REFERENCE EVAPOTRANSPIRATION (ET_O) MAPS FOR CALIFORNIA

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ABSTRACT

The California Irrigation Management Information System (CIMIS) manages over 130 active weather stations throughout the state. Archived data is also available for 75 additional stations that have been disconnected from the network. Most of these stations produce estimates of reference evapotranspiration (ETo) for the station location and their immediate surroundings. Because of California's diverse landmass and climate, however, many locations within the state lack a representative CIMIS station. Some counties, for example, do not have a CIMIS station at all and others have only one or two stations. As a result, there are significant spatial ETo data gaps. In an attempt to mitigate this problem, CIMIS initiated a project in 2003 to investigate the possibility of coupling remotely sensed satellite data with point measurements to generate spatially distributed ETo values.

In cooperation with the University of California Davis's Center for Spatial Technologies and Remote Sensing (UCD CSTARS), CIMIS developed a model that derives daily solar radiation from the visible band of the National Oceanic and Atmospheric Administration's (NOAA) Geostationary Operational Environmental Satellite (GOES) and couples it with air temperature, relative humidity, and wind speed interpolated between point measurements from the CIMIS stations. Two interpolation methods, DayMet and Spline, are selected based on accuracy of results, code availability, and computational efficiency. Daily ETo values are calculated using the American Society of Civil Engineers version of the Penman-Monteith equation (ASCE-PM) at 2-km spatial resolution. The accuracy of the ETo estimate was tested using cross validation techniques and we are confident that this product will assist the people of California in saving water and energy.

INTRODUCTION

The California Irrigation Management Information System (CIMIS) is a program in the California Department of Water Resources (DWR), Division of Statewide Integrated Water Management, Water Use and Efficiency Branch, that manages a network of automated weather stations throughout California. Currently, there are over 130 active weather stations on the CIMIS network that collect and transfer data at prescheduled intervals to polling computers at the DWR headquarters. The polling computers reformat the raw data and import it to the database servers where the data will go through quality

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control processes and stored. There are also about 75 inactive CIMIS stations. Inactive stations are stations that have been removed from the network, for various reasons, but the archived data is still available.

CIMIS was developed by the California Department of Water Resources (DWR) and the University of California Davis (UCD) in 1982. DWR assumed management and operations of CIMIS in 1985 and has since been providing estimates of reference evapotranspiration (ETo) and measured weather parameters at the weather stations. ETo is evaporation plus transpiration from grass surfaces on which the CIMIS weather stations stand. CIMIS uses the modified Penman equation, further modified for conditions in California, to calculate ETo. CIMIS's version of the modified Penman equation is referred to as the CIMIS Penman equation in some literatures. CIMIS also provides ETo values calculated using the American Society of Civil Engineers (ASCE) version of the Penman-Monteith equation for interested users. Studies have shown that there are no significant differences between ETo values calculated by the CIMIS Penman and the ASCE version of the Penman-Monteith methods (Temesgen et al. 2005).

Although CIMIS is one of the largest agro-meteorological weather station networks in the world, the data from its stations represent only a small fraction of microclimates in the State, resulting in significant spatial data gaps. Recognizing this fact, CIMIS and the University of California Davis (UCD) remote sensing scientists have developed a model that couples remotely sensed satellite data with point measurements from the CIMIS stations to provide daily maps of ETo for the entire State.

Remote sensing has made remarkable advances in recent years enabling scientists to produce spatially distributed estimates of ETo and other products. The accuracies of these products, however, depend on the models used and atmospheric conditions at the time of data acquisition. The specific model that CIMIS and UCD developed derives solar radiation data from the Geostationary Operational Environmental Satellites (GOES) and interpolates other weather parameters measured at the CIMIS stations using data interpolation methods that depend on the density of ground stations. The more stations there are in a given area the more accurate the interpolated parameters will be. Two interpolation methods selected for this purpose are the Spline and DayMet methods. Brief descriptions of the methodology used will be presented in the following sections.

ETo Equation

The Penman-Monteith equation has been accepted by many researchers as a standard method for estimating ETo (Smith et al. 1991; Allen et al. 1998; Allen et al. 2000; Walter et al. 2000; Itenfisu et al. 2000; Howell et al. 2000). Therefore, CIMIS decided to use the ASCE version of the Penman-Monteith equation for estimating daily ETo values at 2-km spatial resolution for the entire state of California. The ASCE version of the Penman-Monteith equation for daily ETo calculations is given as:

$$ETo = \frac{0.408\Delta(Rn - G) + \gamma \frac{C_n}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d U_2)} \quad (1)$$

where ETo is reference evapotranspiration (mm d^{-1}), Rn is net radiation(MJ m^{-2} d^{-1}), G is the soil heat flux (MJ m^{-2} d^{-1}), (e_s - e_a) is the vapor pressure deficit of the air (kPa), e_s is the saturation vapor pressure (kPa), and e_a is the actual vapor pressure (kPa), Δ is the slope of saturation vapor pressure-temperature curve (kPa $^oC^{-1}$), γ is the psychrometric constant (kPa $^oC^{-1}$), T is mean daily air temperature (^{o}C), C_n is the numerator constant for the reference type and calculation time step, C_d is a denominator constant for the reference type and calculation time step, U_2 is mean wind speed at 2-m height (m s^{-1}). For grass references, the ASCE Penman-Monteith has a C_n value of 900 and a constant C_d value of 0.34 for daily time steps.

The soil heat flux for a daily time step in Equation 1 is assumed zero. It has been established that this is a reasonable assumption since the fluxes entering and leaving the soil on a daily basis are about the same. The ASCE Penman-Monteith procedure for calculating Rn from measured weather parameters is (Allen et al., 1994, 1998):

$$Rn = (1 - \alpha)Rs - \sigma\left(\frac{T_{K\ max}^4 + T_{K\ min}^4}{2}\right)\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{Rs}{Rso} - 0.35\right) \quad (2)$$

where α = surface albedo, Rs = measured or estimated solar radiation (MJ $m^{-2}d^{-1}$), σ = Stefan-Boltzmann constant (4.901 x 10^{-9} MJ K^{-4} m^{-2} d^{-1}), $T_{K\ max}$ = maximum absolute daily air temperature (^{o}K), $T_{K\ min}$ = minimum absolute daily air temperature (^{o}K),e_a = actual vapor pressure (kPa), and Rso = clear sky solar radiation (MJ $m^{-2}d^{-1}$).

The solar radiation and surface albedo in Equation 2 were derived from the GOES data and will be described later. Saturated and actual vapor pressures in both Equations 1 and 2 were calculated using Tetens method as:

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \quad (3)$$

$$e^o(T) = 0.611\exp\frac{(17.27T)}{T + 237.3} \quad (4)$$

$$e_a = 0.611\exp\frac{(17.27T_{dew})}{T_{dew} + 237.3} \quad (5)$$

where e^o(T) is the saturation vapor pressure (kPa), T is air temperature (^{o}C), and Tdew is the dew point temperature (^{o}C).

The slope of saturation vapor pressure-temperature curve and psychrometric constant in Equation 1 are calculated using various empirical equations listed in Allen et al. (1994, 1998). The clear sky solar radiation is estimated using the Heliosat method. Heliosat is a European model that is designed to convert imagery acquired by the geostationary satellites into maps of solar radiation received at ground level (http://www.helioclim.net/heliosat/index.html). Maximum and minimum air temperature, dew point temperature, wind speed, and relative humidity values are estimated at each 2-km grid point using the two interpolation methods listed above and described below.

THE CIMIS-GOES MODEL

The model that is used to create daily maps of ETo and Rs is referred to as the CIMIS-GOES model in this document since it combines data collected by the CIMIS stations with data collected by the GOES. Figure 1, taken from Ustin et al. (2005) and Hart et al. (2009) , shows an overview of the steps involved in calculating ETo at each 2-km grid. The chart includes steps for the derivation of Rs from the GOES and interpolation of measured weather parameters from CIMIS stations.

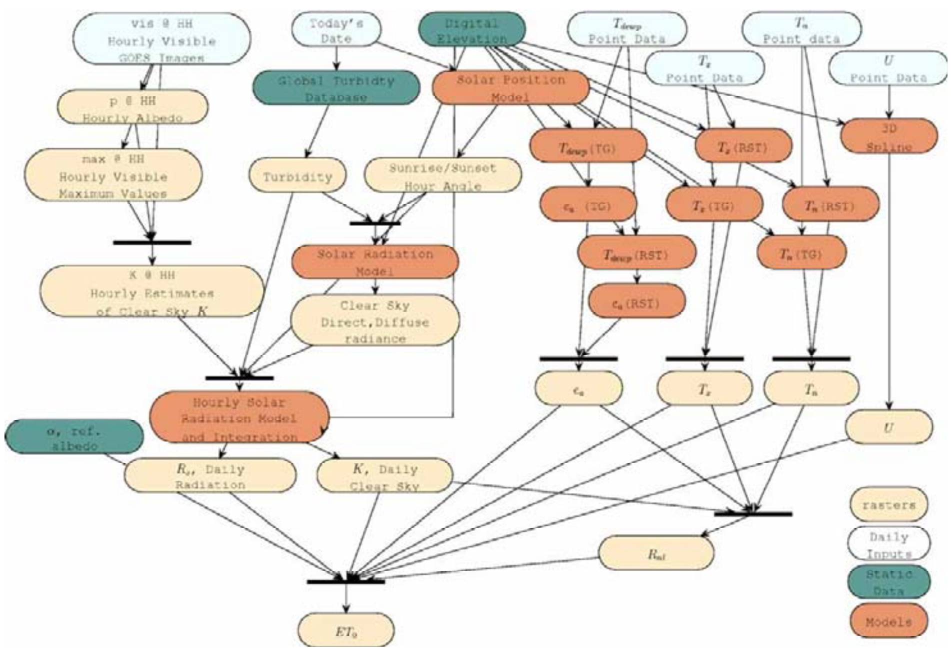


Figure 1. A chart showing the model used by CIMIS to map daily ETo values for the State of California.

Solar Radiation Model

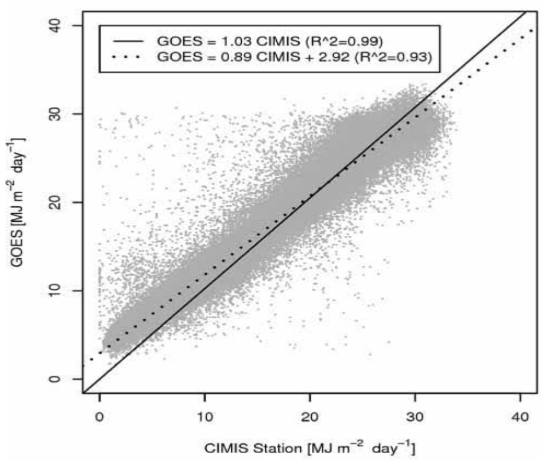
Solar radiation is the most important parameter in the calculation of ETo using the Penman-Monteith equation. Therefore, it is important that Rs estimates be as accurate as possible. The model that was chosen to derive Rs at each 2-km grid from the GOES data is the Heliosat II model. The model estimates Rs by combining model prediction of Rso with estimates of cloud index from the GOES imager visible channel data. Therefore, this method does not depend on measurements of Rs at the individual CIMIS stations. According to Hart et al. (2009), the clear sky solar radiation model used is part of the Heliosat-II program (Rigollier et al. 2000, 2001, Leferve et al. 2002).

The cloud index is estimated by comparing what is observed at the satellite sensor to what would have been observed if there was no cloud (Leferve et al., 2002). Ground surface and atmospheric (cloud) reflectance values needed to calculate the cloud index at each pixel are derived from time series of images. The assumption is that at some point in the time series the clouds are non-stationary and that the minimum value observed will provide estimates of ground reflectance and maximum value observed will provide cloud reflectance. The model then calculates clear sky index from the cloud index using empirical equations. The clear sky index, by definition, is the ratio of the observed radiation to the clear sky radiation. Therefore, solar radiation at each pixel is calculated by multiplying the clear sky index by the clear sky radiation.

For each location in California, the sunrise and sunset times are calculated daily. Within the sunlit period, GOES data are available for each hour. From each of the hourly GOES images, a clear sky index is calculated. This factor is assumed constant over the time intervals chosen. Clear sky solar radiation is also calculated for each of these intervals. The clear sky radiation and clear sky factor are used to calculate the actual radiation for each interval. Finally, the contributions from all intervals are summed to get the daily estimate of solar radiation.

The solar radiation model uses an analytical integration over solar angles and it is simple to change the frequency of the GOES cloud cover estimates. Therefore, missing cloud cover estimates, caused by lost GOES images, can easily be handled by extending the intervals adjacent to the missing time frames. The analytical integration assigns appropriate weights to the remaining cloud cover estimates. Atmospheric transmission in the model combines aspects of aerosols, relative humidity, ozone, and molecular scattering into a single parameter, the Linke turbidity (Ustin et al., 2005; Hart et al., 2009). The larger the Linke Turbidity, the larger will be the attenuation of the radiation by the clear sky atmosphere. Seasonal values of the Linke turbidity are derived from a world database of turbidity estimates (Remund *et al.* 2003).

Figure 4 shows comparison of the estimated and measured Rs values at all of the CIMIS stations from February 2003 through April 2006. Although there are some scatters, regression fits show a very good correlation between the two. It should also be noted that the measured Rs that is used in Figure 2 has not been assessed for potential measurement errors, which is not uncommon when dealing with such a large network. CIMIS is currently in the process of conducting analyses and expect to publish results in the near future.



(a) GOES vs. CIMIS R_{ns}

Figure 2. GOES estimated Rs versus Rs measured at individual CIMIS stations.

Data Interpolation

As stated above, daily maximum air temperature (Tx), daily minimum air temperature (Tn), average daily dew point temperature (Tdew), and average daily wind speed at 2 meters (U2) are derived by spatially interpolating point data from the CIMIS network. Spatial interpolation generates surfaces of continuous fields from data collected at discrete locations. A number of different interpolation methods, ranging from the simplest to the more sophisticated ones, were considered for this model. According to Hart el al. (2009), many researchers have indicated that simple methods can be used to interpolate climatic variables from dense and evenly distributed measurement sets (Philips and Marks 1996, Mardikis *et al.* 2005). However, when generating surfaces of weather data over California using CIMIS data, it is necessary to interpolate over large regions of complex terrain with sparse and unevenly distributed weather stations. Figure 3 shows the spatial distribution of the sparsely distributed CIMIS stations. As can be seen from the figure, areas in central valley have a dense distribution of stations whereas mountainous, urban, and desert regions are less represented. This distribution pattern is the result of CIMIS's original objective of serving California's agricultural growers irrigate efficiently.

It has been suggested that the incorporation of elevation improves interpolation results in cases where topography is an important factor for determining climatic variability (Daly *et al.* 1994, Thornton *et al.* 1997, Price *et al.* 2000). Figure 3a shows CIMIS station locations and groups them by elevation, with higher elevation stations having larger symbols.

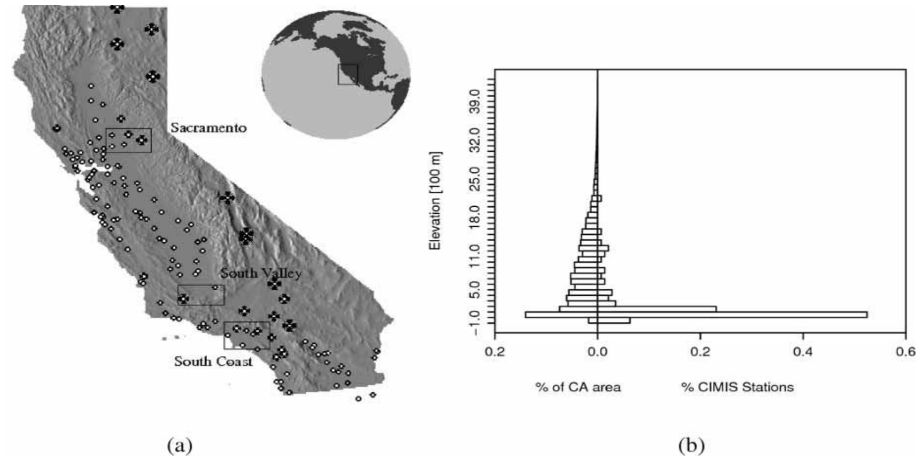


Figure 3. CIMIS weather stations. (a) Station locations, with larger symbols for higher elevations. (b) Histograms of elevations for California versus CIMIS stations.

Figure 3b shows the difference in the distribution and range of the elevation, comparing the CIMIS stations and California as a whole. Figure 3b clearly shows that mountain regions are under-represented. Taking all of these factors into consideration and based on computational efficiency, availability of codes, and accuracy of results, the Spline and DayMet methods were selected to interpolate the weather parameters measured at individual CIMIS stations.

Spline is an interpolation method that fits a surface through or near known points using a function with continuous derivatives. Two- and three-dimensional Splines were used based on which weather parameter is to be interpolated. Parameter values that control the properties of the interpolation function were selected using the cross-validation technique and visual observation of results. Cross-validation involves deliberately leaving out the measured parameter at one or more stations and comparing the model output to the measured value.

DayMet is an interpolation method that was developed at the University of Montana to generate daily surfaces of temperature, precipitation, humidity, and radiation over large regions of complex terrain (http://www.daymet.org/). It applies the spatial convolution of a truncated Gaussian (TG) filter with a set of observations and determines the weights associated with a given weather station for each point where weather parameters are to be determined, depending on the distance and density of the stations. The truncation and shape parameters for the DayMet model are determined by searching the parameter space and selecting the value that minimize the root mean squared error (RMSE) using the cross-validation method.

Maximum daily air temperature, minimum daily air temperature, and average daily dew point temperature from the CIMIS station sites were first normalized to represent values at sea-level. The data is normalized using a statewide average lapse rate adjustment of 5 ^{o}C/km for Tx, Tn, and Tdew. The normalized data was then interpolated using the twodimensional Regularized Spline with Tension (RST) and the DayMet methods. These temperatures were then adjusted for elevation using the lapse rate stated above. Because the CIMIS stations are not located in all geographic locations, both methods have some limitations in some areas of the State. Therefore, a decision was made to use an arithmetic average of values derived using both methods to create spatially distributed temperatures. Figure 4 shows average daily air temperature maps for a single day [June 18, 2005] created using this approach.

Relative humilities are measured at the CIMIS stations and the corresponding vapor pressures calculated by the datalogger. However, we decided to calculate both saturated and actual vapor pressures at each pixel from the interpolated temperatures to minimize the number of interpolated parameters and associated errors. Finally, the wind speed at 2-meters was interpolated using the three-dimensional RST method. It is worth mentioning that we found the wind speed interpolations to be the most unreliable since a single station with high wind speed values can cause anomalous effects. Therefore, we are working on improving wind speed estimation methods as we continue refining the entire CIMIS-GOES model.

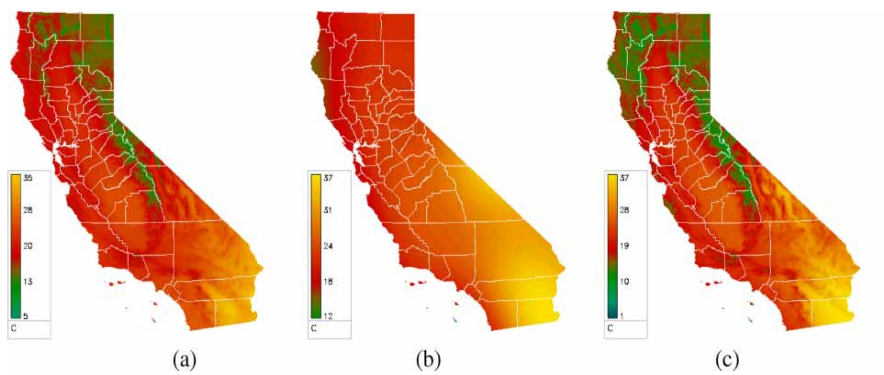


Figure 4. Results of air temperature interpolation using the different methods discussed above for June 18, 2005. (a) The DayMet method, (b) The 2-D Spline on the normalized values, and (c) the final approach with elevation correction.

REFERENCE EVAPOTRANSPIRATION

The final model output is reference evapotranspiration at each pixel. The daily ETo information is used for many purposes including irrigation scheduling and other water management practices. The accuracy of ETo values estimated from these methods depends on many factors. One such factor is the accuracy of the remotely sensed Rs data, which is in turn significantly affected by atmospheric conditions (e.g., cloudiness) and surface conditions (e.g., snow cover). Therefore, mountainous areas with snow cover and coastal areas with cloud and fog are more susceptible to errors.

Another important factor affecting the accuracy of ETo estimation by this model is the accuracy of the interpolation methods used. Interpolation methods in general are affected by the density of the weather stations and geographic features of the region. Since most of the CIMIS stations are concentrated in lowland agricultural areas, the mountains are again more susceptible to errors resulting from data interpolation due to the low density of weather stations. CIMIS is currently working on reducing these potential errors by refining the models. We believe that the ETo estimates provided using this method will be more accurate when compared to using data from a distant weather station with a different microclimate.

PUBLIC ACCESS TO THE DATA

After rigorously testing the product over an extended period of time, CIMIS released it to the public on September 9, 2009. Since then, we have received many positive comments from the public. We have also received information that the data is being used in water conservation programs by many water agencies. The daily ETo and Rs map is located at http://wwwcimis.water.ca.gov/cimis/cimiSatSpatialCimis.jsp. Figure 5 shows the view of the Spatial CIMIS tab and its associated links, such as Spatial Overview, Spatial Model, View Maps, and Map Reports. The Map Reports link is where users go to retrieve the data using an interactive Google Map Interface.

The Map Reports Help link on the Spatial CIMIS page provides detailed technical instructions for selecting locations, saving selections, scheduling automated email delivery, and generating reference evapotranspiration (ETo) and solar radiation (Rs) data reports at a 2-km spatial resolution from the Map Reports page.

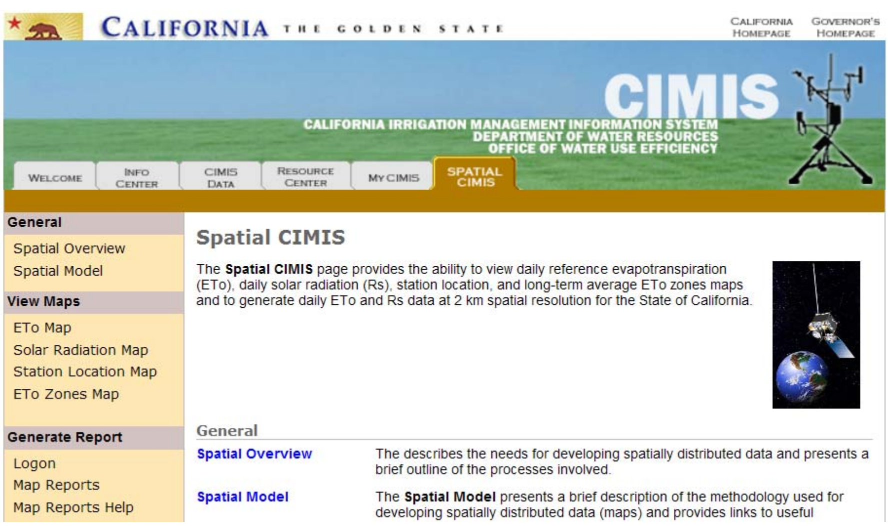


Figure 5. The newly released Spatial CIMIS tab assists users to view maps and retrieve data.

A point of interest can be selected using geographic coordinates, physical addresses, or zip codes. Coordinate selections can be specified by manually entering latitude and longitude values as an Address Search or by clicking points on the Google map interface. A maximum of 10 points can be selected at a time. The names and geographic coordinates of all selected points will display in the text boxes below the Google Map. These names can be replaced with new names that would help users to easily identify the points (example, alfalfa field, golf course, etc.). Plans are also underway to improve the features and make it more user-friendly.

Selections for the unit, date range, and data format for map reports are similar to the standard CIMIS data retrieval process. The user may specify the unit as English or Metric. The size of the data retrieved depends on the number of data points and the Date Range selected. Data can be generated in Web Report, CSV with Headers, and XML formats. Scheduling automated email deliveries will only be in CSV and XML formats.

After selecting data points, delivery methods, units, date range, and data format, users can click on the Submit button at the bottom of the page to generate the report interactively. Scheduled reports will be delivered via email after 6:00 a.m. Pacific Standard Time. The Save button has to be clicked to the selected specifications.

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REFERENCES

Allen, R. G., Smith, M., Perrier, A., and Pereira, L. S. (1994). "An update for the definition of reference evapotranspiration." *ICID Bulletin*, 43(2), 1-34.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). "Crop Evapotranspiration: Guidelines for computing crop water requirements." *Irrig. and Drain. Paper 56*, Food and Agriculture Organization of the United Nations, Rome, 300 pp.

Allen, R. G., Walter, I. A., Elliot, R., Mecham, B., Jensen, M. E., Itenfisu, D., Howell, T. A., Snyder, R., Brown, P., Eching, S., Spofford, T., Hattendorf, M., Cuenca, R. H., Wright, J. L., and Martin, D. (2000). "Issues, requirements and challenges in selecting and specifying a standardized ET equation." *Proc., 4th National Irrig. Symp*., ASAE, Phoenix, AZ, 201-208.

Daly, C., Neilson, R.P., Phillips, D.L. (1994). A statistical topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology*, 33, 140–158.

Ellis, J., and Vonder Haar, T. (1976). *Zonal averaged ERB measurements from satellites for climate studies*. Technical Report Atmospheric Science Paper No. 240, Colorado State University, Ft. Collins, CO.

Hart, Q., Brugnach, M., Temesgen, B. Rueda, C., Ustin, S, and Frame, K. (2009). Daily reference evapotranspiration for California using satellite imagery and weather station measurement interpolation. *Civil Engineering and Environmental Systems*, 26 (1), 19-33.

Howell, T. A., Evett, S.R., Schneider, A. D., Dusek, D. A., and Copeland, K. S. (2000). "Irrigated fescue grass ET compared with calculated reference grass ET." *Proc., 4th National Irrig. Symp*., ASAE, Phoenix, AZ, 228-242.

Itenfisu, D., Elliott, R. L., Allen, R. G., and Walter, I. A. (2000). "Comparison of reference evapotranspiration calculations across a range of climates." *Proc., 4th National Irrig. Symp*., ASAE, Phoenix, AZ, 216-227.

Leferve, M., Aluisson, M., and Wald, L. (2002). *Description of the software Heliosat-II for the conversion of images acquired be Meteosat satellites in the visible band into maps of solar radiation available at ground level*. Technical report, Ecole Des Mines De Paris, November.

Mardikis, M.G., Kalivas, D.P., and Kollias, V.J. (2005). Comparison of interpolation methods for the prediction of reference evapotranspiration-an application in Greece. *Water Resources Management*, 19, 251–278.

Philips, D.L. and Marks, D. (1996). Spatial uncertainty analysis: propagation of interpolation errors in spatially distributed models. *Ecological Modeling*, 91, 213–229.

Remund, J., Wald L, Lefèvre M, Ranchin T, and Page J. (2003). Worldwide Linke turbidity information. *In*: *Proceedings of ISES solar world congress*, Göteborg, Sweden.

Rigollier, C., Bauer, O., and Wald, L. (2003). On the clear sky model of ESRA – European solar radiation atlas – with respect to the Heliosat method. *Solar Energy*, 68 (1), 33–48.

Rigollier, C., Lefèvre, M., and Wald, L., (2001). *The new method Heliosat-II*. Technical Report IST-1999-12245 D3.2, Report to the European Commission, April.

Smith, M., Allen, R. G., Monteith, J. L., Perrier, A., Pereira, L., and Segeren, A. (1991). "Report of the expert consultation on procedures for revision of FAO guidelines for prediction of crop water requirements." Food and Agriculture Organization of the United Nations, Rome, 54 PP.

Temesgen, B., Eching, S., Davidoff, B., and Frame, K. (2005). “Comparison of some reference evapotranspiration equations for California” *J. Irrig. and Drain. Engr*., ASCE, 131(1), 72-84.

Thornton, P.E., Running, S.W., and White, M.A. (1997). Generating surfaces of daily meteorological variables over large regions of complex terrain. *Journal of Hydrology*, 190, 214–251.

Ustin, S., Hart, Q., and Brugnach. M. (2005). Calculation of daily reference evapotranspiration for California using GOES satellite measurements and CIMIS weather station interpolation, final report to California Department of Water Resources.

Walter, I. A., Allen, R. G., Elliot, R., Jensen, M. E., Itenfisu, D., Mecham, B., Howell, T. A., Snyder, R., Brown, P., Eching, S., Spofford, T., Hattendorf, M., Cuenca, R. H., Wright, J. L., and Martin, D. (2000). “ASCE’s standardized reference evapotranspiration equation.” Proc., *4th National Irrig. Symp*., ASAE, Phoenix, AZ, 209-215.