App. Note Code: 4-T

APPLICATION NOTE

Reduced Set Evapotranspiration Station

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Reduced Set Evapotranspiration Station

This application note describes the theory behind the reduced set Penman-Monteith equation, provides the data used to evaluate the accuracy of that equation, discusses the conclusions of the evaluation, and introduces the ET101 Reduced Set Evapotranspiration Station.

Overview

Evapotranspiration is the amount of water lost from the soil through evaporation and plant transpiration. By knowing your crop's evapotranspiration rate, you will understand the water requirements of your crops better. This can help you develop an irrigation schedule that provides sufficient water for your crops without overwatering.

A common and proven method for calculating evapotranspiration is to use the Penman-Monteith equation. This equation calculates evapotranspiration for a reference crop (typically referred to as ET_o). By definition, the reference crop is an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water (see *Doorenbos, J. and Pruitt, W. O., 1975, Crop Water Requirements, Irrigation and Drainage Paper No. 24, FAO Rome, Italy*). A crop coefficient can be used to calculate evapotranspiration for a crop other than the reference crop (typically referred to as ET_c). For specific crop coefficients and a more detailed description of them, see *American Society of Civil Engineers, Hydrology Handbook, 1996*.

The Penman-Monteith equation requires solar radiation, wind speed, relative humidity, and air temperature measurements. Unfortunately the cost of the sensors used to make the measurements is too expensive for some users. To remedy the situation, in 1994 Campbell Scientific began researching whether the Penman-Monteith equation could be modified so that a fewer number of sensors could be used. The goal was to develop a modified Penman-Monteith equation that would provide a growing season ET_o average value that was within ±10% of the standard Penman-Monteith growing season ET_o average value.

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Campbell Scientific's research resulted in the reduced set (RS) Penman-Monteith equation which only requires solar radiation and air temperature measurements. In lieu of actual wind speed measurements, the RS Penman-Monteith equation uses an average value of 2 m s^{-1} (4.5 mph) for low wind areas or an average value of 3 m s^{-1} (6.7 mph) for high wind areas. The RS Penman-Monteith equation calculates the vapor pressure deficit from the previous day's minimum temperature which eliminates the need to measure relative humidity (see the Theory section below).

To evaluate the accuracy of the RS Penman-Monteith equation, we calculated evapotranspiration using both the RS and standard Penman-Monteith equations at several locations. This evaluation showed that the daily ET_o averages varied considerably but weekly averages of the two evapotranspiration calculations agreed reasonably well. Over an entire growing season, the RS Penman-Monteith ET_o average value was within ±5% of the standard Penman-Monteith ET_o average value for most of the well-watered vegetated sites. Four of the sites had a growing season RS ET_o average that varied less than 1% from the standard ET_o average. See the Data and Results sections for more information.

Once the RS Penman-Monteith equation's accuracy was verified, Campbell Scientific designed the ET101 Reduced Set Evapotranspiration Station. See the ET101 section (page 19) for a description of the station.

Other Research

In *Evaluation of Procedures for Estimating Grass Reference Evapotranspiration Using Air Temperature Data Only, August 1995*, Dr. Richard G. Allen also used a fixed wind speed value of 2 or 3 m s^{-1} and calculated the vapor pressure deficit from the previous day's minimum temperature. Unlike the RS Penman-Monteith equation, his study estimated solar radiation by using radiation measurements from neighboring sites. To validate his method, Dr. Allen compared values that were calculated with his evapotranspiration equation to lysimeter measurements. Dr. Allen's research concluded that "...with the assumption that $T_d = T_{min}$, it should be possible to obtain good, representative estimates of ET_o …"

Theory Behind the RS Penman-Monteith Equation

The Penman-Monteith is an energy balance equation that consists of two terms. The first term accounts for water transport due to the energy received from the sun and the energy due to the heating or cooling of the soil. The second term accounts for water transport due to the vapor pressure deficit. In humid environments, solar energy dominates the equation.

The vapor pressure deficit is the difference between the amount of water the air can hold at a given temperature (saturation vapor pressure) and the amount of water the air is currently holding (saturation vapor pressure at dew point). Typically air temperature measurements are used to calculate the saturation vapor pressure and relative humidity measurements are used to calculate the saturation vapor pressure at dew point. However, the most accurate method for calculating saturation vapor pressure at dew point uses dew point temperature and does not require relative humidity measurements. The relative humidity method is commonly used because relative humidity sensors are less expensive than dew point sensors.

For sites surrounded by well-watered vegetated surfaces, the previous day's minimum air temperature is approximately the dew point temperature. This occurs because under well-watered conditions where evaporable water is present, air temperature usually decreases at night until dew point is reached. As the near-surface air temperature approaches the dew point temperature, condensation of vapor from the air and the corresponding heating effect of released latent heat prevent the air temperature from decreasing below the dew point temperature. Under these conditions, the saturation vapor pressure at dew point can be estimated by substituting the previous day's minimum temperature for the dew point temperature and thus eliminating the need to measure relative humidity.

The minimum air temperature may not reach the dew point temperature in arid or semi-arid locations and sites surrounded by bare soil, buildings, asphalt, concrete, or other heat reservoirs. Although Campbell Scientific did not research this, Dr. Richard G. Allen suggested that for these areas the minimum air temperature be adjusted so that the daily minimum temperature is closer to the dew point temperature. For more information about adjusting minimum temperatures, see *Allen, Richard G., Assessing Integrity of Weather Data for Reference Evapotranspiration*

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Estimation, Journal of Irrigation and Drainage Engineering, Vol. 122, 1996.

The influence of wind speed on the standard Penman-Monteith calculation is secondary. Because most sites have a consistent average wind speed from season-to-season, a seasonal average wind speed can be used in the equation.

Research Data

To evaluate the accuracy of the RS Penman-Monteith equation, we calculated evapotranspiration using both the RS and standard Penman-Monteith equations at several locations. This section describes the sites used in the evaluation and lists the data in both tabular and graphical forms. See the Research Results section (page 18) for the conclusion of the evaluation.

Table 1—Site Descriptions

Location	Latitude (deg.)	Longitude (deg.)	Elevation (ft)	Surroundings	Sensors Used
Bethel Mill Park, NJ USA (near Glassboro, NJ)	39.75 N	75.11 W	100	grass cover for 500 ft	Vaisala HMP35C, LiCor LI200S, RM Young Wind Sentry 03001
Chico, CA USA (Chico State Farm)	39.75 N	121.80 W	180	grass cover	Vaisala HMP35C in a NWS wood enclosure, LiCor LI200X, RM Young Wind Monitor (Model 05103)
Edmonton, Alberta Canada	53.30 N	113.58 W	2346	station located at Edmonton International Airport over grass	Vaisala HMP35C, LiCor LI200X, RM Young Wind Sentry 03001
Juniper, ID USA	42 N	114.5 W	4600	station located in an oat field, field is surrounded by sage-brush	Vaisala HMP35C, LiCor LI200X, RM Young Wind Sentry 03001
Las Cruces, NM USA (NWS site)	32.28 N	106.75 W	3881.2	grass cover for 100 ft, asphalt to the East, bare soil and buildings to the West and South, crop cover to the North	CS500 (Vaisala 50Y), LiCor LI200S, Met-One 014A
Las Cruces, NM USA (Leyendecker site)	32.2 N	106.74 W	4058.4	grass cover for 25 ft, then crop cover	CS500 (Vaisala 50Y), LiCor LI200S, Met-One 014A
Lexington, NE USA	40.47 N	99.44 W	2209	grass cover	Vaisala HMP35C, LiCor LI200S, Met-One 014A
Logan, UT USA	41.78 N	111.83 W	4454	station is over turf grass	CS500 (Vaisala 50Y), LiCor LI200X, RM Young Wind Sentry 03001
Mead, NE USA	41.15 N	96.5 W	1160	grass cover	Vaisala HMP35C, LiCor LI200S, Met-One 014A
Scottsbluff, NE USA	41.5 N	103.41 W	3920	grass cover	Vaisala HMP35C, LiCor LI200S, Met-One 014A

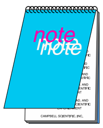
Accuracy of Sensors

Table 1 Notes:

Vaisala HMP35C:	±2% RH (10 to 90% RH), ±3% RH (90 to 100% RH)
CS500 (Vaisala 50Y Intercap sensor):	±3% (10 to 90% RH), ±6% (90 to 100% RH)
LiCor LI200X and LI200S:	±5%
RM Young 03001 Wind Sentry:	±0.5 m s^{-1} (wind speed)
Met One 034A wind set:	±0.12 m s^{-1} (wind speed when < 10.1 m s^{-1}), ±1.1% of reading (wind speed when > 10.1 m s^{-1})
Met One 014A:	±0.11 m s^{-1} (speed < 10.1 m s^{-1}), ±1.5% of reading
RM Young Wind Monitor:	±0.3 m s^{-1} (wind speed)

Table 2—Data Values for Each Site

Site	Date	PM ET_o (mm)	RS PM ET_o (mm)	% Difference	Avg. Daily Difference RS ET_o - ET_o (mm)	7 day RMS (mm/day)	Avg Wind Speed (m s^{-1})	Fixed Wind Speed (m s^{-1})	Avg T_{min}-T_{dew} (°C)
Bethel Mill	May 13-Oct. 27, 1993	626	617.1	-1.42	-0.05	0.25	1.71	2.00	0.20
Bethel Mill	April 11-Oct. 27, 1994	693.3	702.1	1.27	0.04	0.31	1.88	2.00	-0.74
Bethel Mill	April 11-Oct. 27, 1995	738.1	739.3	0.16	0.01	0.21	1.80	2.00	-0.25
Bethel Mill	April 11-Oct. 27, 1996	680.3	689.9	1.41	0.05	0.26	1.82	2.00	-0.59
Chico	Jan. 1 - Dec. 31, 1994	1315.0	1621.0	23.27	0.84	1.09	1.27	2.00	-6.19
Chico	Jan. 1 - Dec. 31, 1995	1119.0	1188.0	6.17	0.21	0.34	1.39	2.00	0.41
Chico	Jan. 1 - Dec. 31, 1996	1275.0	1352.0	6.04	0.21	0.31	1.46	2.00	0.66
Edmonton	July 14-Oct. 13, 1995	230.0	229.0	-0.43	-0.011	0.10	2.19	2.00	-0.38
Juniper	June 28-Oct. 13, 1995	555.2	527.7	-4.95	-0.25	0.35	3.30	3.00	4.84
Las Cruces (Ley)	April 6-Oct. 31, 1994	1288.0	1119.0	-13.12	-0.82	0.95	2.00	2.00	8.44
Las Cruces (Ley)	April 6-Oct. 31, 1995	1307.0	1130.0	-13.54	-0.86	1.04	2.23	2.00	7.80
Las Cruces (Ley)	April 6-Oct. 31, 1996	1197.0	1099.0	-8.19	-0.47	0.65	2.11	2.00	3.40
Las Cruces (NWS)	April 6-Oct. 31, 1994	1266.0	1019.0	-19.51	-1.19	1.34	1.92	2.00	15.41
Las Cruces (NWS)	April 6-Oct. 31, 1995	1202.0	969.5	-19.34	-1.18	1.39	2.07	2.00	13.62
Las Cruces (NWS)	April 6-Oct. 31, 1996	1179.0	1031.0	-12.55	-0.72	0.82	1.99	2.00	7.45
Lexington	May 5-Oct. 8, 1994	653.5	648	-0.84	-0.03	0.51	3.40	3.00	-0.95
Lexington	May 5-Oct. 8, 1995	584.8	598	2.26	0.08	0.49	3.09	3.00	-1.17
Lexington	May 5-Oct. 8, 1996	415.0	477.7	15.11	0.44	0.49	2.82	3.00	-2.62
Logan	June 23-Oct. 13, 1995	482.9	492.6	2.01	0.08	0.15	1.33	2.00	0.92
Logan	May 8-Oct. 13, 1996	646.0	660.2	2.20	0.09	0.19	1.45	2.00	1.05
Logan	May 8-Oct. 13, 1997	641.2	649.7	1.33	0.05	0.12	1.76	2.00	-0.78
Mead	May 1-Oct. 12, 1994	641.1	670.5	4.59	0.18	0.56	2.67	3.00	-1.40
Mead	May 1-Oct. 12, 1995	611.7	608.7	-0.49	-0.02	0.40	3.21	3.00	-1.00
Mead	May 1-Oct. 12, 1996	397.5	460.3	15.8	0.44	0.55	2.81	3.00	-2.71
Scottsbluff	May 11-Sept. 25, 1994	621.6	594.2	-4.41	-0.21	0.45	2.86	3.00	1.41
Scottsbluff	May 11-Sept. 25, 1995	542.9	531.6	-2.08	-0.08	0.28	2.83	3.00	0.44
Scottsbluff	May 11-Sept. 25, 1996	561.5	528.3	-5.91	-0.25	0.40	3.04	3.00	0.95



NOTE

Table 2 Notes:

- For the Bethel Mill, Las Cruces, Lexington, Scottsbluff, and Chico sites, the RS and standard Penman-Monteith values were calculated later using the measurements obtained on the listed days.
- Lexington, NE 1996 has missing data from 5/9 to 5/21; these days weren't included in the averages.
- Mead, NE 1996 has missing data from 6/6 to 6/14, 6/29 to 7/10, and 7/22; these days weren't included in the averages.
- T_{min} is the previous day's minimum temperature; T_{dew} is the current day's average dew point.

Graphs

The following are comparison graphs for each site. The notation used in the graphs are listed below.

PM ET_o	Penman-Monteith Equation
Reduced Set ET_o	Reduced Set Penman-Monteith Equation (solar and air temperature measurements only)
T_{min}	previous day's minimum temperature
T_{dew}	current day's average dew point temperature

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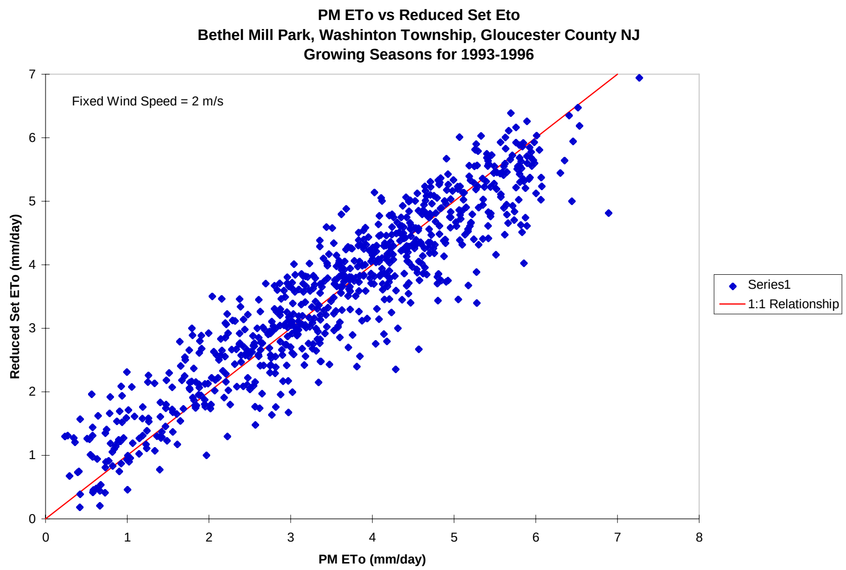
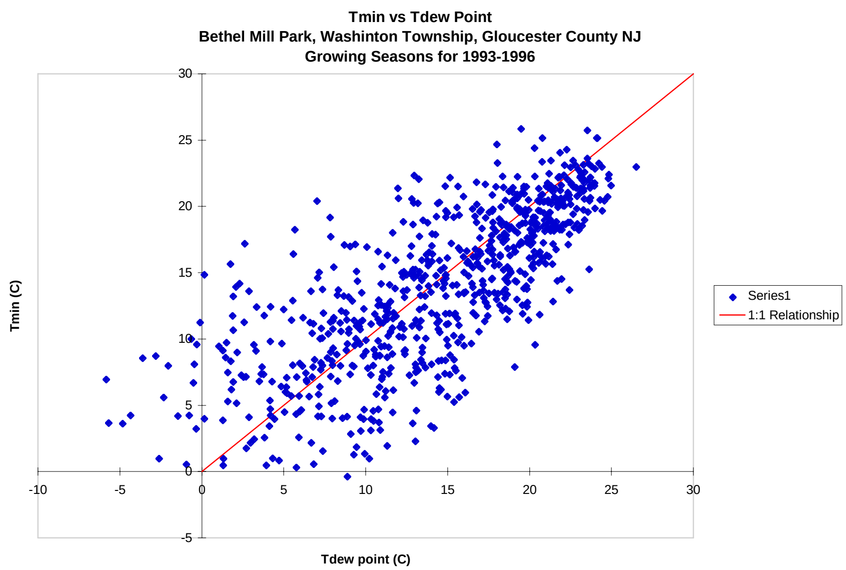
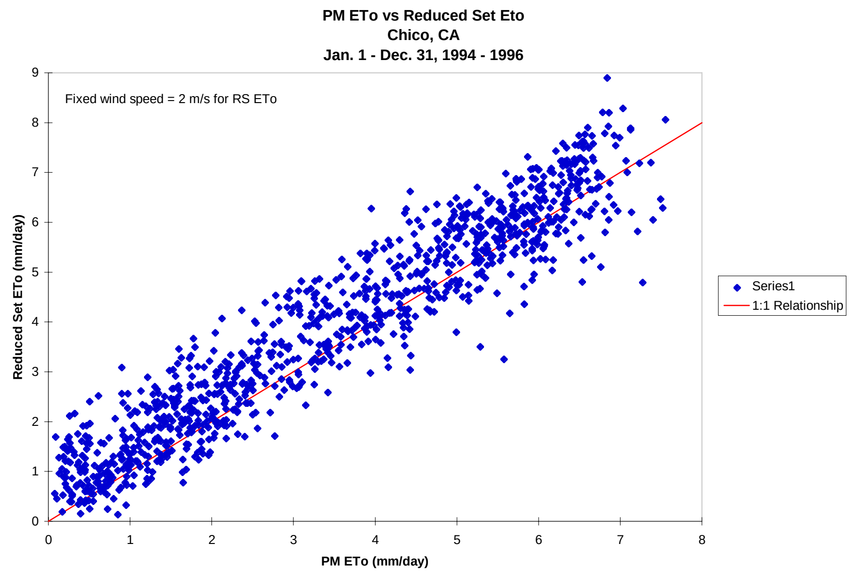
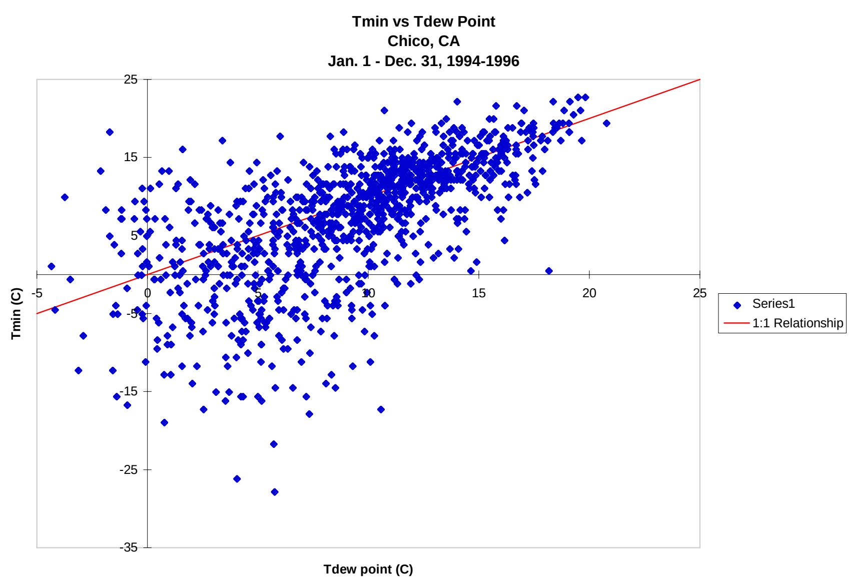
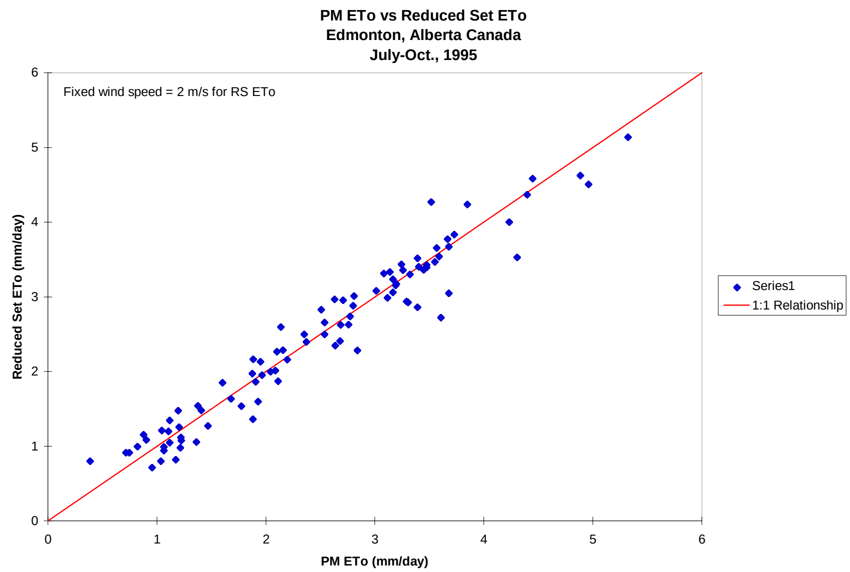
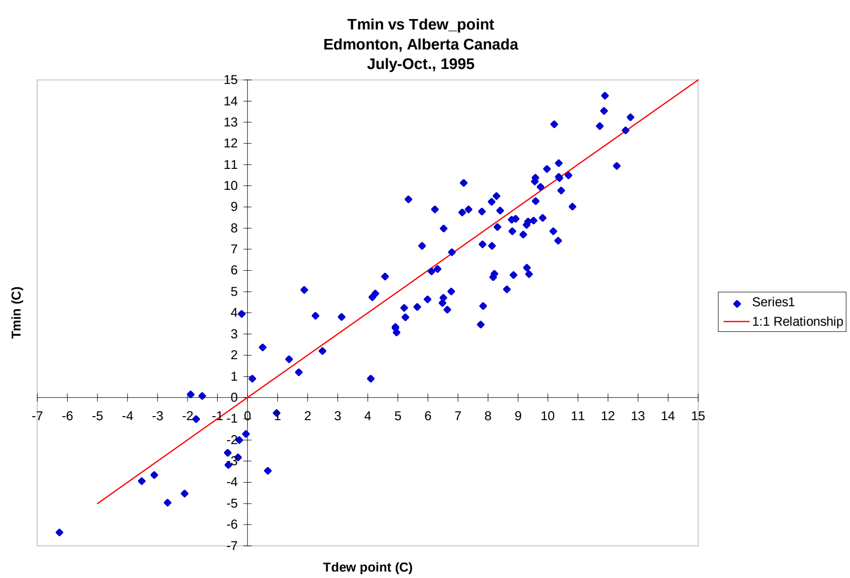

PM ETo vs Reduced Set Eto
Bethel Mill Park, Washinton Township, Gloucester County NJ
Growing Seasons for 1993-1996
Fixed Wind Speed = 2 m/s
Reduced Set ETo (mm/day)
PM ETo (mm/day)
Series1
1:1 Relationship

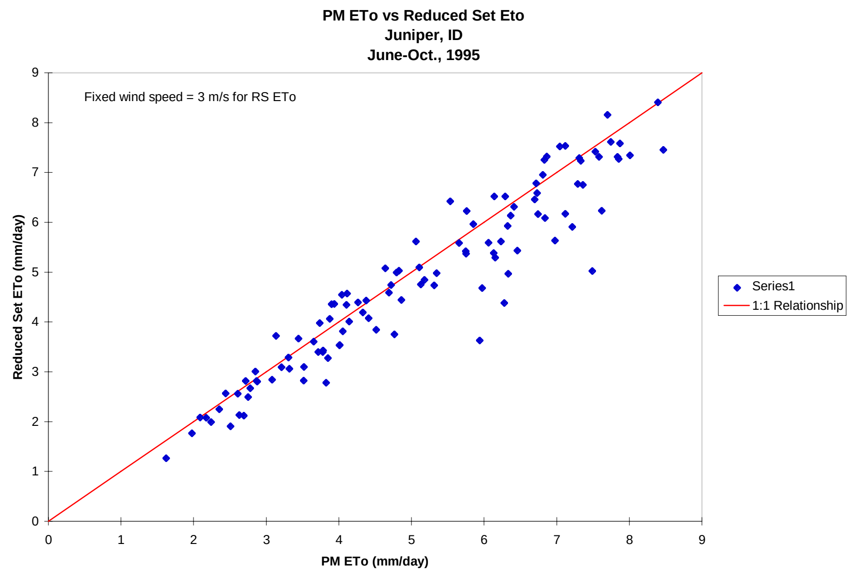

Tmin vs Tdew Point
Bethel Mill Park, Washinton Township, Gloucester County NJ
Growing Seasons for 1993-1996
Tmin (C)
Tdew point (C)
Series1
1:1 Relationship

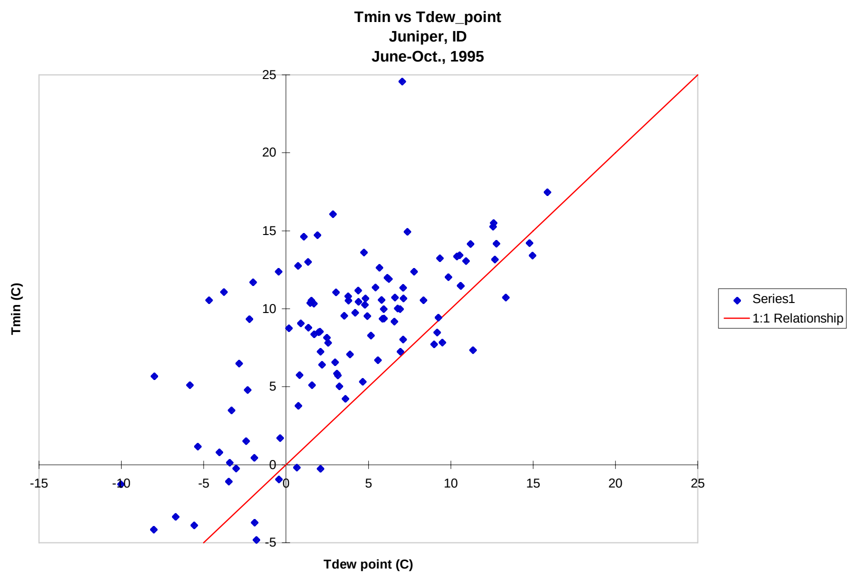

PM ETo vs Reduced Set Eto
Chico, CA
Jan. 1 - Dec. 31, 1994 - 1996
Fixed wind speed = 2 m/s for RS ETo
Reduced Set ETo (mm/day)
PM ETo (mm/day)
Series1
1:1 Relationship

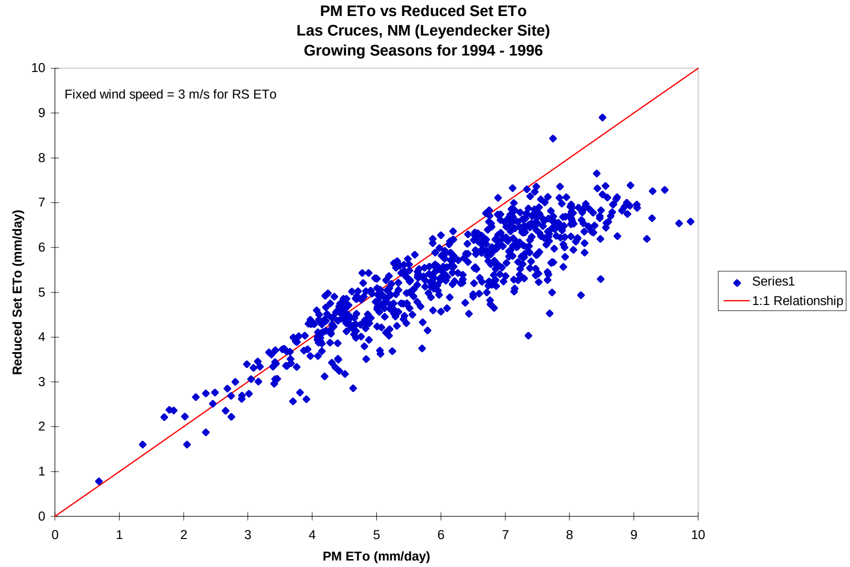

Tmin vs Tdew Point
Chico, CA
Jan. 1 - Dec. 31, 1994-1996
Tmin (C)
Tdew point (C)
Series1
1:1 Relationship

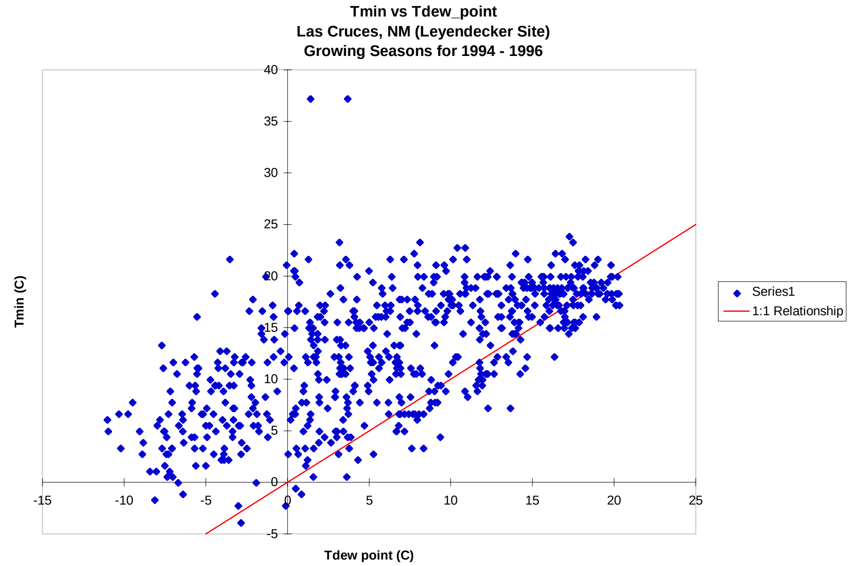

PM ETo vs Reduced Set ETo
Edmonton, Alberta Canada
July-Oct., 1995
Fixed wind speed = 2 m/s for RS ETo
Reduced Set ETo (mm/day)
PM ETo (mm/day)
Series1
1:1 Relationship

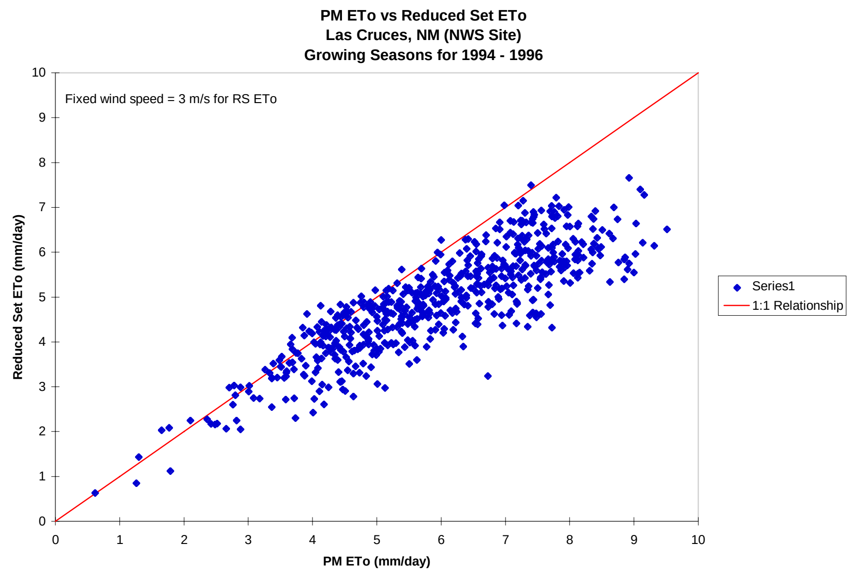

Tmin vs Tdew_point
Edmonton, Alberta Canada
July-Oct., 1995
Tmin (C)
Tdew point (C)
Series1
1:1 Relationship

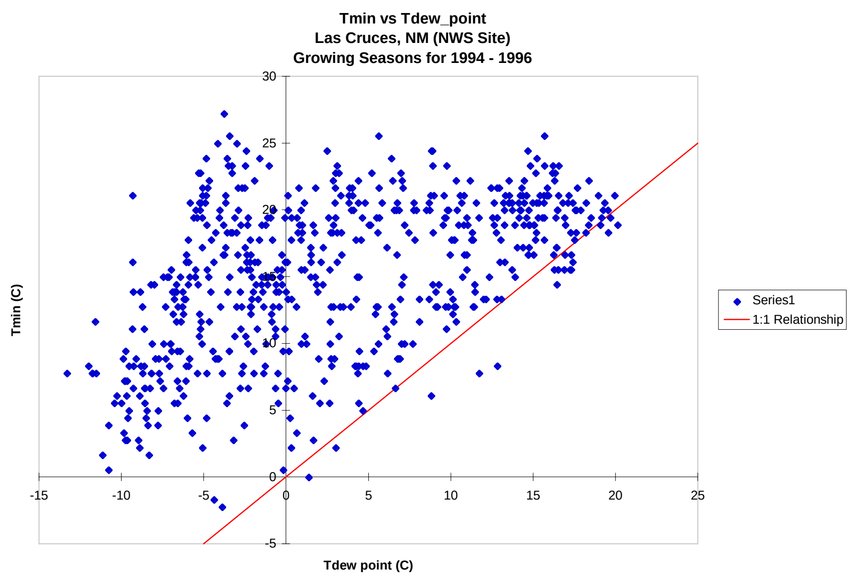

PM ETo vs Reduced Set Eto
Juniper, ID
June-Oct., 1995
Fixed wind speed = 3 m/s for RS ETo
Reduced Set ETo (mm/day)
PM ETo (mm/day)
Series1
1:1 Relationship

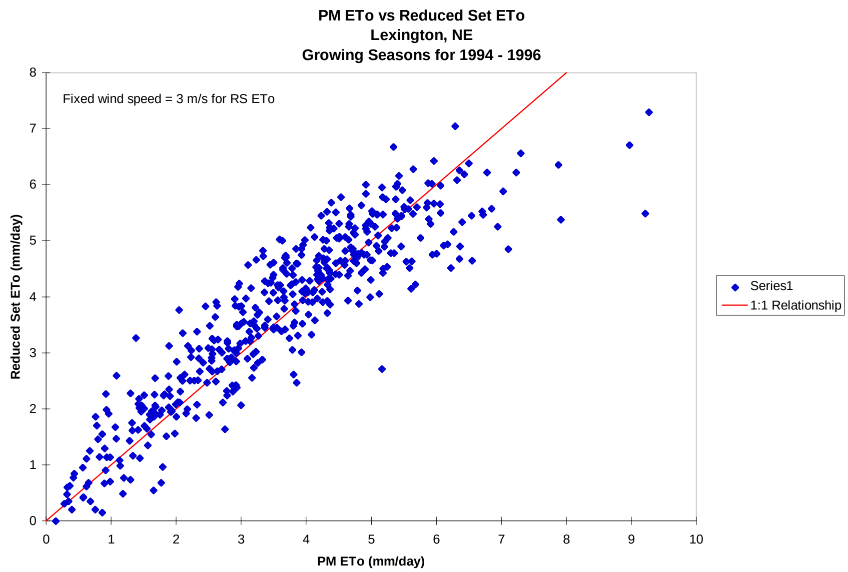

Tmin vs Tdew_point
Juniper, ID
June-Oct., 1995
Tmin (C)
Tdew point (C)
Series1
1:1 Relationship

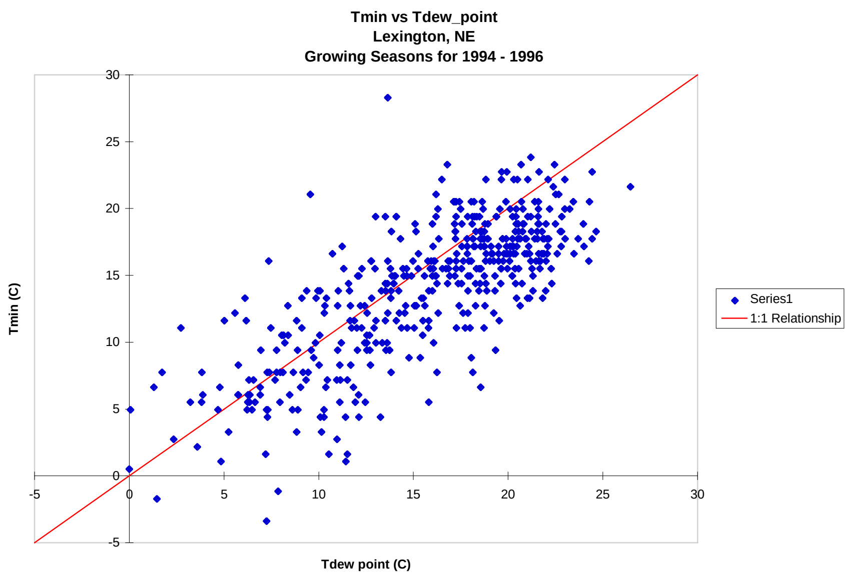

PM ETo vs Reduced Set ETo
Las Cruces, NM (Leyendecker Site)
Growing Seasons for 1994 - 1996
Fixed wind speed = 3 m/s for RS ETo
Reduced Set ETo (mm/day)
PM ETo (mm/day)
Series1
1:1 Relationship
0
1
2
3
4
5
6
7
8
9
10

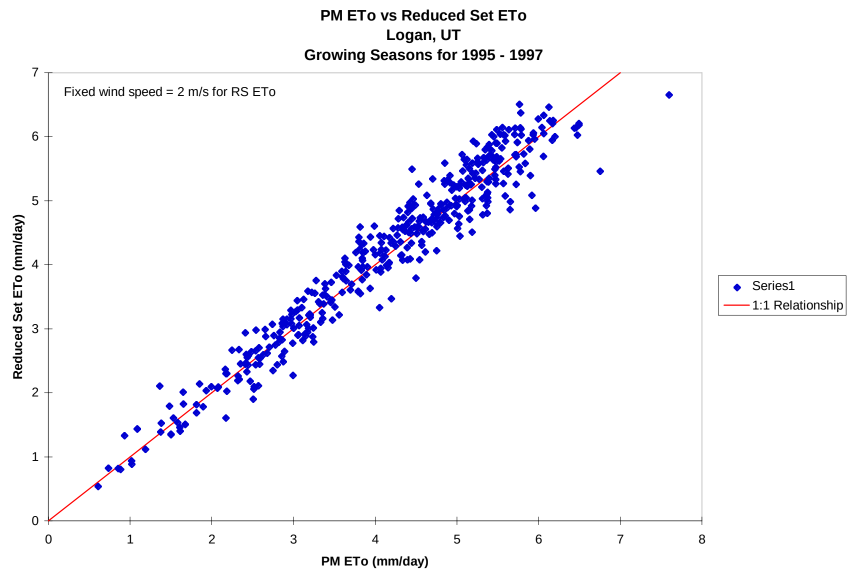

Tmin vs Tdew_point
Las Cruces, NM (Leyendecker Site)
Growing Seasons for 1994 - 1996
Tmin (C)
Tdew point (C)
Series1
1:1 Relationship
-15
-10
-5
0
5
10
15
20
25
30
35
40

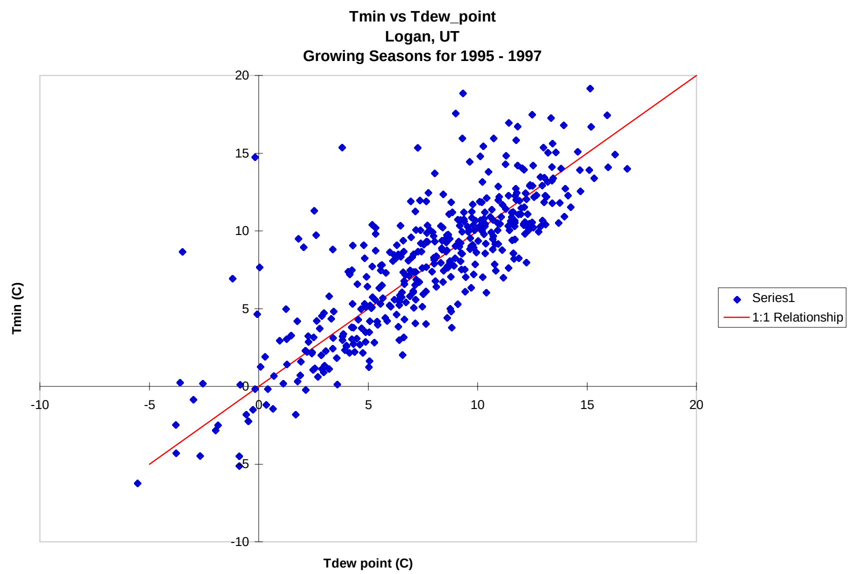

PM ETo vs Reduced Set ETo
Las Cruces, NM (NWS Site)
Growing Seasons for 1994 - 1996
Fixed wind speed = 3 m/s for RS ETo
Reduced Set ETo (mm/day)
PM ETo (mm/day)
Series1
1:1 Relationship


Tmin vs Tdew_point
Las Cruces, NM (NWS Site)
Growing Seasons for 1994 - 1996
Tmin (C)
Tdew point (C)
Series1
1:1 Relationship


PM ETo vs Reduced Set ETo
Lexington, NE
Growing Seasons for 1994 - 1996
Fixed wind speed = 3 m/s for RS ETo
Reduced Set ETo (mm/day)
PM ETo (mm/day)
Series1
1:1 Relationship


Tmin vs Tdew_point
Lexington, NE
Growing Seasons for 1994 - 1996
Tmin (C)
Tdew point (C)
Series1
1:1 Relationship





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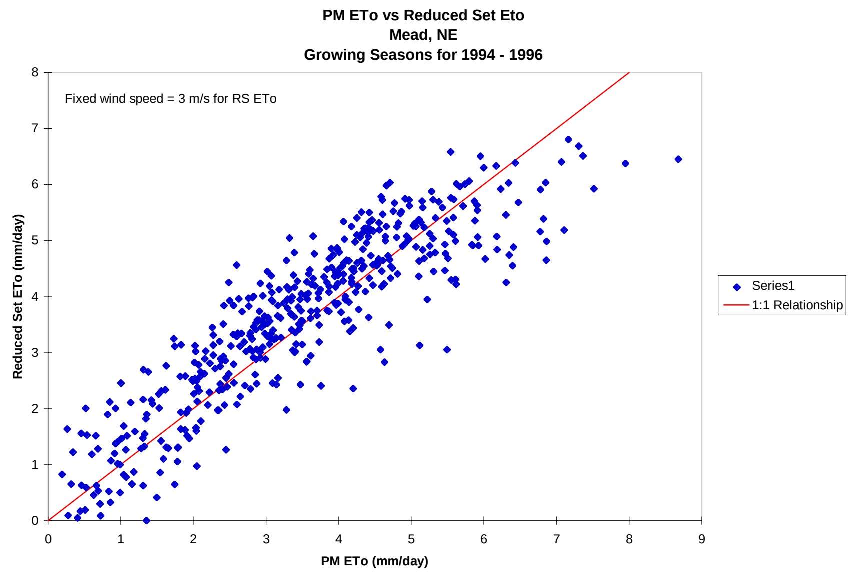
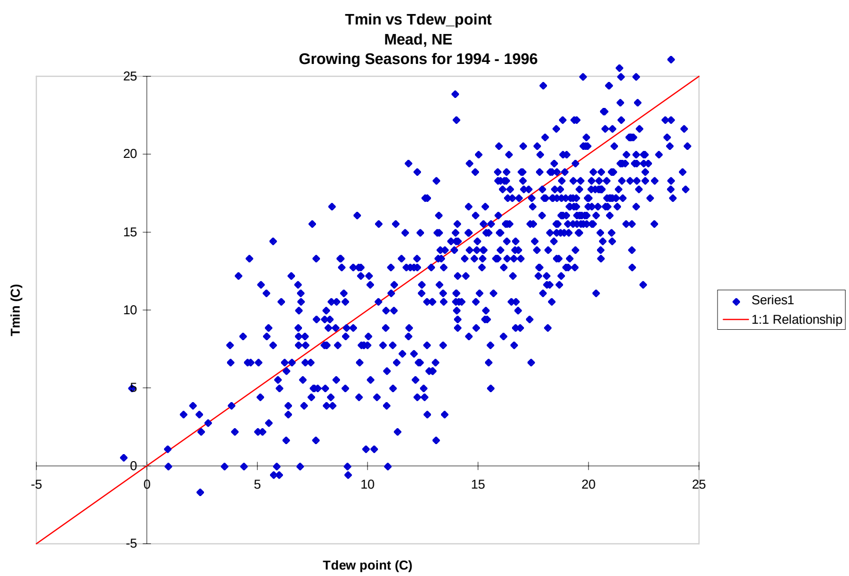
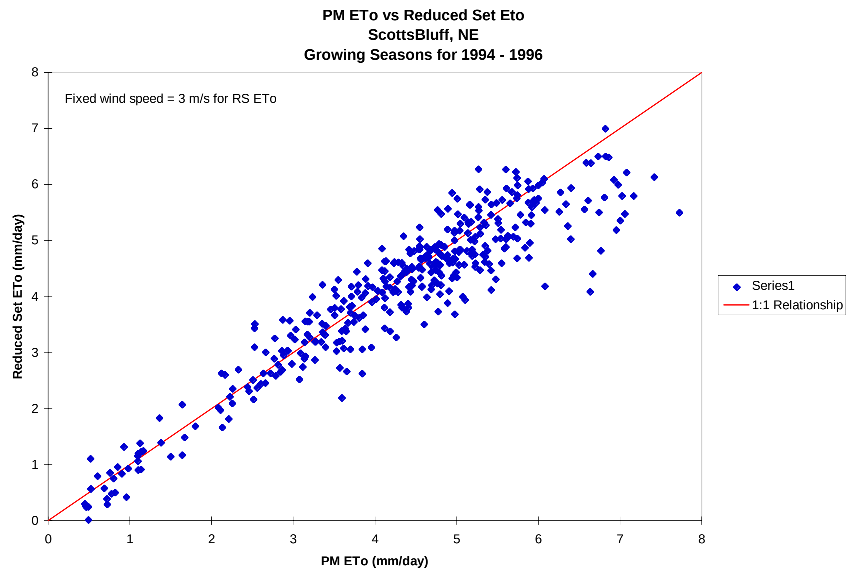
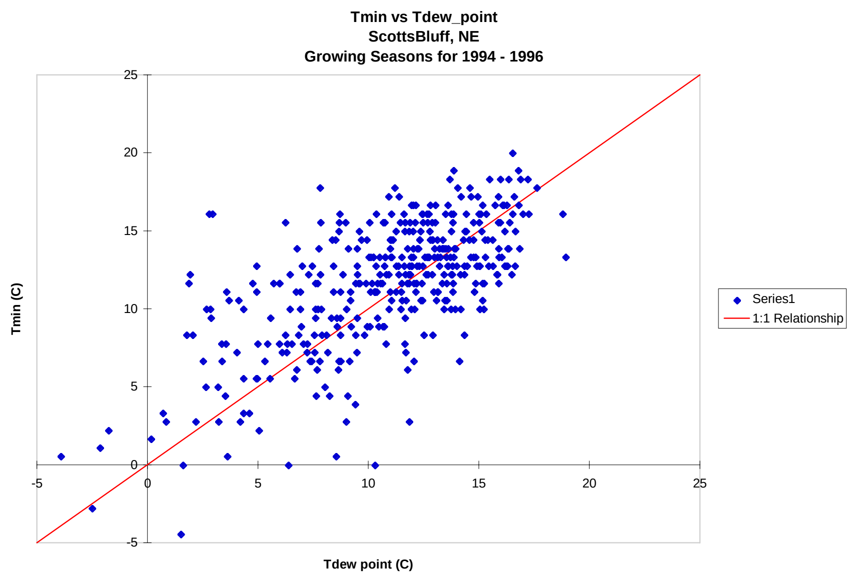

PM ETo vs Reduced Set Eto
Mead, NE
Growing Seasons for 1994 - 1996
Fixed wind speed = 3 m/s for RS ETo
Reduced Set ETo (mm/day)
PM ETo (mm/day)
Series1
1:1 Relationship


Tmin vs Tdew_point
Mead, NE
Growing Seasons for 1994 - 1996
Tmin (C)
Tdew point (C)
Series1
1:1 Relationship


PM ETo vs Reduced Set Eto
ScottsBluff, NE
Growing Seasons for 1994 - 1996
Fixed wind speed = 3 m/s for RS ETo
Reduced Set ETo (mm/day)
PM ETo (mm/day)
Series1
1:1 Relationship


Tmin vs Tdew_point
ScottsBluff, NE
Growing Seasons for 1994 - 1996
Tmin (C)
Tdew point (C)
Series1
1:1 Relationship

Research Results

Conclusions for Individual Sites

Bethel Mill Park, Washington Township, Gloucester County, NJ USA
This site is a perfect candidate for the RS Penman-Monteith equation since the previous day's minimum temperature is close to the current day's average dew point temperature.

Chico, CA USA (Chico State Farm)
This site is a candidate for the RS Penman-Monteith equation. However in 1994 the previous day's minimum temperature was below the current day's average dew point temperature which caused the RS Penman-Monteith to over estimate the ET_o value.

Edmonton, Alberta Canada
The partial growing season's worth of data from this site looks very good. The previous minimum daily temperature was very close to the current day's average dew point temperature and the wind speed was very close to the fixed wind speed. The RS Penman-Monteith could be used in this location.

Juniper, ID USA
This site is an agricultural field (oats) surrounded by arid range land and has strong winds. The previous day's minimum temperature was 4.8 °C above the current day's average dew point temperature and the average wind speed was close to the fixed wind speed. The RS Penman-Monteith could be used here but the equation will underestimate the Penman-Monteith ET_o value due to the difference between the minimum and the dew point temperature.

Las Cruces, NM USA (Leyendecker site)
Because of the site's arid climate, the previous day's minimum temperature is above the current day's average dew point temperature. This causes the RS Penman-Monteith to underestimate the ET_o value. Therefore the RS Penman-Monteith equation should not be used here unless minimum temperature correction is used.

(Note that the ET_o difference for this site is less than that of the Las Cruces, NWS site. This is because this site is surrounded by more vegetation.)

Las Cruces, NM USA (NWS site)
The site's arid climate causes the previous day's minimum temperature to be above the current day's average dew point temperature. This results in the RS Penman-Monteith under estimating the ET_o value. Therefore the RS Penman-Monteith equation should not be used here unless minimum temperature correction is used.

Logan, UT USA
This site is a perfect candidate for the RS Penman-Monteith equation. Although Logan has a semi-arid climate, the station is surrounded by irrigated agricultural land. This caused the previous day's minimum temperature to be close to the current day's dew point temperature.

Lexington, Mead, and Scottsbluff, NE USA
These sites are candidates for the RS Penman-Monteith equation. However in 1996 the previous day's average minimum temperatures recorded at Lexington and Mead were below the current day's dew point temperature. This caused the RS Penman-Monteith to over estimate the ET_o value.

Overall Conclusions

1. The Reduced Set ET_o is more dependent on the assumption that $T_{min} \cong T_{dewpoint}$ than on the fixed wind speed value.

2. The reduced set growing season ET_o average will vary more than 10% from the standard growing season ET_o average if the average daily minimum temperature is 2°C less than the dew point temperature or the average daily minimum temperature is 5°C greater than the dew point temperature.

ET101 Reduced Set ET_o Station

After verifying the RS Penman-Monteith equation, Campbell Scientific designed the ET101, a Reduced Set ET_o station. At a reasonable price, this easy-to-install, low maintenance station provides a pyranometer for measuring solar radiation, a thermistor for measuring air temperature, and a Campbell Scientific datalogger that calculates the RS Penman-Monteith ET_o values. The measurements and ET_o values can be telemetered via phone (including cellular and voice synthesized) or short haul modems. See our product literature for more information.

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