ET-Demands Documentation

Release 1.0.0

Bureau of Reclamation and Desert Research Institute

May 08, 2020

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1.1 Introduction

The ET-Demands model develops daily estimates of crop irrigation water requirements using daily weather data (including reference evapotranspiration) along with crop-specific crop growth curves.

1.1.1 Acknowledgements

The basis for the ET Demands model is the dual crop coefficient method presented in FAO-56 (Allen et al., 1998). Original model code was developed by Dr. Rick Alan at the University of Idaho Kimberly Reserarch and Extension Center in Kimberly, ID.

1.1.2 Model History

Original model code was written in Visual Basic for Windows. Reclamation and the Desert Research Institute ported this code to a non-versioned Python release of the model. This non-versioned Python release served as the basis for the et-demands model found in this repository. This methods used in this model were used to evaluate evapotranspiration and consumptive use irrigation water requirements for the state of Idaho (Allen and Robison, 2007) and the state of Nevada (Huntington and Allen, 2010). This approach has been used to quantify historical and future irrigation water requirements for selected irrigation projects operated by the Bureau of Reclamation (Reclamation, 2016). This approach has also been used to quantify historical and future irrigation water requirements in support of Reclamation's WaterSMART Basin Studies Program.

1.1.3 Model Version History

v1.0.0

Release date: July 15, 2019

This is the first official release of the et-demands model containing workable source code, examples, and documentation. The dual crop coefficient curve approach remains unchanged from previous releases. This version has undergone thorough testing to ensure reliability, with pre-processing and post-processing tools to develop the required input data, and format and visualize model results are much improved. Model workflow has been better refined to rely on ESRI Shapefiles and daily weather timeseries data as the main

v0.1.0

Release date: September 20, 2018

This is a beta release of the et-demands model containing workable source code. The dual crop coefficient curve approach remains unchanged from the original non-versioned Python code, developed from the Visual Basic version of the et-demands model. Structural changes to the code were made to make ESRI Shapefiles and daily weather timeseries the primary source data for running the model. Pre-processing and post-processing tools were written to develop the required input data, and format and visualize model result using the ESRI Shapefile and daily weather timeseries within a standard workflow. Further refinement and testing of this workflow, development of workable examples and source code are required for a v1.0.0 release.

1.1.4 Model License

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1.2 Quick Start

1.2.1 Installing the Model

Model

Required Dependencies

Downloading Examples

Running Examples

1.3 Model Overview

1.4 Getting Started

1.4.1 Installation

Dependencies

ET-Demands requires Python 3.x, the following Python packages:

- bokeh>=0.13.0

- gdal>=2.2.4

- geopandas>=0.4.0

- numpy>=1.15.0

- openpyxl=2.5.5

- pandas>=0.23.4

- pyshp=1.2.12

- pytest=3.8.0

- python=3.6.6

- rtree

- shapely

- xlrd>=1.1.0

- requests

and GDAL. Steps for installing all dependencies are described below.

Python

ET-Demands requires Python 3.x. While any install of Python will work, he easiest way to install Python and the required modules is to use Miniconda and create a separate Python environment.

conda-forge should be added to the list of conda channels

Miniconda can be installed to any location, but the install location should be noted as it will be used later in the setup. This will be referred to in this documentation as PYTHONPATH (e.g. C:Programsminiconda3).

Once installed, several f GDAL ~~~~ The Geospatial Data Abstraction Library (GDAL) is required for ET-Demands. The easiest way to install GDAL for Windows is to use the OSGeo4W installer. Once installed, GDAL

Creating a Python Environment

We encourange the use of a project-specific Python environment when running ET-Demands. An "etdemands" conda environment can be created using the "environment.yml" file in the project main directory.

'' conda env create -f environment.yml ''

This will create an etdemands Python environment as well as install all required Python packages. An alternative if the etdemands Python environment is not desired is to install the required Python packages manually using the following:

'' conda install bokeh=0.13.0 gdal=2.3.1 numpy=1.15.0 pandas=0.23.4 openpyxl=2.5.5 ''

1.4.2 Model Inputs

ET-Demands requires

1.4.3 Model Control Files

1.4.4 Model Structure

ET-Demands is comprised of several modules with *prep* and *refET* containing pre-processing tools, *cropET* containing the crop irrigation water requirement calculations, and *areaET* and *tools* containing post-processing tools. The source code model structure is shown below:

```
et-demands
 |--- prep
 |    |--- download_cdl_raster.py
 |    |--- clip_cdl_raster.py
 |    |--- build_ag_cdl_shapefile.py
 |    |--- download_statsgo_shapefiles.py
 |    |--- et_demands_zonal_stats.py
 |    |--- build_static_files.py
 |    |--- interpolate_spatial_crop_params.py
 |
 |--- refET
 |    |--- run_ret.py
 |    |    |--- mod_ref_et.py
 |    |        |--- ret_config.py
 |    |        |--- met_nodes.py
 |    |            |--- ref_et_data.py
 |    |            |--- ret_utils.py
 |    |--- ret_utils.py
 |
 |--- cropET
 |    |--- run_cet.py
 |    |    |--- mod_crop_et.py
 |    |        |--- crop_et_data.py
 |    |        |    |--- crop_parameters.py
 |    |        |    |--- crop_coefficients.py
 |    |        |--- et_cell.py
 |    |        |    |--- shapefile.py
 |    |        |--- crop_cycle.py
 |    |        |    |--- initialize_crop_cycle.py
 |    |        |    |--- compute_crop_gdd.py
 |    |        |    |    |--- open_water_evap.py
 |    |        |    |--- calculate_height.py
 |    |        |    |--- kcb_daily.py
 |    |        |    |    |--- runoff.py
 |    |        |    |--- compute_crop_et.py
 |    |        |    |    |--- grow_root.py
 |    |--- util.py
 |
 |--- areaET
 |    |--- run_aet.py
 |    |    |--- mod_area_et.py
 |    |        |--- aet_config.py
 |    |        |--- aet_cells.py
 |    |        |    |--- ref_et_.py
 |    |--- aet_utils.py
 |
 |--- tools
 |    |--- compute_growing_season.py
 |    |--- cropweighted_shapefiles_gpd.py
```

```
|      |--- example_check.py
|      |--- indicatormethod_restructure.py
|      |--- plot_crop_daily_groupstats.py
|      |--- plot_crop_daily_timeseries.py
|      |--- plot_crop_summary_maps.py
|      |--- summary_shapefiles_gpd.py
|      |--- util.py
```

1.4.5 Running the Model

1.5 Model Calibration

1.5.1 RefET

Thornton and Running Coefficients

CropET

ETDemands utlizes crop specific parameters to determine crop growth and timing including growing season start and end dates, crop development rates, effective full cover, harvest timings, and killing frosts. Initial values for each of the control parameters are provided, however, users should customize these values for their input meterological data source and study area. Inherent bias in temperature data can lead to incorrect timing of the season start, effective full cover, and termination dates. A detailed decsiption of the various crop parameters can be found here: http: //data.kimberly.uidaho.edu/ETIdaho/ETIdaho_Report_April_2007_with_supplement.pdf

The initial control parameters are located in the CropParams.txt file contained in the static folder. Note: Users should NOT modify the statics files found in the etemands model folder. Running the initial prep steps will build project specific static files that can be changed accordingly. ETDemands can be run with either spatially consistent or spatially varying calibration parameters. This mode is set in the model INI file via the spatial_cal_flag and spatial_cal_folder inputs.

> ## Spatially varying calibration   spatial_cal_flag = True
>
> spatial_cal_folder= C:\example\calibration

Spatially Consistent Calibration Mode (Default)

Spatially consistent calibration mode applies the same crop parameter information to every ETZone in your model. The parameters are read directly from your project specific CropParams.txt file. This mode should be utilized for when the study zones are located in relatively simliar environments and your supplied weather data is consistent from zone to zone.

Spatially Varying Calibration

Spatially varying calibration mode applies different crop parameter information to every ETZone in your model. These varying parameters are orgnaized in crop specific .shp. To create the crop specific calibration .shp, run the build_spatial_crop_params.py script: python ..et-demandset-demandsprepbuild_spatial_crop_params.py –ini example.ini

Running this script creates and populates the calibration folder with crop specific calibration .shp. Each .shp contains an attribute table with rows for each ETZone that contains that crop. The columns or fields of the attribute table are

initially populated with the default crop parameters from the CropParams.txt. Users can now assign specific crop paramters from each ETZone and crop.

Calibration Process

Calibrating the ETDemands model is an iterative process that requires users to perform complete runs followed by adjustments to the CropParam.txt or crop paramater .shp. The user re-runs the model after adjusting the crop parameter until the they are satistfied with the timing and shape of the crop development curves. Literature review should be performed to determine typical planting, effective full cover, and harvest dates. Throughout the calibration process, users can limit the cells and/or crops being processed by the model by setting the 'crop_test_list' and 'cell_test_list' varibles in the [CROP ET] section of the model .ini file. For example, setting the parameters below in the model .ini will run 'crop 07' in 'cell 529813' and skip all other cells/crop combinations.

> crop_test_list = 07 cell_test_list = 529813

Interpolation of Spatial Crop Parameters

For model runs with a large number of ETZones, users may prefer to spatially interpolate crop parameters from a set of preliminary calibration zones. To set-up and interpolate crop parameters from a set of preliminary zones, users should first run the ETDemands model with a subset of cells that are representative of spatial extent and crops selection throughout the larger study area. Once you've finalized the crop parameter .shp for the subset run, you will copy the crop specific .shp to the "preliminary_calibration" folder in the calibration folder of your complete model. Spatial interpolation will only occur for crops with crop parameter .shp located in teh preliminary calibration folder. Note that if the "preliminary_calibration" folder will need to be created if it doesn't already exist.

Users should run the build_spatial_crop_params.py script to create the calibration folder and crop specific .shp before building the preliminary calibration folder.

python ..et-demandset-demandsprepinterpolate_spatial_crop_params.py –ini UC_2018.ini

Notes on Model Calibration: Calibration of the ETDemands Models requires both time and experience. Users are encouraged to experiement with smaller models (limited cell/crop combinations) to build familiarity with each of the paramters before attempting calibartion over large areas with multiple crops. Each crop utilizes specific information related to its curve type and growth cycle. Curve type assignments for each crop are found within the CropParams.txt along with inital parameter values.

Crops are assigned one of four differenct curve types: 1=NCGDD, 2=%PL-EC, 3=%PL-EC,daysafter, 4=%PL-Term

- 1 = normalized cumulative growing degree days (NCGDD)
- 2 = percent of time from planting (or greenup) to effective full cover, applied all season
- 3 = percent of time from planting (or greenup) to effective full cover, then days after effective full cover
- 4 = percent of time from planting (or greenup) until termination

In addition to curve type, each crop also recieves a flag for estimating planting or greenup: 1=CGDD, 2=T30, 3=date, 4 is on all the time

- 1 = Indicates that cumulative growing degree days from January is used
- 2 = Indicates that 30 day mean air temperature is used
- 3 = Indicates a specific date
- 4 = Crop growth is always on

Depending on the assignments above, the crop will utilize different values to determine the start, greenup, effective full cover, harvest, and termination dates.

Tips: In general, it is easier to make small changes to one crop/parameter combination at a time. Large changes to multiple paramters can be difficult to track. Utilize the crop and cell test list varibles to limit your model run and speed up output results. Examining both the daily time series plots and summary .shp created with the postprocessing "tools" scripts will help identify problematic crops/cells.

1.6 Model Inputs

1.6.1 RefET

The RefET module calculates hourly or daily reference ET from meteorological data using the approach described in ASCE-NWRI (2005). If needed, the module will estimate solar radiation and dew point temperature, and gap fill meteorological data.

Meteorology Metadata

Meteorology Data

The RefET module requires hourly or daily meteorological data. If the calculated reference ET will be used in the CropET module, care should be taken to ensure this meteorological data is representative of agricultural conditions. Meteorological data can be obtained from *agricultural weather networks*, or adjustments reference ET can be made within the CropET module.

Timeseries Data

Daily Variables

- Date [in *YYYY-MM-DD* format]

- T_{max} = maximum daily air temperature

- T_{min} = minimum daily air temperature

- T_d = mean daily dew point temperature[a]

- e_a = actual vapor pressure[a]

- u_x = mean daily wind speed at known height[b]

- R_n = calculated net radiation at the crop surface[c]

- P_r = daily precipitation (optional)

- Q = specific humidity (optional)

- S_n = daily accumulated snow (optional)

- S_d = snow depth (optional)

[a] One of these is required. If both T_d and e_a are not provided, mean monthly dew point depression, K_0, must be provided.

[b] Wind measurement height in meters must be provided in the *ini* file.

[c] If R_n is not provided it will be estimated using the approach described in Thornton and Running (1998). The three Thornton and Running coefficients must be provided in the *ini* file.

Hourly Variables

- Date [in *YYYY-MM-DD HH:MM* format]

- T_{mean} = mean hourly air temperature

- T_d = mean hourly dew point temperature[a]

- u_x = mean hourly wind speed at known height[b]

- R_n = calculated net radiation at the crop surface[c]

- P_r = hourly precipitation (optional)

- Q = specific humidity (optional)

- S_n = hourly accumulated snow (optional)

- S_d = snow depth (optional)

[a] One of these is required. If both T_d and e_a are not provided, mean monthly dew point depression, K_0, must be provided.

[b] Wind measurement height in meters must be provided in the *ini* file.

[c] If R_n is not provided it will be estimated using the approach described in Thornton and Running (1998). The three Thornton and Running coefficients must be provided in the *ini* file.

HOW IS THE SNOW OR SNOW DEPTH USED?

File Format

RefET requires the timeseries weather data to be in delimited columns with header of column names. Column names and units are specified in the *ini* file. Files are allowed to have header rows, with the number of header rows specified in the *ini* file. The delimiter is also specified in the *INI* file.

Delimiter	Model Notation
Comma	,
Tab	/t

- Format: **.csv**, **.txt**, **.dat**

- File Name: (DESCRIBE WILDCARDS)

- Structure:

Date	Tmax	Tmin	ux	Rn	Tdew
2017-10-01	9.34	3.70	3.95	120.93	3.21
2017-10-02	5.52	-2.12	7.54	59.10	-3.18
…	…	…	…	…	…

- Units

Class	Variables	Units	Model Notation
Temperature	T_{max}, T_{min}, T_d	°C °F °K	c f k
Wind Speed	u_x	m s^{-1} m d^{-1} mi d^{-1}	m/s, mps m/d, m/day miles/d, miles/day, mpd
Solar Radiation	R_n	MJ m^{-2} d^{-1} W m^{-2} d^{-1} cal cm^{-2} d^{-1} langley	mj/m2, mj/m^2, mj/m2/d, mj/m^2/d, mj/m2/day, mj/m^2/day w/m2, w/m^2 cal/cm2', cal/cm2, cal/cm2/d, cal/cm^2/d, cal/cm2/day, cal/cm^2/day langley
Precipitation	P_r	in d^{-1} mm d^{-1}	in/d, in/day, inches/d, inches/day mm/d, mm/day
Humidity	Q	kg kg^{-1}	kg/kg
Vapor Pressure	e_a	kPa	kPa
Snow	S_n	in d^{-1} mm d^{-1}	in/d, in/day, inches/d, inches/day mm/d, mm/day
Snow Depth	S_g	in mm	in, inches, *in*100* mm

Mean Monthly Data

Mean monthly data are used to calculate a dew point temperature timeseries or gap fill the timeseries data if needed.

- T_{max} = mean monthly maximum daily air temperature

- T_{min} = mean monthly minimum daily air temperature

- u_x = mean monthly wind speed at known height

- K_0 = mean monthly dew point depression

File Format

- Delimiter:

See *Timeseries Data - Delimiter*

- Format: **.csv**, **.txt**, **.dat**

- Structure:

Met Node ID	Met Node Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BFAM	Blackfeet, MT	2.6	3.0	7.3	11.6	16.8	21.5	28.3	23.5	17.9	13.6	7.3	1.7

T:sub:'max' example shown. File structure will be the same for T_{min}, u_x, and K_0. Individual files are provided for each variable.

- Units

See *Timeseries Data - Units*

Ancillary Data

- Thornton and Running Coefficients * TR_{b0} * TR_{b1} * TR_{b2}

Thornton and Running coefficients are used to estimate solar radiation from meteorological data. These coefficients are location-specific and should be calibrated using measured solar radiation data from a representative location. The calibration approach is described in detail *here*

- Wind Measurement Height (in meters)

1.6.2 CropET

Weather Data

Timeseries Data

The user must provide daily weather and reference ET data for each ET zone. This includes:

- Date [in *YYYY-MM-DD* format]

- T_{max} = maximum daily air temperature

- T_{min} = minimum daily air temperature

- T_d = mean daily dew point temperature[a]

- u_x = mean daily or hourly wind speed at known height[b]

- R_n = calculated net radiation at the crop surface[c]

- Q = specific humidity (optional)

- S_n = daily accumulated snow (optional)

- S_d = snow depth (optional)

and one of two reference ET values:

- ASCEr - Daily reference ET from Penman–Monteith

- ASCEg - Daily reference ET from Penman–Monteith

File Format

- Format: **.csv**

- Structure:

Date	TMax	TMin	Precip	Snow	SDep	EstRs	EsWind	EsTDew	*ETRef* [ASCEr; ASCEg]
Units	[C]	[C]	[In]	[In]	[In]	[MJ/m2]	[m/s]	[C]	[mm/day]

Location Shapefile

A shapefile containing the locations of each weather station is also required and is used to generate the static input files. The shapefile must contain the following attributes:

- STATION_ID - Weather station ID

- *ETZONE_ID* - Zone ID. This can include HUC8, HUC10, COUNTRYNAME, OR GRIDMET_ID

- LAT - Weather station latitude

- LON - Weather station longitude

- [*optional*] *ELEV* [ELEV_FT; ELEV_M] - Weather station elevation in feet or meters. This field is optional and only required if running the RefET model to estimate reference ET.

File Format

- Format: **.shp**

- Attribute Table Structure:

STA-TION_ID	*ZONE_ID* [HUC8; HUC10; COUNTRYNAME; GRID-MET_ID]	LAT	LON	*ELEV* [ELEV_FT; ELEV_M]

Study Area

The user must provide a study area polygon shapefile with at least one feature. Each feature in the study area shapefile will become a separate ET cell/unit. Currently, only HUC8, HUC10, county, and gridmet cell shapefiles are fully supported by the prep tools.

Soils Data

Crop Type Data

Static Inputs

These files will be generated automatically by the CropETPrep module

CropCoefs

Crop coefficient curves for each crop. Generally, these values should not be modified. DESCRIBE CROP COEFFICIENTS -

CropParams

Crop parameters that can/should be modified during calibration.

- Format: **.txt**

- Structure:

ETCellsCrops

Flags controlling which crops to simulate. If using the prep workflow, the flags will initially be set based on the CDL acreage.

- Format: **.txt**
- Structure:

EToRatiosMon

Reference ET scale factors by month for each ET cell. This file could be used to account for a seasonal bias in the input weather data. This file is optional.

- Format: **.txt**
- Structure:

ETCellsProperties

Soil properties and weather station data for each ET cell. This file links the stations and the ET cells.

- Format: **.txt**
- Structure:

MeanCuttings

Sets the assumed number of alfalfa cuttings. This is important since the CropET module will use different crop coefficient curves for the first and last cutting.

- Format: **.txt**
- Structure:

1.7 Model Outputs

1.7.1 RefET

1.7.2 CropETPrep

1.7.3 CropET

1.7.4 AreaET

PostProcessing

1.8 Running the Model

1.8.1 RefET

1.8.2 CropETPrep

1.8.3 CropET

1.8.4 AreaET

1.8.5 PostProcessing

1.9 Model Description

The ET-Demands package

1.9.1 RefET

Reference evapotranspiration is calculated according to the ASCE Standardized Reference Evapotranspiration Equation (ASCE-EWRI, 2005).

Gap Filling and QA/QC

Missing Data

Missing values of maximum air temperature (T_{max}), minimum air temperature (T_{min}), and mean wind speed (u_x), up to six timesteps, are first filled through linear interpolation. Additional missing values not handled by the linear interpolation are filled using mean monthly values. Missing values of precipitation (P_r), snow, (S_n), and snow depth (S_d) are set to 0.

Maximum and Minimum Air Temperature

Maximum air temperature (T_{max}) values greater than 120°F are set to 120°F. Minimum air temperature (T_{min}) values greater than 90°F are set to 90°F. Maximum air temperature is checked against minimum air temperature at every time step. If minimum air temperature is greater than maximum air temperature, maximum air temperature is set to minimum air temperature.

ASCE Standardized Reference Evapotranspiration Equation

Daily Reference Evapotranspiration

$$ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma\frac{C_n}{T_{mean}+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

where:

ET_{sz} = standardized reference crop evapotranspiration for short ET_{os} or tall ET_{rs} surfaces [mm d^{-1} for daily time steps or mm h^{-1} for hourly time steps]

R_n = calculated net radiation at the crop surface [MM m^{-2} d^{-1} for daily time steps or MM m^{-2} h^{-1} for hourly time steps]

G = soil heat flux density at the soil surface [MM m^{-2} d^{-1} for daily time steps or MM m^{-2} h^{-1} for hourly time steps]

T_{mean} = mean daily or hourly air temperature at 1.5 to 2.5-m height [°C]

u_2 = mean daily or hourly wind speed at 2-m height [m s^{-1}]

e_s = saturation vapor pressure at 1.5 to 2.5-m height [kPa]

e_a = mean actual vapor pressure at 1.5 to 2.5-m height [kPa]

Δ = slope of the saturation vapor pressure-temperature curve [kPa °C^{-1}]

γ = psychrometric constant [kPa °C^{-1}]

C_n = numerator constant that changes with reference type and calculation time step [K mm s^3 Mg$_{-1}$ d^{-1} for daily time steps or K mm s^3 Mg$_{-1}$ h^{-1} for hourly time steps]

C_d = denominator constant that changes with reference type and calculation time step [s m^{-1}]

For a grass reference surface (ET_o),

C_n = 900

C_d = 0.34

For an alfalfa reference surface (ET_r),

C_n = 1600

C_d = 0.38

As soil heat flux density is positive when the soil is warming and negative when the soil is cooling, over a day period it is relatively small compared to daily R_n. For daily calculations it is ignored,

G = 0

Hourly Reference Evapotranspiration

The equation for ET_{sz} is the same as daily, with

For a grass reference surface (ET_o),

C_n = 37.0

At night, when R_n < 0,

C_d = 0.96

G = 0.5

For an alfalfa reference surface (ET_r),

C_n = 66.0

At night, when R_n < 0,

C_d = 1.7

G = 0.2

UNIT CONVERSION

Mean Air Temperature (T$_{mean}$)

ASCE-EWRI (2005) advises to use the mean of daily minimum and daily maximum temperature to calculate mean daily temperature as opposed to the mean of hourly temperatures.

$$T_{mean} = \frac{T_{max} + T_{min}}{2}$$

where:

T$_{mean}$ = mean daily air temperature [°C]

T$_{max}$ = maximum daily air temperature [°C]

T$_{min}$ = minimum daily air temperature [°C]

Ultimately, the ET$_{sz}$ equation requires actual vapor pressure (e$_a$). This can be calculated from dew point temperature (T$_d$), specific humidity (q), or relative humidity (RH). If needed, dew point temperature can be calculated from minimum air temperature (T$_{min}$) and mean monthly dew point depression values (K$_0$).

Dew Point Temperature

$$T_d = T_{min} - K_0$$

where:

T$_d$ = mean hourly or daily dew point temperature [°C]

T$_{min}$ = mean hourly or daily minimum daily air temperature [°C]

K$_0$ = mean monthly dew point depression [°C]

Actual Vapor Pressure (e$_a$) from Dew Point Temperature (T$_d$)

$$e_a = 0.6108 \cdot \exp \frac{17.27 \cdot T_d}{T_d + 237.3}$$

where:

e$_a$ = actual vapor pressure [kPa]

T$_d$ = mean hourly or daily dew point temperature [°C]

CALCULATE ACTUAL VAPOR PRESSURE FROM RELATIVE HUMIDITY

Actual Vapor Pressure (e$_a$) from Relative Humidity (RH)

$$e_a = \frac{RH}{100} \cdot e_s$$

where:

e$_a$ = actual vapor pressure [kPa]

RH = relative humidity [%]

e$_s$ = saturation vapor pressure [kPa]

Actual Vapor Pressure (e_a) from Specific Humidity (q)

$$e_a = \frac{q \cdot P}{0.622 + 0.378 \cdot q}$$

where:

e_a = actual vapor pressure [kPa]

q = specific humidity [kg/kg]

P = mean atmospheric pressure at station elevation [kPa]

Atmospheric Pressure (P)

$$P = 101.3 \cdot \left(\frac{293.15 - 0.0065z}{293.15} \right)^{(9.80665/(0.0065 \cdot 286.9))}$$

where:

P = mean atmospheric pressure at station elevation [kPa]

z = station elevation above mean sea level [m]

This equation differs slightly from ASCE 2005 as it reflects full precision per Dr. Allen (pers. comm.).

Psychrometric Constant (γ)

$$\gamma = .0000665 \cdot P$$

where:

γ = psychrometric constant [kPa °C^{-1}]

P = mean atmospheric pressure at station elevation [kPa]

Slope of the Saturation Vapor Pressure-Temperature Curve ($\triangle$)

$$\Delta = 4098 \cdot \frac{0.6108 \cdot \exp\left(\frac{17.27 T_{mean}}{T_{mean} + 237.3} \right)}{(T_{mean} + 237.3)^2}$$

where:

Δ = slope of the saturation vapor pressure-temperature curve (kPa °C^{-1}]

T_{mean} = mean daily air temperature [°C]

Saturation Vapor Pressure (e_s)

$$e_s = 0.6108 \cdot \exp\left(\frac{17.27 T_{mean}}{T_{mean} + 237.3} \right)$$

where:

e_s = saturation vapor pressure

Tetens (1930)

Vapor Pressure Deficit (VPD)

$$VPD = e_s - e_a$$

where:

VPD = vapor pressure deficit [kPa]

e_s = saturation vapor pressure [kPa]

e_a = actual vapor pressure [kPa]

Extraterrestrial Radiation (R_a)

The calculations for hourly and daily extraterrestrial radiation (R_a) differ slightly as the hourly calculations require hourly solar time angles (ω) in addition to the sunset hour angle (ω_s) while the daily calculations just require the sunset hour angle.

Hourly and daily calculations require solar declination (δ), sunset hour angle (ω_s), and inverse square of the earth-sun distance (d_r).

Solar Declination (δ)

$$\delta = 23.45 \cdot \frac{\pi}{180} \cdot \sin\left(\frac{2\pi}{365} \cdot (\text{DOY} + 284)\right)$$

where:

δ = solar declination [radians]

DOY = day of year

Sunset Hour Angle (ω_s)

$$\omega_s = \arccos(-\tan(\text{lat}) \cdot \tan(\delta))$$

where:

ω_s = sunset hour angle [radians]

lat = Latitude [radians]

δ = solar declination [radians]

To calcuate the inverse quare of the earth-sun distance, the day-of-year fraction (DOY_{frac}) is needed

Day-of-Year Fraction (DOY_{frac})

$$\text{DOY}_{\text{frac}} = \text{DOY} \cdot \left(\frac{2\pi}{365}\right)$$

where:

DOY_{frac} = day-of-year fraction

DOY = day-of-year

Inverse Square of the Earth-Sun Distance (d_r)

$$d_r = 1 + 0.033 \cos(\text{DOY}_{\text{frac}})$$

where:

d_r = inverse square of the earth-sun distance [d^{-2}]

ω_s = sunset hour angle [radians]

lat = Latitude [radians]

δ = solar declination [radians]

Daily Extraterrestrial Radiation

$$\theta = \omega_s \cdot \sin(\text{lat}) \cdot \sin(\delta) + \cos(\text{lat}) \cdot \cos(\delta) \cdot \sin(\omega_s)$$

$$R_a = \frac{24}{\pi} \cdot (1367 \cdot 0.0036) \cdot d_r \cdot \theta$$

where:

ω_s = sunset hour angle [radians]

lat = Latitude [radians]

R_a = daily extraterrestrial radiation [MJ m^{-2} d^{-1}]

δ = solar declination [radians]

d_r = inverse square of the earth-sun distance [d^{-2}]

Hourly Extraterrestrial Radiation

Hourly calculations also require the calculation hourly solar time angles (ω), which requires the calculation of solar time (t_s).

Seasonal Correction (sc)

$$b = \frac{2\pi}{364} \cdot (\text{DOY} - 81)$$

$$sc = 0.1645 \cdot \sin(2b) - 0.1255 \cdot \cos(b) - 0.0250 \sin(b)$$

where:

sc = seasonal correction [hours]

DOY = day-of-year

Solar Time (t:sub:'s')

$$t_s = t + (\text{lon} \cdot \frac{24}{2\pi} + sc - 12)$$

where:

t_s = solar time (i.e. noon is 0) [hours]

lon = Longitude [radians]

t = UTC time at the midpoint of the period [hours]

sc = seasonal correction [hours]

Solar Time Angle (ω)

$$\omega = \frac{2\pi}{24} \cdot t_s$$

where:

ω = solar hour angle [radians]

t_s = solar time (i.e. noon is 0) [hours]

Hourly Extraterrestrial Radiation

$$\omega_1 = \omega - \frac{\pi}{24} \cdot t$$
$$\omega_2 = \omega + \frac{\pi}{24} \cdot t$$

Checks on ω_1 and ω_2

$$\text{if } \omega_1 < -\omega_s \text{ then } \omega_1 = -\omega_s$$
$$\text{if } \omega_2 < -\omega_s \text{ then } \omega_2 = -\omega_s$$
$$\text{if } \omega_1 > \omega_s \text{ then } \omega_1 = \omega_s$$
$$\text{if } \omega_2 > \omega_s \text{ then } \omega_2 = \omega_s$$
$$\text{if } \omega_1 > \omega_2 \text{ then } \omega_1 = \omega_2$$

$$\theta = (\omega_2 - \omega_1) \cdot \sin(\text{lat}) \cdot \sin(\delta) + \cos(\text{lat}) \cdot \cos(\delta) \cdot \sin(\omega_2 - \omega_1)$$

$$R_a = \frac{24}{\pi} \cdot (1367 \cdot 0.0036) \cdot d_r \cdot \theta$$

where: ω_1 = solar time angle at the beginning of the period [radians]

ω_2 = solar time angle at the end of the period [radians]

ω = solar hour angle [radians]

t = UTC time at the midpoint of the period [hours]

ω_s = sunset hour angle [radians]

lat = Latitude [radians]

δ = solar declination [radians]

R_a = hourly extraterrestrial radiation [MJ m^{-2} h^{-1}]

d_r = inverse square of the earth-sun distance [d^{-2}]

Clear-Sky Radiation (R$_{so}$)

Sin of the Angle of the Sun above the Horizon (sin:sub:'β24')

$$\sin_{\beta24} = \sin(0.85 + 0.3 \cdot \text{lat} \cdot \sin(\text{DOY}_{\text{frac}}) - 1.39)) - 0.42 \cdot \text{lat}^2$$
$$\sin_{\beta24} = \max(\sin_{\beta24}, 0.1)$$

where:

sin:sub:'β24'= sine of the angle of the sun above the horizon [radians]

lat = Latitude [radians]

DOY_{frac} = day-of-year fraction

Precipitable Water (w)

$$w = P \cdot 0.14 \cdot e_a + 2.1$$

where:

w = precipitable water [mm]

P = mean atmospheric pressure at station elevation [kPa]

e_a = actual vapor pressure [kPa]

Clearness Index for Direct Beam Radiation (k:sub:'b')

$$k_b = 0.98 \cdot \exp\left(\frac{-0.00146P}{sin_{\beta 24} - 0.0075}\right) - 0.075\left(\frac{w}{\sin_{\beta 24}}\right)^{0.4}$$

where:

k_b = clearness index for direct beam radiation

P = mean atmospheric pressure at station elevation [kPa]

sin:sub:'$\beta 24$'= sine of the angle of the sun above the horizon [radians]

w = precipitable water [mm]

Transmissivity Index for Diffuse Radiation (k:sub:'d')

$$k_d = \min \begin{cases} -0.36 \cdot k_b + 0.35 \\ 0.82 \cdot k_b + 0.18 \end{cases}$$

where:

k_d = transmissivity index for diffuse radiation

k_b = clearness index for direct beam radiation

Daily Clear-Sky Radiation

$$R_{so} = R_a \cdot (k_b + k_d)$$

where:

R_{so} = daily clear-sky radiation [MJ m^{-2} d^{-1}]

R_a = daily extraterrestrial radiation [MJ m^{-2} d^{-1}]

k_b = clearness index for direct beam radiation

k_d = transmissivity index for diffuse radiation

Hourly Clear-Sky Radiation

Several calculations, including the sin of the angle of the sun above the horizon ($\sin_\beta$) and the clearness index for direct beam radiation (k_b) change when calculating hourly clear-sky radiation.

Sin of the Angle of the Sun above the Horizon (sin:sub:'β')

$$\sin_\beta = \sin(\text{lat}) \cdot \sin(\delta) + \cos(\text{lat}) \cdot \cos(\delta) \cdot \cos(\omega)$$

$$\sin_{\beta,c} = \max \begin{cases} \sin_\beta \\ 0.01 \end{cases}$$

where:

sin:sub:'β'= sine of the angle of the sun above the horizon [radians]

$\sin_{\beta,c}$= sin:sub:'β' limited to 0.01 so that k_b does not go undefined

lat = Latitude [radians]

δ = solar declination [radians]

ω = solar hour angle [radians]

Clearness Index for Direct Beam Radiation (k:sub:'b')

$$k_t = 1.0$$

$$k_b = 0.98 \cdot \exp\left(\frac{-0.00146P}{k_t \cdot \sin_{\beta,c}}\right) - 0.075\left(\frac{w}{\sin_{\beta,c}}\right)^{0.4}$$

where:

k_t = atmospheric turbidity coefficient

k_b = clearness index for direct beam radiation

P = mean atmospheric pressure at station elevation [kPa]

sin:sub:'β,c'= sine of the angle of the sun above the horizon, limited to 0.01 [radians]

w = precipitable water [mm]

Transmissivity Index for Diffuse Radiation (k:sub:'d')

$$k_d = \min \begin{cases} -0.36 \cdot k_b + 0.35 \\ 0.82 \cdot k_b + 0.18 \end{cases}$$

where:

k_d = transmissivity index for diffuse radiation

k_b = clearness index for direct beam radiation

Hourly Clear-Sky Radiation

$$R_{so} = R_a \cdot (k_b + k_d)$$

where:

R_{so} = hourly clear-sky radiation [MJ m^{-2} h^{-1}]

R_a = hourly extraterrestrial radiation [MJ m^{-2} h^{-1}]

k_b = clearness index for direct beam radiation

k_d = transmissivity index for diffuse radiation

Cloudiness Fraction (fcd)

Daily Cloudiness Fraction

$$fcd = 1.35 \cdot \frac{R_s}{R_{so}} - 0.35$$

$$0.3 < \frac{R_s}{R_{so}} \leq 1.0$$

where:

fcd = daily cloudiness fraction

R_s = measured solar radiation [MJ m^{-2} d^{-1}]

R_{so} = clear sky solar radiation [MJ m^{-2} d^{-1}]

R_s / R_{so} is limited to 0.3 < R_s / R_{so} 1.0

Hourly Cloudiness Fraction

At low sun angles (β), cloudiness fraction (fcd) is set to 1.

$$\beta = \arcsin(\sin(\text{lat}) \cdot \sin(\delta) + \cos(\text{lat}) \cdot \cos(\delta) \cdot \cos(\omega))$$

$$\text{fcd}[R_{so} > 0] = 1.35 \cdot \frac{R_s}{R_{so}} - 0.35$$

$$0.3 < \frac{R_s}{R_{so}} \leq 1.0$$

$$\text{fcd}[\beta < 0.3] = 1$$

where:

β = angle of the sun above the horizon [radians]

lat = Latitude [radians]

δ = solar declination [radians]

ω = solar hour angle [radians]

fcd = hourly cloudiness fraction

R_s = measured solar radiation [MJ m^{-2} h^{-1}]

R_{so} = clear sky solar radiation [MJ m^{-2} h^{-1}]

Net Longwave Radiation (R$_{nl}$)

Daily Net Longwave Radiation

$$R_{nl} = 4.901\text{e-}9 \cdot \text{fcd} \cdot (0.34 - 0.14 \cdot \sqrt{e_a} \cdot 0.5((T_{max} + 273.16)^4 + (T_{min} + 273.16)^4)$$

where:

R_{nl} = daily net longwave radiation [MJ m^{-2} d^{-1}]

fcd = daily cloudiness fraction

e_a = actual vapor pressure [kPa]

T_{max} = maximum daily air temperature [°C]

T_{min} = minimum daily air temperature [°C]

Hourly Net Longwave Radiation

$$R_{nl} = 2.042\text{e-}10 \cdot \text{fcd} \cdot (0.34 - 0.14 \cdot \sqrt{e_a} \cdot (T_{mean} + 273.16)^4$$

where:

R_{nl} = hourly net longwave radiation [MJ m^{-2} h^{-1}]

fcd = daily cloudiness fraction

e_a = actual vapor pressure [kPa]

T_{mean} = mean hourly air temperature [°C]

Net Radiation (R$_n$)

Daily Net Radiation

$$R_n = 0.77 \cdot R_s - R_{nl}$$

where:

R$_n$ = daily net radiation [MJ m^{-2} d^{-1}]

R$_{nl}$ = daily net longwave radiation [MJ m^{-2} d^{-1}]

R$_s$ = measured solar radiation [MJ m^{-2} d^{-1}]

Hourly Net Radiation

$$R_n = 0.77 \cdot R_s - R_{nl}$$

where:

R$_n$ = hourly net radiation [MJ m^{-2} h^{-1}]

R$_{nl}$ = hourly net longwave radiation [MJ m^{-2} h^{-1}]

R$_s$ = measured solar radiation [MJ m^{-2} h^{-1}]

Windspeed Adjustment

The standardized reference crop evapotranspiration equation assumes a 2-m height windspeed. Windspeed measured at different heights can be approximated as

$$u_2 = u_z + \frac{4.87}{\ln\left(67.8 z_w - 5.42\right)}$$

where:

u$_2$ = wind speed at 2 m above ground surface [m s^{-1}]

u$_z$ = measured wind speed at z$_w$ m above ground surface [m s^{-1}]

z$_w$ = height of wind measurement about ground surface [m]

CACLULATE MIN AND MAX MONTHLY MEAN TEMPERATURES

Thornton and Running Solar Radiation Estimate

If measured solar radiation (R$_s$) is not provided, it can be estimated using the approach described in Thorton and Running (1999). This approach requires three calibrated coefficients [LINK TO PAGE ON HOW TO DO THIS].

T$_{diff}$ = temperature difference [°C]

T$_{max}$ = maximum daily air temperature [°C]

T$_{min}$ = minimum daily air temperature [°C]

T$_{mon,diff}$ = mean monthly temperature difference [°C]

T$_{mon,max}$ = mean monthly maximum air temperature [°C]

T$_{mon,min}$ = mean monthly minimum air temperature [°C]

TR_{b0} = Thornton and Running b_0 coefficient

TR_{b1} = Thornton and Running b_1 coefficient

TR_{b2} = Thornton and Running b_2 coefficient

B_{TR} = Thorton and Running parameter

R_s = calculated solar radiation [MJ m^{-2} d^{-1}]

R_{so} = clear sky solar radiation [MJ m^{-2} d^{-1}]

For arid stations, [REFERENCE FOR THESE COEFFICIENTS]

TR_{b0} = 0.023

TR_{b1} = 0.1

TR_{b2} = 0.2

[DISCUSSION OF THESE PARAMETERS, AND HOW TO GET THEM]

Other Potential ET Estimates

The RefET module code can also calculate potential evapotranspiration using several different approaches. This provides a comparison with reference ET.

Latent Heat of Vaporization (λ)

The latent heat of vaporization is calculated from mean air temperature. This differs from ASCE-EWRI (2005) which advises to use a constant value of 2.45 MJ kg^{-1} as it varies only slightly over the ranges of air temperature that occur in agricultural or hydrologic systems. The equation used is from XXX.

$$\lambda = 2500000 - 2360 \cdot T_{mean}$$

where:

λ = latent heat of vaporization [MJ kg^{-1}]

T_{mean} = mean daily air temperature [°C]

Penman

$$ET_o = W \cdot R_n + (1 - W) \cdot f(ur) \cdot (e_a - e_d)$$

where:

ET_o = grass reference evapotranspiration [mm d^{-1}]

W = weighting factor (depends on temperature and altitude)

R_n = net radiation in equivalent evaporation [mm d^{-1}]

f(ur) = wind-related function

(e_a - e_d) = difference between saturation vapor pressure at mean air temperature and the mean actual vapor pressure of the air [hPa]

$$f(ur) = 0.27(1 + (ur_2/100))$$

where:

f(ur) = wind-related function

ur$_2$ = daily wind run at 2-m height [km d^{-1}]

(Penman, 1948).

Kimberly Penman 1982

Hargreaves-Samani

(Hargreaves and Samani, 1985).

Priestley-Taylor

'(Priestley and Taylor, 1972) <https://doi.org/10.1175/1520-0493(1972)100//<0081:OTAOSH//>2.3.CO;2>'_ .

Blaney-Criddle

[THIS CURRENTLY ISN'T SUPPORTED]

(Blaney and Criddle, 1950).

1.9.2 CropETPrep

1.9.3 CropET

The CropET module of the ET Demands model is the FAO-56 dual crop coefficient model (Allen et al., 1998) .

$$ET_c = (K_c K_{cb} + K_e)ET_o$$

ET$_c$ = crop evapotranspiration

K$_c$ = crop coefficient

K$_{cb}$ = Basal crop coefficient

K$_e$ = coefficient representing bare soil evaporation

ET$_o$ = reference crop evapotranspiration from a grass reference surface

Aridity Rating

Allen and Brockway (1983) estimated consumptive irrigation requirements for crops in Idaho, and developed an aridity rating for each meteorological weather station used to adjust temperature data. The aridity rating ranges from 0 (fully irrigated) to 100 (arid) and reflects conditions affecting the aridity of the site. The aridity rating was based on station metadata information, questionnaires, and phone conversations, and includes conditions close to the station (within a 50m radius),the area around the station (within a 1600m radius in the upwind direction), and the region around the station (within a 48km radius in the upwind direction).

$$AR_{cum} = 0.4AR_{St} + 0.5AR_{Ar} + 0.1AR_{Reg}$$

Allen and Brockway (1983) used empirical data from Allen and Brockway (1982) to develop monthly aridity effect values (A_e). These values were used as adjustment factors for the temperature data based on the aridity rating. Stations with an aridity rating of 100 applied the adjustment factor directly, while stations with aridity ratings less than 100, weighted the adjustment factor by the aridity rating.

$$T_{adj} = \frac{AR_{cum}}{100} \cdot A_e$$

The empirical temperature data and aridity effect values used are show in the table below. These data are the average monthly departure of air temperatures over arid areas from air temperatures over irrigated areas in southern Idaho during 1981, and the aridity effect.

Month	T_{max}	T_{min}	T_{mean}	A_e
April	2.7	2.4	2.5	1.0
May	1.3	0.6	0.9	1.5
June	2.4	1.8	2.1	2.0
July	4.8	2.9	3.8	3.5
August	5.2	4.3	4.7	4.5
September	3.3	2.7	3.0	3.0
October	0.3	1.6	0.9	0.0

HOW WAS THE ARIDITY EFFECT DETERMINED. ARE THESE DATA GENERAL ENOUGH TO USE AT OTHER LOCATIONS IF AN ARIDITY RATING IS DEVELOPED? IF NOT, CAN WE GENERALIZE THE APPROACH TO DEVELOPING AN ARIDITY RATING, AND ASSOCIATED ARIDITY EFFECT ADJUSTMENTS? ALSO, THE 'CropET' MODULE HAS A WAY OF PULLING IN ARIDITY EFFECT VALUES, HOWEVER, THE 'RefET' MODULE DOES NOT. THIS MEANS THAT WHILE TEMPERATURES USED IN THE CropET MODULE ARE ADJUSTED, TEMPERATURES USED TO CALCUATE REFERENCE ET ARE NOT. IF WE WANT TO CONTINUE TO SUPPORT THE ARIDITY RATING, THIS SHOULD BE ADDRESSED. WOULD ALSO REQUIRE PASSING THE MODEL THE ARIDITY EFFECT ADJUSTMENT FACTORS.

1.9.4 AreaET

1.9.5 PostProcessing

1.9.6 References

Allen, R. G., & Brockway, C. E. (1982). Weather and Consumptive Use in the Bear River Basin, Idaho During 1982.

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1.10 Analysis Tools

ETDemands provides post-processing tools to assist with summarizing and viewing the raw daily, monthly, and annual .csv datasets. In general, there are two types of outputs: Timeseries Plots and Summary Shapefiles

The timeseries scripts analyze specific crops and years to create interactive .html plots that can be used to visualize temporal patterns or changes in the data. Each .html plot contains all the data used to generate the plot and can be easily shared with team members and stakeholders.

The shapefile scripts batch the output .csv files into spatial summaries that can be visualized with any standard GIS software (e.g. ArcGIS, QGIS). Each output shapefile will contain summary statistics for each ET Zone for the crop(s) and year(s) of interest.

Note: Many of these tools offer options to process single or multiple years. Passing the "-h" argument to each script will display input argument options.

1.11 Timeseries Tools

1.11.1 Daily Timeseries (plot_crop_daily_timeseries.py)

This analysis tool creates an .html time series figure from the daily ETact/ETbas/ETr, Kc/Kcb, PPT/Irrigation datasets. A figure is generated for each ET Zone/Crop combination. Input arguments for start/end date and crop allow the user to only process specific date ranges and crops. Output figures can be found in the 'daily_plots' subfolder. The following input arguments can be specified to customize the output:

-i, --ini	ini_path (str): file path of project INI file
--show	figure_show_flag (bool): if True, show figures
--save	figure_save_flag (bool): if True, save figures
--size	figure_size (tuple): width, height of figure in pixels
--start	start_date (str): ISO format date string (YYYY-MM-DD)
--end	end_date (str): ISO format date string (YYYY-MM-DD)
-c, --crops	crop_str (str): comma separate list or range of crops to compare

1.11.2 Average Annual Timeseries (plot_crop_daily_groupstats.py)

The groupstats timeseries script averages daily input data from multiple years and creates a single average annual timeseries plot of ETact/ETr, Kc, and Kcb information for each ET Zone/crop combination. This timeseries plot includes 25th, 50th, 75th percentile information. Output figures can be found in the 'daily_plots' subfolder. The following input arguments can be specified to customize the output:

-i, --ini	ini_path (str): file path of project INI file

--show	figure_show_flag (bool): if True, show figures
--save	figure_save_flag (bool): if True, save figures
--size	figure_size (tuple): width, height of figure in pixels
--start	start_date (str): ISO format date string (YYYY-MM-DD)
--end	end_date (str): ISO format date string (YYYY-MM-DD)
-c, --crops	crop_str (str): comma separate list or range of crops to compare

1.12 Shapefile Summary Tools

1.12.1 Summary Shapefiles (summary_shapefiles_gpd.py)

This analysis tool converts the daily output .csv files into crop specific summary shapefiles for viewing and analysis of the spatial distribution of evaporation. Specific time periods can be specified to process statistics for annual, growing season (as determined by ETDemands), or custom day of year ranges. The output shapefiles contain 'ET (ETo or ETr)', 'ETact', 'ETpot', 'ETbas', 'Kc', 'Kcb', 'PPT', 'Irr', 'Runoff', 'DPerc', 'NIWR', 'Season' information for each ET Zone containing the crop of interest.

Summary shapefiles can be created for a specific year of interest or for a range of years using "year filter" input argument. Note that both mean ('_mn') and median ('_mdn') statistics are output for each variable. If only one year is specified, mean and median statistics are the identical. Output files can be found in the 'summary_shapefiles' folder where 'summary_YYYY' or 'summary_YYYYtoYYYY' specifies the minimum and maximum years included in the analysis. The following input arguments can be specified to customize the summary output:

-i, --ini	ini_path (str): file path of the project INI file
-y, -year	year_filter (list): include specific years in summary (single YYYY or range YYYY:YYYY)
-t, --time_filter	time_filter (str): 'annual' (default), 'growing_season', 'doy'
-s, --start_doy	start_doy (int): starting julian doy (inclusive)
-e, --end_doy	end_doy (int): ending julian doy (inclusive)

*start and end doy of year must be included when using the 'doy' time_filter

1.12.2 Cropweighted Summary Shapefile (cropweighted_shapefiles_gpd.py)

This analysis tool converts the daily output .csv files into cropweighted summary shapefiles for viewing and analysis of the spatial distribution of evaporation and net irrigation water requirements (NIWR). Specific Time periods can be specified to process statistics for annual, growing season (as determined by ETDemands), or custom day of year ranges. The output shapefiles contain the standard 'ETCells' shapefile information as well as cropweighted 'ETact', 'NIWR' information for each ET Zone.

Cropweighted shapefiles can be created for a specific year of interest or for a range of years using "year filter" input argument. Note that both mean ('_mn') and median ('_mdn') statistics are output for each variable. If only one year is specified, mean and median statistics are the identical. Output files can be found in the 'cropweighted_shapefiles' folder where 'cropweighted_YYYY' or 'cropweighted_YYYYtoYYYY' specifies the years included in the analysis. Each specific .shp within the subfolders contains the specific time period information (annual, growing season, doy range) in the filename. The following input arguments can be specified to customize the output:

-i, --ini	ini_path (str): file path of the project INI file

-y, -year	year_filter (list): include specific years in summary (single YYYY or range YYYY:YYYY)
-t, --time_filter	time_filter (str): 'annual' (default), 'growing_season', 'doy'
-s, --start_doy	start_doy (int): starting julian doy (inclusive)
-e, --end_doy	end_doy (int): ending julian doy (inclusive)

*start and end doy of year must be included when using the 'doy' time_filter

1.13 Miscellaneous Summary Tools

1.13.1 Growing Season Summary (compute_growing_season.py)

This script processing the daily output files to summarize growing season length and cutting information for each ET Zone/crop combination. Two summary .csv files are generated:

'growing_season_full_summary.csv' contains information for ET Zone/crop growing season information for each year included in the analysis.

'growing_season_mean_annual.csv' contains averages of all years included in the analysis.

Both .csv files can be found in the 'growing_season_stats' folder. The following input arguments can be specified to customize the output:

-i, --ini	ini_path (str): file path of project INI file
--start	start_date (str): ISO format date string (YYYY-MM-DD)
--end	end_date (str): ISO format date string (YYYY-MM-DD)
-c, --crops	crop_str (str): comma separate list or range of crops to compare

1.14 Data Sources

1.14.1 RefET

Meteorological data can be obtained from numerous sources.

Agricultural Weather Networks

Network	Supporting Organization	Coverage
CoAgMet	Colorado State University	Colorado
AZMET	University of Arizona	Arizona
AgWeatherNet	Washington State University	Washington

AgWeatherNet | Washington State University | Washington |

AgriMet-GP	Bureau of Reclamation Great Plains Regional Office	Montana
AgriMet-PN	Bureau of Reclamation Pacific Northwest Regional Office	Washington, Oregon, California (northern), Nevada, Utah, Idaho, Montana
CIMIS	California Department of Water Resources	California
NICE Net	Desert Research Institute	Nevada
West Texas Mesonet	Texas Tech University	Texas (western)

Other Weather Networks

Network	Supporting Organization	Coverage
Montana Mesonet	University of Montana	Montana
TexMesonet	Texas Water Development Board	Texas
Lower Colorado River Authority Hydromet	Lower Colorado River Authority (TX)	Texas (Colorado River Basin)
Kansas Mesonet	Kansas State University	Kansas
Nebraska Mesonet	University of Nebraska, Lincoln	Nebraska
Mesonet	University of Oklahoma, Oklahoma State University	Oklahoma

Multi-Network Sources

Source	Supporting Organization	Coverage
MesoWest and SynopticLabs	University of Utah	United States
Integrated Surface Database	NOAA National Center for Environmental Information (NCEI)	Global

1.14.2 CropET

Study Area

HUC8 and HUC10 features can be extracted from the full - [USGS Watershed Boundary Dataset](http://nhd.usgs.gov/wbd.html) (WBD) geodatabase. A subset of the WBD HUC polygons can downloaded using the [USDA Geospatial Data Gateway](https://gdg.sc.egov.usda.gov/) or the full dataset can be downloaded using the [USGS FTP](ftp://rockyftp.cr.usgs.gov/vdelivery/Datasets/Staged/WBD/).

County features can be downloaded from the [USDA Geospatial Data Gateway](https://gdg.sc.egov.usda.gov/). For the zonal stats prep tool to work, the shapefile must have a field called "COUNTYNAME". Other county features (such as the [US Census Cartographic Boundary Shapefiles](https://www.census.gov/geo/maps-data/data/tiger-cart-boundary.html) could eventually be supported (or the name field could be manually changed to COUNTYNAME).

The GRIDMET grid cells can be constructed how?

Crop Type Data

Cropland Data Layer (CDL)

The Cropland Data Layer (CDL) is a product of the USDA National Agricultural Statistics Service (NASS) with the mission "to provide timely, accurate and useful statistics in service to U.S. agriculture" (Boryan et al 2011). The CDL is a crop-specific land cover classification product of more than *100 crop categories* grown in the United States developed using remote sensing. The CDL can be downloaded using NASS's CropScape tool. Updates about and references for the CDL can be found at NASS. A version of the CDL has been released annually from 1994-Present.

Soils Data

The average agricultural area available water capacity (AWC) and hydrologic soils group are needed for each ET cell/unit. The hydrologic soils group can be estimated based on the percent sand and clay for each ET cell/unit.

The AWC, percent clay, and percent sand data cannot (currently) be directly downloaded. The easiest way to obtain these soils data is to download the [STATSGO] (http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053629) database for the target state(s) using the [USDA Geospatial Data Gateway](https://gdg.sc.egov.usda.gov/). Shapefiles of the soil properties can be extracted using the [NRCS Soil Data Viewer](http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/home/?cid=nrcs142p2_053620) The [SURGO](http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053627) databases can also be used, but these typically cover a smaller area and may have areas of missing data.

It may also be possible to used the gridded SSRUGO data, but this has not been tested.

Add additional details about which options were used in the Soil Data Viewer

To use the soil prep tools, the soils data must be provided as separate shapefiles for each product. The names of the soil shapefiles are hard coded in the rasterize_soil_polygons.py script as "{}_WTA_0to152cm_statsgo.shp", where {} can be "AWC", "Clay", or "Sand" (see [Model Structure](structure.md)). For each shapefile, the value field name is hardcoded as the upper case of the property (i.e. "AWC", "CLAY", or "SAND").

1.15 Appendix

1.15.1 Cropland Data Layer (CDL) Crop Codes

Crops [1-20]

Categorization Code	Land Cover
1	Corn
2	Cotton
3	Rice
4	Sorghum
5	Soybeans
6	Sunflower
10	Peanuts
11	Tobacco
12	Sweet Corn
13	Pop or Orn Corn
14	Mint

Grains, Hay, Seeds [21-40]

Categorization Code	Land Cover
21	Barley
22	Durum Wheat
23	Spring Wheat
24	Winter Wheat
25	Other Small Grains
26	Dbl Crop WinWht/Soybeans
27	Rye
28	Oats
29	Millet
30	Speltz
31	Canola
32	Flaxseed
33	Safflower
34	Rape Seed
35	Mustard
36	Alfalfa
37	Other Hay/Non Alfalfa
38	Camelina
39	Buckwheat

Crops [41-60]

Categorization Code	Land Cover
41	Sugarbeets
42	Dry Beans
43	Potatoes
44	Other Crops
45	Sugarcane
46	Sweet Potatoes
47	Misc Vegs; Fruits
48	Watermelons
49	Onions
50	Cucumbers
51	Chick Peas
52	Lentils
53	Peas
54	Tomatoes
55	Caneberries
56	Hops
57	Herbs
58	Clover/Wildflowers
59	Sod/Grass Seed
60	Switchgrass

Non-Crops [61-65]

Categorization Code	Land Cover
61	Fallow/Idle Cropland
63	Forest
64	Shrubland
65	Barren

Crops [66-80]

Categorization Code	Land Cover
66	Cherries
67	Peaches
68	Apples
69	Grapes
70	Christmas Trees
71	Other Tree Crops
72	Citrus
74	Pecans
75	Almonds
76	Walnuts
77	Pears

Other [81-109]

Categorization Code	Land Cover
81	Clouds/No Data
82	Developed
83	Water
87	Wetlands
88	Nonag/Undefined
92	Aquaculture

NLCD-Derived Classes [110-195]

Categorization Code	Land Cover
111	Open Water
112	Perennial Ice/Snow
121	Developed/Open Space
122	Developed/Low Intensity
123	Developed/Med Intensity
124	Developed/High Intensity
131	Barren
141	Deciduous Forest
142	Evergreen Forest
143	Mixed Forest
152	Shrubland
176	Grass/Pasture
190	Woody Wetlands
195	Herbaceous Wetlands

Crops [195-255]

Categorization Code	Land Cover
204	Pistachios
205	Triticale
206	Carrots
207	Asparagus
208	Garlic
209	Cantaloupes
210	Prunes
211	Olives
212	Oranges
213	Honeydew Melons
214	Broccoli
216	Peppers
217	Pomegranates
218	Nectarines
219	Greens
220	Plums
221	Strawberries
222	Squash
223	Apricots
224	Vetch
225	Dbl Crop WinWht/Corn
226	Dbl Crop Oats/Corn
227	Lettuce
229	Pumpkins
230	Dbl Crop Lettuce/Durum Wht
231	Dbl Crop Lettuce/Cantaloupe
232	Dbl Crop Lettuce/Cotton
233	Dbl Crop Lettuce/Barley

Table 1 – continued from previous page

Categorization Code	Land Cover
234	Dbl Crop Durum Wht/Sorghum
235	Dbl Crop Barley/Sorghum
236	Dbl Crop WinWht/Sorghum
237	Dbl Crop Barley/Corn
238	Dbl Crop WinWht/Cotton
239	Dbl Crop Soybeans/Cotton
240	Dbl Crop Soybeans/Oats
241	Dbl Crop Corn/Soybeans
242	Blueberries
243	Cabbage
244	Cauliflower
245	Celery
246	Radishes
247	Turnips
248	Eggplants
249	Gourds
250	Cranberries
254	Dbl Crop Barley/Soybeans

1.16 HUC8 Example Prep Workflow

The following documentation outlines the prep workflow for running ETDemands over 6 HUC8 watersheds in the Upper Colorado River Basin from 2017-2018. The example utilizes 2015 CDL crop layer information along with historical weather data from gridMET. Each HUC8 watershed was assigned weather data from a single gridMET cell. Two of the ETZones utilize the same weather station in order to demonstrate the ETZone/Wx Station pairing options.

NOTE: The ETDemands repository contains many of the files created by the following workflow for demonstration purposes. Re-running the prep workflow will not cause any issues and will write over the existing files with identical (updated) files.

1.16.1 Clone the repository

If you already have a local copy of the et-demands repository, make sure to pull the latest version from GitHub. If you don't already have a local copy of the repository, either clone the repository locally or download a zip file of the scripts from Github.

NOTE: For this example, it is assumed that the repository was cloned directly to the C: drive (i.e. C:\et-demands).

1.16.2 Command prompt / Terminal

All of the CropET prep scripts should be run from the command prompt or terminal window. In Windows, to open the command prompt, press the "windows" key and "r" or click the "Start" button, "Accessories", and then "Command Prompt".

Within the command prompt or terminal, change to the target drive if necessary:

```
> C:
```

Then change directory to the et-demands folder:

```
> cd C:\et-demands
```

You may need to build the common folder if it doesn't exist:

```
> mkdir common
```

1.16.3 Building the Example

NOTE: For this example, all scripts and tools will be executed from the "exampleshuc8" folder.

Build the example folder if it doesn't exist:

```
> mkdir examples\huc8
```

Change directory into the example folder:

```
> cd examples\huc8
```

1.16.4 Cell Shapefile

For this example, ET-Demands will be run for a six HUC8 watersheds in the Upper Colordo River Basin (14080001, 14080002, 14080003, 14080004, 14080005). These ETZones were extracted from the full USGS Watershed Boundary Dataset (WBD) geodatabase. Each individual ETZone within the .shp must be assigned a unique 'CELL_ID' and 'CELL_NAME'. These unique identfiers are used throughout the model for identification and output file naming. In addition to 'CELL_ID', the Cell .shp must also contain a 'STATION_ID' field to pair each ETZone with its specific weather dataset (see Weather Stations section below).

1.16.5 Weather Stations

The example stations are single 4km cells selected from the University of Idaho Gridded Surface Meteorological Data. Each ETZone was assigned a specific historical weather dataset in the 'STATION_ID' field of the Cell Shapefile. Note that it is possible to assign the same historical weather dataset to multiple ETZones. The historical weather data file naming format is specific using the 'name_format' variable in the model .INI file (huc_example.INI).

For this example each weather station data file follows the format: 'gridmet_historical_XXXXXX.csv' where XXXXXX represents a 6-digit wx station identifier. In the REFET section of the model .INI file, name_format = gridmet_historical_%s.csv. A similar ID/Filenaming structure should be used to link each 'STATION_ID' with its corresponding timeseries file.

Historical gridMET time series supplied with this repor wer acquired using the download_gridmet_opendap.py tool found in the gridwxcomp repository. The climate folder contains a .txt list of gridMET stations (gridmet_huc8_stations.csv). This can be used with download_gridmet_opendap.py to download station data. Output format from the download_gridmet_opendap.py script is ready for the INI supplied with this example.

1.16.6 Crop Shapefile

For this example, the crop shapefile will be built from the 2015 Cropland Data Layer (CDL) raster.

For this example the CDL raster will be downloaded directly to the project GIS folder.

```
> python ..\..\et-demands\prep\download_cdl_raster.py --ini huc_example_prep.ini -o
```

If the download script doesn't work, please try downloading the 2015_30m_cdls.zip file directly from your browser or using a dedicated FTP program.

Clip the CDL raster to the cell shapefile extent:

```
> python ..\..\et-demands\prep\clip_cdl_raster.py --ini huc_example_prep.ini -o
```

Convert the clipped CDL raster to a polygon, with the non-agricultural areas removed:

```
> python ..\..\et-demands\prep\build_ag_cdl_shapefile.py --ini huc_example_prep.ini -o
```

1.16.7 Soils

Download the pre-computed STATSGO2 shapefiles:

```
> python ..\..\et-demands\prep\download_statsgo_shapefiles.py --ini huc_example_prep.
↪ini -o
```

1.16.8 Zonal Stats

Compute the soil properties and crop acreages for each ETZone polygon.

```
> python ..\..\et-demands\prep\et_demands_zonal_stats.py --ini huc_example_prep.ini
```

1.16.9 Static Text Files

Build the static text files from the templates in "et-demands\static".

```
> python ..\..\et-demands\prep\build_static_files.py --ini huc_example.ini
```

1.17 gridMET Example Prep Workflow

The following documentation outlines the prep workflow for running ETDemands for the Upper Carson River Basin (HUC16050201) in northeastern Nevada for 2017-2018. The Upper Carson watershed was separated into 4km grid cells based on the gridMET meteroloical dataset. Out of the 184 gridMET cells overlapping the Upper Carson Basin, 70 cells contained irrigated agriculture. Irrigated cells were determined using the 2015 Crop Data Layer (CDL). Each grid cell represents an ETZone of interest for this region. ETDemands will calculate crop area and evaporation metrics for each ETZone separately. Historical climate timeseries were aquired from 2017-20187 for each unique ETZone from the gridMET climate dataset.

NOTE: The ETDemands repository contains many of the files created by the following workflow for demonstration purposes. Re-running the prep workflow will not cause any issues and will write over the existing files with identical (updated) files.

1.17.1 Clone the repository

If you already have a local copy of the et-demands repository, make sure to pull the latest version from GitHub. If you don't already have a local copy of the repository, either clone the repository locally or download a zip file of the scripts from Github.

NOTE: For this example, it is assumed that the repository was cloned directly to the C: drive (i.e. C:\et-demands).

1.17.2 Command prompt / Terminal

All of the CropET prep scripts should be run from the command prompt or terminal window. In Windows, to open the command prompt, press the "windows" key and "r" or click the "Start" button, "Accessories", and then "Command Prompt".

Within the command prompt or terminal, change to the target drive if necessary:

```
> C:
```

Then change directory to the et-demands folder:

```
> cd C:\et-demands
```

You may need to build the common folder if it doesn't exist:

```
> mkdir common
```

1.17.3 Building the Example

NOTE: For this example, all scripts and tools will be executed from the "examplesgridmet" folder.

Build the example folder if it doesn't exist:

```
> mkdir examples\gridmet
```

Change directory into the example folder:

```
> cd examples\gridmet
```

1.17.4 Cell Shapefile

For this example, ET-Demands will be run for a 70 gridMET cells in the Upper Carson River Basin. Each individual ETZone within the shapefile must be assigned a unique 'CELL_ID' and 'CELL_NAME'. The unique identfiers are used throughout the model for identification and output file naming. In addition to 'CELL_ID', the cells .shp must also contain a 'STATION_ID' field to pair each ETZone with its specific weather dataset (see Weather Stations section below).

1.17.5 Weather Stations

The example stations are single 4km cells selected from the University of Idaho Gridded Surface Meteorological Data. Each ETZone was assigned a specific historical weather dataset in the 'STATION_ID' field of the Cell Shapefile. The historical weather data file naming format is specific using the 'name_format' variable in the model .INI file (gridmet_example.INI).

Historical gridMET time series was acquired using the download_gridmet_opendap.py tool found in the gridwx-comp repository. The climate folder contains a .txt list of gridMET stations. This can be used with download_gridmet_opendap.py to download station data. Output format from the download_gridmet_opendap.py script is ready for the INI supplied with this example:

```
> python download_gridmet_opendap.py -i D:\et-
→demands\examples\gridmet\climate\upperCarson_agpts.txt -o D:\et-
→demands\examples\gridmet\climate -y 2017-2018
```

For this example each weather station data file follows the format: 'gridmet_historical_XXXXXX.csv' where XXXXXX represents a 6-digit gridMET cell identifier. In the REFET section of the model .INI file, name_format = gridmet_historical_%s.csv. A similar ID/Filenaming structure should be used to link each 'STATION_ID' with its corresponding timeseries file.

NOTE: The user should take caution when applying large gridded climate datasets to irrigated agricultural settings. Gridded climate datasets often represent larger scale natural landscape conditions and do not factor in the impacts of localized irrigation (i.e. evaportive cooling, changes in surface roughness, increased vapor pressure, etc.). ETDemands offers options to scale (or bias correct) the input ETo/ETr values based on comparisons with local weather station data. Please refer to 'et_ratios' functionality in the XXXXX documentation for further details.

1.17.6 Crop Shapefile

For this example, the crop shapefile will be built from the 2015 Cropland Data Layer (CDL) raster.

For this example the CDL raster will be downloaded directly to the project GIS folder.

```
> python ..\..\et-demands\prep\download_cdl_raster.py --ini gridmet_example_prep.ini -
→o
```

If the download script doesn't work, please try downloading the 2015_30m_cdls.zip file directly from your browser or using a dedicated FTP program.

Clip the CDL raster to the cell shapefile extent:

```
> python ..\..\et-demands\prep\clip_cdl_raster.py --ini gridmet_example_prep.ini -o
```

Convert the clipped CDL raster to a polygon, with the non-agricultural areas removed:

```
> python ..\..\et-demands\prep\build_ag_cdl_shapefile.py --ini gridmet_example_prep.
→ini -o
```

1.17.7 Soils

Download the pre-computed STATSGO2 shapefiles:

```
> python ..\..\et-demands\prep\download_statsgo_shapefiles.py --ini gridmet_example_
→prep.ini -o
```

1.17.8 Zonal Stats

Compute the soil properties and crop acreages for each ETZone polygon.

```
> python ..\..\et-demands\prep\et_demands_zonal_stats.py --ini gridmet_example_prep.
→ini
```

1.17.9 Static Text Files

Build the static text files from the templates in "et-demands\static".

```
> python ..\..\et-demands\prep\build_static_files.py --ini gridmet_example.ini
```

CHAPTER 2

Indices and tables

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