Detecting Trends in Evapotranspiration in Colorado

W. Austin Clifford
Nolan J. Doesken

December 2009

Completion Report No. 217

Colorado Water Institute

Colorado State University

Acknowledgments

The authors wish to thank the Colorado Water Institute for funding support. Thanks to Dr. Harold Duke and Troy Bauder for their guidance and knowledge, as well as their continued support of the CoAgMet network. The assistance of June Caves of NCWCD was integral to this study. Assistance from Wendy Ryan and John Kleist from the Colorado Climate Center was greatly appreciated.

This report was financed in part by the U.S. Department of the Interior, Geological Survey, through the Colorado Water Institute. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Additional copies of this report can be obtained from the Colorado Water Institute, E102 Engineering Building, Colorado State University, Fort Collins, CO 80523-1033 970-491-6308 or email: cwi@colostate.edu, or downloaded as a PDF file from http://www.cwi.colostate.edu.

Abstract

Evidence shows that temperatures over portions of Colorado and the southwestern U.S. have warmed over the past 20 years. What this means for Colorado's water resources is uncertain, since increased temperatures could be associated with either more or less precipitation, or with seasonal changes in the distribution of precipitation. Year-to-year variations in precipitation are so significant that it may require many decades to assess systematic changes. The less studied and possibly more answerable question is, "What does this mean for evapotranspiration (ET) rates—the consumptive use of Colorado's precious and limited water supplies?" In particular, do we have the capability, with existing weather data, to detect local and regional differences, year-to-year variations, and potential long-term changes in ET and consumptive use?

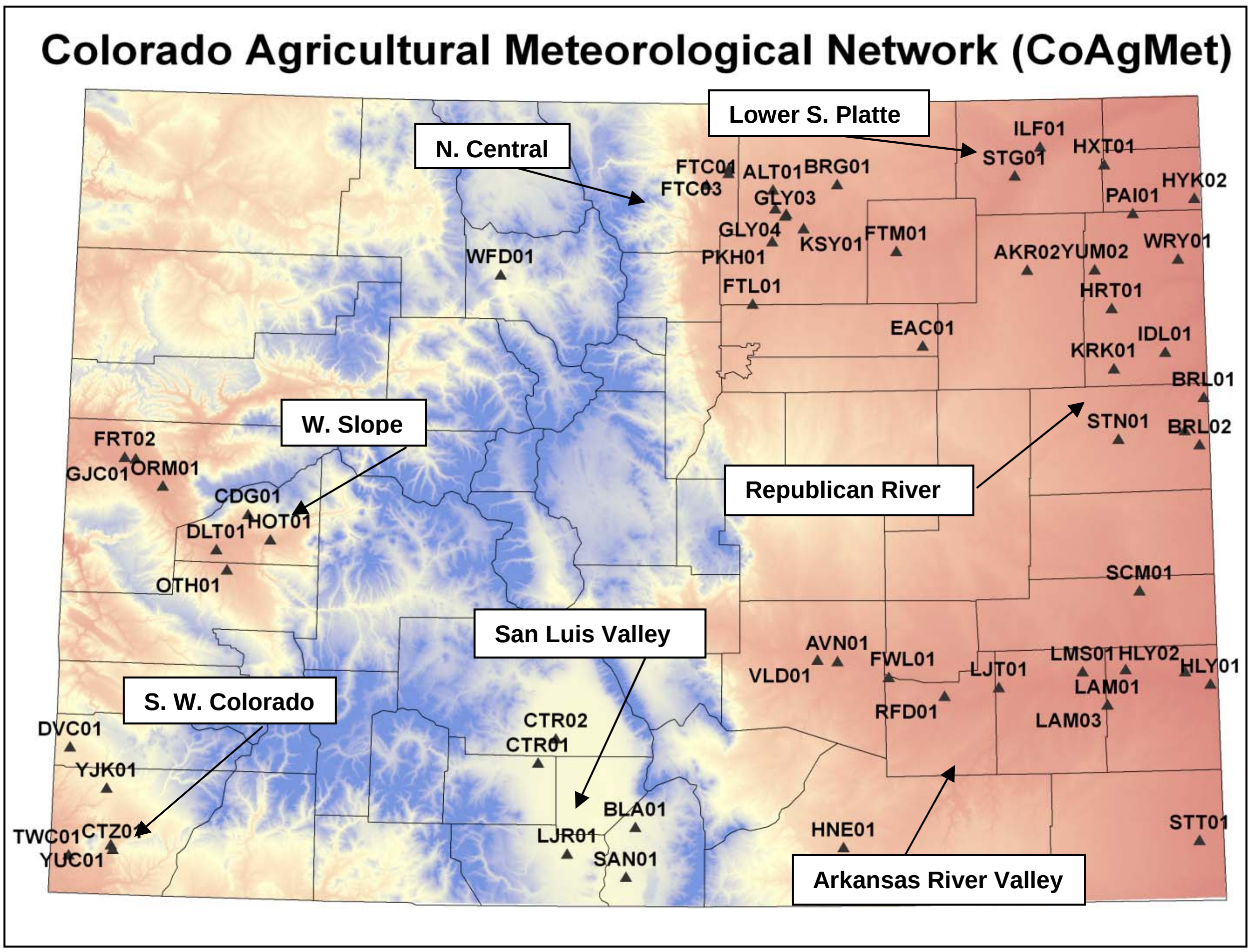

Figure 1: *Map of active CoAgMet automated weather station network.*

This exploratory study examined data from the Colorado Agricultural Meteorological Network (CoAgMet, http://ccc.atmos.colostate.edu/~coagmet) for the period 1992–2008 to determine if spatial and temporal variations in evapotranspiration could be detected. CoAgMet is the only statewide network of weather-observing sites that measure all of the standard climate elements known to affect ET rates: temperature, humidity, wind movement, solar radiation, and precipitation. The Standardized ASCE (American Society of Civil Engineers) Penman-Monteith model was used to compute alfalfa reference ET. Results showed that average May-September ET was highest in the Arkansas River Basin, where the average seasonal reference ET was 51 inches, and lowest in the north-central region of Colorado, where the seasonal average was 41 inches. At any given station, growing season ET varied from a wet year to a dry year by about 7 inches. The highest reference ET values were noted statewide in 2002, which was Colorado's extreme drought year. High ET values also occurred statewide in 1994, and in northern Colorado in 2006. Lower ET rates were observed in 1995-1999.

A slight upward trend in reference ET was observed statewide, but with a maximum of 17 years of data, these results are preliminary. Comparisons with data from Northern Colorado Water Conservancy District (NCWCD) showed that CoAgMet ET estimates correlate well with data from NCWCD's well maintained weather station network. However, CoAgMet stations showed higher ET rates at many stations and more station-to-station variability.

CoAgMet demonstrates considerable potential to provide important climate information for water resource assessments and decision support. However, periods of missing data, infrequent instrument calibration, and potentially unrepresentative locations for some weather stations have compromised CoAgMet data quality for long-term ET applications. Improvements in station maintenance, better distribution of stations across Colorado's agricultural lands, and more representative siting and instrument exposure are encouraged so that the CoAgMet network can become a more valuable part of Colorado water management and planning for the future.

Introduction

In 1989, two separate agricultural research programs in Colorado, both collecting detailed weather data for specific research programs, began to informally share resources and combine efforts to improve and expand access to timely agricultural weather data (Doesken *et. al.*, 1998). The result of this collaboration was the establishment of the Colorado Agricultural Meteorological Network (CoAgMet)—a system of automated weather stations that measure and report temperature, humidity, wind speed and direction, solar radiation, precipitation, and soil temperatures (see station photos in *Figures 5-7*). The majority of the stations are located in areas of intensive irrigated agriculture (*Figure 1*). These weather stations continuously monitor the meteorological elements that directly influence the amount of water used by plants: temperature, humidity, wind, solar radiation, and precipitation.

Functionally, CoAgMet is a group of motivated organizations with a shared interest in weather data serving Colorado's diverse agricultural needs. CoAgMet has gradually grown and evolved to include 60 active stations. New stations have been added when a local sponsor or research project had specific needs, but the network has never been centrally planned, funded, or staffed and has relied on informal agreements and collaborations. As a result, network design, data management, and station maintenance have been performed informally. The Colorado Agricultural Experiment Station has provided reliable annual monetary support, and the Colorado Climate Center at CSU and the USDA Agricultural Research Service in Fort Collins, Colorado, have been providing management support for several years.

Several new stations were added in 2003–2005 in the lower Arkansas River Basin as a direct consequence of the litigation of Colorado's Arkansas River interstate compact with Kansas. In conjunction with the large lysimeter project at the Arkansas Valley Research Center near Rocky Ford, Colorado, shared staff have held the CoAgMet weather stations in the Arkansas Valley to higher standards of maintenance, calibration, and data quality control. Ideally, this same standard could be achieved for the rest of the state. In the spring of 2009, three new stations were added to the CoAgMet network to collect ET data from the intensely irrigated, high-altitude hay meadow areas in North Park, Colorado. Figure 2 shows the evolution of the CoAgMet network over time.

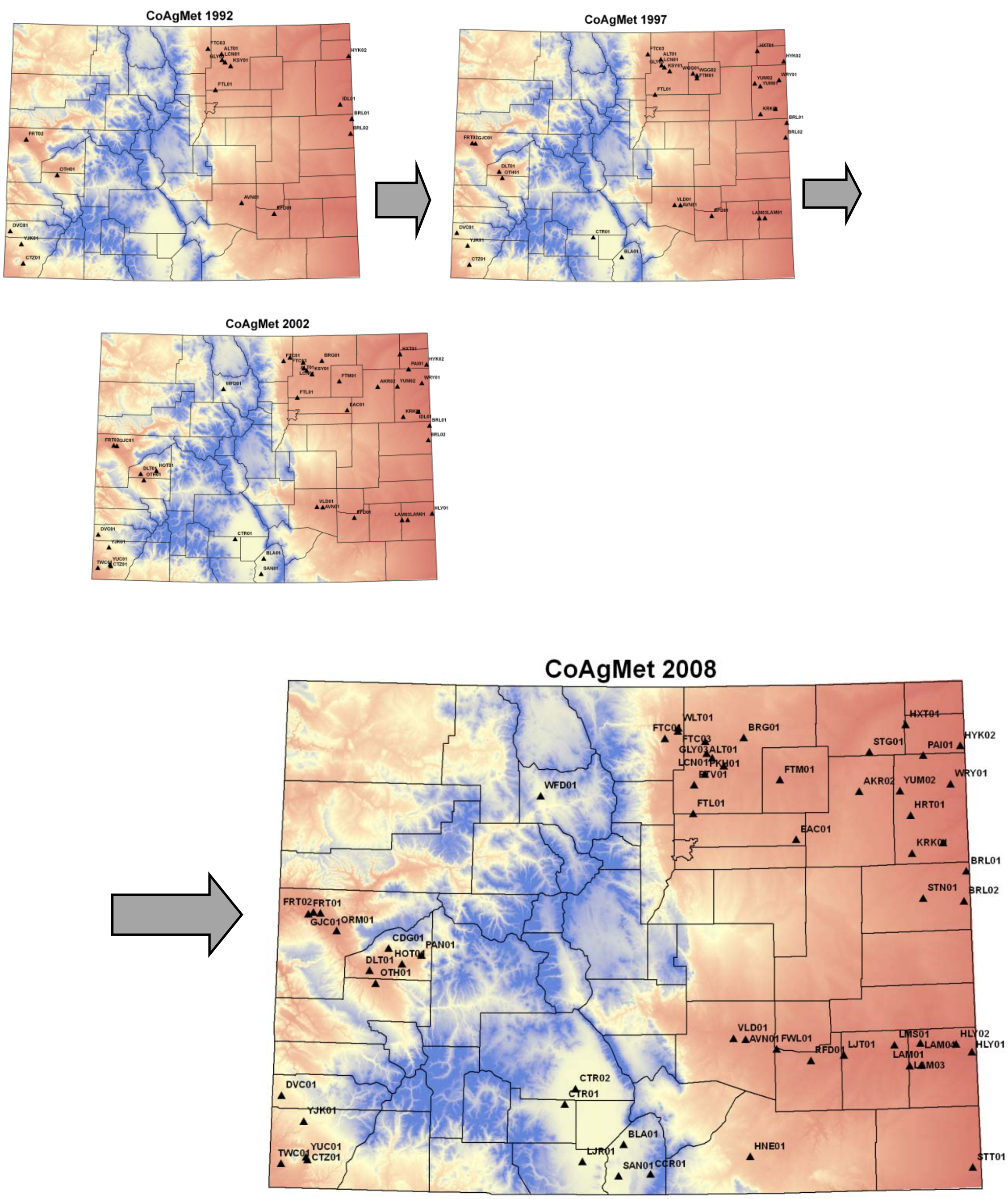

Figure 2: *History of CoAgMet (1992-2008).*

A literature review was conducted to investigate capabilities and limitations in estimating the consumptive use of water by irrigated crops using weather station data. ET has long been a topic of research, and many methods have been derived to estimate it. Allen (1998) explained the processes and principles of combined evaporation from bare soil and vegetative transpiration. It is important to distinguish between potential evapotranspiration and actual evapotranspiration. Brutsaert (1982) describes potential evapotranspiration as “evaporation that would occur if energy is the only limiting factor.” Potential evapotranspiration exceeds actual evapotranspiration if soil moisture is limited, which is often the situation in Colorado.

McKenney and Rosenberg (1993) evaluated eight methods of computing ET. These methods had previously been used to investigate the impacts of climate change on ET and runoff. Put more simply, temperature-based methods require only mean monthly climatic inputs (Blaney-Criddle, 1950) and assume all climatic variables co-vary with temperature in some manner. Physically based methods may be more accurate but are more computationally complex and require daily climatic inputs of elements that have only recently been easy to measure. Penman (1948), Penman-Monteith (1964), and Priestly-Taylor (1972) equations are all known as “combination methods” because they combine the effects of solar radiation, vegetative cover index, and climatic variables. The Penman-Monteith equation requires inputs of air temperature, solar radiation, humidity, wind speed, and various vegetation characteristics (McKenney and Rosenberg, 1993.)

In 1999, the ASCE, Environmental and Water Resources Institute-Evapotranspiration in Irrigation and Hydrology Committee, compiled a standardized equation and set of procedures for estimating the parameters to gain consistency and wider acceptance of ET models (Howell and Evett, 2004). The result was the modified Penman-Monteith standardized model. This widely accepted model is used for this study. Irmak et al., (2006) conducted a sensitivity analysis for the ASCE Modified Penman-Monteith method and concluded that ET was most sensitive to ambient humidity, especially in the arid and semi-arid climates.

Colorado water law has long accepted estimates of consumptive use based on the simpler Blaney-Criddle (1950) model. The ASCE Standardized Penman-Monteith model is now being used, but wide usage is still limited by the lack of sufficient long-term meteorological data, which is now being provided by CoAgMet.

Methods

To explore potential trends and variations in ET, all available data were compiled for active and inactive CoAgMet stations. Table 1 provides metadata for CoAgMet stations. Seven regional groups were established, based on geographic location and hydrologic boundaries: North Central, Lower South Platte, Republican River, Arkansas River Valley, San Luis Valley, Southwest Colorado, and the Western Slope (Figure 1). Three stations were included in the Lower South Platte regions that are actually located in the northwestern portion of the Republican River watershed. This decision was based on the geographic proximity to the Lower South Platte region and the assumption that climatic elements would have a higher correlation due to the regional proximity, as opposed to hydrologic boundaries. EAC01 was listed in the North Front Range region despite its distance from neighboring stations, but it was not included in regional averages due to the dryland environment.

Daily data were compiled into monthly averages and annual time-series for air temperature, vapor pressure, solar radiation, and wind run. Daily maximum and minimum air temperatures were averaged to determine the mean daily temperature at each station. If three or more days of data for any of the variables were missing, the month was deemed missing. Plots of monthly averages were made for each variable at each station and then compared to data from other stations in each region (Figure 3). Figure 4 shows an example of the interannual variability and the frequency of incomplete data at PKH01. Because of our emphasis on variability over time, stations with less than five years of data were only used for short-term analysis.

After completing the network-wide data quality assessment and comparison, the ASCE Penman-Monteith seasonal ET was calculated for all stations and all years from the available daily data sets. The growing season was defined as the period from May 1 to September 30.

ID	Station Name	Location	Latitude	Longitude	Elev.	First Obs.	Last Obs.
AKR02	Akron	USDA-ARS-GPRC	40.1548	-103.142	4537	7/1/1992	11/19/2009
ALT01	Ault	1 mi SE Ault	40.569	-104.72	4910	3/17/1992	11/19/2009
AVN01	Avondale	1 mi SE Avondale	38.2166	-104.341	4580	6/4/1992	11/19/2009
BLA01	Blanca	8 mi SW Blanca	37.3905	-105.557	7755	2/24/1997	9/14/2008
BRG01	Briggsdale	3 mi S Briggsdale	40.5947	-104.319	4858	7/31/2002	11/19/2009
BRL01	Burlington North (#1)	18 mi NNE Burlington	39.4998	-102.074	3900	5/7/1992	11/19/2009
BRL02	Burlington South (#2)	6 mi SE Burlington	39.2651	-102.109	4170	1/2/1992	6/10/2009
BRL03	Burlington 3	4 mi NE of Burlington	39.3374	-102.196	4068	3/21/2008	11/19/2009
CDG01	Cedaredge	Cedaredge	38.9142	-107.932	6404	2/18/2006	11/19/2009
COW01	Cowdrey	9 miles north of Walden	40.8659	-106.336	7895	5/7/2009	9/14/2009
CTR01	Center	CSU San Luis Valley Expt Sta	37.7067	-106.144	7702	10/8/1993	11/19/2009
CTR02	Center #2	Coors Research Farm	37.8288	-106.038	7608	10/2/2003	11/19/2009
CTZ01	Cortez	9 mi SW Cortez	37.2248	-108.673	6015	1/2/1992	10/10/2009
DLT01	Delta	3 mi W Delta	38.7342	-108.118	5010	4/19/1995	11/19/2009
DVC01	Dove Creek	4 mi NW Dove Creek	37.7265	-108.954	6595	10/28/1992	11/19/2009
EAC01	Eastern Adams County	10 mi W Last Chance	39.7857	-103.798	4907	7/17/2000	11/19/2009
FRT01	CSU Fruita Expt	2 mi ENE of Fruita	39.1667	-108.75	4500		
FRT02	CSU Fruita Expt Station	2 mi ENE Fruita	39.1803	-108.7	4519	6/16/1992	11/19/2009
FTC01	Fort Collins AERC	Fort Collins AERC	40.5947	-105.137	5120	2/1/1992	11/19/2009
FTC03	CSU - ARDEC	6 mi NE Fort Collins	40.6525	-105	5110	5/8/1992	11/19/2009
FTL01	Fort Lupton	6 mi SSW Fort Lupton	40.0011	-104.849	5055	3/17/1992	11/19/2009
FTM01	Fort Morgan	8 mi W Fort Morgan	40.2585	-103.954	4320	4/21/1995	11/19/2009
FWL01	Fowler	Fowler Golf Course	38.1351	-104.032	4335	3/17/2005	11/19/2009
GJC01	Grand Junction	3 mi NW Grand Junction	39.1752	-108.632	4869	10/1/1993	5/10/2009
GLY03	Greeley	2.5 mi NE Greeley	40.4394	-104.647	4680	3/4/1992	11/19/2009
GLY04	Greeley 4	1.5 mi N of Greeley Airport	40.4487	-104.638	4683	6/5/2008	11/19/2009
HEB01	Hebron	13 miles SW of Walden	40.5455	-106.388	8170	6/10/2009	9/14/2009
HLY01	Holly	5 mi NW Holly	38.07	-102.09	3636	9/27/2001	11/19/2009
HLY02	Holly #2	8.5 mi NW Holly	38.1361	-102.241	3570	5/21/2005	11/19/2009
HNE01	Hoehne	NE Trinidad	37.2893	-104.313	5625	2/14/2000	11/19/2009
HOT01	CSU Rogers Mesa Expt Sta	4 mi W Hotchkiss	38.7917	-107.792	5547	5/21/1998	11/19/2009
HRT01	Heartstrong	12 mi SSE Yuma	39.9552	-102.625	4129	5/30/2005	2/28/2008
HXT01	Haxtun	2.5 mi NW Haxtun	40.6722	-102.647	4040	3/27/1997	11/19/2009
HYK02	Holyoke	12 mi SE Holyoke	40.4909	-102.089	3735	1/2/1992	11/19/2009
IDL01	Idalia	2 mi N Idalia	39.7312	-102.302	3975	1/2/1992	11/19/2009
ILF01	Iliff	1.5 mi NE of Iliff	40.7678	-103.045	3822	2/2/2008	11/19/2009
KRK01	Kirk	3 mi W Joes	39.6554	-102.621	4213	5/13/1996	11/19/2009
KSY01	Kersey	2 mi SE Kersey	40.3768	-104.532	4625	5/1/1992	11/19/2009
LAM01	Lamar #1	4.5 Mi S Lamar	37.9807	-102.596	3776	8/3/1996	11/19/2009
LAM02	Lamar #2	7 mi NNE Lamar	38.1734	-102.559	3736	7/31/2002	6/14/2005
LAM03	Lamar #3	10 mi SW Lamar	37.9798	-102.713	3918	7/31/2002	11/19/2009
LAM04	Lamar #4	4.5 mi NNE Lamar	38.1539	-102.599	3705	5/11/2005	11/19/2009
LAR01	Larand	8 miles south of Walden	40.6126	-106.3	8252	5/8/2009	9/14/2009
LCN01	Lucerne	1/4 mi SW Lucerne	40.4756	-104.707	4750	3/4/1992	11/19/2009
LJR01	LaJara	2 mi S LaJara	37.2551	-105.964	7595	5/19/2005	7/2/2009
LJT01	LaJunta	11 mi NE LaJunta	38.0778	-103.366	3960	3/17/2005	11/19/2009
LMS01	Las Animas	1 mi NW McClave	38.1478	-102.859	3895	3/17/2005	11/19/2009
ORM01	Orchard Mesa	Orchard Mesa	39.042	-108.46	4600	1/2/2006	11/19/2009
OTH01	Olathe	3 mi NE Olathe	38.6351	-108.05	5324	7/28/1992	11/19/2009
PAI01	Paoli	RD U & 59	40.4248	-102.475	3875	9/26/2001	11/19/2009
PAN01	Paonia	Paonia	38.8656	-107.599	5643		
PBL01	Pueblo	Pueblo	38.2317	-104.467	4710	8/4/1993	5/21/1995
PKH01	Peckham	3 mi ENE Peckham	40.3125	-104.727	4701	3/17/1992	11/19/2009
PTV01	Platteville	1 mi NW Platteville	40.2278	-104.835	4700		
RFD01	CSU Expt Stn Rocky Ford	2.5 mi SE Rocky Ford	38.0385	-103.695	4180	6/4/1992	11/19/2009
RFD02	CSU Expt Stn Rocky Ford NRCS	Moved to HLY01	38.0385	-103.695	4180	1/2/1999	6/29/2005
SAN01	San Acacio	2 mi N Mesita	37.1417	-105.611	7753	8/12/2000	11/18/2008
SCM01	Sand Creek Massacre HS	7.5 mi NNE of Chivington	38.5439	-102.503	3963	7/24/2008	11/19/2009
STG01	Sterling	Sterling	40.2744	-103.014	4472	3/24/2006	11/19/2009
STN01	Stratton	Stratton	39.2987	-102.522	4321	4/2/2006	11/19/2009
STT01	Stonington	Stonington	37.1613	-102.122	3841	4/2/2006	1/8/2008
TWC01	Towaoc	Ute Mtn Ute Farm	37.1891	-108.935	5319	6/30/1998	11/15/2009
VLD01	Vineland	13 mi SE Pueblo	38.2235	-104.461	4420	8/4/1993	11/19/2009
WFD01	Wolford Mtn Reservoir	5 mi NNW Kremmling	40.1387	-106.415	7520	11/30/2004	11/19/2009
WGG01	Wiggins 06	NNE of Wiggins	40.3333	-104.036	4447	4/1/1997	10/31/2004
WGG02	Wiggins 39	ENE of Wiggins	40.2998	-103.952	4421	4/1/1997	7/31/2005
WLT01	Wellington	I25 & 58.5 Rd	40.6762	-104.997	5144	8/8/2005	11/19/2009
WRY01	Wray	10 mi N Wray	40.1924	-102.203	3681	5/9/1996	11/19/2009
YJK01	Yellow Jacket	2.5 mi NW Yellow Jacket	37.5289	-108.724	6900	1/2/1992	11/19/2009
YUC01	Yucca House	Mesa Verde Natl Monument	37.2478	-108.687	5975	8/23/2002	11/19/2009
YUM01	Yuma	6 mi E of Yuma	40.1035	-102.606	4000	5/19/1993	5/9/2001
YUM02	Yuma	2 mi N Yuma	40.1504	-102.724	4104	5/8/1996	11/19/2009

Table 1: CoAgMet station metadata. Station codes are used in the text to reference stations.

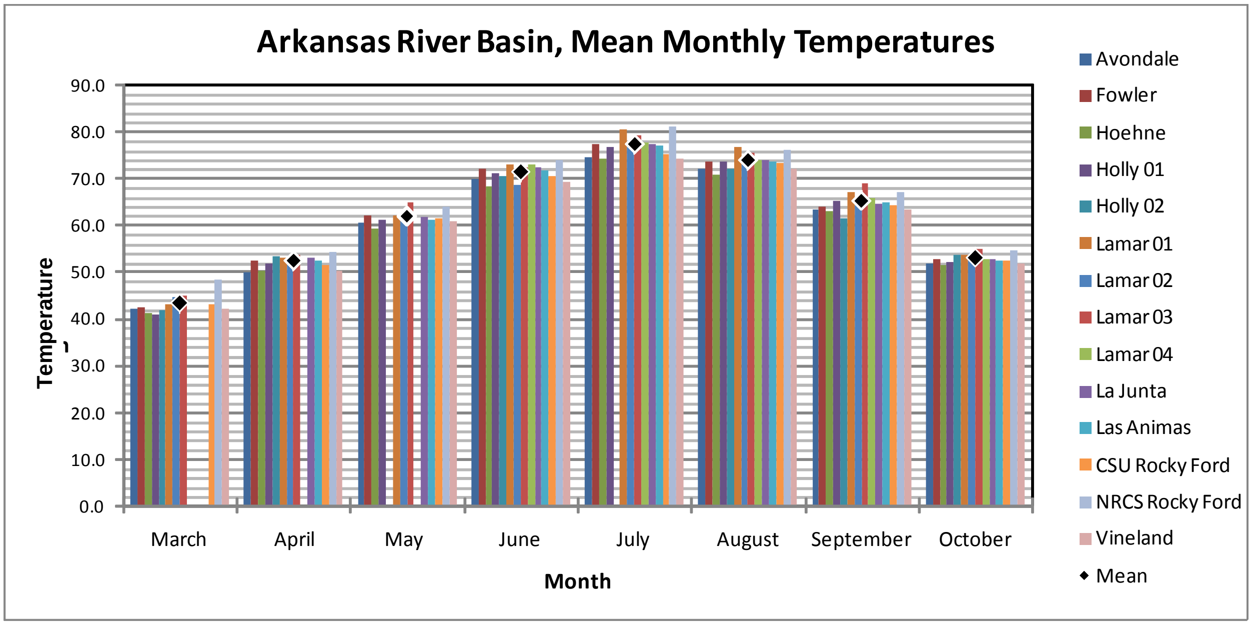

Figure 3: *Arkansas River Mean Monthly Air Temperature.*

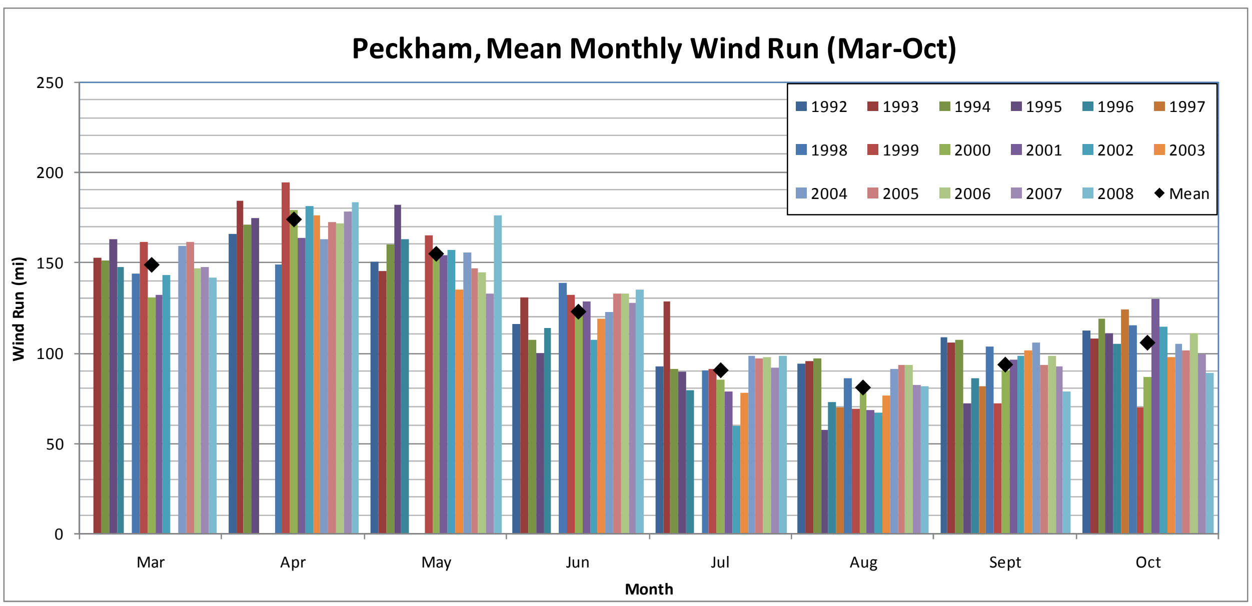

Figure 4: *Average Daily Wind Run (miles per day) by month, March-October, for the Peckham CoAgMet station.*

Alfalfa reference ET was computed for each station, month, and year. Total July ET values were closely examined since July is typically the time of year with highest ET rates. Station-to-station differences in summer ET can provide insight on station siting and representativeness. Stations with unusually high mid-summer ET rates may not be representative of fully-irrigated environments. Stations with unusually low ET rates may have issues with reduced wind speeds due to obstructions. Figure 5 illustrates the differences in average daily July ET from selected stations across the state.

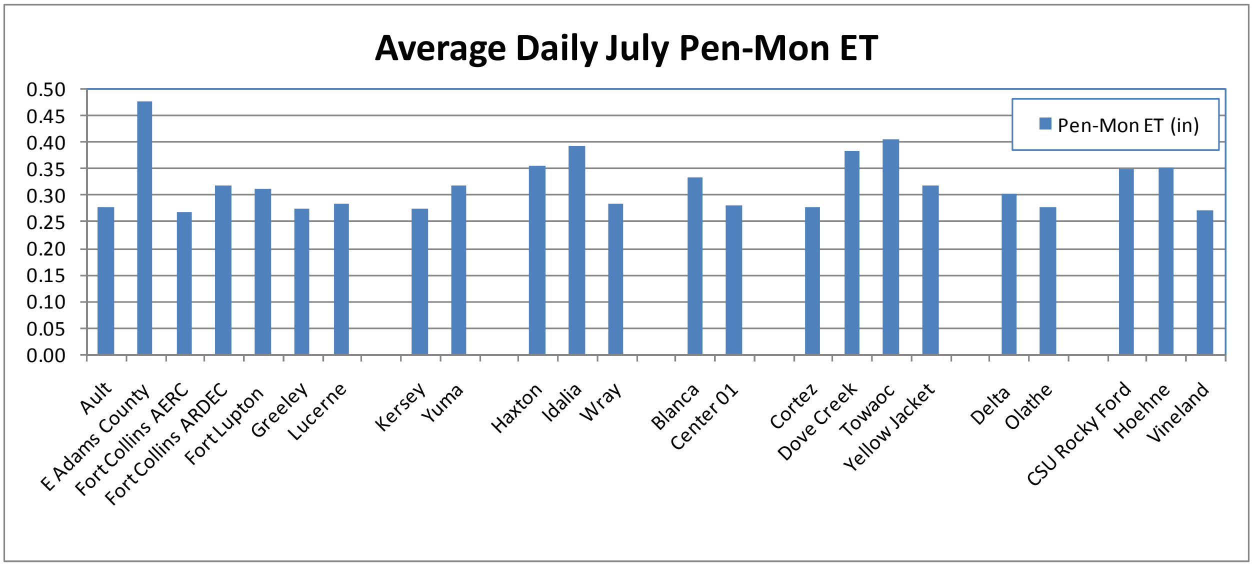

Figure 5: *Average daily July Penman-Monteith ET (inches) for select CoAgMet stations.*

It should be noted the CoAgMet network has traditionally used the Kimberly-Penman (1982) model for estimating ET. Since the initiation of this study, ASCE Penman-Monteith estimates are now co-generated by CoAgMet. All results shown here use ET data from the ASCE Penman-Monteith method.

Relatively large differences in monthly and seasonal ET values were noted among stations in each region. To help explain these variations, station locations, elevation, and proximity to irrigated land were assessed. Photographs of the CoAgMet stations were examined, and interviews were conducted with CoAgMet collaborators familiar with each station.

Figure 6: *CoAgMet volunteer Dr. Harold Duke (USDA Agricultural Research Service, retired) services the Dove Creek CoAgMet station. Due to sparse ground vegetations, sites like this are not ideal for ET applications.*

Results

The ASCE Standardized ET equations require seasonally complete daily or hourly temperature, humidity, wind run, and solar radiation data. Based on the results of this study, no CoAgMet stations have serially complete data for all of these variables since 1992. However, data were found to be more than 90% complete for many stations making useful ET computations and comparisons possible. The San Luis Valley region had the most data gaps overall, and the North Central region typically had the most complete data. The Lower South Platte and the Arkansas River Valley Basins showed reasonably complete and consistent data. Some of the best data in the Arkansas River Valley were measured by stations relatively new to the network; therefore, long time series of high-quality data were not yet available. In recent years, CoAgMet data quality in the region has significantly improved due to the necessity of high-quality data for the weighing lysimeter research project at the CSU Arkansas Valley Research Center.

Due to the voluntary nature of CoAgMet and its ad hoc history, station siting has not been uniform. Some sites are in non-ideal reference conditions (Figure 6). Some sites are in or on the edge of non-irrigated areas (Figure 7), and some are located over or adjacent to clipped grass or alfalfa providing reference or near reference conditions (Figure 8). As will be shown later, some sites may not fully represent weather conditions observed over irrigated fields and may not be ideal or appropriate for ET applications (Figure 6 & 7).

Regardless of location, CoAgMet meteorological data are still valuable for many applications, but the exact local siting affects how suitable each station is for representing ET rates for adjacent cropland. Unrepresentative data can be seen at many stations sited in non-reference conditions. Variables especially affected by ground cover are air temperature, humidity, and soil temperatures. Soil temperature data are not essential for ET calculations but are useful for assessing local ground conditions. CoAgMet has not achieved consistent ground cover for soil temperature comparisons. Some sites are nearly bare or have just seasonal grasses and weeds (Figure 6). Other sites, especially in eastern Colorado, have thick year-round unclipped ground cover. Soil temperature data discrepancies can be seen at the following stations, possibly due to non-ideal ground cover: ALT01, BRL01, BRL02, DVC01, FRT02, FTM01, KRK01, ORM01, STN01, and TWC01.

Figure 7: *FRT02 has non-ideal ground cover; however, the typical up-wind fetch of the station is irrigated agriculture.*

Figure 8: *HLY02 is an example of proper siting within clipped fully irrigated alfalfa.*

Mean daily July Penman-Monteith estimated reference ET varied significantly across the state. Vineland, with mid-summer wind obstruction due to the proximity of tall corn fields, showed 23% lower mean July ET compared to its neighbors in the Arkansas Valley. Overall, the Arkansas River Valley region experiences the highest region-wide mean growing season ET at 51 inches, and the North Central and the Lower South Platte regions had the lowest growing season alfalfa reference ET of 43 inches. The individual station with the highest growing season average reference ET was LAM01 *(*Arkansas River Valley region), with 61 inches. This station is located in dryland conditions and should not be used for estimating crop ET. The station with the highest mean growing season reference ET, which is appropriate for estimating ET based on data quality and appropriate siting, is LAM04, with 50 inches. The lowest statewide seasonal reference ET, on average, was ALT01 (North Central region), with 39 inches.

North Central Region

The nine-station North Central region representing primarily eastern Larimer and western Weld Counties had moderate ET variability among stations. The long-term seasonal average ET for the region was 41 inches, the lowest in the state. EAC01 was not used in this calculation, because it is not located within irrigated agriculture and is classified as dryland siting. EAC01 computed ET rates were much higher than the regional average. Most stations within the North Central region had relatively complete and high-quality data sets. Time series from stations in the North Central region showed a slight upward trend in growing season ET and modest season-to-season variability (Figure 9). The highest ET rates in this region occurred in 1994 and 2006, with relatively low ET reported for the wet years of 1995-1997.

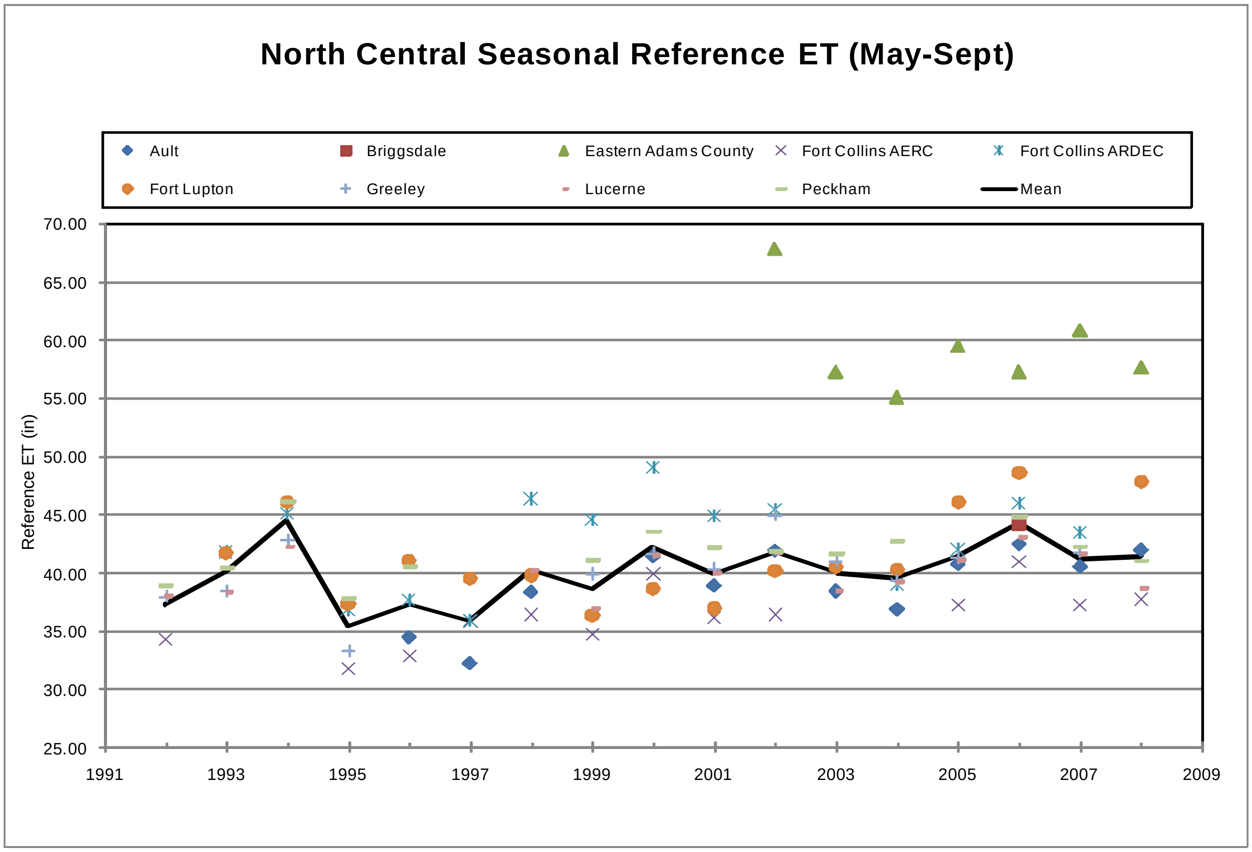

Figure 9: *North Central CoAgMet region seasonal ET time series (1992-2008).*

Lower South Platte Region

The Lower South Platte region consists of seven stations, which are mainly located within close proximity to irrigated agriculture. An eighth station (ILF01) was added to the region in 2008. ILF01 was not used in ET trend analysis due to its short length of data record. Two stations near Wiggins had relatively short records and have now been discontinued. CoAgMet has relatively few stations, since this area is heavily monitored by the irrigation water management network maintained by NCWCD (described later in this report).

As seen in Figure 10, the KSY01 CoAgMet station was consistently below the regional average for the time-series and is known to have lower wind speeds compared to others in the region. PAI01 had the highest average seasonal reference ET with 50 inches, which was 14% higher than the regional average of 44 inches. Regionally, the data sets were sufficiently complete for preliminary time series analysis. While 2002 showed the highest reference ET rates on average, 1994 was higher for several individual stations. The years 1993, 1996, 1997, and 1999 all had relatively low ET. Only two stations had sufficiently complete data for the 2008 season. While there appears to be a small upward trend in ET in this region since 1992, these results are not significant, since there are too few stations with complete data for the entire period.

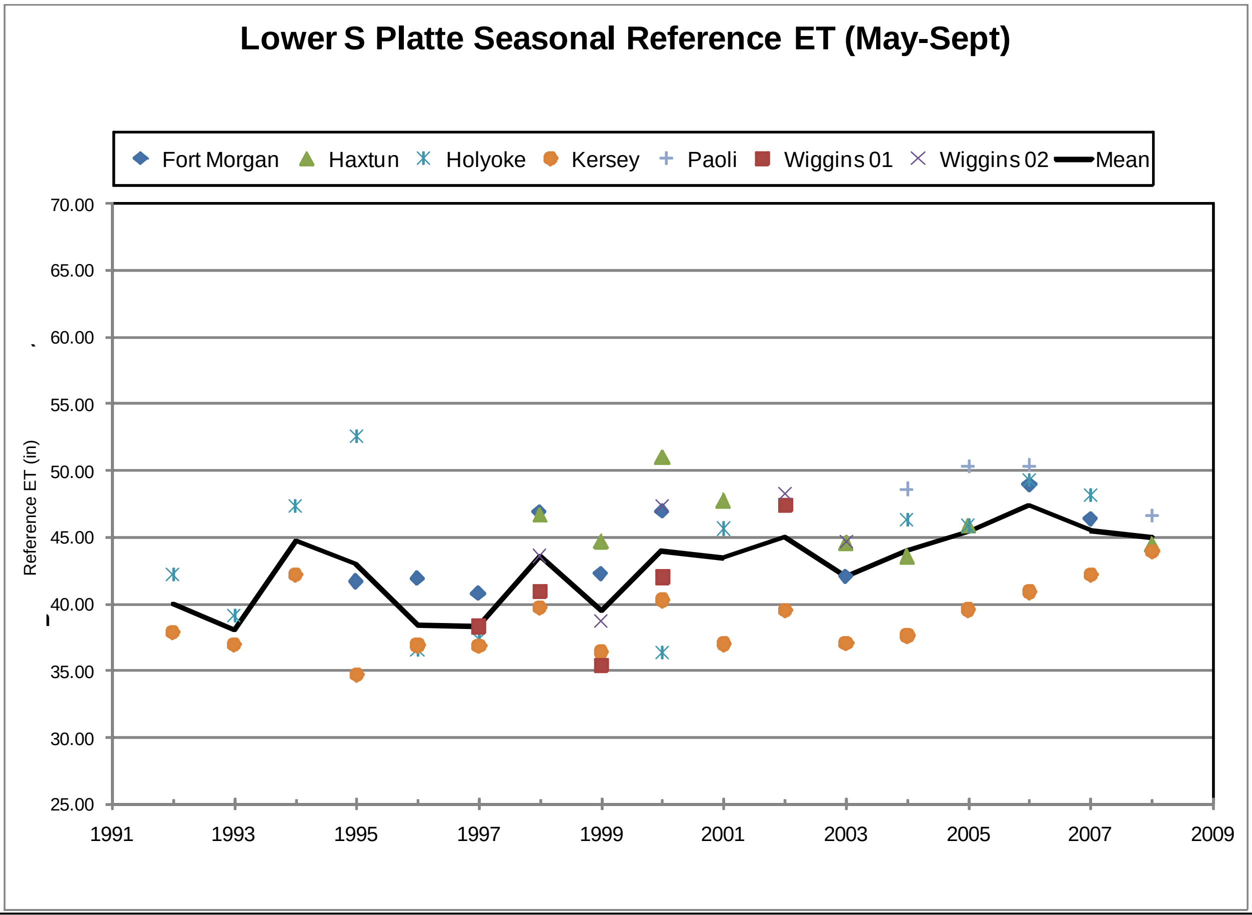

Figure 10: *CoAgMet Lower South Platte region seasonal ET time series (1992-2008).*

Republican River Region

The Republican River region is composed of six stations with relatively consistent long-term data. Two additional stations were added recently (STN01 and BRL03) but were not included in this time series analysis. The average seasonal reference ET for this region was 48 inches. The region experienced similar variations in ET to the Lower South Platte region *(Figure 11)*. The growing season of 1994, 2000, and 2002 all stand out with very high reference ET, while the period 1995-1999 was consistently low. No significant long-term trend is apparent in this time series.

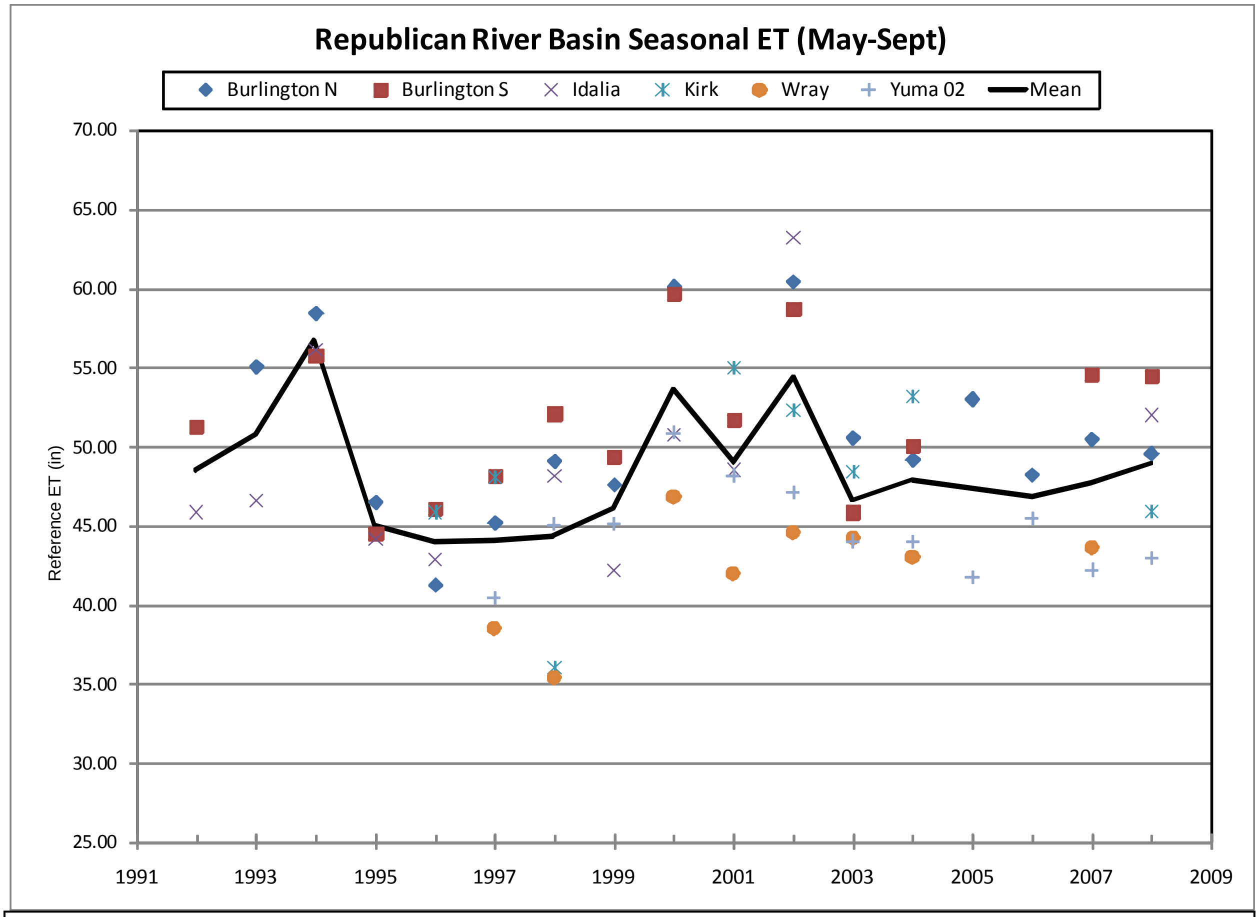

Figure 11: *Republican River region seasonal ET time series (1992-2008).*

Arkansas River Region

Prior to 2001, the Arkansas Valley region had only a small number of CoAgMet weather stations. Six new stations were added in recent years, including three new stations for the 2005 growing season. These stations were added to the network as a result of new water management requirements resulting from Arkansas River interstate compact litigation with the state of Kansas and the inception of the weighing lysimeter at the CSU Arkansas Valley Research Center. As of 2008, there are 14 active stations in the region. Most of the new stations have been generating high-quality data thus far. The mean seasonal reference ET for this region is 51 inches, the highest in the state. Figure 12 shows the interannual variability of growing season ET in the Arkansas River Valley. LAM01 has the highest long-term seasonal reference ET average, with 62 inches. It is an exposed dryland site, however, and should not be used for most ET applications. The growing season of 2002—an extreme drought year in southeast Colorado—stands out as the highest year by far for reference ET. Since then, the Arkansas Valley has seen an overall decline in the average ET levels. Keep in mind that stations added since 2002 have generally been placed in fully irrigated areas representative of reference conditions. LAM04 had the highest mean seasonal ET for a fully irrigated, at 50 inches. VLD01 is the lowest long-term station for ET in the region with an average of 41 inches; however, this low value may be associated with siting issues (surrounded by tall corn), which were corrected in 2008. Because of the significant change in the number and location of stations in the region, trends in ET since 1992 cannot yet be assessed.

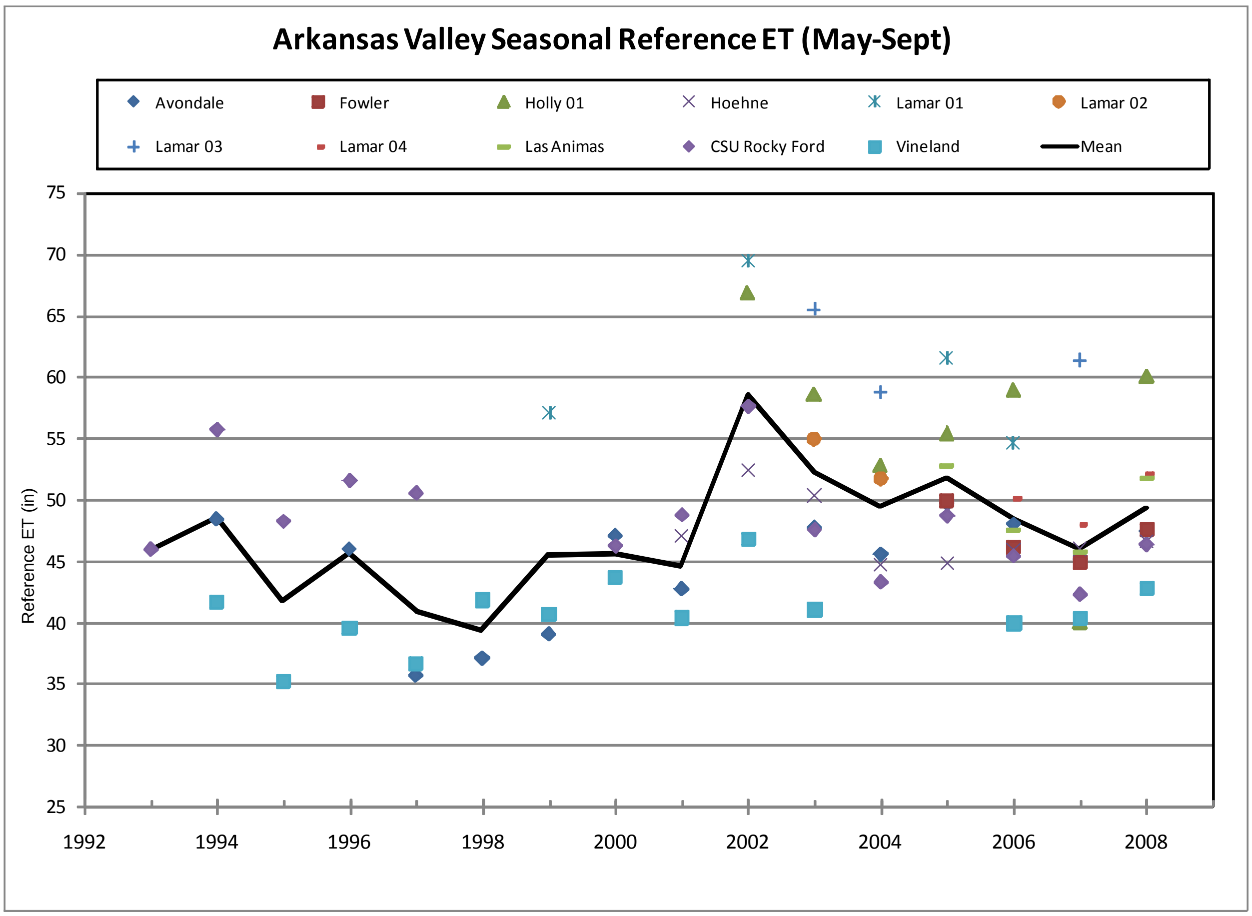

Figure 12: *Arkansas River Valley region seasonal ET time series (1993-2008).*

San Luis Valley Region

The San Luis Valley region is the highest-elevation agricultural region, with a mean elevation of 7,500 feet. Thus, its temperatures are also coolest. However, it is the sunniest and driest region, with annual average precipitation less than eight inches, which results in a unique regional climate. Unfortunately, this CoAgMet region had significant amounts of missing data from the four long-term CoAgMet stations located within the Valley, adding uncertainty to this analysis. Recent years have seen much improvement in data quality and quantity. Figure 13 shows the interannual variability in growing season ET in the San Luis Valley. The mean seasonal ET for the valley was 44 inches; 2007 was clearly a year with lower reference ET rates (42 inches).

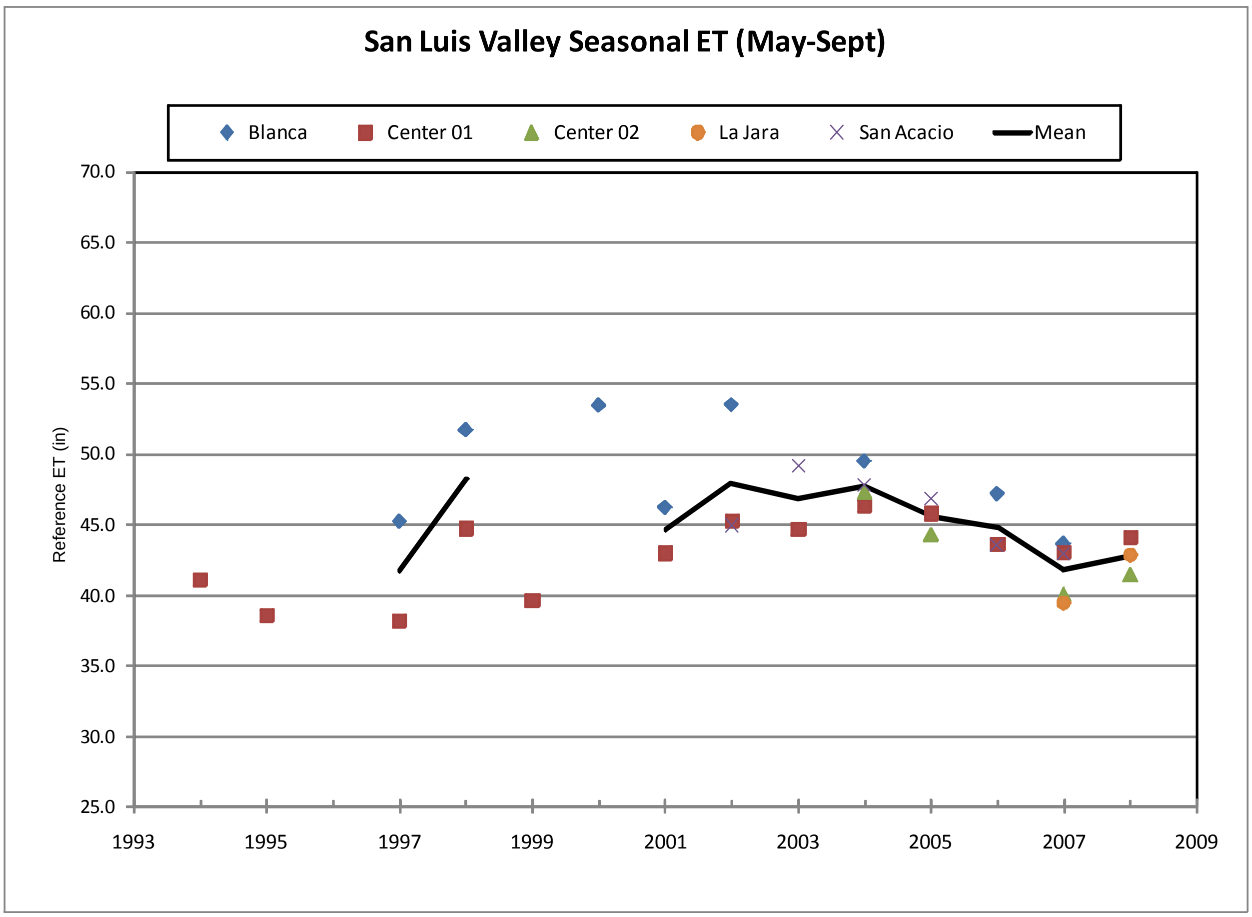

Figure 13: *San Luis Valley region seasonal ET time series (1994-2008).*

Southwest Colorado Region

The Southwest Colorado region was composed of five stations, and the overall long-term data quality for the region has been good. The long-term average reference ET was 49 inches. This region of the state has experienced high interannual variability in seasonal reference ET *(Figure 14)*, likely as a result of variations in the southwest monsoon circulation, which has a strong influence on July-August humidity and precipitation. The stations in the region are well correlated with each other, but they differ greatly in magnitude as a result of differences in elevation and proximity to irrigated lands. TWC01 clearly has the highest average growing season reference ET levels of 55 inches, as opposed to the lowest of 40 inches at CTZ01. Only CTZ01 and YJK01 had complete data for 2008, and both had lower growing season ET rates than the other stations in the region, which biased the long-term time series.

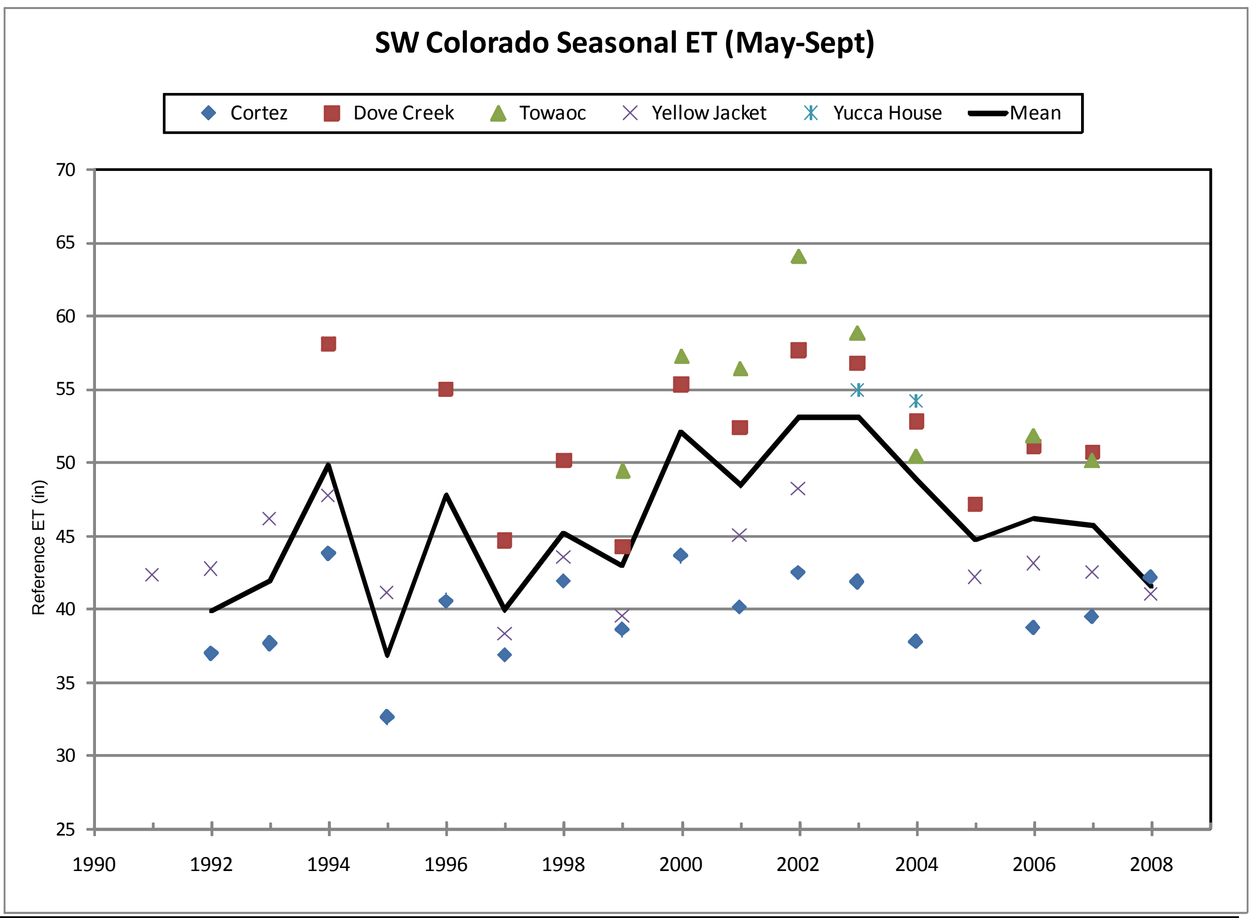

Figure 14: *Southwest Colorado regional ET time series (1991-2008).*

Western Slope Region

The Western Slope region is composed of five stations and experienced the lowest interannual variability in reference ET of any region. Despite high temperatures, low humidity, and abundant sunshine in this region, it had a modest seasonal average reference ET at 43 inches. Figure 15 shows the interannual variability in growing season ET in the Western Slope region. Wind speeds are low in this area during the summer months compared to the other regions of Colorado, possibly explaining these results. Long-term trends and variations in this region differ noticeably from other parts of the state. The year 1994 stands out as a high year for reference ET. Unlike other parts of the state, where 2002 was significantly higher than most other years, 2002 shows only average reference ET. OTH01 was the lowest in the region with 39 inches of seasonal reference ET, more than 10% below the regional average. FRT02 had the highest reference ET, but there are unresolved data quality issues with this station. Due to the changing mix of stations over time and concerns over data quality, we do not feel that conclusions about variability and trends should be made for this region at this time. Several Western Slope CoAgMet stations are situated within fruit orchards and may not be ideal for alfalfa reference ET estimates.

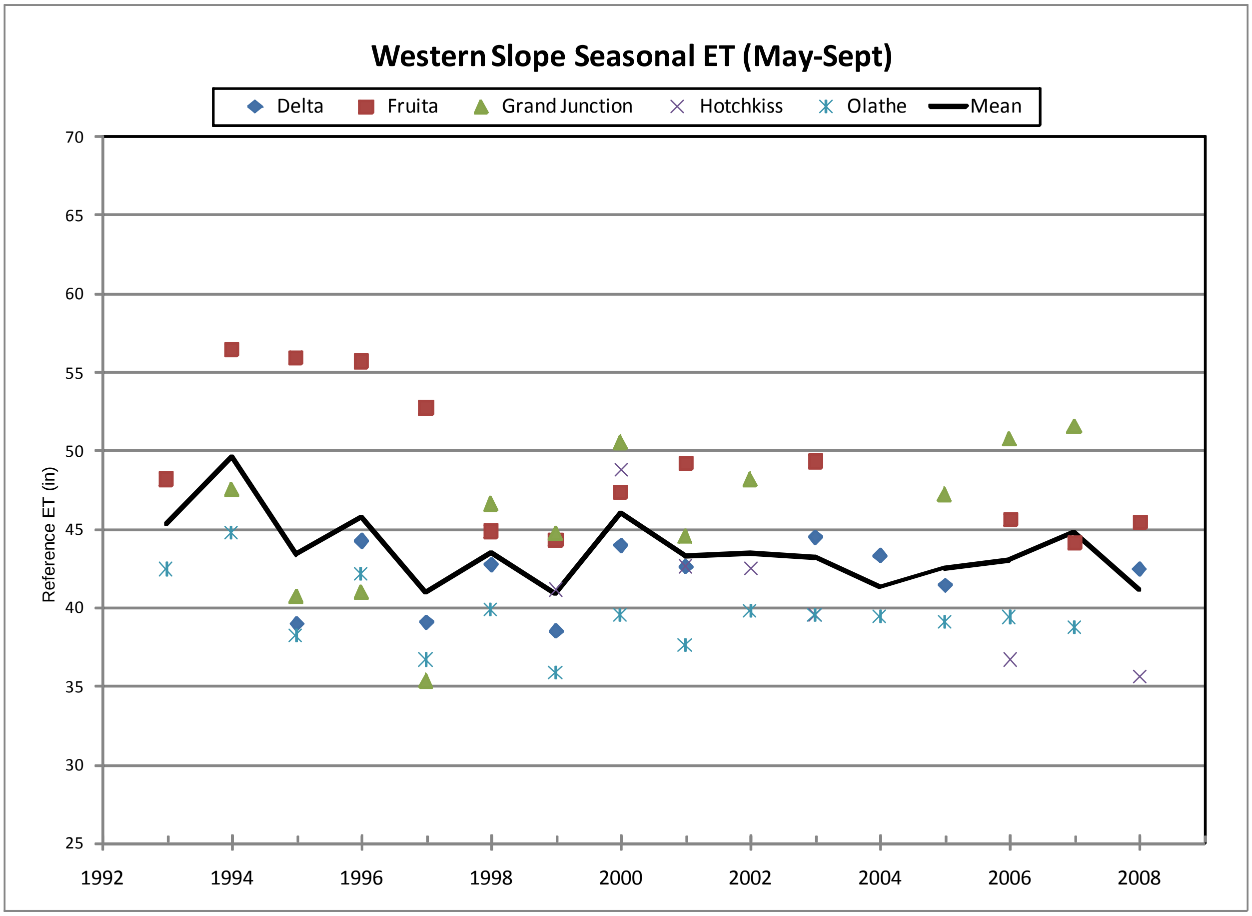

Figure 15: *Western Slope region seasonal ET time series (1993-2008).*

NCWCD Reference ET Estimates

NCWCD operates 23 automated weather stations within the CoAgMet North Central and Lower South Platte regions (data are available online at www.ncwcd.org). These weather stations measure all climate variables used in the ASCE Penman-Monteith equation. The NCWCD has a long history of high standards in station maintenance and siting. The close proximity of many NCWCD weather stations to CoAgMet stations in northern Colorado provided an opportunity to compare results.

Seasonal cumulative reference ET was obtained and compiled into growing season totals for 1996-2008 for NCWCD stations in agricultural areas located over alfalfa. Appropriate NCWCD weather stations were grouped into similar regions as CoAgMet stations for data comparison. The NCWCD data added five stations to the North Central region and five to the Lower South Platte region. Cumulative seasonal reference ET time-series charts were plotted combining CoAgMet stations with NCWCD stations within the same regions.

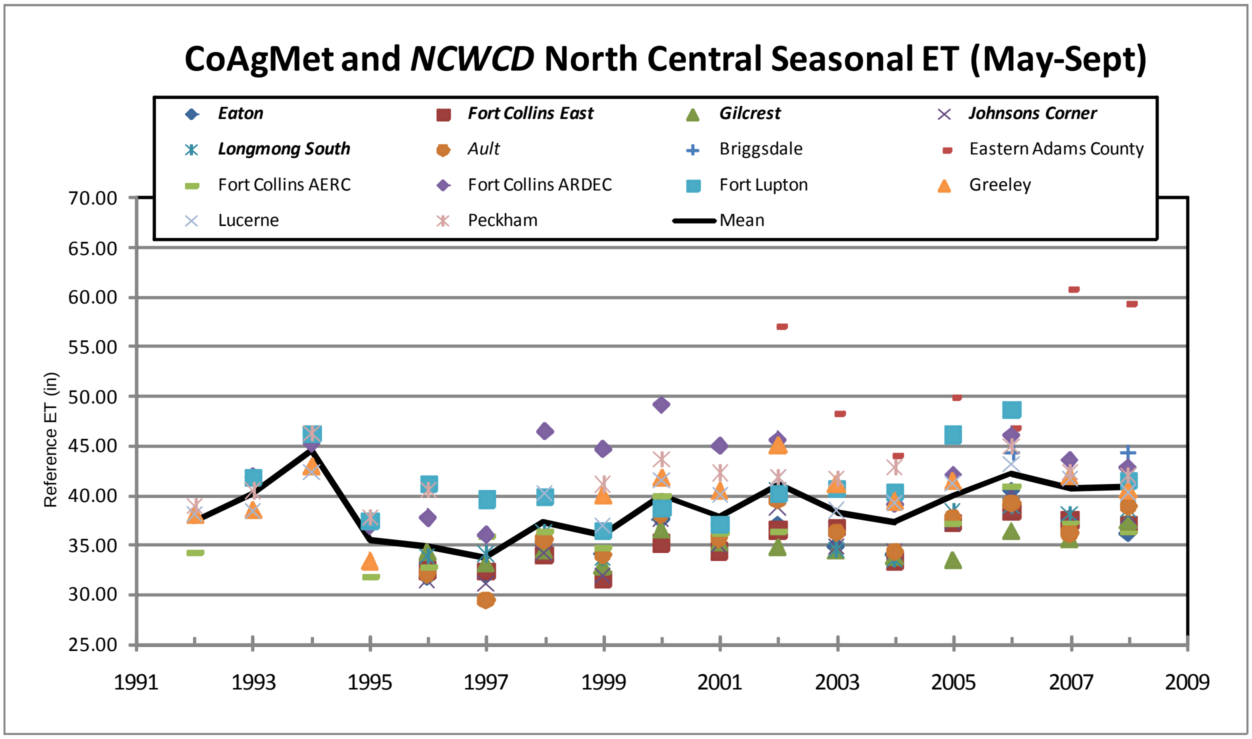

Figure 16: *Seasonal cumulative time-series ET time series for North Central CoAgMet & NCWCD stations (italicized stations denote NCWCD).*

The cumulative seasonal reference ET time series for CoAgMet and NCWCD *(Figure 16)* in the North Central region follow similar patterns. The five NCWCD stations had systematically lower seasonal ET values and less interannual variability compared to CoAgMet. Looking only at data after 1995 when NCWCD data are included, 2006 showed the highest ET rates in this region. In fact, this part of the state was extremely hot and dry in 2006 with severe drought conditions comparable or drier than in 2002. Overall, CoAgMet stations showed seasonal reference ET values on average six inches greater than NCWCD in the North Central region.

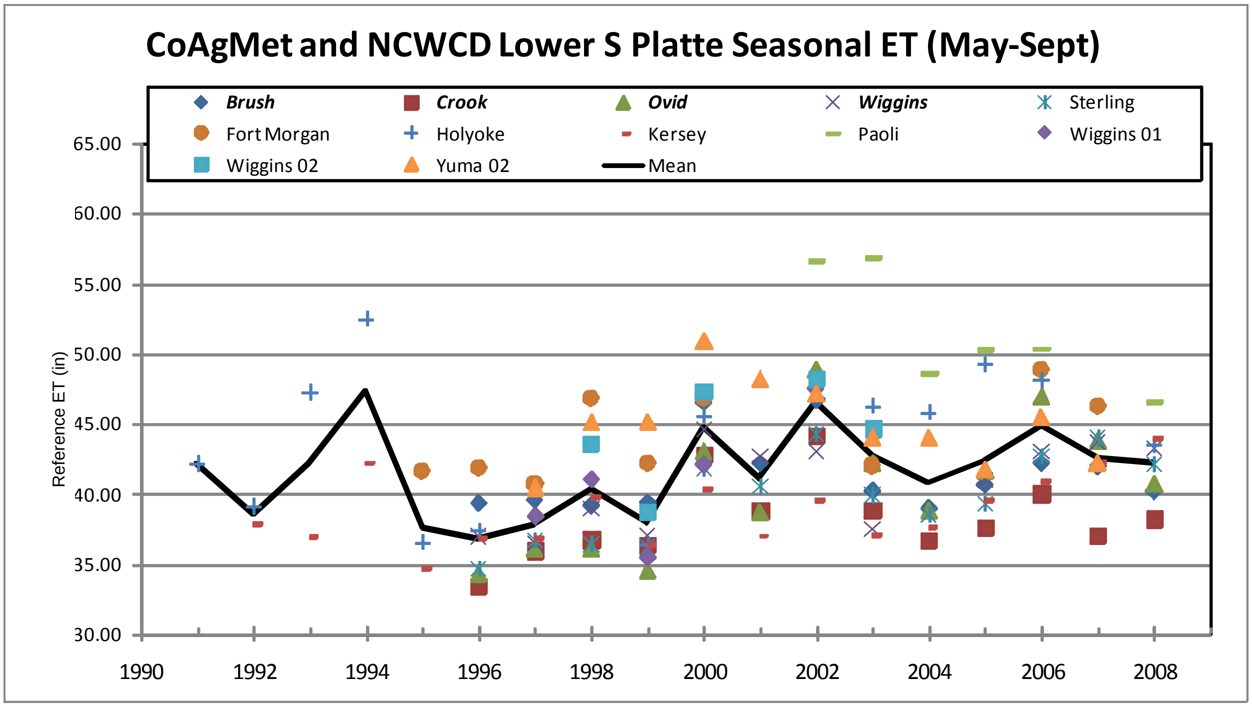

Figure 17: *Seasonal cumulative time-series ET time series for Lower South Platte CoAgMet and NCWCD stations (italicized denote NCWCD).*

The Lower South Platte region contained six CoAgMet stations and five NCWCD sites. Both networks showed very similar year-to-year variations (Figure 17). The seasonal reference ET totals for the CoAgMet stations in this region averaged approximately four inches more than NCWCD. Both networks experienced the highest ET levels during the growing season of 2002, and distinctly lower ET during the wetter years of 1996-1999.

NCWCD's well maintained stations and high-quality data provide an important independent check for CoAgMet. While CoAgMet reference ET estimates are biased higher with respect to NCWCD, the high correlation and similar interannual variability are reassuring and suggest that CoAgMet results are capturing the actual year-to-year variability in growing season ET. The systematically higher ET values for CoAgMet stations compared to NCWCD are not surprising, since NCWCD stations are located near the center of fully irrigated alfalfa fields achieving ideal reference conditions, while CoAgMet stations are often nearer to the edge of irrigated fields.

2008–2009 Additional Work

Preliminary results of this study were presented and reviewed by members of the Colorado Water Institute's Advisory Board, as well as by members of the Colorado Water Congress in early 2008. For CoAgMet to reach its potential as a data source for computing and tracking "consumptive use" over time, two specific recommendations were made: 1) CoAgMet data need to be serially complete (no missing data) for representative long-term stations in each region, and 2) users of CoAgMet weather station data need to know which stations represent fully irrigated, partially irrigated, or dryland environments so that users select only data that are appropriate for ET and consumptive use applications. Based on these recommendations, additional tasks were performed.

A data quality analysis for all stations was conducted for the 2008 calendar year (http://ccc.atmos.colostate.edu/~austin/CoAgMet/2008_Data_Quality_Assesment). Overall data quality improved in 2008, with vast improvements seen in the Arkansas River Valley. Temperature data are of high quality throughout the CoAgMet network with very few problems noted. Relative humidity and solar radiation data have improved considerably in recent years with the implementation of a bi-annual calibration schedule. Wind data continuity is still somewhat problematic, due in part to the network-wide two-meter height standard used for all stations. Obstructions like tall vegetation, fences, farm implements, etc. may be affecting wind movement at some sites. Soil temperatures are not used in the ET computations. Nevertheless, soil temperatures are the least consistent measured variable network wide. Soil temperature remains a low priority compared to other measured variables. Many stations with high soil temperature variability were observed to have non-ideal ground cover (i.e., bare soil or non-irrigated seasonal grasses and weeds).

A regression analysis was conducted for all stations. This was done to test if the essential weather variables for estimating ET (temperature, humidity, wind speed, and solar radiation) are sufficiently correlated in each of the agricultural regions of the state so that regression techniques could be used to fill in missing data. All available data points during the extended growing season (March-October) for a daily maximum and minimum air temperature, mean daily vapor pressure, daily total solar radiation, and wind run were compared between stations within close proximity of each other. Selected results are shown below. Typically, air temperature had the highest correlation (Table 2), and wind run had the lowest (Table 3). Stations that were closest to each other typically correlated best. Differences in elevation and instrument exposure also affected correlations. These results are now being used to objectively compute estimated values for missing data for selected CoAgMet stations. Results may be available by 2010 that will consist of serially complete data for the stations with the longest complete time series with appropriate flags so that users will recognize estimated data and how those values were determined.

NORTH CENTRAL

MAX TEMPERATURE r^2

	ALT01	BRG01	EAC01	GLY01	KSY01	FTC01	FTC03	FTL01	FTM01	LCN01	PKH01	WLT01
ALT01		0.984		0.990			0.985			0.991		
BRG01	0.984			0.985	0.987				0.979	0.984		
EAC01								0.957	0.966			
GLY01	0.990	0.985			0.993				0.970	0.993	0.970	
KSY01		0.987		0.993				0.979	0.976	0.989	0.968	
FTC01							0.987					0.989
FTC03	0.985					0.987						0.990
FTL01			0.957		0.979				0.961		0.958	
FTM01		0.979	0.966	0.970	0.976			0.961			0.945	
LCN01	0.991	0.984		0.993	0.989						0.971	
PKH01				0.970	0.968			0.958	0.945	0.971		
WLT01						0.989	0.990					

Table 2: *Station-to-station correlations, R^2, for daily maximum temperatures in the North Central region of Colorado.*

NORTH CENTRAL

WIND RUN r^2

	ALT01	BRG01	EAC01	GLY01	KSY01	FTC01	FTC03	FTL01	FTM01	LCN01	PKH01	WLT01
ALT01		0.542		0.876			0.623			0.884		
BRG01	0.542			0.507	0.606				0.708	0.598		
EAC01								0.257	0.532			
GLY01	0.876	0.507			0.863				0.650	0.897	0.840	
KSY01		0.606		0.863				0.610	0.760	0.871	0.842	
FTC01							0.611					0.684
FTC03	0.623					0.611						0.879
FTL01			0.257		0.610				0.467		0.679	
FTM01		0.708	0.532	0.650	0.760			0.467			0.651	
LCN01	0.884	0.598		0.897	0.871						0.861	
PKH01				0.840	0.842			0.679	0.651	0.861		
WLT01						0.684	0.879					

Table 3: *Station-to-station correlations, R^2, for daily wind movement data in the North Central region of Colorado.*

Siting assessments were made for all stations within the network to identify and label the stations that best represented fully irrigated, partially irrigated, and dry-land environments. Site photographs, satellite photographs, and reports from CoAgMet collaborators were gathered and surveyed. Primary wind direction analysis was performed for extended growing season months for all stations to aid the siting location analysis. The determination of the primary wind direction was integral for stations with non-ideal siting. A station that is sited downwind of irrigated agriculture may be considered adequately sited, despite nearby obstructions or bare or non-ideal ground cover. Figure 18 illustrates this point for the FRT02 station.

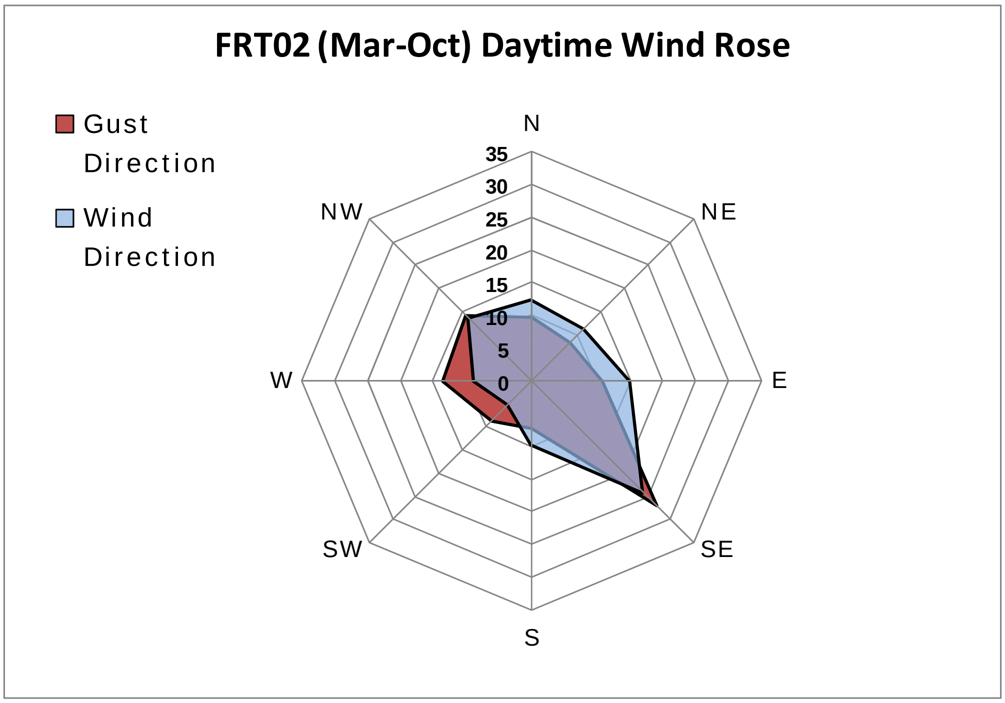

Figure 18: *Growing season wind rose for the CoAgMet station near Fruita, Colorado (FRT02). This station does not have an ideal location, but is typically downwind of irrigated crops.*

Over time, stations change locations or land use, which may affect their future irrigation and siting status. It is advised that all ET estimates taken from stations that do not have a fully irrigated status be used with caution, due to the fact they are not sited in reference conditions.

Seven new stations were added to the CoAgMet network in 2008. These included one new station at the USDA Agricultural Research Center's research farm near Greeley in north-central

Colorado (GLY04), a station at CSU's limited irrigation research plots near Iliff in the Lower South Platte region (ILF01), a new site near Burlington in the Republican River Basin (BRL03), and a new dryland site that was added at the new Sand Creek Massacre historical site north of the Arkansas River (SCM01). In addition, data from CSU's long-term dryland cropping system research sites were added near Sterling, Stratton, and Stonington in eastern Colorado.

Three new sites have been added to CoAgMet in 2009. These stations are in the North Platte River Basin in Jackson County and are part of a study funded through the State of Colorado Interbasin Compact Commission (IBCC) to better track and document ET from Colorado's high elevation hay meadow grasses in the North Park region. These sites will not be grouped into their own region.

Conclusions

A thorough examination of weather data and computed reference ET estimates for seven agricultural regions of Colorado have been completed for the period 1992-2008 using weather data from the CoAgMet. May-September alfalfa average accumulated reference ET was shown to be highest in the Arkansas River Basin (51 inches) and lowest in the North Central region (41 inches). Interannual variations in computed reference ET are not large and are generally less than 15% of the long-term average. At any given station, the difference in cumulative ET from a low ET year to a high ET year is about seven inches. The highest reference ET values for most areas of Colorado were noted in 2002, Colorado's extreme drought year. ET was also very high statewide in 1994, and in northern Colorado in 2006. Low ET rates were observed for 1995-1999. Overall, there is a small upward trend in reference ET, but with only 17 years of data these results are preliminary. Comparisons with data from NCWCD showed that CoAgMet ET estimates correlate well with data from NCWCD's well maintained weather station network. CoAgMet shows systematically higher ET rates and more station-to-station variability than NCWCD. This is likely due to the fact that NCWCD stations are usually located in the center of large fields of fully irrigated alfalfa, while CoAgMet stations are situated in a variety of irrigated, partially irrigated, and dryland locations.

This study shows that CoAgMet has the potential to provide critical weather information to assess year-to-year variations in reference ET necessary for irrigation scheduling, water resource assessments, and decision support. However, periods of missing data, infrequent instrument calibration, and potentially unrepresentative locations for some weather stations have compromised CoAgMet data quality for long-term ET applications. Improvements in station maintenance and exposure are encouraged so that the CoAgMet network can become a more valuable part of Colorado water management and planning for the future.

Future Plans for CoAgMet

Serially complete time series will be generated for many CoAgMet stations. A series of flags will be developed so that users will know what data were estimated, how these estimates were made, and the confidence of these estimates. This will give a much-needed increase in available data for long-term trend analysis and consumptive use assessments. Time series will then be recomputed and reevaluated. Efforts to provide reliable funding for CoAgMet and to assure proper instrument siting and proper maintenance must be given high priority to ensure ongoing high-quality data from this important network.

Acknowledgments

The authors wish to thank the Colorado Water Institute for funding support. Thanks to Dr. Harold Duke and Troy Bauder for their guidance and knowledge, as well as their continued support of the CoAgMet network. The assistance of June Caves of NCWCD was integral to this study. Assistance from Wendy Ryan and John Kleist from the Colorado Climate Center was greatly appreciated.

Literature Cited

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration–Guideliness for computing crop water requirements, *FAO Irrigation and drainage paper 56*. FAO Food and Agricultural Organization of the United Nations. Rome 1998.

Blaney, H. F., and Criddle, W. D., 1950. Determining water requirements in irrigated areas from climatological and irrigation data. *U.S.D.A. Soil Conservation Service Rep. SCS-TP 96*, Washington, DC, 49.

Brutsaert, W., 1982. Evaporation into the atmosphere. Reidel, Dordrecht, Nederlands.

Doesken, N.J., Duke, H.R., Hamblen, B.L., Kleist, J., McKee, T.B., McMillan, M.S., Schwartz, H.F., 1998. The Colorado Agricultural Meteorological Network (CoAgMet) – A Unique Collaborative System Supporting Colorado Agriculture. *23rd Conference on Agriculture and Forest Meteorology.* 2-6 November 1998, Albuquerque, NM, pp. 240-242.

Howell, T.A., Evett, S.R., 2004. The Penman-Monteith Method. *United States Department of Agriculture-Agricultural Research Service*. Conservation and Production Laboratory. www.cprl.ars.usda.gov accessed: 29 Aug, 2007.

Irmak, S., Payero, J.O., Derrel, L.M., Irmak, A., Howell, T.A., 2006. Sensitivity Analyses and Sensitivity Coefficients of Standardized Daily ASCE-Penman-Monteith Equation. *Journal of Irrigation and Drainage Engineering*. Nov-Dec., pp. 564-578.

McKinney, M.S., Rosenberg, N.J., 1993. Sensitivity of some potential evapotranspiration. Estimation methods to climate change. *Agricultural and Forest Meteorology*. 64: 81-110.

Penman, H.L., 1948. Natural evaporation from open water, bare soil, and grass. *Proc. R. Soc. Ser.* A 193: 120-145.

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evapotranspiration using large-scale parameters. *Mon. Weather Rev.,* 100: 81-92.