrence of hurricanes during the months of August through October in southern Texas. These few large rain events are what cause the trend line to have a positive slope. Additional plots for the remaining cities are shown in the Appendix.

The annual rainfall and TPW plots described above all show the general moistening of the atmosphere during the late summer months in the southern

Great Plains region. The rainfall plots also show that a few large rain events have a significant influence on the overall trend in rainfall patterns, however larger rainfall amounts seem to occur more often in the summer than in the winter months. Another feature that can be seen from analyzing all of the rainfall and TPW plots is that the TPW and rainfall amounts are generally the highest in Houston. The largest rainfall amount in Houston totaled almost 12 cm, whereas the largest rainfall amount in Vici totaled only slightly above 4 cm. It can also be seen that the TPW in Houston peaks at a higher value than the TPW in Amarillo or Vici.

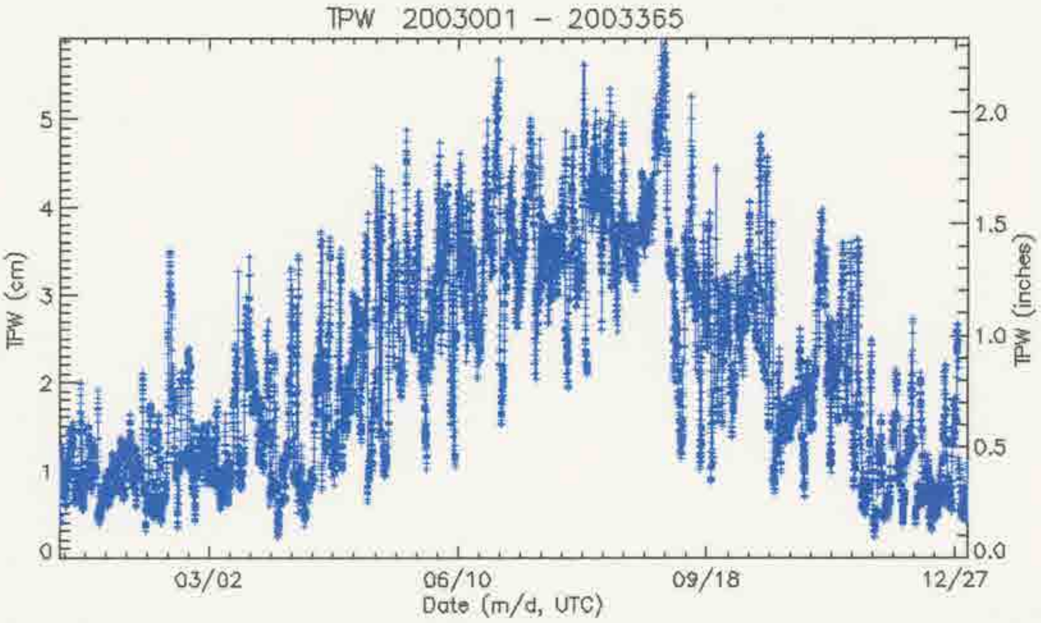


Figure 5.1. Time series of TPW in Purcell, OK for the year 2003. (From NOAA-FSL GPS-Met Observing Systems Branch).

Due to strong daytime heating during the spring and summer months along with moisture from the Pacific Ocean and Gulf of Mexico, this region of the country develops localized convection on a fairly regular basis. Surface winds that carry moisture into the region tend to converge at a dryline or frontal boundary, or in regions of low pressure, which are created by warm rising air. In the area of wind and moisture convergence, moisture is transported up into the atmosphere, forming clouds and possibly leading to rain. In this case, the mechanism that brings the moisture into the area (the winds) also creates the clouds and rainfall through surface convergence.

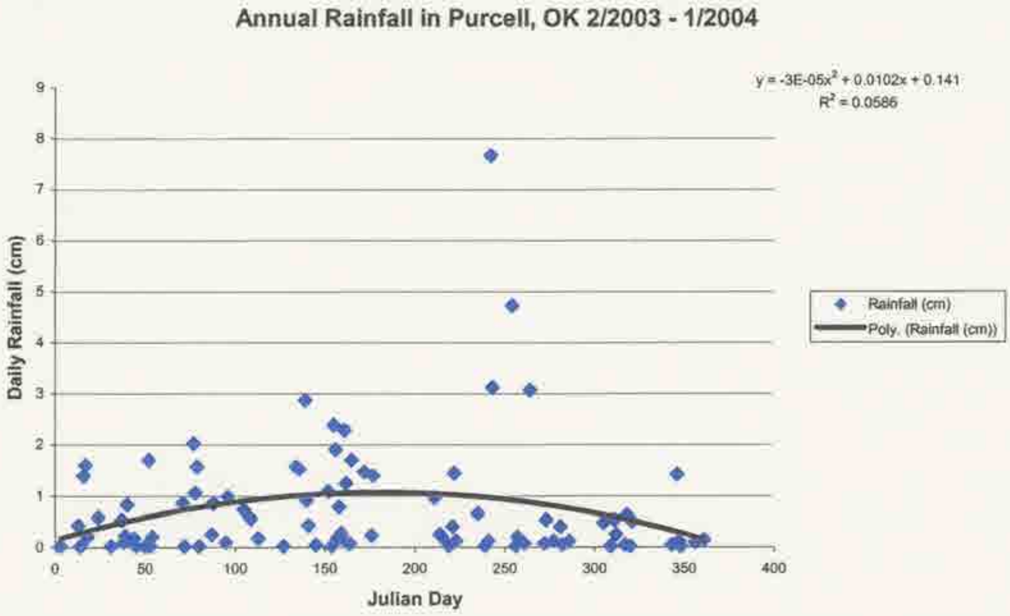


Figure 5.2. Plot of daily rainfall amounts during the time period 2/2003 through 1/2004 in Purcell, OK. Error bars are as shown in Figure 3.4.

Other areas of the country experience different meteorological processes that create rain. Mountainous regions, especially near the slopes and foothills of the Rocky Mountains, experience precipitation events due to uplift. When moist air travels over the mountains, it is forced upward, where it cools and condenses into rain. Even air masses that are not extremely moist lose most of their moisture when traveling over high mountain ranges. In this case, it would be difficult to predict rain events using water vapor in the air; it may be more accurate to use wind direction. Whenever winds travel upslope, a rain forecast could be made. In more moist areas of the country, such as the Pacific Northwest or Southeast, moisture is much more prevalent than in the southern Great Plains region. TPW peaks in these moist areas may not be as well defined as they are in the southern Great Plains due to the consistently higher level of moisture.

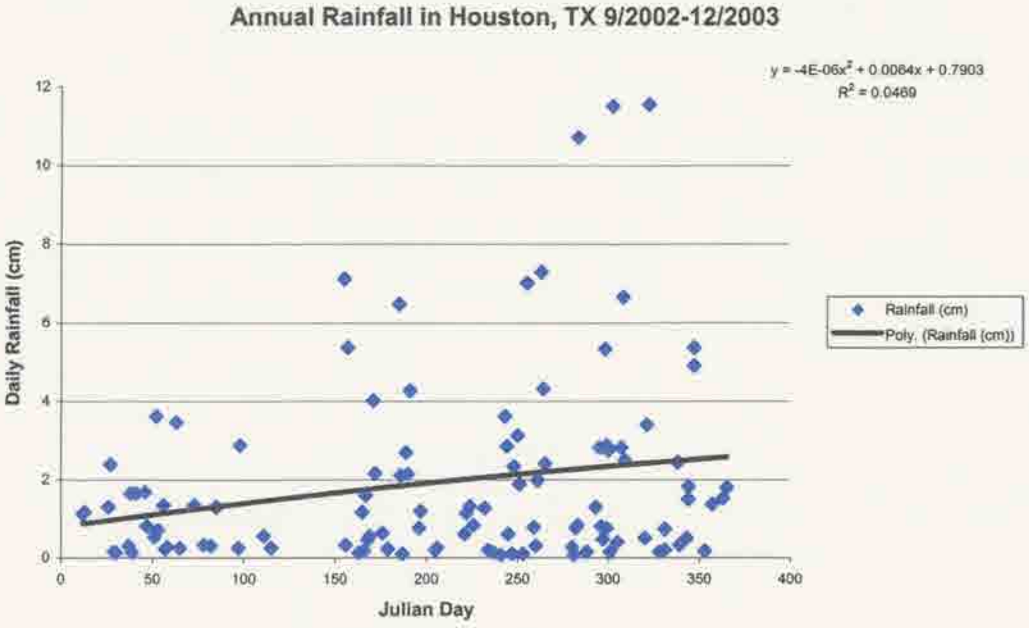


Figure 5.3. Plot of daily rainfall amounts during the time period 9/2002 through 12/2003 in Houston, TX. Error bars are as shown in Figure 3.9.

Northern regions in the country also do not experience as much convective precipitation as the SGP region does. Most rain that occurs in places like Washington and Oregon is stratiform precipitation from the Pacific Ocean that lasts for long periods of time. These locations also have many hills and trees, which the SGP region does not have. These features tend to block winds that carry moist air, making it difficult to predict where rain may occur based on TPW peaks. Trees, along with the moist soil underneath them, can also be a source of moisture during the day due to evapotranspiration; however this moisture does not necessarily rise and form clouds, as it tends to do in the SGP region during the spring and summer months. Since heavy forests block winds, the moisture released from the forests is not able to travel to areas of low pressure and contribute to rainfall.

All of the features discussed above create different forecasting situations. The Southern Great Plains locality is ideal for using TPW amounts to forecast rain events due to its flat terrain and multiple moisture sources. Unique to this area is the stream of upper atmospheric moisture that moves eastward from the Pacific Ocean, supplying moisture for storm and rain formation. This region is also relatively dry due to desert winds blowing from the west, which makes atmospheric water vapor more noticeable when it travels in from the nearby oceans. The lack of dense forests in the area allows moist winds to blow directly to an area of relative low pressure. This process creates moisture buildup in a previously dry region, which produces the water vapor peak on a TPW time series plot (shown in Figure 3.1). This ability to easily define water vapor influxes, along with the occurrences of strong daytime heating and dryline or frontal boundaries, are what makes forecasting with water vapor in the Southern Great Plains region feasible.

5.2 Future Work

The research done in this thesis has paved the road for many future areas of research. Rain forecasts are still considered unreliable and leave much room for improvement. While peak storm total rain can be reasonably estimated, there is still little or no information about the distribution of rain in space or time (USWRP, 2004). The improvement of rain forecasts is one of the main goals of the USWRP. By assimilating GPS TPW data into hydrological forecast models, forecasts for rain events greater than one inch have been shown to improve (Gutman et al, 2003). Three-hour relative humidity forecasts at pressure levels below 500 hPa have also improved (Gutman et al, 2003). The improvement in forecast skill due to the assimilation of GPS-TPW data has increased each year as the number of GPS ground stations has increased, which suggests that as the GPS ground network becomes more dense, forecasts will continue to improve (Gutman et al, 2003). By continuing to assimilate GPS TPW data into forecast models in the future, and by continuing to research the TPW-rainfall relationship and its effect on model forecasts, rain forecast accuracy may increase even more.

TPW could also be used to predict other events, such as Mesoscale Convective Complexes (MCCs) or Mesoscale Convective Systems (MCSs). These large systems require significant amounts of moisture in order to form and stay active, and therefore they may be more dependent on a large influx of water vapor than the rain events outlined in this thesis. While some of the rain events in this thesis were undoubtedly due to MCSs, we did not research each type of rain event and therefore do not know which events these were. These events may have been the events that were predicted the best in this thesis, but that will have to be left up to future research to determine.

GPS ground stations only give TPW directly above the GPS site, and in this research were only used to determine rainfall within 22 km of the site. We do not know what a TPW measurement might imply about rainfall greater than 22 km away from the GPS site. One of the next steps of this research would be to attempt to forecast rain in zones – use a TPW measurement from a single GPS sensor to create a rain forecast for a larger area of up 2.5 degrees latitude by 2.5 degrees longitude, and compare this to reality to determine how well the forecast works. Another thing to do would be to linearly interpolate GPS TPW amounts between GPS ground stations and use these values to forecast rain events for cities without GPS sensors. While this may work, there is room for error in interpolating TPW amounts. This method assumes that TPW changes smoothly and evenly between GPS sites, when in reality there could be an extremely moist or dry area between sites. Other instruments that take measurements between cities, such as the GOES Sounder, would need to be used to confirm that the interpolation had a minimal amount of error.

To be able to fully understand how the meteorological processes that occur in the SGP region work to positively correlate water vapor with rainfall, other areas of the country (and the world) should also be analyzed. The method used in this thesis may be more or less accurate in the SGP region than anywhere else, however this cannot be determined without doing the same TPW-rainfall comparison with GPS stations worldwide. Also, more field experiments, similar to IHOP 2002, could also be done globally. The GPS network density is increasing with time, which will provide increasing amounts of detail to water vapor distributions as time goes on.

In order to make a complete and detailed forecast both spatially and temporally, other variables besides TPW need to be considered. Precipitation also depends on horizontal and vertical wind distributions, daytime heating, atmospheric instability, and lifting mechanisms such as mountains and frontal boundaries (Doswell et al, 1996). Looking for surface wind convergence along with boundary movement might give more detail to the location of rainfall. The correlations shown in Chapter 3 of this thesis might increase substantially when other variables are included with TPW. These additional variables also allow for a forecast to cover a larger area. Using GPS TPW only allows for a forecast in the immediate vicinity of the GPS sensor. Precipitation forecasts, however, are striving to cover both of these situations – to forecast for a specific location as well as an entire region or state.

Several years (or even decades) from now, this same study should be completely redone using more years of data. By doing this, the correlations and cutoff values will be more reliable and not subject to change when a day or two is added to or taken away from the dataset. Also, by adding years to this study, more climatological settings will be included. Dry and wet years can be compared in each city to determine forecast accuracy for each. This study was a good preliminary determination of the TPW-rainfall relationship, however more work needs to be done before it can be used in daily forecasting and expected to perform with a high degree of accuracy.

6. References

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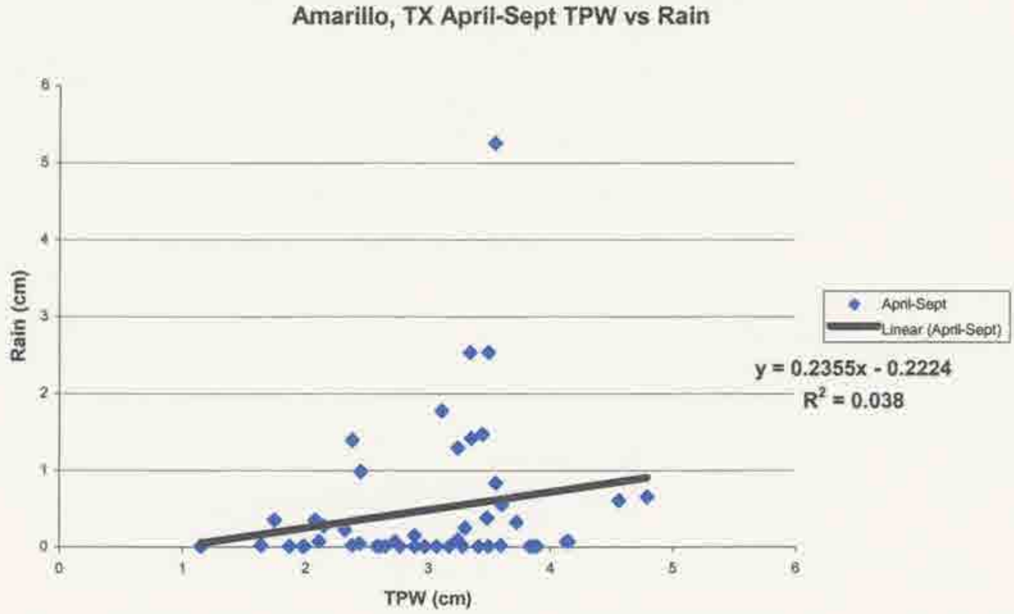
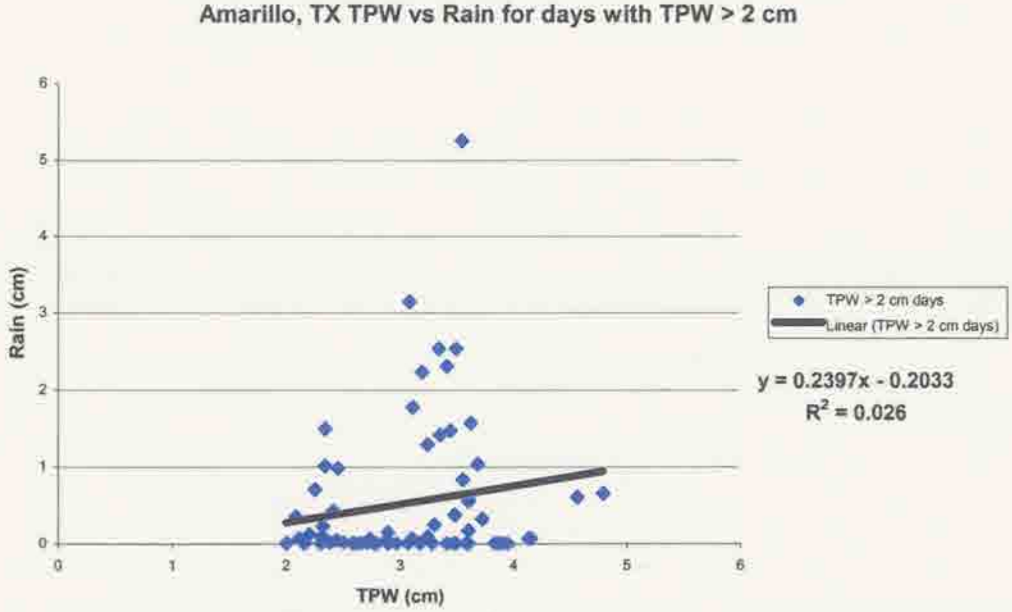
Appendix: Figures and Tables



Amarillo, TX April-Sept TPW vs Rain

Figure A.1. Scatter plot of TPW and Rainfall Amounts during the months of April through September in Amarillo, TX. Correlation is .195. Error bars are as shown in Figure 3.4.



Amarillo, TX TPW vs Rain for days with TPW > 2 cm

Figure A.2. Scatter plot of TPW and Rainfall Amounts on rainy days with TPW greater than 2 cm in Amarillo, TX. Correlation is .161. Error bars are as shown in Figure 3.4.

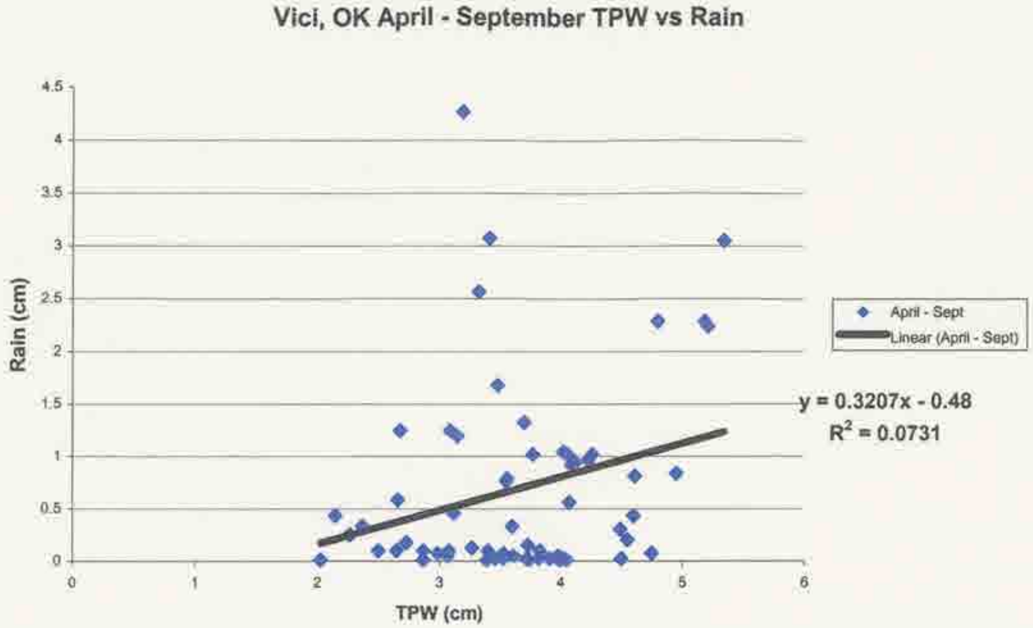


Figure A.3. Scatter plot of TPW and Rainfall Amounts during the months of April through September in Vici, OK. Correlation is .278. Error bars are as shown in Figure 3.4.

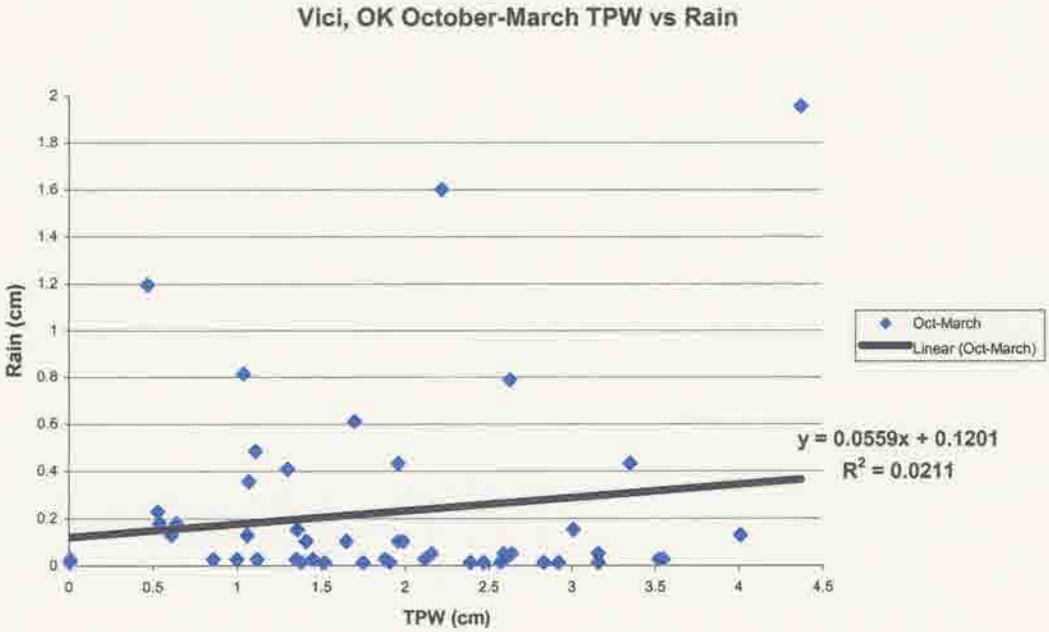


Figure A.4. Scatter plot of TPW and Rainfall Amounts during the months of October through March in Vici, OK. Correlation is .145. Error bars are as shown in Figure 3.4.

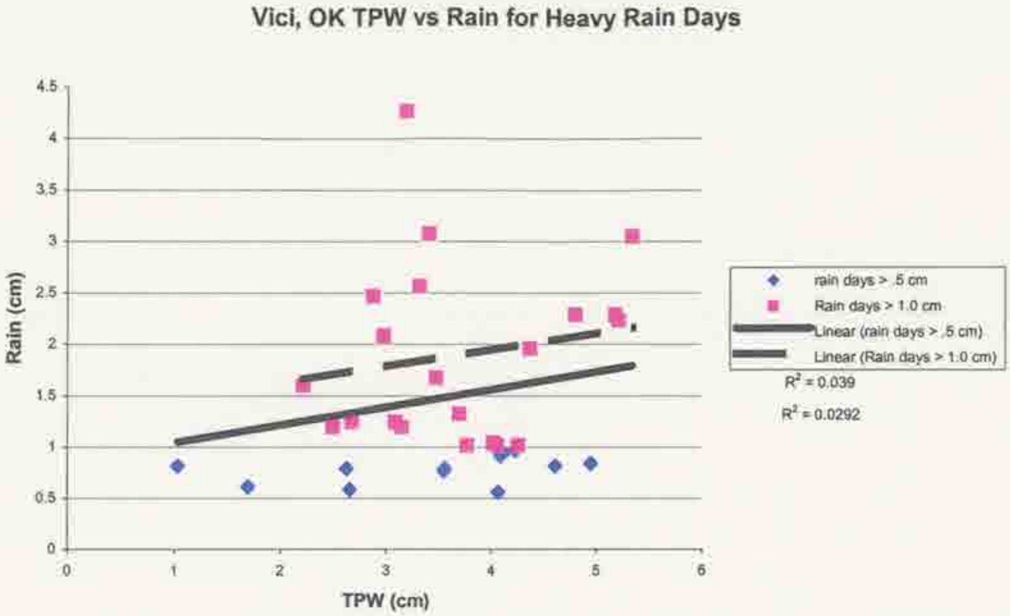


Figure A.5. Scatter plot of TPW and Rainfall Amounts on heavy rain days (rain greater than .5 or 1.0 cm) in Vici, OK. Correlations are .197 and .17, respectively. Error bars are as shown in Figure 3.4.

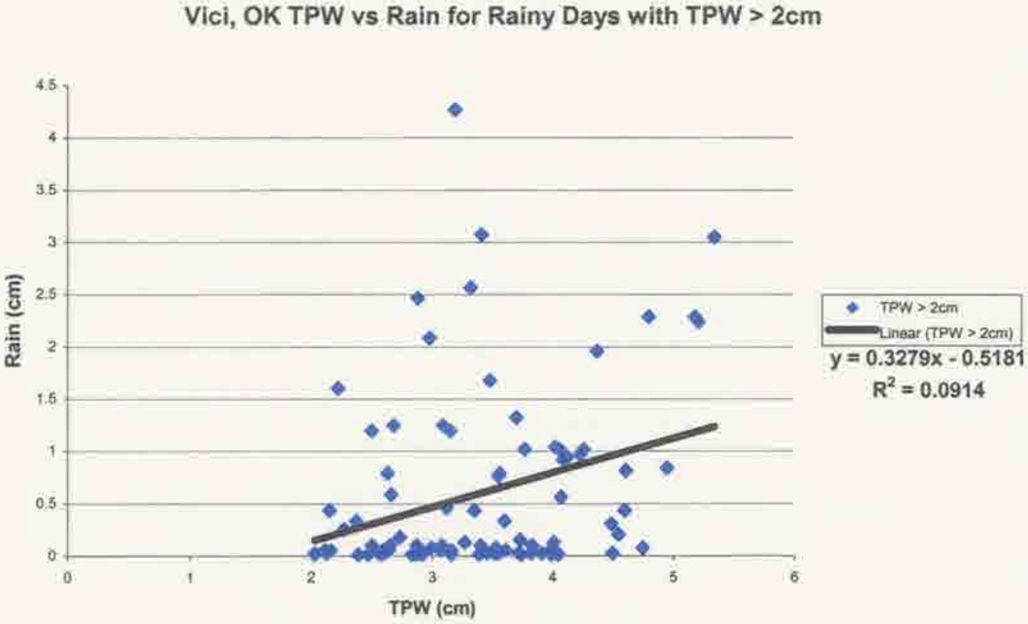


Figure A.6. Scatter plot of TPW and Rainfall Amounts on rainy days with TPW greater than 2 cm in Vici, OK. Correlation is .302. Error bars are as shown in Figure 3.4.

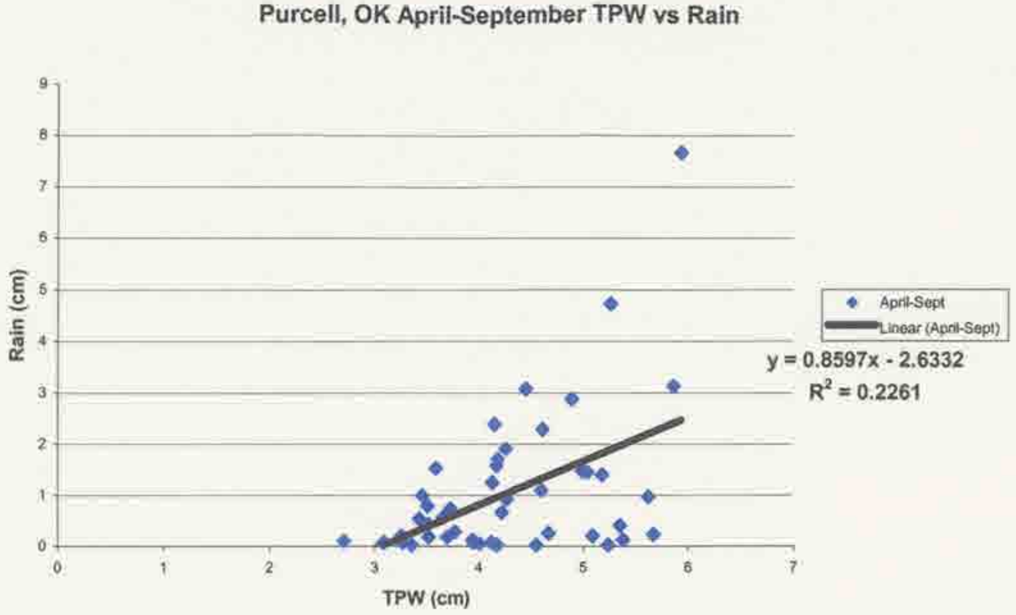


Figure A.7. Scatter plot of TPW and Rainfall Amounts during the months of April through September in Purcell, OK. Correlation is .475. Error bars are as shown in Figure 3.4.

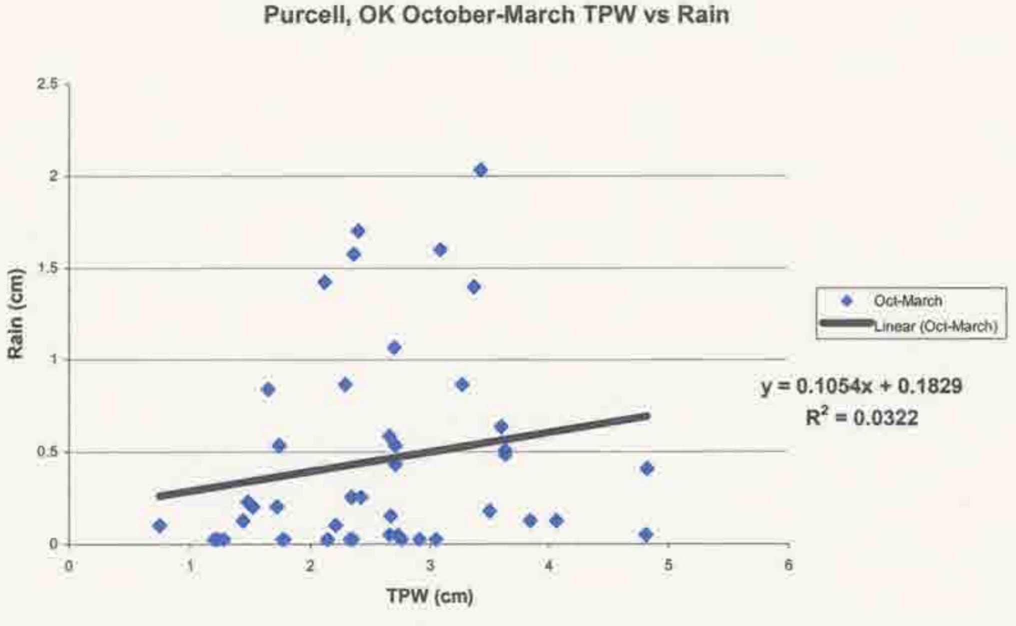


Figure A.8. Scatter plot of TPW and Rainfall Amounts during the months of October through March in Purcell, OK. Correlation is .179. Error bars are as shown in Figure 3.4.

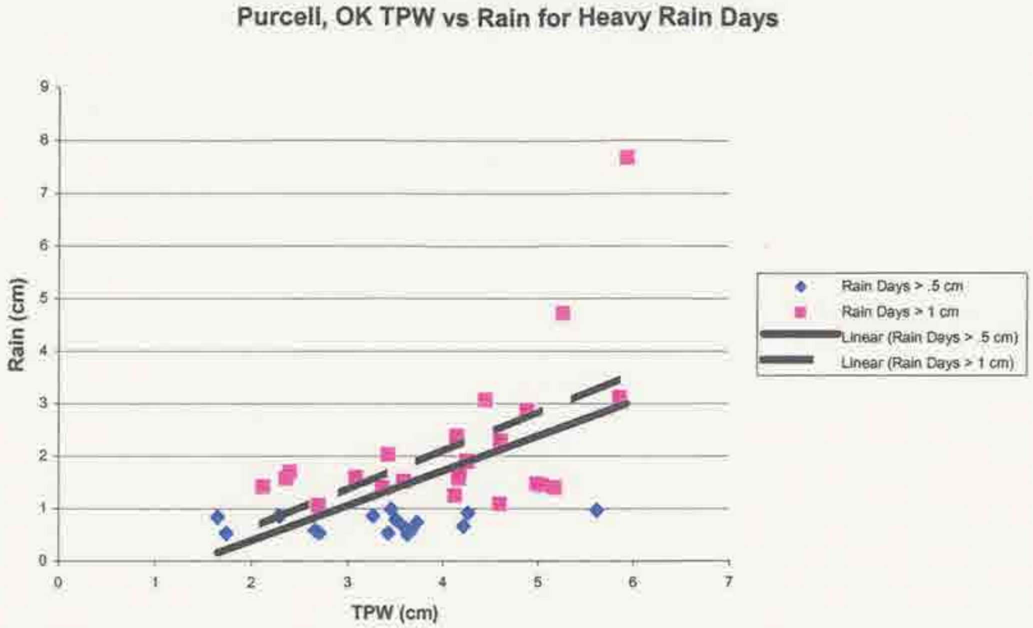


Figure A.9. Scatter plot of TPW and Rainfall Amounts on heavy rain days (rain greater than .5 or 1.0 cm) in Purcell, OK. Correlations are .549 and .55, respectively. Error bars are as shown in Figure 3.4.

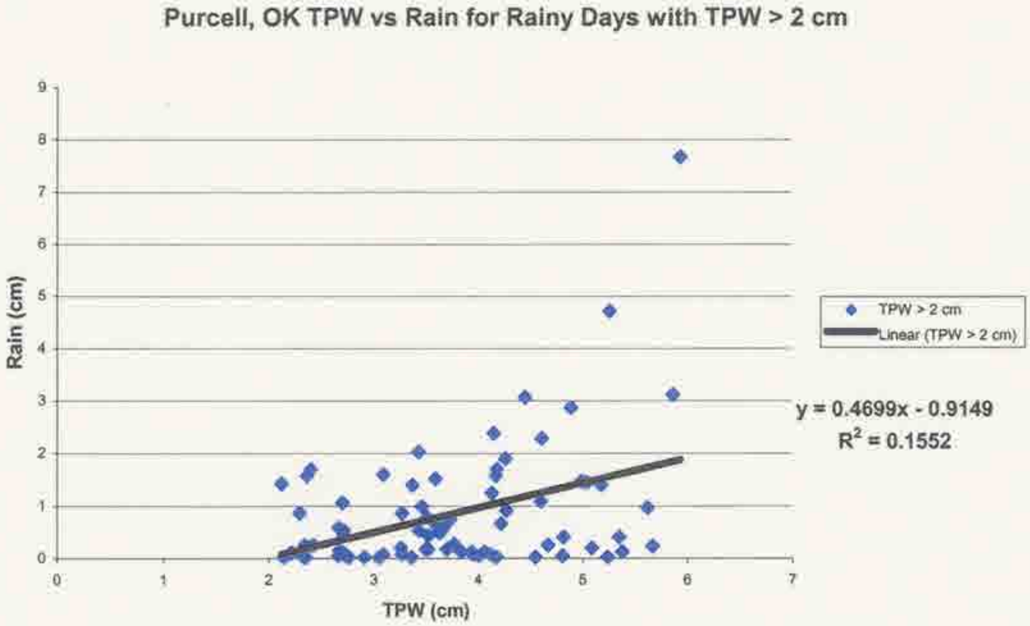


Figure A.10. Scatter plot of TPW and Rainfall Amounts on rainy days with TPW greater than 2 cm in Purcell, OK. Correlation is .394. Error bars are as shown in Figure 3.4.

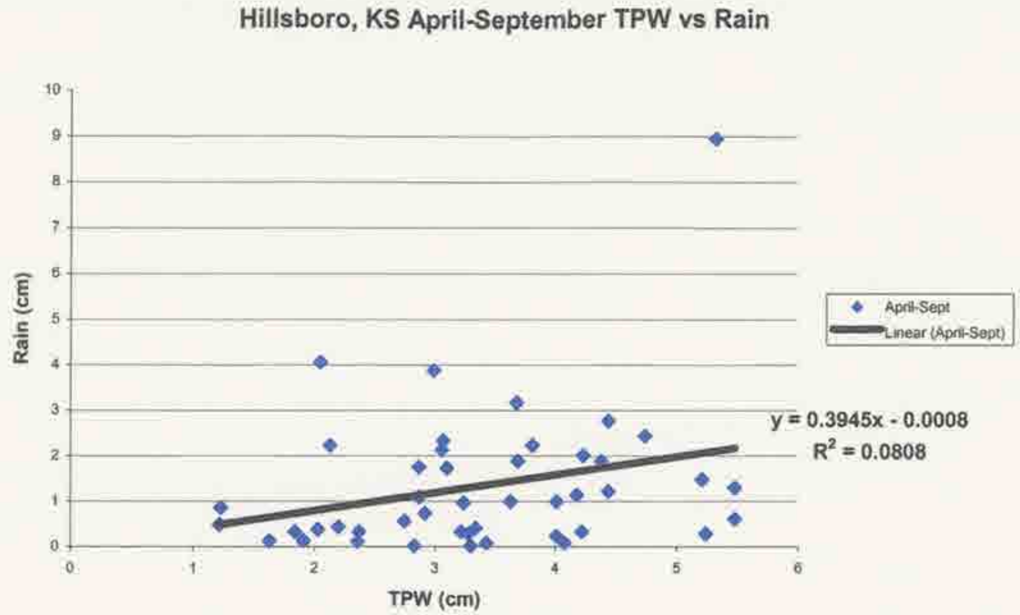


Figure A.11. Scatter plot of TPW and Rainfall Amounts during the months of April through September in Hillsboro, KS. Correlation is .284. Error bars are as shown in Figure 3.9.

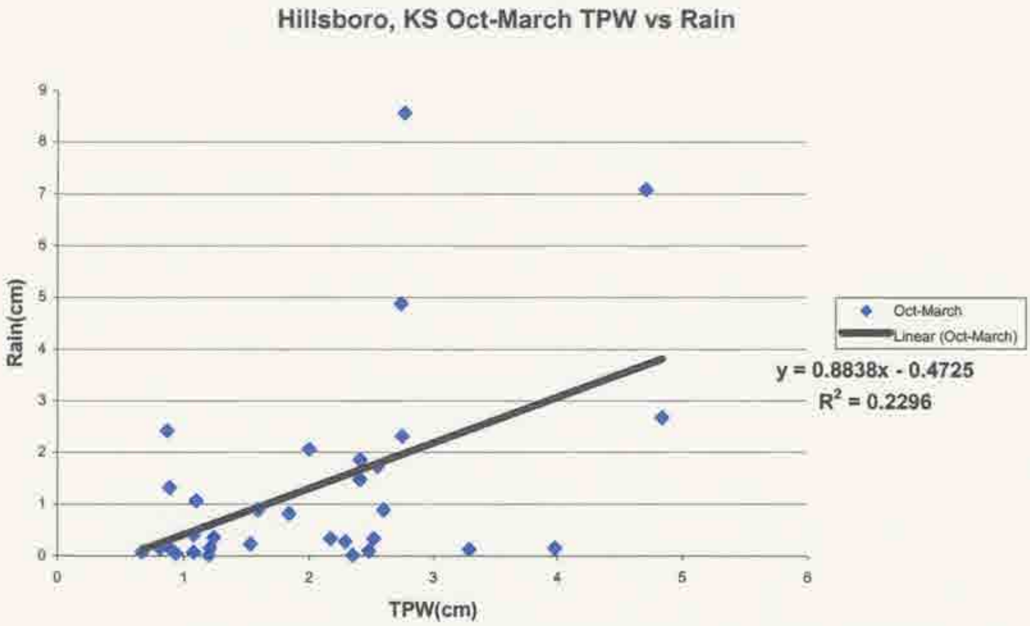


Figure A.12. Scatter plot of TPW and Rainfall Amounts during the months of October through March in Hillsboro, KS. Correlation is .48. Error bars are as shown in Figure 3.9.

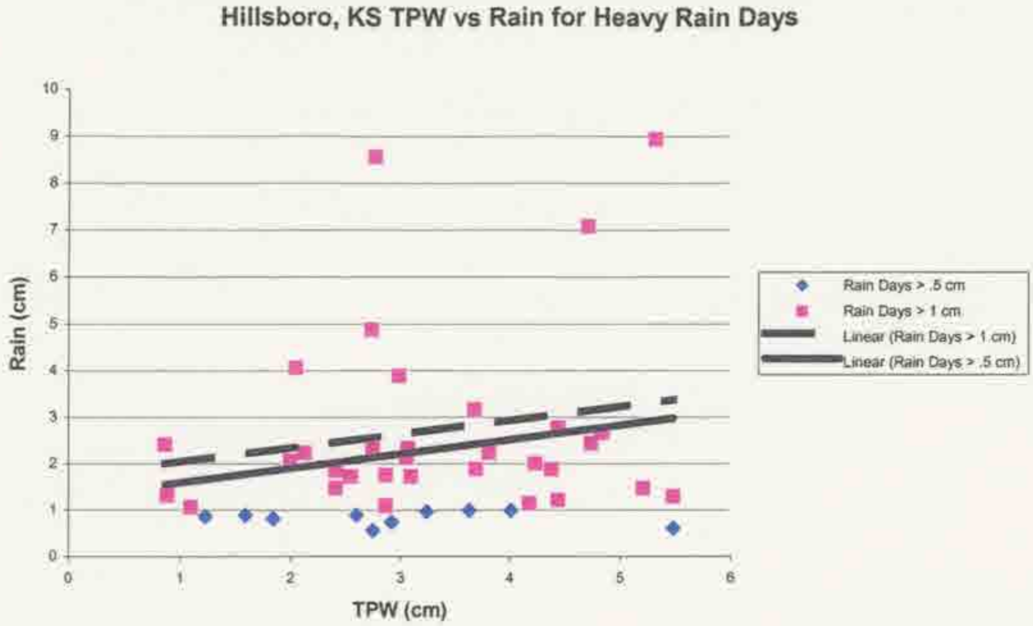


Figure A.13. Scatter plot of TPW and Rainfall Amounts on heavy rain days (rain greater than .5 or 1.0 cm) in Hillsboro, KS. Correlations are .202 and .19, respectively. Error bars are as shown in Figure 3.9.

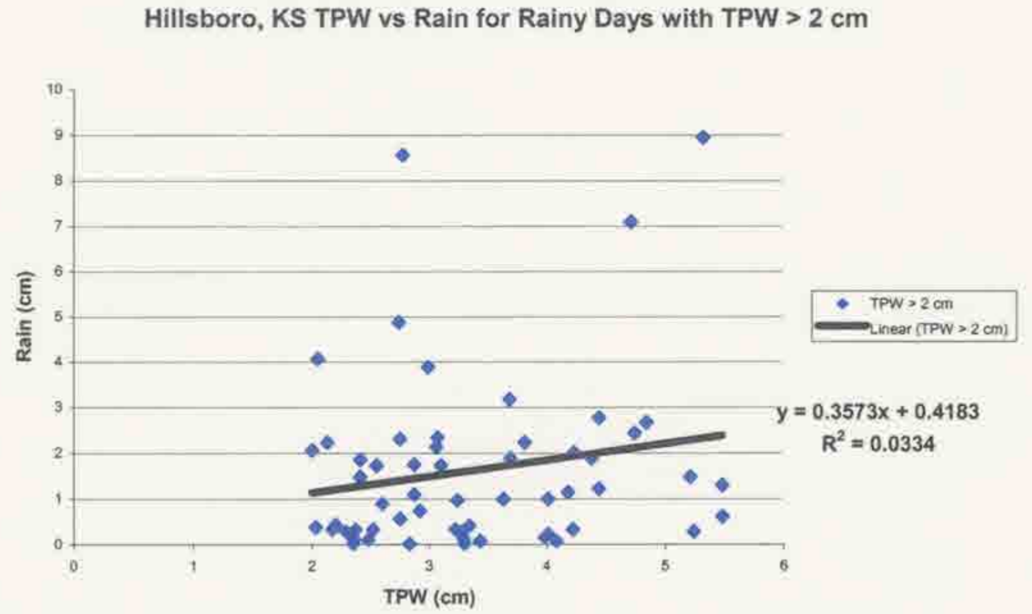


Figure A.14. Scatter plot of TPW and Rainfall Amounts on rainy days with TPW greater than 2 cm in Hillsboro, KS. Correlation is .183. Error bars are as shown in Figure 3.9.

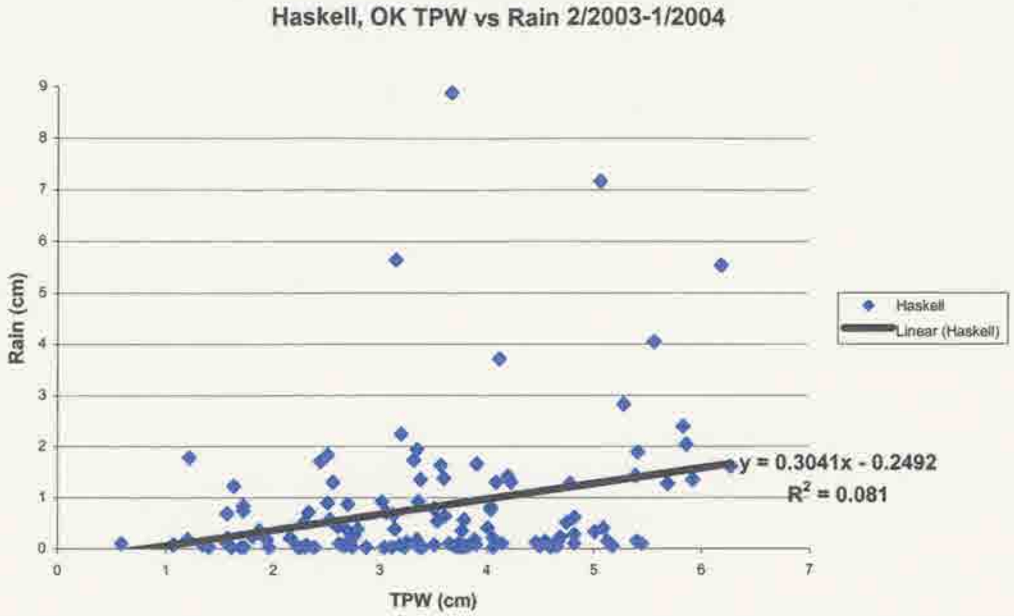


Figure A.15. Scatter plot of TPW and Rainfall amounts on rainy days in Haskell, OK. Correlation is .285. Error bars are as shown in Figure 3.4.

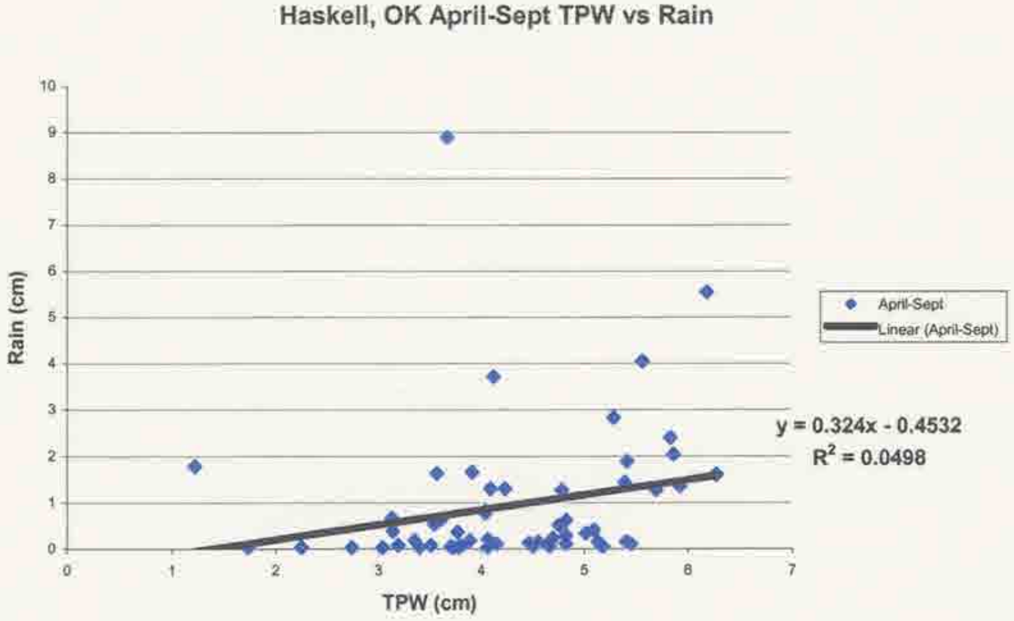


Figure A.16. Scatter plot of TPW and Rainfall Amounts during the months of April through September in Haskell, OK. Correlation is .223. Error bars are as shown in Figure 3.4.

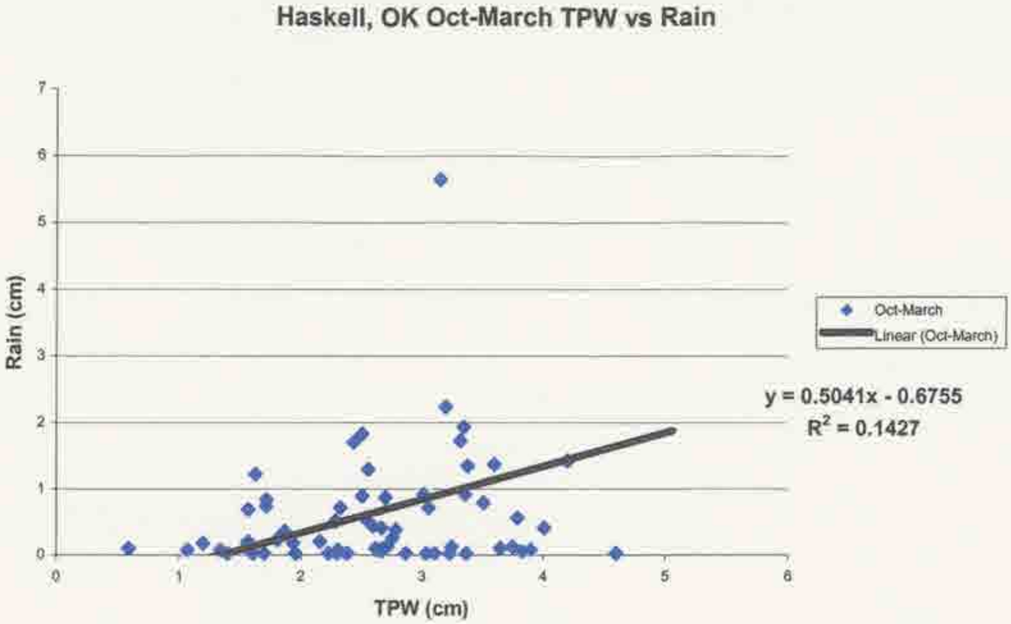


Figure A.17. Scatter plot of TPW and Rainfall Amounts during the months of October through March in Haskell, OK. Correlation is .378. Error bars are as shown in Figure 3.4.

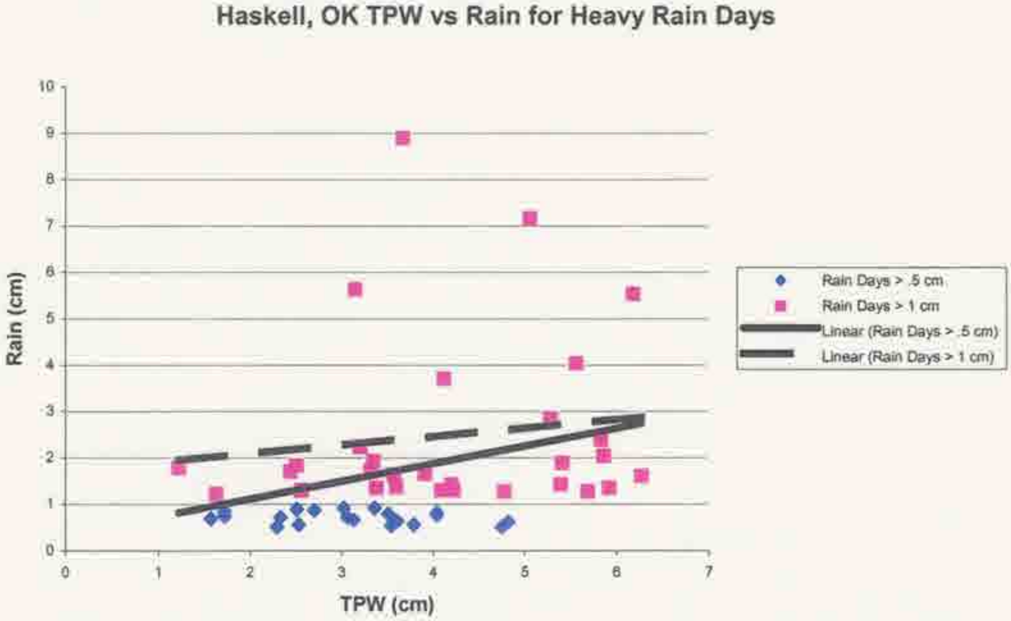


Figure A.18. Scatter plot of TPW and Rainfall Amounts on heavy rain days (rain greater than .5 or 1.0 cm) in Haskell, OK. Correlations are .292 and .133, respectively. Error bars are as shown in Figure 3.4.

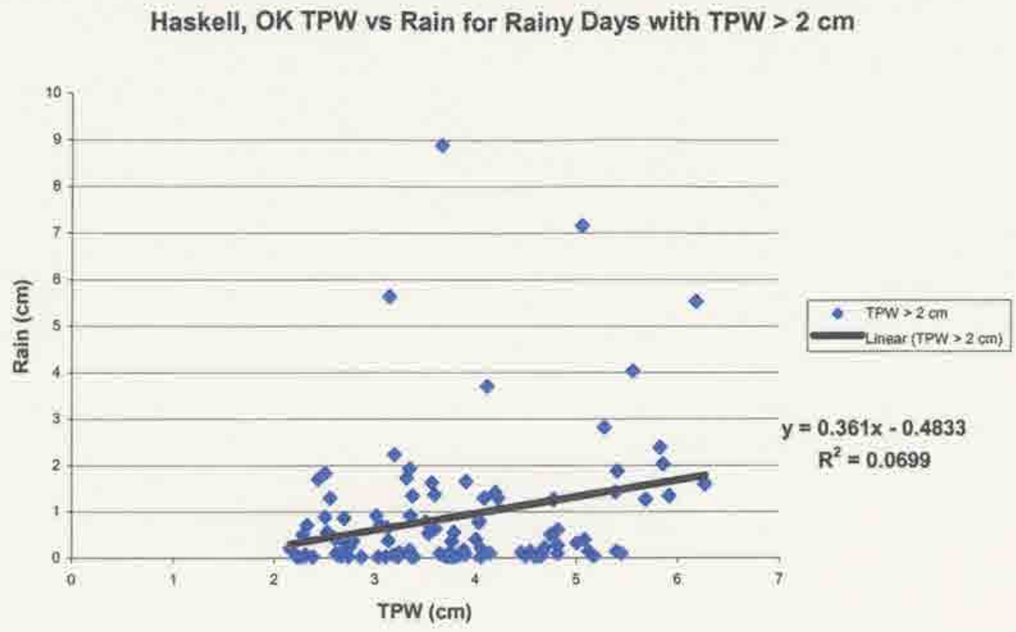


Figure A.19. Scatter plot of TPW and Rainfall Amounts on rainy days with TPW greater than 2 cm in Haskell, OK. Correlation is .264. Error bars are as shown in Figure 3.4.

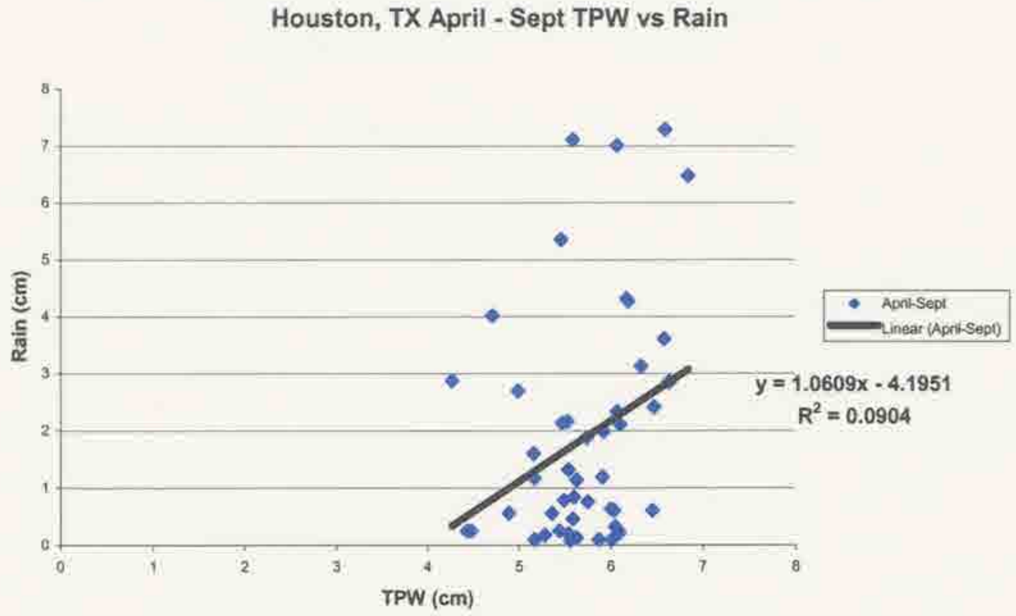


Figure A.20. Scatter plot of TPW and Rainfall Amounts during the months of April through September in Houston, TX. Correlation is .301. Error bars are as shown in Figure 3.9.

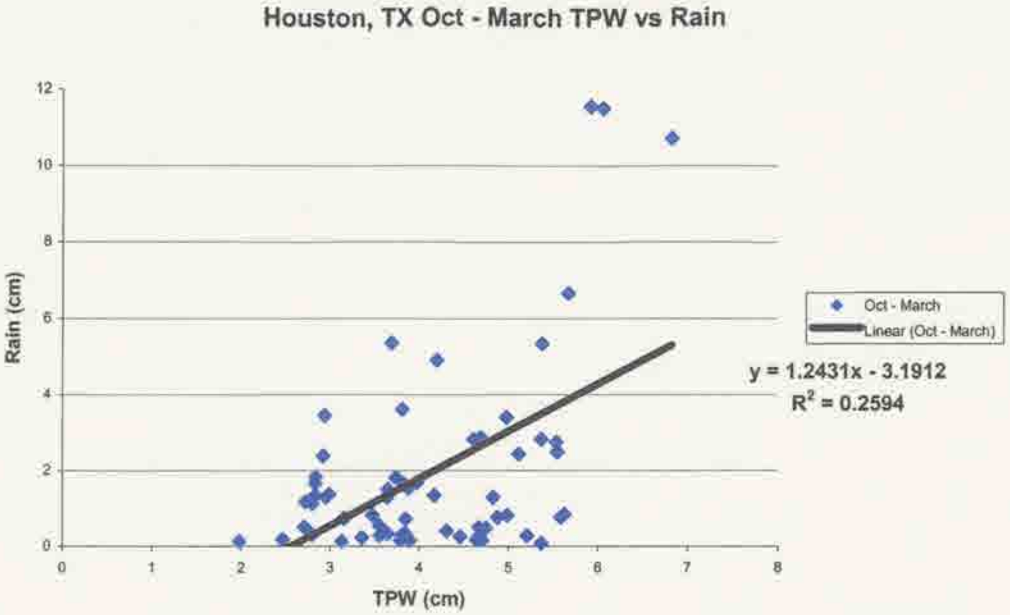


Figure A.21. Scatter plot of TPW and Rainfall Amounts during the months of October through March in Houston, TX. Correlation is .51. Error bars are as shown in Figure 3.9.

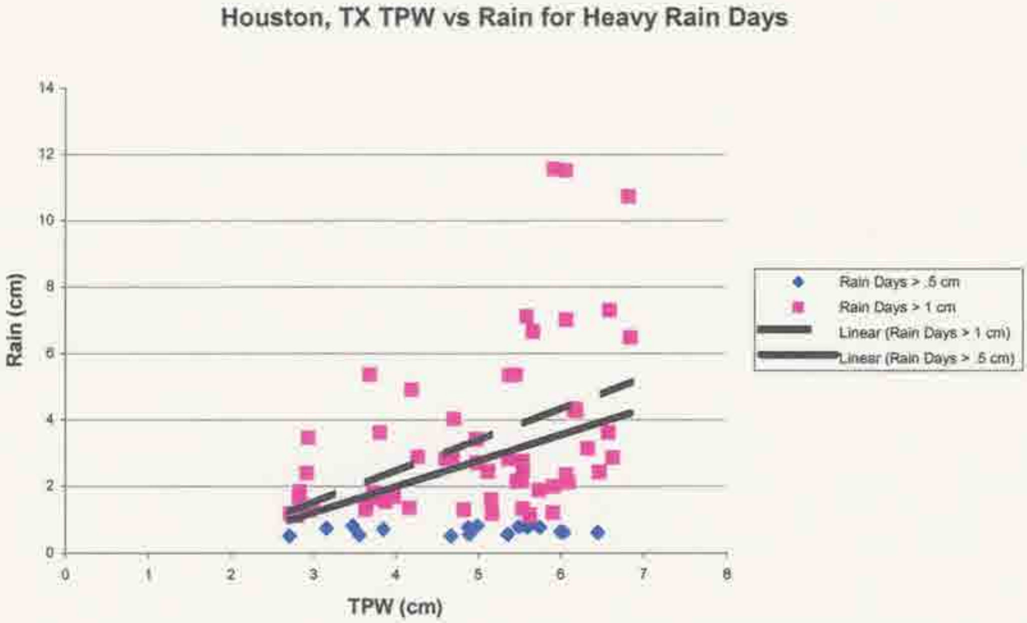


Figure A.22. Scatter plot of TPW and Rainfall Amounts on heavy rain days (rain greater than .5 or 1.0 cm) in Houston, TX. Correlations are .38 and .47, respectively. Error bars are as shown in Figure 3.9.

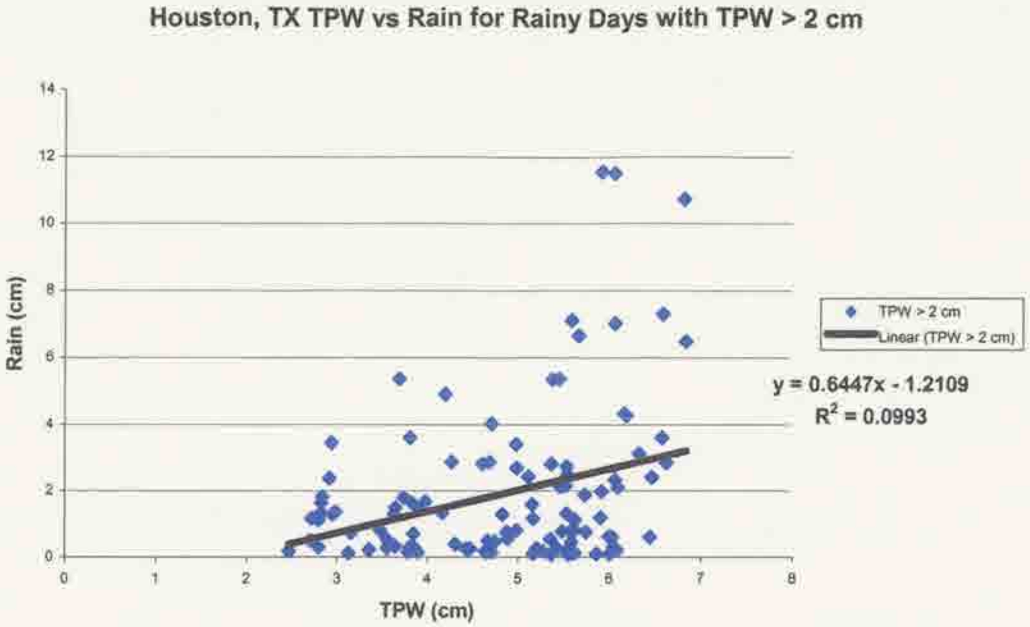


Figure A.23. Scatter plot of TPW and Rainfall Amounts on rainy days with TPW greater than 2 cm in Houston, TX. Correlation is .315. Error bars are as shown in Figure 3.9.

Table A.1. Contingency Table showing the number of days in October 2002 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Amarillo, TX.

10/2002	Peak TPW Amount (cm)							
Daily Rainfall (cm)	0.0-1.0	1.01-1.5	1.51-2.0	2.01-2.5	2.51-3.0	3.01-3.5	3.51-4.0	Total days
0.0	1	6	3	5	1		1	17
.01-.13		2	4	2	1			9
.14-.26								0
.27-.39								0
.40-.64				1				1
.65-1.02			1					1
1.03-1.28								0
1.29-1.91				1			1	2
1.92-2.54								0
2.55-3.18						1		1
Total days	1	8	8	9	2	1	2	31

Table A.2. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in October 2002 in Amarillo, TX.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
3.5 cm	50%	13 out of 14	3.18 cm
3 cm	33.3%	12	1.91 cm
2.5 cm	40%	11	1.91 cm
2 cm	50%	7	1.02 cm
1.5 cm	45.5%	2	.13 cm
1 cm	53.3%	0	0.0 cm

Table A.3. Contingency Table showing the number of days in June 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Vici, OK.

6/2003	Peak TPW Amount (cm)						
Daily Rainfall (cm)	2.01-2.5	2.51-3.0	3.01-3.5	3.51-4.0	4.01-4.5	4.51-5.0	Total days
0.0	1		5	2		1	9
.01-.13		1	2	4	1		8
.14-.26							0
.27-.39				1			1
.40-.64	1						1
.65-1.02				2	4		6
1.03-1.28		1			1		2
1.29-1.91			1	1			2
1.92-2.54							0
2.55-3.18			1				1
Total days	2	2	9	10	6	1	30

Table A.4. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in June 2003 in Vici, OK.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
4cm	14.3%	15 out of 21	3.18 cm
3.5 cm	17.6%	7	3.18 cm
3 cm	31%	3	1.28 cm
2.5 cm	28.6%	1	.64 cm

Table A.5. Contingency Table showing the number of days in September 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Vici, OK.

9/2003	Peak TPW Amount (cm)							
Daily Rainfall (cm)	0.0-2.0	2.01-2.5	2.51-3.0	3.01-3.5	3.51-4.0	4.01-4.5	4.51-5.0	Total days
0.0	2	5	6	4	1			
.01-.13		1	2	2	3			
.14-.26								
.27-.39		1				1		
.40-.64								
.65-1.02							1	
1.03-1.28				1				
1.29-1.91								
Total days								

Table A.6. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in September 2003 in Vici, OK.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
4 cm	0%	10 out of 12	1.28 cm
3.5 cm	16.7%	7	1.28 cm
3 cm	38.5%	4	.39 cm
2.5 cm	52.4%	2	.39 cm
2 cm	57%	0	0.0 cm

Table A.7. Contingency Table showing the number of days in November 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Vici, OK.

11/2003	Peak TPW Amount (cm)							
Daily Rainfall (cm)	0.0-1.0	1.01-1.5	1.51-2.0	2.01-2.5	2.51-3.0	3.01-3.5	3.51-4.0	Total days
0.0	6	9	2			1		18
.01-.13		1	1	3	4	1	1	11
.14-.26								0
.27-.39								0
.40-.64								0
.65-1.02					1			1
Total days	6	10	3	3	5	2	1	30

Table A.8. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in November 2003 in Vici, OK.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
3.5 cm	0%	11 out of 12	1.02 cm
3 cm	33%	10	1.02 cm
2.5 cm	12.5%	5	.13 cm
2 cm	9%	2	.13cm
1.5 cm	14.3%	1	.13 cm
1 cm	50%	0	0.0 cm

Table A.9. Contingency Table showing the number of days in February 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Purcell, OK.

2/2003	Peak TPW Amount (cm)						
Daily Rainfall (cm)	0.5-1.0	1.01-1.5	1.51-2.0	2.01-2.5	2.51-3.0	3.01-3.5	Total Days
0.0	4	8	4	1	1		18
.01-.13	1	1	1			1	4
.14-.26		1	1			1	3
.27-.39							
.40-.64			1				1
.65-1.02			1				1
1.03-1.28							
1.29-1.91				1			1
Total Days	5	10	8	2	1	2	28

Table A.10. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in February 2003 in Purcell, OK.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
3.0 cm	0%	8 out of 10	1.91 cm
2.5 cm	33.3%	8	1.91 cm
2.0 cm	40%	7	1.02 cm
1.5 cm	46.2%	3	.26 cm
1.0 cm	60.9%	1	.13 cm

Table A.11. Contingency Table showing the number of days in June 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Hillsboro, KS.

6/2003	Peak TPW Amount (cm)							
Daily Rainfall (cm)	2.01-2.5 cm	2.51-3.0 cm	3.01-3.5 cm	3.51-4.0 cm	4.01-4.5 cm	4.51-5.0 cm	5.01-5.5 cm	Total Days
0.0	1	3	5	2	8		1	20
.01-.13	1	1						2
.14-.26					1			1
.27-.39								
.40-.64								
.65-1.02								
1.03-1.28								
1.29-1.91				1	1			2
1.92-2.54			2			1		3
Totals	2	4	7	3	10	1	1	28

Table A.12. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in June 2003 in Hillsboro, KS.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
4.5 cm	50%	7 out of 8	2.54 cm
4.0 cm	75%	5	2.54 cm
3.5 cm	73.3%	4	2.54 cm
3.0 cm	72.7%	2	.13 cm

Table A.13. Contingency Table showing the number of days in June 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Haskell, OK.

6/2003	Peak TPW Amount (cm)								
Daily Rainfall (cm)	2.01-2.5	2.51-3.0	3.01-3.5	3.51-4.0	4.01-4.5	4.51-5.0	5.01-5.5	5.51-6.0	Total days
0.0	1	1	3	5	4	3	1		18
.01-.13				1	2		1		4
.14-.26				1		1			2
.27-.39						1			1
.40-.64						1			1
.65-1.02									0
1.03-1.28						1			1
1.29-1.91					1				1
1.92-2.54									0
3.83-4.45								1	1
Total days	1	1	3	7	7	7	2	1	29

Table A.14. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in June 2003 in Haskell, OK.

Cutoff	False Alarm Rate	Rain Days Missed	Largest Rain Amount Missed
5.5cm	0%	10 out of 11	1.91 cm
5 cm	33%	9	1.91 cm
4.5 cm	40%	5	1.91 cm
4 cm	47%	2	.26 cm
3.5 cm	54%	0	0.0 cm

Table A.15. Contingency Table showing the number of days in August 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Haskell, OK.

8/2003	Peak TPW Amount (cm)							
Daily Rainfall (cm)	3.01-3.5	3.51-4.0	4.01-4.5	4.51-5.0	5.01-5.5	5.51-6.0	6.01-6.5	Total days
0.0		2	9	5	3			19
.01-.13		1		1	2			4
.14-.26			1	1				2
.27-.39					1			1
.40-.64								
.65-1.02								
1.03-1.28						1		1
1.29-1.91							1	1
1.92-2.54						2		2
2.55-3.18								
3.19-3.82								
3.83-4.45								
4.46-5.09								
5.10-6.35							1	1
Total days		3	10	7	6	3	2	31

Table A.16. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in August 2003 in Haskell, OK.

Cutoff	False Alarm Rate	Rain Days Missed	Largest Rain Amount Missed
5.5 cm	0%	7 out of 11	.39 cm
5cm	27%	4	.26 cm
4.5cm	44%	2	.26 cm
4 cm	61%	1	.13 cm

Table A.17. Contingency Table showing the number of days in September 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Haskell, OK.

9/2003	Peak TPW Amount (cm)									
Daily Rainfall (cm)	1.51-2.0	2.01-2.5	2.51-3.0	3.01-3.5	3.51-4.0	4.01-4.5	4.51-5.0	5.01-5.5	5.51-6.0	Total days
0.0	1	3	1	6	7					18
.01-.13	1			2	1	2				6
.14-.26								1		1
.27-.39										
.40-.64					1					1
.65-1.02										
1.03-1.28										
1.29-1.91								2	1	3
1.92-2.54										
2.55-3.18										
3.19-3.82						1				1
Total days	2	3	1	8	9	3		3	1	30

Table A.18. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in September 2003 in Haskell, OK.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
4cm	0%	5 out of 11	.64 cm
3.5 cm	44%	3	.13 cm
3 cm	54%	1	.13 cm

Table A.19. Contingency Table showing the number of days in November 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Haskell, OK.

11/2003	Peak TPW Amount (cm)								
Daily Rainfall (cm)	0.0-1.0	1.01-1.5	1.51-2.0	2.01-2.5	2.51-3.0	3.01-3.5	3.51-4.0	4.01-4.5	Total days
0.0	4	4	2	1	2	1	2	1	17
.01-.13		1		2	1	2	1		7
.14-.26					1				1
.27-.39									
.40-.64								1	1
.65-1.02						2			2
1.03-1.28									
1.29-1.91							1	1	2
1.92-2.54									
2.55-3.18									
Total days	4	5	2	3	4	5	4	3	30

Table A.20. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in November 2003 in Haskell, OK.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
4cm	33%	11 out of 13	1.91 cm
3.5 cm	43%	9	1.02 cm
3 cm	33%	5	.26 cm
2.5 cm	37.5%	3	.13 cm
2 cm	37%	1	.13 cm
1.5 cm	43%	1	.13 cm
1.0 cm	50%	0	0.0 cm

Table A.21. Contingency Table showing the number of days in October 2002 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Houston, TX.

10/2002	Peak TPW Amount (cm)										
Daily Rainfall (cm)	1.51 -2.0	2.01 -2.5	2.51 -3.0	3.01 -3.5	3.51 -4.0	4.01 -4.5	4.51 -5.0	5.01 -5.5	5.51 -6.0	6.01 -6.5	Total days
0.0	2	3	2	1	2	3	3	1			17
.01-.13								1			1
.14-.26					1		1				2
.27-.39								1			1
.40-.64							1				1
.65-1.02							2		2		4
1.03-1.28											0
1.29-1.91							1				1
1.92-2.54											0
2.55-3.18							1		1		2
5.10-5.72								1			1
11.51										1	1
Total days	2	3	2	1	3	3	9	4	3	1	31

Table A.22. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in October 2002 in Houston, TX.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
5.5 cm	0%	10 out of 14	5.72 cm
5 cm	12.5%	7	3.18 cm
4.5 cm	23.5%	1	.26 cm
4 cm	35%	1	.26 cm
3.5 cm	39.1%	0	0.0 cm

Table A.23. Contingency Table showing the number of days in July 2003 when the listed Peak TPW Amounts and the corresponding Rainfall Amounts occurred in Houston, TX.

7/2003	Peak TPW Amount (cm)					
Daily Rainfall (cm)	4.51-5.0	5.01-5.5	5.51-6.0	6.01-6.5	6.51-7.0	Total days
0.0	7	7	6			20
.01-.13				1		1
.14-.26		1	1			2
.27-.39						0
.40-.64						0
.65-1.02			1			1
1.03-1.28			1			1
1.29-1.91						0
1.92-2.54		1		1		2
2.55-3.18	1					1
4.3				1		1
6.48					1	1
Total days	8	9	9	3	1	30

Table A.24. False Alarm Rates and Missed Rain Amounts for rainfall forecasts in July 2003 in Houston, TX.

Cutoff	False Alarm Rate	# Rain Days Missed	Largest Rain Amount Missed
6.0 cm	0%	6 out of 10	3.18 cm
5.5 cm	46.2%	3	3.18 cm
5.0 cm	59.1%	1	3.18 cm

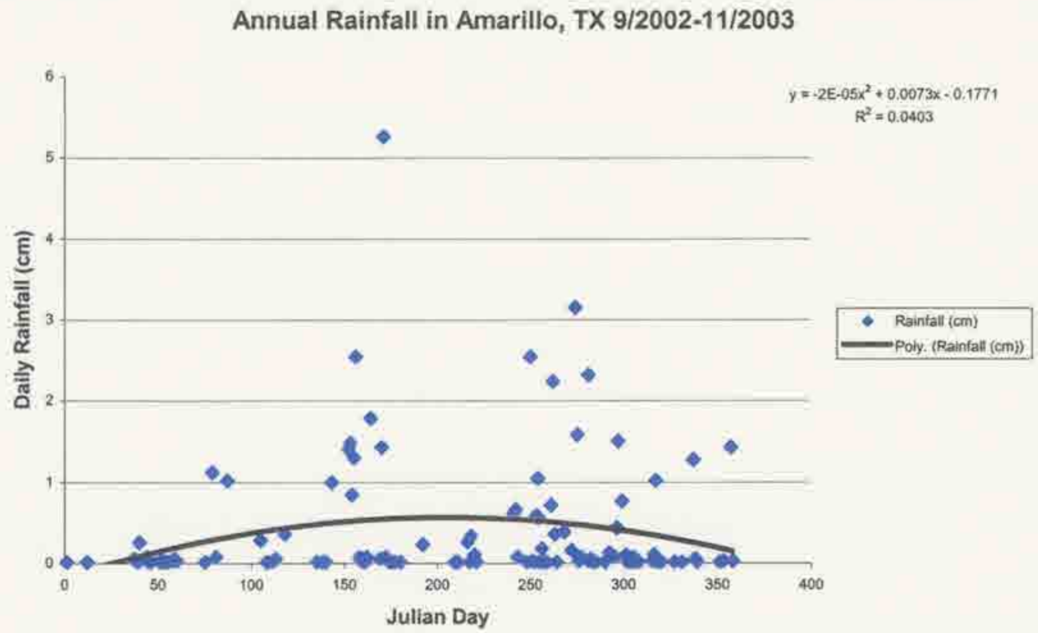


Figure A.24. Plot of daily rainfall amounts during the time period 9/2002 through 11/2003 in Amarillo, TX. Error bars are as described in Figure 3.4.

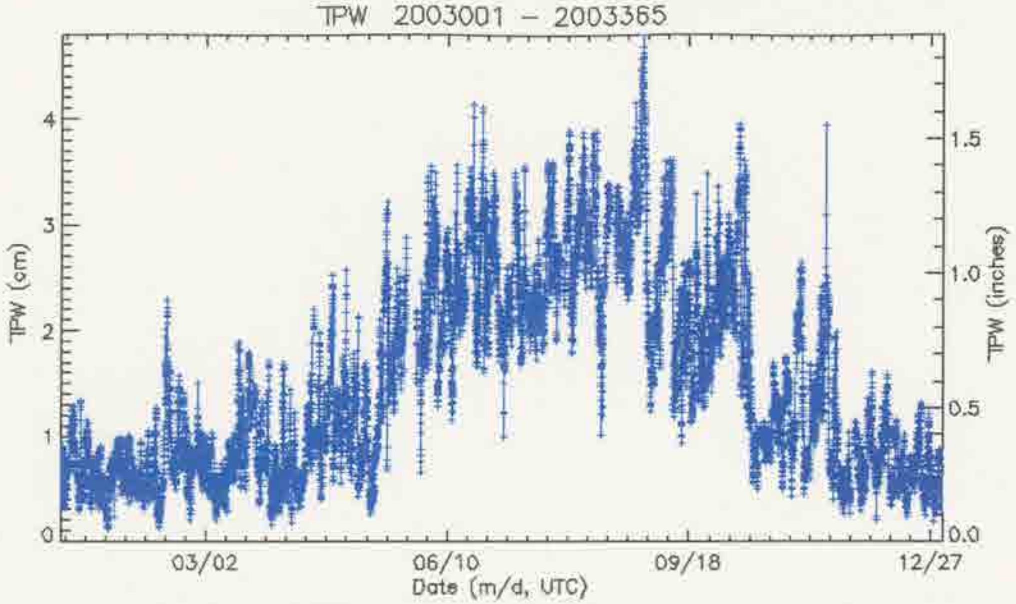


Figure A.25. Time series of TPW in Amarillo, TX for the year 2003. (From NOAA-FSL GPS-Met Observing Systems Branch).

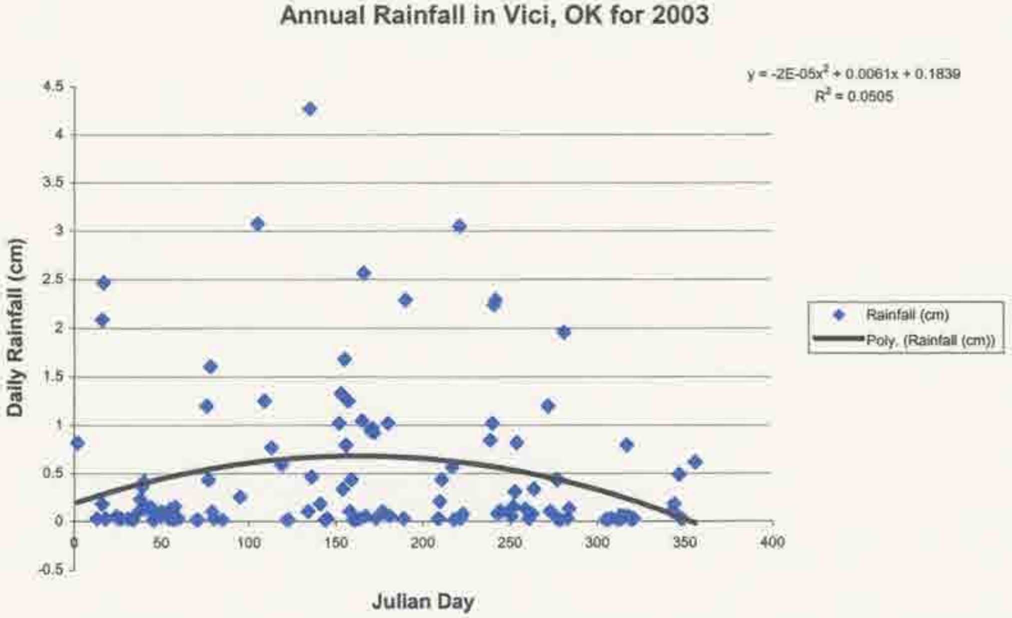


Figure A.26. Plot of daily rainfall amounts during the year 2003 in Vici, OK. Error bars are as described in Figure 3.4.

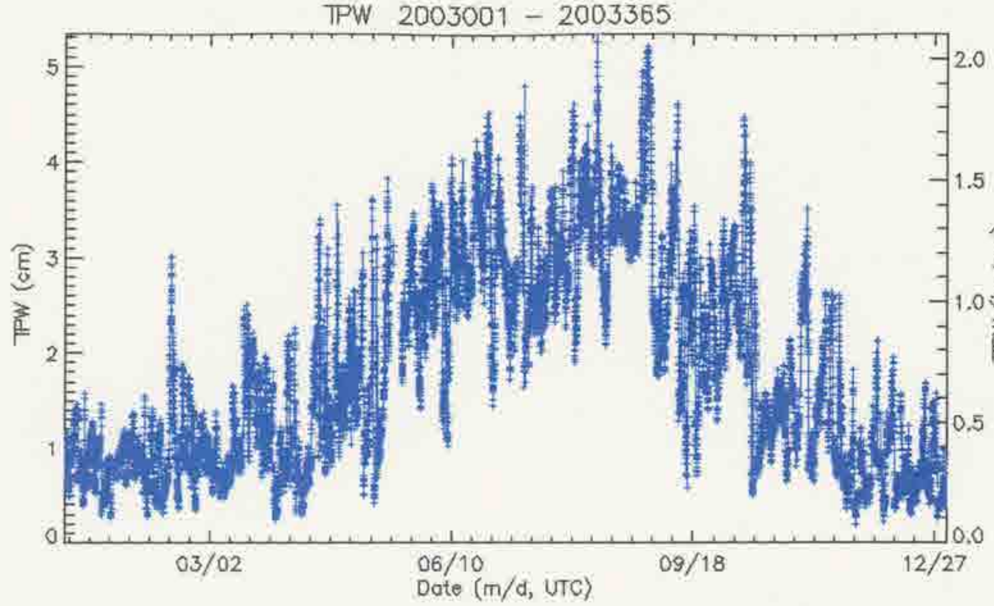


Figure A.27. Time series of TPW in Vici, OK for the year 2003. (From NOAA-FSL GPS-Met Observing Systems Branch).

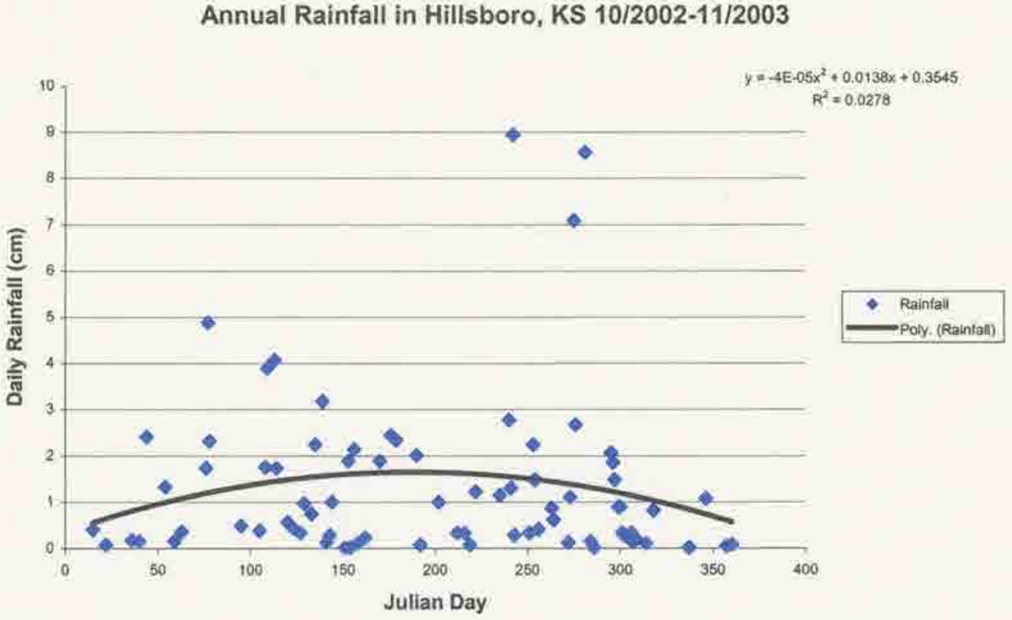


Figure A.28. Plot of daily rainfall amounts during the time period 10/2002 through 11/2003 in Hillsboro, KS. Error bars are as described in Figure 3.9.

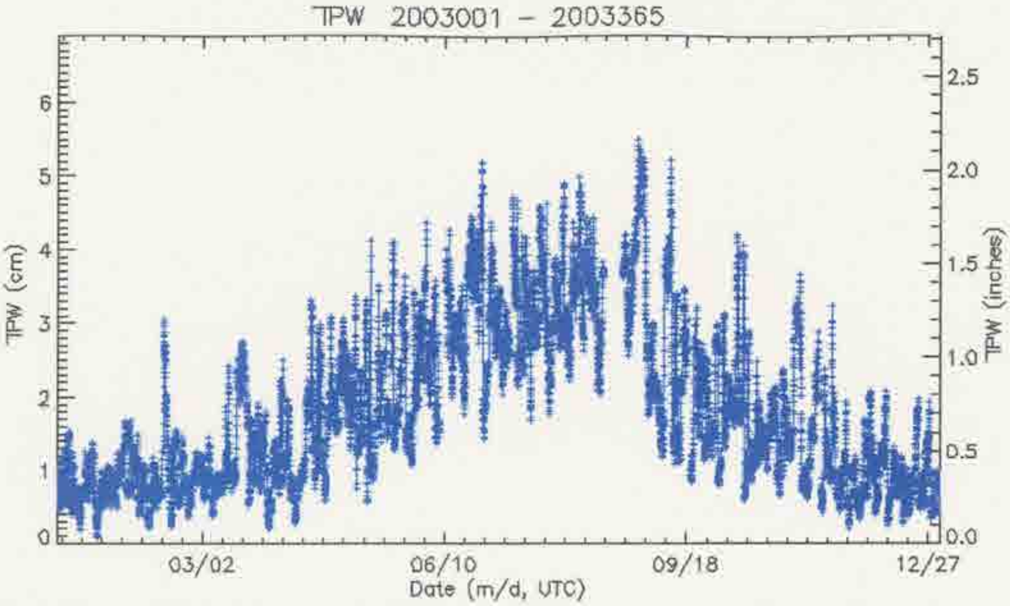


Figure A.29. Time series of TPW in Hillsboro, KS for the year 2003. (From NOAA-FSL GPS-Met Observing Systems Branch).

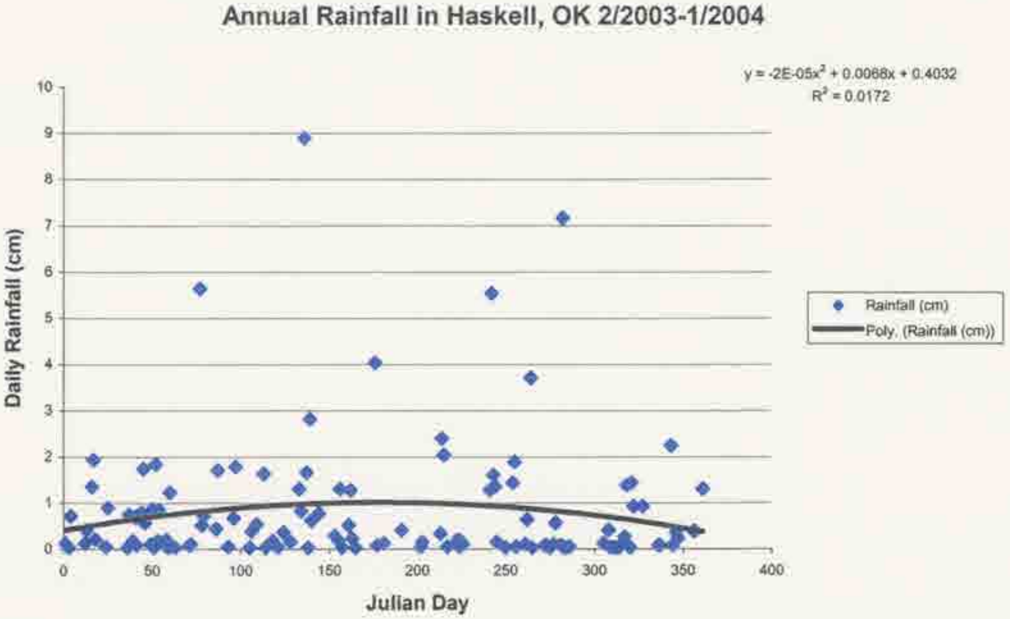


Figure A.30. Plot of daily rainfall amounts during the time period 10/2002 through 11/2003 in Haskell, OK. Error bars are as described in Figure 3.4.

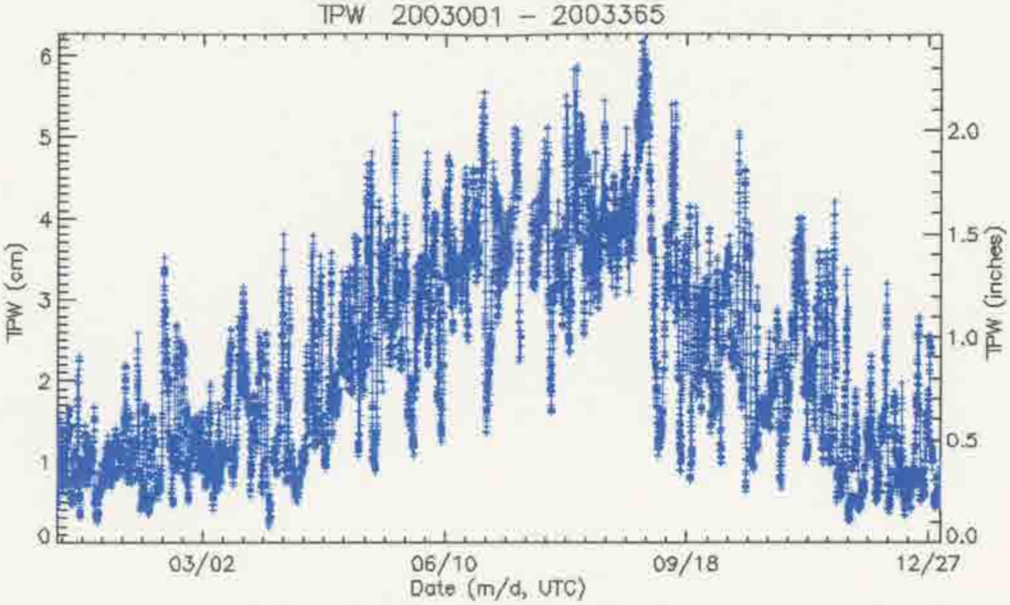


Figure A.31. Time series of TPW in Haskell, OK for the year 2003. (From NOAA-FSL GPS-Met Observing Systems Branch).

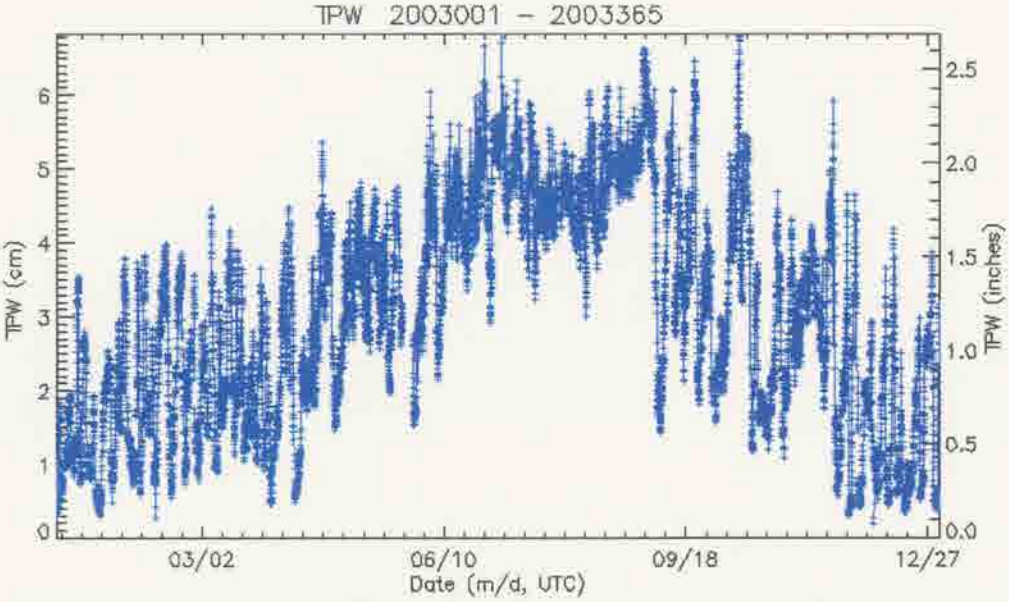


Figure A.32. Time series of TPW in Houston, TX for the year 2003. (From NOAA-FSL GPS-Met Observing Systems Branch).