Technical Elements of CIMIS

The California Irrigation Management Information System

December 1998

State of California, The Resources Agency, Department of Water Resources, Division of Planning and Local Assistance

ERRATA

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1. Page 23
   Equation 5, e_s should be changed to e_a

2. Page 27
   Insert the word relative into the definition of E_o; that is,
   E_o = the relative Earth -Sun distance

3. Page 28
   Equation (27) should be

$$\varphi = Y\frac{\pi}{180}$$

   where
   Y = latitude of the station location (degrees)

4. Page 30
   The second paragraph is corrected and is reproduced below.

   The equation of time is used to correct for solar day length (not necessarily 24 hours). It corrects for the effect of perturbation in the earth's rate of rotation (wobble in earth's axis rotation) on the time the sun crosses the meridian of the weather station.

Foreword

The California Irrigation Management Information System (CIMIS) is an important tool for California water users. It assists farmers, homeowners, landscape and park managers improve irrigation management. In California, there are 2,900 registered CIMIS users and nearly 72,000 direct requests for data annually. Developed by the Department with data from many agencies, CIMIS provides timely reference evapotranspiration data and on-demand local irrigation information to the public.

There are several CIMIS publications designed to assist CIMIS users such as *CIMIS Resource* books and *CIMIS Alert*. This publication explains the technical aspects of CIMIS, including station site selection and maintenance, sensor specifications, calibration, data collection, quality control, and the equations used to estimate reference evapotranspiration. Those interested in the CIMIS program's technical elements will find this report useful.

CIMIS assistance can be obtained by contacting the Department's CIMIS staff listed in Appendix H, or telephoning (916) 327-1788.

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Introduction

The California Irrigation Management Information System, comprising a network of automated weather stations, is the Department's primary program for automated estimation and dissemination of reference evapotranspiration (ETo) data. ETo is the amount of water lost from the soil surface (evaporation) combined with the amount of water used by 10 to 15 centimeter tall unstressed irrigated grass (transpiration) at the weather station site. CIMIS ETo and data from the Department's evaporation pans provide the basis for estimating crop, landscape, and vegetative water use. This information is valuable for irrigation water management, water demand management programs, and planning. In addition to evapotranspiration data, CIMIS disseminates solar radiation, vapor pressure, relative humidity, air temperature, wind speed and direction, and precipitation data.

Although CIMIS data is used primarily for irrigation scheduling and water management, it is increasingly used in areas such as pest control, modeling atmospheric particulate matter, calculating degree days and calculating chill hours, and designing irrigation projects. Many agencies and individuals request CIMIS technical information. With the increased demand for CIMIS data, the advent of precision farming, public agencies' interest, and improved irrigation scheduling, it is important that CIMIS technical information be readily accessible to the public. This publication provides an understanding of the data's origin and possible limitations of using the data for purposes other than for which CIMIS was designed.

Weather Stations

The CIMIS network of integrated computerized automated weather stations covers the entire state of California. As of October 1998, there are 98 stations, making CIMIS the nation's largest standardized automated agricultural weather station network. Fifty-seven stations are owned and maintained by cooperating private or public agencies, making CIMIS a partnership between the Department and the public and private sectors. Figure 1 shows the locations of current weather stations. CIMIS data is also available from 45 historical stations that are not shown in Figure 1. Historical stations are stations that have been relocated or discontinued because of a land use change that did not meet the site criteria.

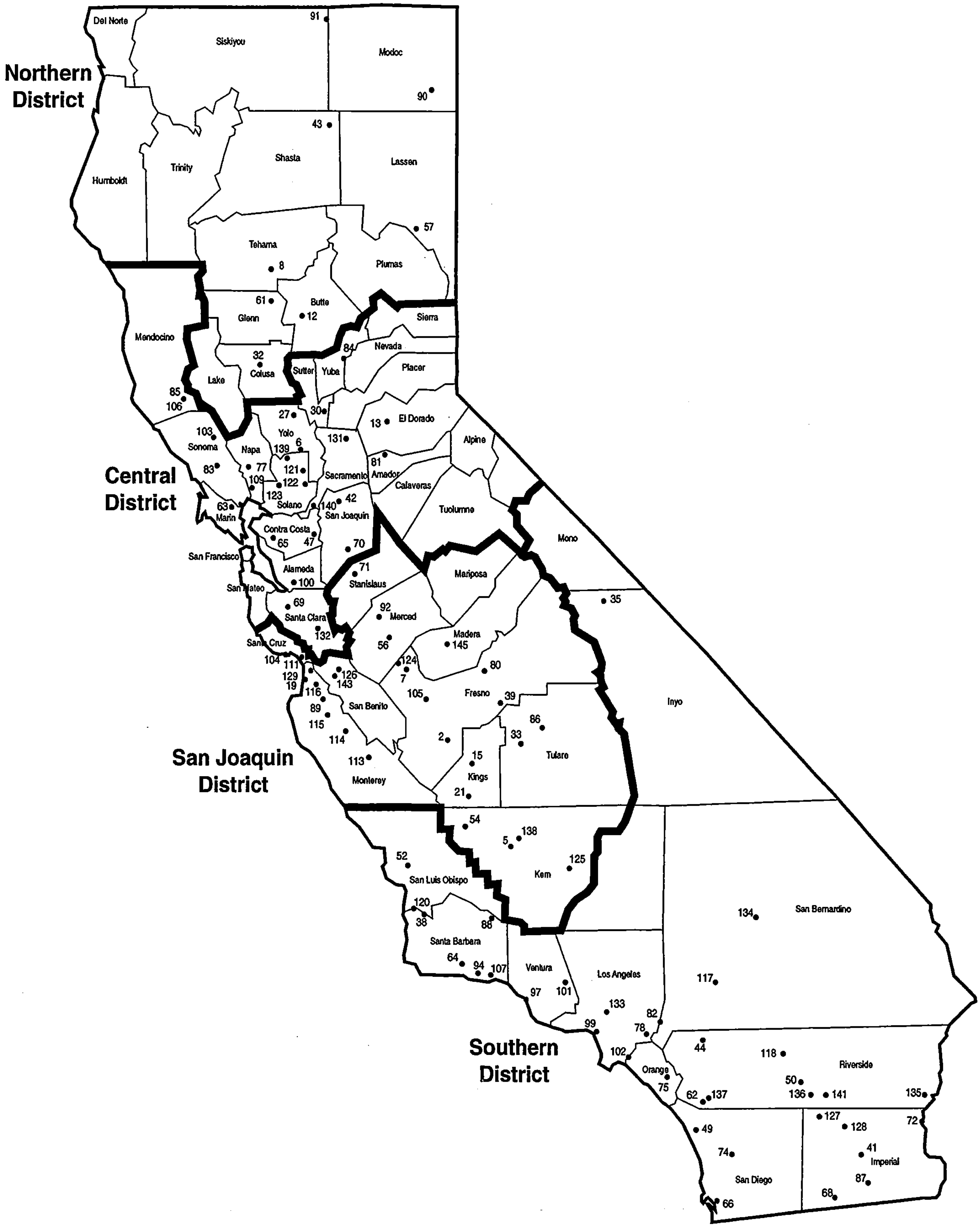
Weather Station Siting Criteria

The placement of a weather station and the local environment of a weather station site can affect the accuracy of ETo (estimated using the stations' weather data) for the area in which it is located. Buildings or trees close to a weather station can affect wind speed data, which affects the estimated ETo. The absence of a healthy green grass under a weather station affects humidity, which will adversely affect ETo. Bare soil, instead of cropped land, can increase advective energy, increasing temperatures, and decreasing humidities, which would tend to increase the ETo value.

A CIMIS weather station should be located in the area that the station is meant to represent. The overriding factor in locating any CIMIS weather station is that the station should be representative of the largest possible surrounding area. This ensures the most efficient use of weather stations for supplying accurate ETo information. The ideal site for a CIMIS weather station would be located in a 20-acre or larger pasture. The grass would be well maintained (properly irrigated and fertilized) and mowed or grazed frequently to maintain a height between 10 to 15 cm (4 to 6 inches).

Unfortunately, ideal sites are often unavailable; therefore, with the help of the University of California, Davis, the Department has prepared criteria to find and judge prospective CIMIS weather stations sites. The criteria were developed to ensure collection of high quality data suitable for estimation of ETo. If these criteria are adhered to, uncertainty in data because of obstructions, thermal radiation from all sources, and condensation due to lack of wind movement can be eliminated or minimized. These guidelines are used pending the adoption of the American Society of Agricultural Engineers Project X505 Standards. The present guidelines are in Appendix B.

Current CIMIS Station Locations
September 1998



Weather Station Maintenance

The Department has standardized the operation and maintenance of the weather station network. Those stations owned by the Department are maintained by Department staff or with help from local agencies. Stations in the CIMIS network owned by cooperators are maintained by the owners under the Department's direction.

Maintenance standards call for a maintenance visit every three to four weeks during the warmer months. Visits decrease to every five or six weeks in the cooler months. The purpose of the maintenance visit is to check the sensors for accuracy and/or operation and to clean or replace sensors as required. The grass under each weather station site is mowed regularly to a height between 10 and 15 cm. The grass is irrigated and fertilized to keep it growing. All stations are annually calibrated for accuracy by the Department. Stations' sensors are compared against a set of standardized sensors used only for calibrations.

Sensors

Each CIMIS weather station is equipped with seven core electronic sensors. All the weather stations are identical, having the same equipment and sensors and operating similarly. All stations have their equipment and sensors mounted on a mast, which is mounted on a tripod base. A typical CIMIS station with the seven sensors is shown in Figure 2. The seven sensors are: pyranometer, soil temperature sensor (thermistor), air temperature sensor (thermistor), relative humidity sensor, anemometer, wind vane, and rain gauge. These sensors measure solar radiation, soil temperature, air temperature, relative humidity, wind speed, wind direction, and precipitation, respectively. In addition, vapor pressure is calculated from relative humidity and air temperature. For details on sensor specifications see Appendix C.

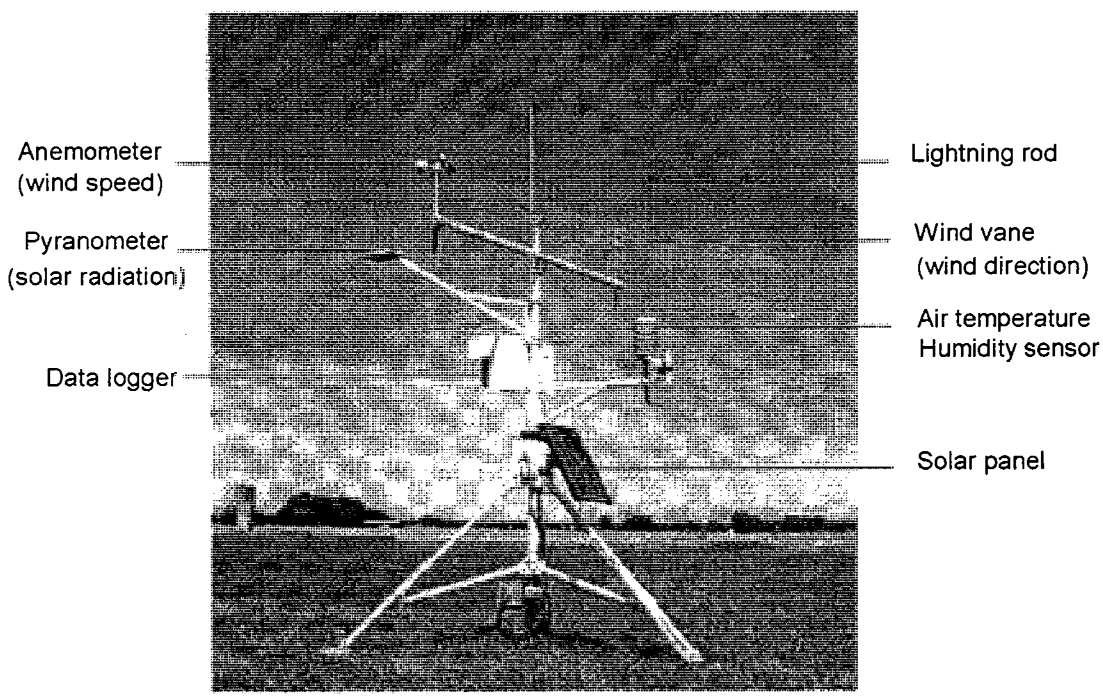


Figure 2. Typical CIMIS Weather Station

Network Operation

The electronic sensors measuring the various parameters are connected by wires to a datalogger mounted on the mast of each station. All the dataloggers are manufactured by Campbell Scientific[1], and are composed of the following three models: 78 percent CR10, 21 percent 21X, and 1 percent CR21. The dataloggers are powered by solar panels.

Once every minute, the datalogger takes a reading of each sensor and records it. It continues for one hour, then averages the 60 readings for an hourly average, or accumulates the 60 readings for an hourly total, and stores all these in memory. It continues collecting data in this manner throughout the day (midnight to midnight). After 24 hours, the datalogger calculates the daily averages and totals using the 24 hourly averages and totals and stores them. The datalogger also determines the maximum and minimum temperatures and relative humidities. These values are the highest and lowest of the one-minute readings during the day.

After midnight (Pacific Standard Time), a microcomputer in the main Sacramento CIMIS computer begins the interrogation of the stations. This communication is done using telephone lines. Each station has its own telephone service and modem. The microcomputer makes a phone connection with a datalogger and the data is downloaded to the microcomputer; this process continues through the early morning hours and, usually, all stations are interrogated by 4 a.m. If a station does not answer the phone call from the microcomputer during the early morning hours because of problems with the telephone lines, the station is interrogated again at 9 a.m.

[1]Mention of a trademark or vendor does not imply product approval by the Department.

The collected data is processed into daily files and then put into the CIMIS computer. The CIMIS computer then performs two tasks:
(1) estimates ETo, and (2) runs the data through a quality control program and flags data.

The weather and ETo data are stored in a database for public access through a dial-up service and telnet through the Internet. Some of the data are archived for access through the World Wide Web from the CIMIS home page.

Weather Parameters

Three sets of data are available on the CIMIS database. These are hourly, daily, and monthly. The time for hourly data is the end of each hour (Pacific Standard Time).

The hourly data available from the CIMIS database are listed in Table 1. For explanation of units, refer to Appendix D.

Table 1. Hourly Weather Parameters

Parameter No.	Parameter name	Units	
		Metric	English
1	SOLAR RADIATION	W/sq.m	Ly/day
2	NET RADIATION	W/sq.m	Ly/day
3	SOIL TEMPERATURE 15cm	°C	°F
4	AIR TEMPERATURE	°C	°F
5	VAPOR PRESSURE	kPa	mBars
6	EXPERIMENTAL #1		
7	EXPERIMENTAL #2		
8	WIND SPEED	m/s	mph
9	RESULTANT WIND	m/s	mph
10	WIND DIRECTION	0-360 degrees	0-360
11	STD. DEV. OF WIND DIRECTION		
12	PRECIPITATION	mm	in
13	NOT USED		
14	NOT USED		
15	HOURLY ETo	mm	in
16	RELATIVE HUMIDITY	%	%
17	DEW POINT TEMPERATURE	°C	°F

Daily data are 24-hour totals or averages measured from midnight to midnight. Daily data are listed in Table 2.

Table 2. Daily Weather Parameters

Parameter No.	Parameter name	Units	
		Metric	English
1	SOLAR RADIATION AVG.	W/sq.m	Ly/day
2	NET RADIATION AVG.	W/sq.m	Ly/day
3	MAXIMUM SOIL TEMPERATURE 15cm	°C	°F
4	MINIMUM SOIL TEMPERATURE 15cm	°C	°F
5	AVERAGE SOIL TEMPERATURE 15cm	°C	°F
6	MAXIMUM AIR TEMPERATURE	°C	°F
7	MINIMUM AIR TEMPERATURE	°C	°F
8	AVERAGE AIR TEMPERATURE	°C	°F
9	MAXIMUM VAPOR PRESSURE	kPa	mBars
10	MINIMUM VAPOR PRESSURE	kPa	mBars
11	AVERAGE VAPOR PRESSURE	kPa	mBars
12	EXPERIMENTAL	NA	NA
13	EXPERIMENTAL	NA	NA
14	NOT USED	NA	NA
15	NOT USED	NA	NA
16	AVERAGE WIND SPEED	m/s	mph
17	WIND ROSE: NNE	m/s	mph
18	WIND ROSE: ENE	m/s	mph
19	WIND ROSE: ESE	m/s	mph
20	WIND ROSE: SSE	m/s	mph
21	WIND ROSE: SSW	m/s	mph
22	WIND ROSE: WSW	m/s	mph
23	WIND ROSE: WNW	m/s	mph
24	WIND ROSE: NNW	m/s	mph
25	PRECIPITATION	mm	in
26	NOT USED	NA	NA
27	NOT USED	NA	NA
28	NOT USED	NA	NA
31*	EXPERIMENTAL	NA	NA
32	MAXIMUM RELATIVE HUMIDITY	%	%
33	MINIMUM RELATIVE HUMIDITY	%	%
34	NOT USED	NA	NA
35	REFERENCE ETo	mm	in
36	BATTERY VOLTAGE DC	V	V
37	AVERAGE RELATIVE HUMIDITY	%	%
38	DEW POINT	°C	°F
39	WIND RUN	km	miles

**** No data collected from 29 and 30***

The following monthly data summaries are available on the CIMIS database:

1. Average solar radiation
2. Average soil temperature at 15 centimeters
3. Average maximum air temperature
4. Average minimum air temperature
5. Average air temperature
6. Average vapor pressure
7. Average wind speed
8. Total precipitation
9. Average maximum relative humidity
10. Average minimum relative humidity
11. Average relative humidity
12. Total evapotranspiration
13. Average dew point temperature
14. Average wind run

Parameter Descriptions

Solar Radiation

Description: Average amount of solar radiation received on a horizonal surface, i.e., at the sensor.

Data: Hourly, daily, and monthly

Sensor: Pyranometer

Remarks: The Li-Cor LI200s pyranometer is located on an extension arm on the south side of the station tripod at 2 meters above the ground. The southern location is to avoid the tripod shadow. The pyranometer measures total incoming solar radiation with silicon photodiodes.

Net Radiation

Description: The difference in the amount of incoming radiation and the amount of radiation returning from the surface. Net radiation is not measured but is estimated from solar radiation, vapor pressure, and air temperature

Data: Hourly and daily

Sensor: None

Remarks: Net radiation is estimated using a modified version of the Monteith equation. It is an earlier version of the method described by Dong, et al (1992).

Soil Temperature

Description: The average soil temperature at 15 cm (6 inches) below actively growing grass that is not water stressed and clipped to a height of about 15 cm.

Data: Hourly, daily, and monthly

Sensor: Thermistor

Remarks: The thermistors are buried horizontally on the south side of the tripod.

Maximum and minimum of daily temperatures and average maximum, and average minimum of monthly temperatures are reported.

Air Temperature

Description: The average temperature of air surrounding the station measured at 1.5 meters above a grass-covered ground.

Data: Hourly, daily, and monthly

Sensor: Thermistor

Remarks: The thermistor is combined with a relative humidity sensor to form a dual probe-- the HMP35C. The HMP35C probe is enclosed in a 12-plate naturally aspirated radiation shield. It is typically located on the south side of the station tripod. The thermistor is a very reliable sensor; however, since temperature sampling is done inside a naturally aspirated shield, temperature errors may occur under calm winds (less than 1 meter per second) and high radiation (800 W/sq.m or higher). Maximum and minimum daily temperatures, and average maximum and minimum monthly temperatures are also recorded.

Vapor Pressure

Description: The pressure exerted by water vapor in moist air (partial pressure exerted by the water vapor). Vapor pressure is not measured but is computed at the station from air temperature and relative humidity

Data: Hourly, daily, and monthly

Sensor: None

Remarks: Vapor pressure is computed every minute, when air temperature and relative humidity are measured. The hourly data is an average of the minute-by-minute computed values for the past hour. Maximum and minimum daily and monthly data are also reported.

Average Wind Speed

Description:	The average wind speed at 2 meters.
Data:	Hourly, daily, and monthly
Sensor:	Three-cup anemometer
Remarks:	The average wind speed is the arithmetic average speed. It is independent of wind direction. The anemometer is typically located on the west side of the tripod on a crossarm.

Wind Direction

Description:	Vector average wind direction measured at a height of 2 meters.
Data:	Hourly and daily wind rose
Sensor:	Wind vane
Remarks:	Wind direction is measured in terms of the number of degrees clockwise from true North (0 or 360 degrees). The direction is always the direction from which the wind is blowing. The wind vane is typically located on the east side of the tripod on the crossarm.

Resultant Wind

Description:	Average wind velocity during the last hour measured at a height of 2 meters.
Data:	Hourly
Sensor:	Anemometer and wind vane
Remarks:	The average wind velocity is a vector average, both speed and direction are taken into account.

Standard Deviation of Wind Direction

Description: The standard deviation of wind direction over the last hour.

Data: Hourly

Sensor: Computed from wind vane measurements.

Remarks: The standard deviation of wind direction is a measure of the steadiness of wind direction. A small standard deviation indicates the wind direction did not change significantly over the last hour.

Precipitation

Description: Total amount of precipitation measured at a 1-meter height.

Data: Hourly, daily, and monthly

Sensor: Tipping-bucket rain gauge

Remarks: The accuracy of a tipping-bucket rain gauge is affected by rainfall intensity. In very light rain (0.1 mm/hr), there may be a delayed measurement (i.e., measurement may occur in next hour instead of at the hour that most of the rain fell.) In very heavy rainfall, some water may splash out of the bucket, resulting in underestimation of total rainfall.

The bucket underestimates hourly snow or freezing rain totals. This is because snow can clog both the bucket and funnel orifice. Very few CIMIS stations are located in areas where this is a factor. Under windy conditions, dry snow can be blown away before the bucket tips.

Relative Humidity

Description: Average relative humidity measured at 1.5 meters above actively growing grass that is not water stressed.

Data: Hourly, daily, and monthly

Sensor: Sorption sensor (combined with air temperature sensor)

Remarks:	The relative humidity sensor is combined with the temperature sensor to form a dual probe--the HMP35C. The HMP35C probe is enclosed in a 12-plate naturally aspirated radiation shield on the south side of the station tripod. Maximum and minimum daily and monthly data are reported.

Reference Evapotranspiration (ETo)

Description:	Total ETo for the time period indicated. (ETo is not measured but estimated from net radiation, air temperature, vapor pressure, and wind speed.)
Data:	Hourly, daily, and monthly
Sensor:	None
Remarks:	ETo is estimated using a version of Penman's equation modified by Pruitt and Doorenbos (proceeding of the International Round Table Conference on "Evapotranspiration," Budapest, Hungary, 1977).

Dew Point Temperature

Description:	The temperature to which air must be cooled (at constant pressure) for the air to become saturated without adding water. Dew point temperature is not measured but is computed from air temperature and relative humidity.
Data:	Hourly, daily, and monthly
Sensor:	None
Remarks:	Dew point is a more conservative measure of the moisture content of air than relative humidity.

Wind Run

Description:	Average wind speed in distance per day.
Data:	Daily, monthly
Sensor:	Cup anemometer
Remarks:	Wind run, though not measured directly, is calculated by multiplying the average daily wind speed (m/s or mph) by 24 hours.

Estimation of Reference Evapotranspiration

The equation used in CIMIS to estimate ETo is a version of Penman's equation (Penman, 1948) modified by Pruitt and Doorenbos (proceeding of the International Round Table Conference on "Evapotranspiration," Budapest, Hungary, 1977). It employs a wind function developed at the University of California, Davis. The inputs used in the equation from CIMIS weather stations are mean hourly solar radiation (from which net radiation is calculated), air temperature, wind speed, and vapor pressure.

The use of hourly data to obtain daily ETo values has proven superior to one in which daily average data are used, as in the original Penman procedure.

Hourly ETo is calculated using Eq.1. Daily ETo equals the sum of 24 hourly ETo.

$$ET_o = W * R_n + (1 - W) * VPD * FU_2 \qquad \textbf{(1)}$$

where

W = Weighting function (dimension less);
R_n = Net Radiation (mm);
VPD = Vapor Pressure Deficit (kPa); and
FU_2 = Wind function (mm kPa^{-1}).

Net radiation in Wm^{-2} is estimated from solar radiation, air temperature, and vapor pressure; it is then converted to mm by dividing by the latent heat of vaporization as follows:

$$R_n\ (mmhr^{-1}) = \frac{R_n\ (Wm^{-2})}{694.5\ (1-0.000946T_a)} \qquad \textbf{(2)}$$

Where T_a = mean hourly temperature (°C)

The method used to calculate net radiation is based on a modification of the Monteith equation (Monteith, 1980).

$$R_n = (1 - \alpha)R_s + \varepsilon_s\left[\varepsilon_o(1 - c)\sigma T_o^4 + c(\sigma T_c^4 - k)\right] - \varepsilon_s \sigma T_s^4 \tag{3}$$

Where

α = surface albedo;
R_s = measured solar radiation received at the station (Wm^{-2});
T_o = clear sky effective temperature (Kelvin)
T_c = cloud base temperature (Kelvin)
ε_s = surface emissivity (approximately=0.98, but 1 is used in Eq.3);
ε_o = sky emissivity from clear portions of the sky;
c = fraction of cloud cover;
σ = Stefan-Boltzmann constant, $5.67 * 10^{-8}\ J\ m^{-2}\ K^{-4}\ s^{-1}$;
k = an empirical coefficient for local cloud properties (Monteith 1980); and
T_s = surface temperature (Kelvin).

Because T_o, T_c, and T_s are unknown, the air temperature (T_a) in Kelvin is substituted for each of the three variables. The factor k is the difference in flux due to the substitution of air temperature for cloud-base temperature. Other variables in Eq. 1 are computed as follows:

i) **W - Weighting function**

$$W = \frac{\Delta}{\Delta + \gamma} \tag{4}$$

Δ - the slope of the saturation vapor pressure versus air temperature curve at the mean hourly air temperature (kPa °C^{-1})

$$\Delta = \left[6790.5 - 5.02808\ T_a + 4916.8 * 10^{-0.0304 T_a}\ T_a^2 + 174209 * 10^{-1302.88/T_a} \right] \frac{es}{T_a^2} \quad \textbf{(5)}$$

where

T_a = mean hourly temperature (Kelvin)

γ - psychrometer constant (kPa °C^{-1}) is calculated using Eq.6 from Fritschen and Gay (1979)

$$\gamma = 0.000646\ (1 + 0.000946\ (T_a - 273.16))\ P \quad \textbf{(6)}$$

where

P = barometric pressure (kPa); and
T_a= mean hourly air temperature (Kelvin)

ii) **VPD - Vapor pressure deficit** (kPa)

$$VPD = (e_a - e_d) \quad \textbf{(7)}$$

here

e_a = Saturation vapor pressure (kPa) based on mean hourly Ta;
e_d = Mean hourly vapor pressure (kPa)

iii) **FU_2- Wind function** (mm kPa^{-1})

Nighttime, Rn ≤ 0

$$FU_2 = 0.125 + 0.0439\, U_2 \quad \textbf{(8)}$$

Daytime, Rn > 0

$$FU_2 = 0.030 + 0.0576\,U_2 \qquad \textbf{(9)}$$

Where

U_2 = mean hourly wind speed measured at 2 meters(ms^{-1})

The barometric pressure in Eq.6 is estimated from station elevation (A) above sea level using Eq. 10 from Doorenbos and Pruitt (1977).

$$P = 101.3 - 0.01152A + 5.44A^2 * 10^{-7} \qquad \textbf{(10)}$$

where

P = barometric Pressure (kPa); and

A = elevation of the station above mean sea level (m)

Net Radiation Equation For Daylight Hours

The modified net radiation equation (Eq.3) used in CIMIS is

$$R_n = (1 - \alpha)R_s + \varepsilon_o\,(1 - c)\sigma T_a^4 + c\sigma T_a^4 - \sigma T_a^4 - ck\,\frac{\pi}{2}\cos\,\omega \qquad \textbf{(11)}$$

or

$$R_n = R_n(o) - ck\,\frac{\pi}{2}\cos\,\omega \qquad \textbf{(12)}$$

where

ck = empirically determined factor to adjusts for cloud base temperature;
ω = hour angle (see equation 29).

The cloud coefficient ck is site specific for each month. The multiplication factor, $\pi/2 \cos \omega$, converts average daily *ck* for a given month to an hourly value.

Cloud coefficient ck at particular sites for each month was computed from average hourly *ck* values.

$$ck = Rn(o) - Rn(m) \qquad \textbf{(13)}$$

where

Rn(o) = calculated net radiation assuming *k*=0 in Eq.3; and
Rn(m)= measured net radiation.

The empirical equations used to calculate various parameters in Eq. 11 for daylight hours, when solar altitude, Θ is $\geq$ 10 degrees are:

i) **Surface albedo**, α-based on Paltridge and Platt (1976)

$$\alpha = 0.00158\Theta + 0.386 \exp(-0.0188\Theta) \qquad when\ \frac{R_S}{I} > 0.375 \qquad \textbf{(14)}$$

$$\alpha = 0.26 \qquad when\ \frac{R_S}{I} < 0.375 \qquad \textbf{(15)}$$

$$\Theta = abs\left(\left(\arccos(\cos Z) * \frac{180}{\pi}\right) - 90\right) \qquad \textbf{(16)}$$

where

R_s= Solar radiation(W m^{-2}); and
I = extraterrestrial radiation (solar radiation on horizontal surface at the top of the atmosphere)(Wm^{-2})

ii) **Clear sky emissivity**, ε_o - based on Satterlund (1979)

$$\varepsilon_o = 1.08 \left[1 - \exp \left(- (10 e_d)^{\frac{T_a}{2016}} \right) \right] \tag{17}$$

where

e_d = hourly mean vapor pressure (kPa); and
T_a = air temperature (Kelvin).

iii) **Fraction of cloud cover**, c - based on Kasten and Czeplak (1980)

$$c = \left(1.3333 - 1.7778 \frac{R_s}{I} \right)^{0.2941176} \tag{18}$$

If $c > 1$ then set $c = 1$
If $c < 0$ then set $c = 0$

Net Radiation Equation For Nighttime

For nighttime hours(Θ<10 degrees), R_s = 0. Although there may be some positive R_s measured at 0<Θ<10 degrees, these values may not be accurate because of pyranometer measurement errors at low sun angles. Thus, with R_s =0, equation (11) reduces to:

$$R_n = \varepsilon_o (1 - c)\, \sigma T_a^4 + c \sigma T_a^4 - \sigma T_a^4 - ck \frac{\pi}{2} \cos \omega \tag{19}$$

Furthermore,

$$ck = 0$$
$$c = c\ (daylight) - 0.25 \qquad (20)$$

where c(daylight) from evening to midnight is,

$$c\ (daylight) = c\ (last\ evening\ hour\ when\ \Theta > 10^{o}) \qquad (21)$$

and c(daylight) from midnight to early morning is,

$$c\ (daylight) = c\ (first\ morning\ hour\ when\ \Theta > 10^{o}) \qquad (22)$$

Dong et al., (1988) examined the ability of Eq. 19 to predict measured *Rn* during hours when $0<\Theta<10$ degrees. They found that the monthly mean difference between measured and calculated Rn (Eq.19) ranged from -5 to 8 Wm^{-2} averaging 2 $W\ m^{-2}$. They concluded that no additional correction was needed for low sun angles. Also, Dong et al., (1988) found that the use of *ck*=0 to estimate nighttime *Rn* provided a better estimate than using *ck* as generated for daylight hours.

Extraterrestrial Radiation Equation

Equations (14),(15), and (18) require the value of extraterrestrial radiation *I*. The calculation of *I* is based on the method described by Iqbal (1983).

$$I = 1367 E_o \cos Z \qquad (23)$$

where

1367 = the solar constant ($W\ m^{-2}$);

E_o = the Earth-Sun distance; and *cos Z* = cosine correction for the angle of incidence (cosine of the solar zenith angle, rad).

E_o is computed from:

$$E_o = (1.00011 + 0.034221 \cos\Gamma + 0.00128 \sin\Gamma + 0.000719 \cos 2\Gamma + 0.000077 \sin 2\Gamma) \quad \textbf{(24)}$$

where

Γ = the day angle, day of year (rad).

$$\Gamma = 2\pi \frac{(d - 1)}{365} \quad \textbf{(25)}$$

where

d = day of the year, and for leap years 366 is used in the denominator.

The cosine correction, *cos Z*, in equation 23 is given by:

$$\cos Z = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega \quad \textbf{(26)}$$

where

φ = latitude (rad, positive for northern hemisphere);
δ = declination, angle between sun and equatorial plane (rad); and
ω = hour (azimuth) angle (rad).

$$\varphi = L \frac{\pi}{180} \quad \textbf{(27)}$$

where

L = longitude of the station location (degrees).

$$\delta = 0.006918 - 0.399912 \cos\Gamma + 0.070257 \sin\Gamma - 0.006758 \cos 2\Gamma + 0.000907 \sin 2\Gamma - 0.002697 \cos 3\Gamma + 0.001480 \sin 3\Gamma \quad \textbf{(28)}$$

where

L_t= local apparent time, local time corresponding to the midpoint of each standard time hour.

$$\omega = 15\ (L_t - 12)\ \frac{\pi}{180} \tag{29}$$

$$L_t = (\ t - 0.5\ ) - 1 + F + E_t \tag{30}$$

where

t = local standard time (1 to 24);
F = longitude time correction, time difference (hours) from standard meridian west of the location; and
E_t = equation of time.

The longitude time correction is calculated by determining the difference between the longitude of the weather station location and the longitude of the standard meridian west of the station location. Time zones run approximately 7.5 degrees on either side of the standard meridian. The standard meridians increase by 15 degrees from 0 to 345 degrees (i.e., 0, 15, 30, 45, .., 345).

$$F = \frac{4\ (\ ST - L\ )}{60} \tag{31}$$

$$ST = 15 \left[FIX\ (\ \frac{L}{15}\ ) + 1 \right] \tag{32}$$

where

ST = Longitude of standard meridian immediately west of the station location

FIX truncates the fraction leaving an integer. Note: in equation 31, if *ST-L* is less than 7.5 then $F = F + 1.0$.

The equation of time is used to correct for day length not equal to 24 hours.

$$E_t = \left(0.000075 + 0.001868 \cos\Gamma - 0.032077 \sin\Gamma - 0.014615 \cos 2\Gamma - 0.04089 \sin 2\Gamma\right) \frac{229.18}{60} \qquad (33)$$

Proposed Modification to the Net Radiation Equation

The method used by CIMIS to calculate net radiation is rigorous, computer intensive, and involves several variables. As a result, CIMIS staff will explore the possibility of simplifying the calculation without compromising accuracy. This will involve the following modifications:

1. Using a constant α value of 0.23 instead of using Eq. 14. Generally, α is approximately equal to 0.23 during the main part of the day when solar radiation, *Rs*, values are big, so there is little error in estimating $(1-\alpha)R_s$ using a constant α value.

2. Using site specific calibrated hourly values of maximum possible solar radiation (clear sky solar radiation) instead of extraterrestrial radiation in Eq. 18 as follows:

$$c = \left(1.3333 - 1.3333 \frac{R_s}{R_{so}}\right)^{0.2941176} \qquad (34)$$

Where R_{so}= clear sky solar radiation, is compiled from archived solar radiation data. This eliminates the need to calculate extraterrestrial radiation.

3. Using a constant value of k in Eq. 3. Monteith (1980) suggested a value of k = 9.0 W m^{-2} as typical. CIMIS will test the suitability of this value, and the possibility that is will vary with the type and height of clouds during the year. Once a suitable value of k is determined, ck will be eliminated.

The proposed net radiation equation is:

$$R_n = 0.77R_s + \varepsilon_o(1 - c)\sigma T_a^4 + c(\sigma T_a^4 - k) - \sigma T_a^4 \qquad \textbf{(35)}$$

CIMIS will adapt equation 35 if it produces net radiation values that are sufficiently accurate for the estimation of *ETo*.

Vapor Pressure Equation

Vapor pressure is calculated at the weather station using an equation from Tetens (1930), and relative humidity. It is calculated once a minute using the minute-by-minute relative humidity and air temperature measurements. Hourly means of the 1-minute vapor pressure are then used in the calculations above.

$$e_d = 0.6108 \exp\left[\frac{17.27\, T_a}{T_a + 237.3}\right]\frac{RH}{100} \qquad \textbf{(36)}$$

Where

e_d = Vapor pressure (kPa);
T_a = Air temperature (^oC); and
RH = Relative humidity (%).

Dew Point Temperature Equation

Dew point temperature is the temperature to which the air must be cooled for it to become saturated. Dew point temperature indicates the amount of moisture in the air. The higher the dew point temperature, the higher the air's moisture content at a given air temperature. Dew point temperature is always lower than the air temperature. When the surface temperature of a leaf is lower than the dew point temperature, vapor will condense. Frost will form on the surface if the temperature (inferred from the air temperature) is below freezing. It is possible to predict frost by comparing the dew point temperature to air temperature. It is calculated below as:

$$T_{dp} = \frac{237.3\left[(17.27\,T_a)/(T_a + 237.3) + \ln\frac{RH}{100}\right]/17.27}{\left[1 - \left[(17.27\,T_a)/(T_a + 237.3) + \ln\frac{RH}{100}\right]/17.27\right]} \qquad (37)$$

Where

T_{dp} = Dew point temperature (°C);
T_a = Air temperature in (°C); and
RH= Relative humidity (%)

For reference evapotranspiration equations that use daily weather data, daily mean dew point temperatures provide the best estimate of daily vapor pressures. The vapor pressure can be calculated by substituting dew point temperature for air temperature in equation 36.

Data Quality Control and Quality Assurance

CIMIS data QC/QA is composed of two parts: (1) site selection, regular site visitation, equipment calibration, and high-quality equipment; and (2) a data quality control program that scans collected data for conformance with a list of data standards.

Station site selection, scheduled site visitation for the purpose of maintenance, and equipment calibration have been described in the weather station siting criteria and the weather station maintenance sections. After equipment calibration, a copy of the calibration report is distributed to local personnel to help them plan maintenance activities. Data received by the CIMIS computer are quality tested and flagged if they fall outside a set standard. Missing data are also flagged. After data are quality tested, it is archived for on-demand access by CIMIS users. The quality control flags identify specific data problems. While their immediate use is to inform users of data credibility as related to the set of standards, the flags are also used to monitor sensor performance daily and to observe long-term trends in data quality, thus, test the performance of specific stations. The quality control program printout is examined by local personnel on a daily basis to detect potential malfunction of station sensors, and it is used to schedule repair trips.

Before 1995, the quality control program data standards used were based on theoretical and historical data limits from 1982 through 1985. A new data quality control criteria program is being developed, based on CIMIS historical data. Data means and standard deviations for each station are used to test data quality. For stations that have less than ten years of historical data, nearby station statistics are used.

Use of means and standard deviation may not be appropriate for evaluating parameters such as radiation, vapor pressure, wind speed, and wind direction. For that reason, other data control methods are being evaluated. Once the new data quality criteria is refined, archived data after 1990 will be quality tested using the new criteria and flagged accordingly. In the meantime, a hybrid of the old and the new quality control standards is used on the system.

New Quality Control Criteria

Flag	Description
A	Historical average
C	Not collected
E,T	Historical average of one of the sensors used to calculate a parameter
H	Daily data value flagged when corresponding hourly data are flagged E, Q, or S
I	Ignore no meaning
M	Missing data
Q	Related sensor is missing
R	Data value is more than 3 standard deviations from the mean
S	Not in service
Y	Data value is more than 2 standard deviations from the mean, but less than 3 standard deviations

Quality Control Criteria as of this Publication

While the new data quality criteria are being refined, the criteria used at present are based on the new criteria, except that Y and R flags are replaced with F. Also, the old quality control flags are used for radiation, vapor pressure, wind speed, and precipitation.

Old Quality Control Criteria

Because archived CIMIS data before 1993 are flagged with the old quality control flags, a short description of the flags is given below. The testing procedure used for specific parameters is in Appendix E. A complete description of the data quality tests is given by Snyder et al. (1985).

The two categories of flags are:

(1) Severe where:

Flag	Descriptions
N/C	Data value is not collected by this station
N/A	Data value is not available
S	Sensor is not in service or data is out of sensor threshold
I	Data value has no meaning/ignore
R	Data are far out of historical limits

(2) Informative where:

Flag	Descriptions
H	Daily data value flagged when corresponding hourly data is severe. This flag is not set when the corresponding hourly data is N/C.
Y	Data is moderately out of historical limits
Q	All quality control could not be performed because a comparison sensor is severe. This flag is not set when the comparison sensor is N/C

Quality Control and Station Performance

While the use of the quality control flags identifies potential data and sensor problems daily, they are also used to evaluate the performance and maintenance of each station.

Quality control flags for each station are counted regularly and the flag rate is used to examine the reliability of the station. From the cumulated count of flags for each parameter, the percent of flagged data is calculated as a function of the number of possible data flags for the parameter. These flag rates are used to identify and correct specific sensor problems. For example, sensors can deteriorate quickly due to environmental factors such as salt, dust, and agricultural chemicals. Other problems include poor site maintenance, or a change in the condition of the site around the station. If flag rates remain high, it may be used as a basis for relocating the station.

The Department's goal is to collect and disseminate accurate data in a timely manner; however, it is possible that data can bypass the QC/QA process. Although data quality tests are regularly performed, it is nearly impossible to identify all data inaccuracies, and sometimes inaccurate data are missed for short periods, Snyder et al. (1992). Also, when problems are identified, time is needed to make sensor repairs or replacements.

Accessing the CIMIS Computer

The two main ways of accessing weather and ETo data from the CIMIS database are by telephone, using a computer with communication software and a modem, or telnet via the Internet. At present, these two methods allow for access to complete historical data. Use of the computer is free and the system operates 24-hours a day, every day of the year, except during maintenance hours. A user identification and password are required to access the computer via dial-up and telnet. To have access authorization, or information on the CIMIS computer, contact a Department District near you; the phone numbers are given in Appendix H.

In addition to telnet, there are two other ways of accessing information by Internet, World Wide Web and file transfer protocol (ftp). CIMIS daily weather and ETo data from all weather stations for the past seven days and monthly summaries for the past year are available via the world wide web on the CIMIS home page at URL **http://wwwdpla.water.ca.gov/cgi-bin/cimis/cimis/hq/main.pl**. A user ID is not required to access CIMIS data on the web.

Telnet (ID required) and ftp share the same host name **aviion.water.ca.gov**. When accessing data via ftp, log in with the username **"anonymous"** and use your e-mail address or "anonymous" as the password. Change to the directory **pub/cimisad** where you will find files with the last 7 days and the last 12 months of monthly summaries. Data are grouped by county.

Appendix A
References

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Appendix B
Guidelines for Siting CIMIS Weather Stations

The criteria below are used pending adoption of ASAE project X505 standards.

Regional and Local Criteria

1. A station should be sited within the region it is meant to represent.

2. Avoid locating a station in a transition area between two regions of distinct climates unless you are attempting to characterize that transitional area.

3. Topographic depressions should be avoided, as the temperature is frequently higher during the day and lower at night. High points should also be avoided in most cases.

4. There should be a long-term commitment to maintain the same land use in and around the site, to avoid moving the station in the future.

Surrounding Environment Criteria

1. Avoid wind obstructions within 90 m (100 yards) of the site. Avoid linear obstructions (windbreaks, buildings) within 137 m (150 yards) perpendicular to the direction of the prevailing wind.

2. Avoid placing a station in a field where there are frequent rotations of crops, because between the crops, the field will have bare soil.

3. Avoid abrupt crop/vegetation changes (i.e., pasture to row crops) within 45 m (50 yards) of site, or 90 m (100 yards) upwind of site.

4. Avoid roads within 45 m (50 yards) of the site. Roads should be no closer than 90 m (100 yards) upwind of the site.

5. Small rivers should be no closer than 90 m (100 yards) of the site and larger rivers should be no closer than 180 m (200 yards) of the site. Lakes should be no closer than 900 m (1,000 yards) of the site if the prevailing wind is from the lake.

6. Avoid areas where extensive or frequent use of agricultural chemicals are used (can cause increasing degradation of sensors).

Other General/Desirable Criteria

1. Site should have nearby dwellings (no closer than 100 yards) to reduce risk of vandalism.

2. The station enclosure should be a 9 x 9 m by 1.5 m high fence, livestock-tight where necessary. The posts, boards, and fencing material should not affect wind or shade any instruments.

3. Site should have unrestricted access, seven days a week. There should be vehicle access to the site enclosure (except when wet).

4. Site should be close to existing telephone lines (within 150 yards) for economical connections.

5. There should be local personnel (private or public) to help maintain the site to meet DWR's requirements.

Appendix C
Sensors' Specifications

The following sensor specifications, except sensor heights, are provided by the particular sensor manufacturer.

1. **Total solar radiation**

Sensor:	Pyranometer–high stability silicon photovoltaic detector (blue enhanced)
Model:	LI200S
Maker:	Li-Cor
Height:	2.0 meters

Specifications

Sensitivity:	±5 percent error under natural sunlight conditions. Typically 80 micro Ampere per 1,000 watts per square meter.
Linearity:	Maximum deviation of 1 percent up to 3,000 watts per square meter.
Response time:	10 micro seconds.
Correction:	Cosine corrected up to 80 degrees angle of incidence.
Azimuth:	±1 percent error over 360 degrees at 45 degrees elevation

2. **Soil temperature**

Sensor:	Soil Thermistor--Fenwal Electronic UUT51J1 thermistor in water-resistant coating.
Model:	107b
Maker:	Fenwal/ modified by Campbell Scientific Inc.
Height:	15 cm (6 in) below soil surface under irrigated grass.

Specifications

Accuracy:	Worst case ±0.4 degrees C over -33 to 48 degrees C, ±0.5 degrees C at -40 degrees C

3. **Air temperature/relative humidity**

Sensor:	Fenwall Thermistor/HUMICAP H-sensor
Model:	HMP35C
Maker:	Vaisala/modified by Campbell Scientific, Inc.
Height:	1.5 m

Specifications

Range:	0 to 100% RH
	-35 to +50 degrees C
Accuracy:	±2% RH (0-90% RH), ±5% RH (90-100%)
	±0.1 °C over -24 to 48 °C range

Note: Both sensors are enclosed in a 12-plate naturally aspirated radiation shield made by R. M. Young.

4. **Wind Direction**

Sensor:	10K Ohm potentiometer vane
Model:	024A
Maker:	Met-One
Height:	2 m

Specifications

Range:	0-360 degrees
Output:	0-10 * 10^3 Ohms
Threshold:	0.45 m per sec (1 mph)
Accuracy:	±5%
Delay distance:	less than 1.5 m

5. **Wind Speed**

Sensor:	Three-cup anemometer utilizing a magnet activated reed switch whose frequency is proportional to wind speed
Model:	014A
Maker:	Met-One
Height:	2 m

Specifications

Range:	0-45 m per sec (0-100 mph)
Threshold:	0.45 m per sec (1 mph)
Gust Survival:	0-53 m per sec (0-120 mph)
Accuracy:	1.5% or 0.11 m per sec (0.25 mph)

Distance constant is less than 4.6 m (15 ft). Distance constant is the distance air travels before the anemometer reaches 63 percent of the new speed after a sharp-edged gust has occurred.

6. Precipitation

Sensor:	Tipping-bucket rain gauge with magnetic reed switch.
Model:	TE525MM
Maker:	Texas Electronics
Height:	1 m

Specifications

Orifice:	24.5 cm (9.644 in)
Resolution:	0.1 mm
Accuracy:	±1% at 5 cm per hr or less.

Appendix D
Explanation of Unit Symbols

Metric Unit	Explanation
km	kilometers
mm	millimeters
m/s	meters per second
kPa	kilo Pascal
W/sq.m	watts per square meter

English Unit	
in	inches
Ly/day	langley (calorie per square centimeter) per day
mBars	millibars
mph	mile per hour

Appendix E
Specific Parameter Quality Control Flags for Data Before 1995

Hourly Data

Hourly solar radiation

Solar radiation data is flagged based on hourly extraterrestrial radiation.

Flag	Description
Y	When the sun is more than 10 degrees above the horizon and the ratio of measured hourly solar radiation to calculated extraterrestrial radiation is greater than 0.85.
R	When the sun is more than 10 degrees above the horizon and the ratio of measured hourly solar radiation to calculated extraterrestrial radiation is greater than 1.00 and when measured hourly solar radiation is equal to or less than 0 Wm^{-2}.
Y	When the sun is less than 10 degree above the horizon and the absolute value of measured hourly solar radiation is equal to or greater than 6.00 Wm^{-2}.
R	When the sun is less than 10 degrees above the horizon and the absolute value of measured hourly solar radiation is equal to or greater than 10.00 Wm^{-2}.
S	When measured hourly solar radiation is less than or equal to -50.00 Wm^{-2}, or it is equal to or greater than 4,000.00 Wm^{-2}.

Hourly net radiation

Net radiation quality test is based on theoretical extremes, measured solar radiation, and air temperature.

Flag	Description
R	When the sun is more than 10 degrees above the horizon and net radiation is equal to or greater than 1.15 times the estimate (for a given value of solar radiation) of the maximum net radiation plus 30 Wm^{-2}.

R	When the sun is more than 20 degrees above the horizon and one of the following conditions apply: (1) Net radiation is equal to or greater than 1.3 times the maximum net radiation for a given value of solar radiation; or (2) Net radiation is less than or equal to 0.6 times the estimate (for a given value of solar radiation) of a positive minimum daytime net radiation minus 30 Wm^{-2}.
Y	When the sun is more than 10 degrees above the horizon and one of the following conditions apply: (1) Net radiation is equal to or less than 0.7 times the estimate (for a given value of solar radiation) of a positive minimum daytime net radiation minus 20 Wm^{-2}; (2) Net radiation is equal to or less than 1.25 times the estimate (for a given value of solar radiation) of a negative minimum daytime net radiation; and (3) Net radiation is equal to or greater than 1.1 times the estimate (for a given value of solar radiation) of the maximum net radiation plus 20 Wm^{-2}.
Y	When the sun is less than 10 degrees above the horizon and either: (1) Net radiation is greater than -0.1 Wm^{-2}; or (2) Net radiation is less than 1.15 times the estimate of the minimum nighttime net radiation for a given value of solar radiation.
S	When net radiation is greater than or equal to 4,000 Wm^{-2}.
Q	When temperature or solar radiation is severe, that is, flagged S.

Hourly air temperature

Hourly air temperature quality test is based on extreme values.

Flag	Description
R	Temperature is less than -15 or greater than 60 °C.
Y	Temperature is less than -10 or greater than 55 °C.

Hourly actual vapor pressure

Flag	Description
R	Actual vapor pressure is less than or equal to 0.00 kPa or actual vapor pressure is greater than 1.05 times the saturation vapor pressure.
Y	Relative humidity is less than 50 percent during an hour with 1.00 mm or more of precipitation and when actual vapor pressure is 1.01 times the saturation vapor pressure.
Q	Air temperature or precipitation is severe (either or both are flagged R).

Hourly wind speed

Flag	Description
R	Wind speed is equal to or less than 0.447 for three consecutive hours and the sun is at or greater than 20 degrees above the horizon.
Y	Wind speed is equal to or less than 0.447 for two consecutive hours.
S	Wind speed less than 0.447 ms^{-1} or greater than 60 ms^{-1}

Hourly evapotranspiration

Flag	Description
R	When either net radiation, air temperature, vapor pressure, or wind speed is severe.

Hourly precipitation

Precipitation data quality test is based on extreme values and season of the year inferred from calculated extraterrestrial radiation.

Flag	Description
Q	When solar radiation is severe.
R	When precipitation is negative, more than 100.00 mm, or is not a whole number.
R	When measured solar radiation is greater than 75 percent of calculated extraterrestrial radiation, the sun is 10 or more degrees above the horizon and the station shows recorded precipitation (i.e., precipitation is greater than 0.0).
y	When measured solar radiation is greater than 65 percent of calculated extraterrestrial radiation, the sun is 10 or more degrees above the horizon and the station shows recorded precipitation.

Daily Data

Daily average solar radiation

Flag	Description
H	When one or more hourly solar radiation is severe.
R	When solar radiation is equal to or less than 0.0 or solar radiation is greater than 80 percent of daily incident solar radiation. Where incident solar radiation is the sum of hourly incident solar radiation divided by 24.
S	When solar radiation is equal to or greater than 4,000 Wm^{-2}.

Daily average net radiation

Flag	Description
H	When one or more hourly net radiation is severe.

R	When net radiation is equal to or less than -20 Wm^{-2} or net radiation is more than 60 percent of the daily incident solar radiation.
S	When net radiation is equal to or greater than 6,000 Wm^{-2}.

Daily average air temperature

Flag	Description
H	When one or more hourly air temperature is severe.
R	When average air temperature is far out of range of site specific historical range.
Y	When average air temperature is moderately out of range of site specific historical range.
S	When average air temperature falls under one of the following categories: (1) Average air temperature is equal to or less than 50 ^{o}C or equal to or greater than 100 ^{o}C. (2) Average air temperature is equal to the maximum temperature and to the minimum temperature. (3) Maximum temperature is less than minimum temperature. (4) Average air temperature is less than minimum temperature. (5) Average air temperature is greater than maximum temperature.

Daily average vapor pressure

Flag	Description
H	When one or more hourly vapor pressure is severe.
R	When average vapor pressure is equal to or less than 0 kPa; or average vapor pressure is equal to or greater than 4 kPa.

S When average vapor pressure falls under one of the following:

(1) Average vapor pressure is equal to the maximum vapor pressure and to the minimum vapor pressure.

(2) Maximum vapor pressure is less than minimum vapor pressure.

(3) Average vapor pressure is less than minimum vapor pressure.

(4) Average vapor pressure is greater than maximum vapor pressure.

Average wind speed

Flag	Description
H	When one or more hourly wind speed is severe.
R	When average wind speed is equal to or less than 0.45 ms^{-1}, or average wind speed is greater than 25 ms^{-1}.
Y	When average wind speed is equal to or less than 0.5 ms^{-1}, or average wind speed is greater than 15 ms^{-1}.
S	When average wind speed is equal to or less than 0.447 ms^{-1}.

Daily reference evapotranspiration

Flag	Description
R	When one or more hourly evapotranspiration is not available or is flagged as R and could not be estimated.

Daily precipitation

Flag	Description
H	When one or more hourly precipitation is severe.
R	When precipitation is negative, equal to or greater than 300 mm, or is not a whole number.
Y	When precipitation is not equal to total hourly precipitation.

Appendix F
List of Symbols and Definitions

Equation number	Symbol	Description
10	A	Station elevation (m)
3,11,18,19,20,21,22,34,35	c	Fraction of cloud cover
25	d	Day of the year
7,17,36	e_d	Actual vapor pressure(kPa)
5,7	e_a	Saturation vapor pressure (kPa)
23,24	E_o	Earth-Sun distance (radians)
30,33	E_t	Equation of time
1	ETo	Reference evapotranspiration (mm)
30,31	F	Longitude time correction (hours)
1,8,9	FU2	Wind function (mm kPa^{-1})
14,15,18,23	I	Extraterrestrial radiation (Wm^{-1})
3,35	k	Cloud coefficient
27,31,32	L	Latitude (degrees)
29,30	Lt	Local time corresponding to mid point of standard time
6,10	P	Barometric pressure (kPa)
1[2],2,3 11,12,19,35	Rn	Net radiation (Wm^{-2})
3,11,14,15,18,34,35	R_s	Measured solar radiation (W m^{-2})
34	R_{so}	Clear sky solar radiation (W m^{-2})
36,37	R.H	Relative humidity (%)
31,32	ST	Longitude of standard meridian immediately west of the station location
30	t	Local standard time
3,5,11,17,19,35,36[3],37[3]	T_a	Air temperature (Kelvin)
3	Tc	Cloud base temperature (Kelvin)
3	T_o	Sky temperature (Kelvin)
3	T_s	Surface temperature (Kelvin)
37	T_{dp}	Dew point temperature (°C)
8,9	U_2	Wind speed at 2 meters (m s^{-1})
1,7	VPD	Vapor pressure deficit (kPa)
1,4	W	Humidity function

[2] Equation 1. (mm)

[3] Equations 36 and 37. (°C)

16,23,26	Z	Zenith angle
3,11,14,15	α	Surface albedo over well-watered grass
4,6	γ	Psychrometer constant (kPa °C^{-1})
24,25,28,33	Γ	Day angle (radians)
26,28	δ	Declination angle (radians)
4,5	Δ	Slope of saturation vapor pressure curve (kPa °C^{-1})
3,11,17,19,35	ε_o	Emissivity for clear portions of sky
3	ε_s	Crop surface absorptivity (emissivity)
14,16,21,22	θ	Solar altitude (degrees)
11,12,16,19,29	π	3.1415927 (pi)
3,11,19,35	σ	Stefan-Boltzmann constant 5.67 * 10^{-8} Jm^{-2} K^{-4} s^{-1}
26,27	φ	Latitude (radians)
11,12,19,26,29	ω	Hour (azimuth) angle (radians)

Appendix G
List of CIMIS and Related Publications

Title	Source
Basic Irrigation Scheduling Leaflet 21199	U.C. Cooperative Extension Communication Services University of California 6701 San Pablo Avenue Oakland, CA 94608-1239 (510) 642-2431
CIMIS Agricultural Resource Book	Department of Water Resources Bulletins and Reports P.O. Box 942836 Sacramento, CA 94236-0001 (916) 653-1097
CIMIS Urban Resources Book	CA Department of Water Resources (See above address)
CIMIS Alert	Department of Water Resources (See above address)
CIMIS Leaflet: The California Irrigation Management Information System	Department of Water Resources (See above address)
CIMIS Brochure: Providing Information to Help California Irrigate Efficiently	Department of Water Resources (See above address)
Crop Water Use in California Bulletin 113-4	Department of Water Resources (See above address)
Determining Daily Reference Evapotranspiration (ETo)	U.C. Cooperative Extension (See above address)
Rev. 1992. Leaflet 21426	
Does Drip (and Other Low-Flow) Irrigation Save Water? 1984. Leaflet 21380	U.C. Cooperative Extension (See above address)

List of CIMIS and Related Publications (continued)

Title	Source
Drip Irrigation Management. 1981. Leaflet 21259	U.C. Cooperative Extension (See address)
Drought Irrigation Strategies for Deciduous Orchards. 1989. Leaflet 21453	U.C. Cooperative Extension (See address)
Drought Tips 92-09 Managing Irrigation in Fruit and Nut Trees During Drought	Department of Water Resources (See address)
92-20 Water Balance Irrigation Scheduling Using CIMIS ETo	Department of Water Resources (See above address)
92-29 Irrigation Management Made Simple	Department of Water Resources (See address)
92-38 Field Use of Tensiometers	Department of Water Resources (See address)
92-45 Central Coast Crop Coefficients for Field and Vegetable Crops	Department of Water Resources (See address)
92-52 Irrigating Up Crops Efficiently With Sprinklers	Department of Water Resources (See address)
Estimating Orchard Water Use with CIMIS	Mission RCD (619) 728-1332
Fifteen Years of Growth and a Promising Future: CIMIS	Department of Water Resources (See address)
How Much Water has Your Crop Used Since Your Last Irrigation?	Department of Water Resources (See address)

List of CIMIS and Related Publications (continued)

Title	Source
Irrigation Scheduling: A Guide for Efficient On-farm Water Management. 1989. Leaflet 21454	U.C. Cooperative Extension (See address)
The Economic Costs and Benefits Associated with CIMIS	Department of Water Resources (See address)
The Water Budget Method Irrigation Scheduling for Southern San Joaquin Valley Deciduous Orchards. 1986. Leaflet 21419	U.C. Cooperative Extension (See address)
Using Reference Evapotranspiration (ETo) and Crop Coefficients to Estimate Crop Evapotranspiration (ETo): Agronomic Crops, Grasses, and Vegetable Crops. 1987 Leaflet 21427	U.C. Cooperative Extension (See address)
Using Reference Evapotranspiration (ETo) and Crop Coefficients to Estimate Crop Evapotranspiration (ETO): Trees and Vines. 1987 Leaflet 21428	U.C. Cooperative Extension (See address)