Eddy Covariance and Surface Renewal Estimates of Evapotranspiration at Modena, Utah Site

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Submitted by Dr. Lawrence Hipps, Utah State University

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Eddy Covariance Estimates of ET at Modena Site

The eddy covariance approach was employed to estimate the ET of an alfalfa field (field xx) at the Modena site. The required instrumentation for this method included:

- 3-dimensional sonic anemometer and IRGASON gas analyzer (Campbell Scientific Inc.)
- Four-way net radiometer (CNR4 – Kipp & Zonen)
- Aspirated air temperature and humidity measurements (Apogee Instruments, E + E Elektronik)
- Soil heat flux plates (2) (REBS Inc.)
- Soil temperature sensors (4) (1099SS - Campbell Scientific)
- Soil water content (TDR 310 - Acclima Inc.)

Additional instrumentation used in the surface renewal method or as standard agricultural weather measurements included:

- Fine wire thermocouples (2) (Campbell Scientific Inc.)
- Infrared radiometer (Apogee Instruments)
- Slow response wind speed and direction (RM Young)
- Tipping bucket precipitation (Texas Electronics)
- 4” soil temperature (Apogee ST-110)
- 8” soil temperature and moisture (TDR 310 - Acclima Inc.)
- Incoming shortwave radiation (Apogee Instruments)

The site was located based upon the expected wind directions, so that it would measure the fluxes from the actual alfalfa field as often as possible. The expected wind directions were based on 2013 – 2020 growing season data from a nearby weather station operated as a part of the Utah Climate Center Ag Weather network. As a result, the sensors were sited to capture south and southwesterly flow, approximately 15 degrees east of due north on the edge of center-pivot irrigated alfalfa.

A photo of the EC station lying at the edge of the field is shown in Figure 1. In addition to the eddy covariance and weather sensors, other measurements were made a separate location about 20 m into the alfalfa. These included: soil temperature, soil moisture, and soil heat flux plates. This allowed calculation of the surface soil heat flux. In addition, the net radiation and infrared temperature of the alfalfa were measured there. Finally, several fine wire and rapid response thermocouples were mounted at this same location, as inputs for the surface renewal method. All these data were collected by the main data logger on the EC tower.

The eddy covariance sensors for wind and humidity were mounted 2.78 m above the surface and sampled at 20 Hz. The other sensors were sampled every 2 seconds and averaged into 15-minute periods. All data was written to storge cards on the data logger, which were periodically removed and brought back to the lab to be stored permanently.

Figure 1. Eddy covariance tower sited at north edge of the alfalfa.

ET Estimation Procedures

Eddy Covariance

The eddy covariance time series data were used in a set of procedures to calculate the sensible and latent heat (ET) fluxes. A number of steps are required to accomplish this, and involves large data sets – over 1.7 million lines of data per day.

Documenting and Removing Finite Sections of Bad Data
The QA/QC process begins with a manual analysis of all daily graphs of the 20 Hz time series data to identify and remove any observed coarse sections of bad data, clearly physically impossible under the given conditions. These coarse sections are longer than can be replaced by linear interpolation (> a minute). If the sections removed are much smaller than the timescale of flux calculations (~ 1 hour), then the flux computations can still be conducted, though advanced time series analyses cannot. These coarse sections of removed data usually result from sustained periods of precipitation or irrigation hitting the IRGASON sensor, any particles or insects creating obstructions to the path of the turbulence sensors, or from instrument malfunction.

Spike Detection and Correction
Spikes refer to clearly incorrect data values occurring over very short periods, usually on the order of seconds or less. These bogus values must be removed and replaced with realistic ones, as they can have a disproportionate effect on the computed fluxes and time series analyses. They are identified and replaced using a supervised Fortran algorithm written in-house at the USU Biomet Lab. Windows of various time lengths are passed over the time series, and calculations are made to identify the credibility of each point. These include the number of standard deviations the data point differs from the average value in the window and compared to the user-defined threshold. A second approach looks at the difference of each variable at each point compared to the average in the window and hour. The changes between the values are compared to assigned limits that represent changes that are physically unlikely.

When a data point is flagged, the user decides whether the point (and perhaps a series of them) warrant replacement by linear interpolation. The user decision is based on knowledge of micrometeorology, turbulence, and energy balance processes. Again, these are short term periods of seconds, and always under a minute. Longer sections of bad data are treated as explained above.

Flux Calculations
After the data sets have been checked and cleaned by the QA/QC procedures above, the final flux values can be calculated. The Biometeorology lab at USU has developed a set of software written in Fortran to do the final computations for turbulence fluxes of momentum, sensible heat, and ET for the proper averaging periods (for the purpose of daily ET values, a one-hour integration interval is usually used). The cleaned raw data consist of single day time-series files for each site.

The flux calculations incorporate the raw covariances of vertical wind and associated wind components and scalars, followed by a set of corrections for various factors and effects. The initial raw covariances for the sensible heat and water vapor fluxes are:

$$H = \rho \, c_p \, \overline{U_z' \, T'} \quad (1)$$

$$E = \rho \, \overline{U_z' \, \rho_v'} \quad (2)$$

U_z is the vertical wind velocity, ρ is density of the air, c_p is specific heat capacity of the air, and T is air temperature and ρ_v the water vapor density. These covariances are the starting point for the set of analyses to calculate the final fluxes, that incorporate various additional analyses.

These flux calculations include: ensuring data are all synchronous (sampled at the same moment), rotating the geometric coordinate system to remove spurious vertical velocity averages caused by any tilt of the sonic anemometer, adjusting the fluxes for high frequency losses due to sensor response, sensor path length, any sensor separations etc., correcting sonic derived temperatures to actual air temperatures using humidity of the air, and determining the exact values for various atmospheric properties used in the thermodynamic calculations related to the fluxes. Most of these corrections are presented in Massman and Lee (2002). In addition, the legitimacy of the averaging period is periodically checked by occasionally analyzing the cospectra of the vertical velocity & temperature as well as vertical velocity and humidity. In simple terms, these quantify the proportion of the total flux contributed by any scale of time and can show the averaging period used was long enough to recover realistic fluxes.

Gap Filling

When periods of data cannot be used to calculate ET, such as when the wind was not blowing over the alfalfa field, the fluxes were estimated used a gap filling algorithm. The spatial limitations of operating on the edge of a center pivot meant that only wind directions between 120 and 270 degrees could be considered to have enough fetch. All other wind directions had to be gap filled using the algorithm developed by the Department of Biogeochemical Integration at the Max Planck Institute for Biogeochemistry (https://www.bgcjena.mpg.de/bgi/index.php/Services/REddyProcWeb). This processing package known as ReddyProc (Wutzler et al. 2018) performs gap filling of eddy covariance and meteorological data using methods similar to Falge et al. (2001). It also considers the co-variation of fluxes with meteorological variables and the temporal autocorrelation of the fluxes (Reichstein et al. 2005).

Surface Renewal

This method was originally developed by scientists at UC-Davis, and over the years has been reported in various publications. For example, a recent study was reported by Parry et al. (2019). The approach uses rapid time series measurements of air temperature using fine wire thermocouples, sampled about the same rate as eddy covariance. The resulting patterns of air temperature are analyzed using the structure function and other analyses to eventually yield an estimate of the sensible heat flux from the surface. The available energy (net radiation and soil heat flux) must be measured or estimated. The best case is when the available energy is directly measured at the site. The latent heat flux or ET is then determined as the residual of the other terms using equation (3).

The analyses of the time series data used in surface renewal are not trivial, though a little less complex than eddy covariance.. But the equipment costs are less than eddy covariance since one does not require a fast response sonic anemometer or fast response humidity sensor.

Dr. Nicolas Bambach at UC-Davis is a colleague of Dr. Hipps. He has a great deal of experience in the surface renewal methodology, applying it in research projects and has developed his own software. He agreed to analyze the data from this study at Modena, using the surface renewal approach. Although these analyses could have been done at USU, UC-Davis could do them much faster, and the credibility would be guaranteed.

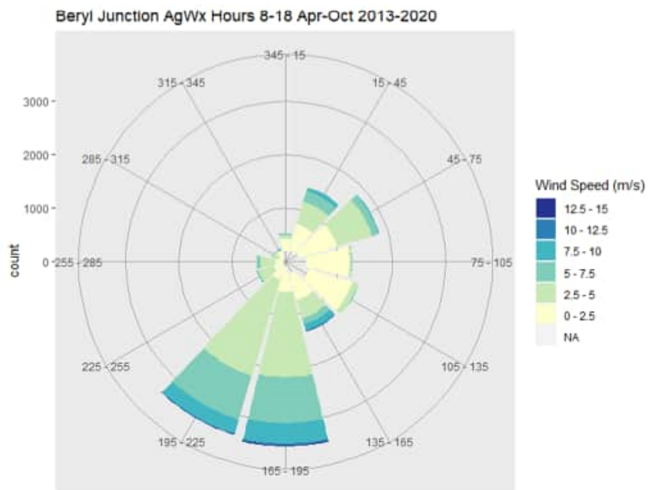
As the wind directions at Modena did not conform to what was expected by weather data, a number of times had to be gap filled as described above. In order to use the most reliable and credible data sets for the surface renewal and its comparison with eddy covariance, only days that had favorable wind directions were used for the surface renewal calculations. This assured that the comparison with the eddy covariance would be done for the best quality and most reliable data set.

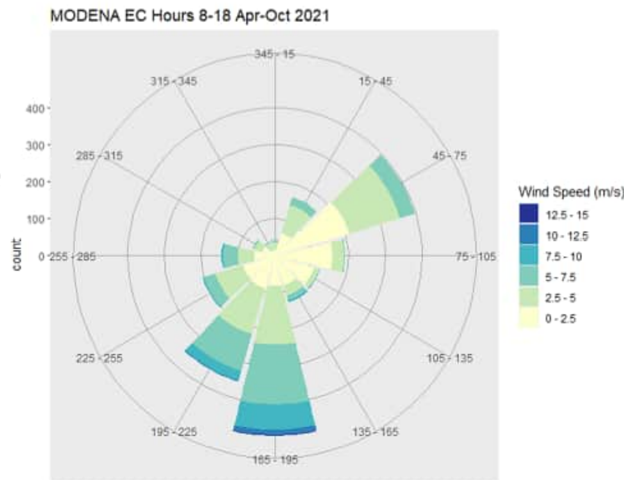
Results and Discussion

Wind Direction Issue 2021

The wind rose for the eight years of available data from the Beryl Junction weather station located 5 miles SE of the study site was used to determine the location of the tower. It is displayed in Figure X along with the actual wind rose measured at the alfalfa in 2021. Based upon the Beryl Junction wind data, locating the tower 15 degrees east of due north was the logical choice, as the vast majority of wind directions would be favorable for calculating the ET. There was a small occurrence of a NE direction, which would be unacceptable for our purposes. However, it existed for only a small fraction of time. And was not deemed to be a problem.

The observed wind rose at the study site for the growing season of 2021 is shown on the right side of Figure X. Note that the NE wind direction was much more prominent that what the Beryl Junction data would suggest. It is not clear whether this is a spatial variation on the wind direction, or 2021 having unusual wind directions. But it meant that a larger than expected number of hours of data needed to be gap filled.





Gap filling was also increased by the combination of many precipitation events in the latter part of the summer combined with continued frequent irrigation in spite of all the precipitation. Water sprayed onto the sensors causes bad data for a period of time until it dries off.

In spite of the above issues, the final results for ET are adequately reliable to address the objectives of the project. However, the data set collected at this site and year was not the most optimal possible.

Eddy Covariance Results for Actual ET

Since eddy covariance is the scientific standard for estimating Et from the surface, these results represent the actual ET of the study site.

Checking Energy Balance Closure

In addition to the eddy covariance fluxes of sensible heat and latent heat (energy equivalent of water vapor flux), the net radiation and heat flow in/out of the soil surface were calculated. This allows a quantification of the energy balance of the surface.

$$R_n = H + LE + G \quad (3)$$

Where R_n is the net available radiation at the surface, G is the flow of energy in/out of the soil, H is the flux of sensible heat at the surface and LE is the surface latent heat flux. A useful analysis of the internal consistency of all the measurement is to examine how well the equation balances. In a perfect world with no errors in measurements or calculations:

$$\frac{H+LE}{R_n-G} = 1 \quad (4)$$

Since the H and LE fluxes are covariances as shown earlier, and any error reduces a covariance, then it is expected that the ratio above should be less than 1. Several approaches are currently followed to address the imbalance. Some argue that the available energy terms are not spatially or temporally aligned with the surface sensed by the eddy covariance, and that nothing should be done about the apparent imbalance. Others assume the ration of H/LE is likely correct, but that each is underestimated. They then add to those fluxes according to their relative importance (observed H/LE) to force the equation to balance – forced closure. We provide both the original and forced closure values here.

Final Daily ET Values from Eddy Covariance

Figure 1 shows the daily ET values in mm for the site in the growing season of 2021. The green bars represent the original daily values, while the red bars reflect the results when energy balance closure was forced as described earlier. The average daily closure value was 0.86, which is quite good. So, the daily totals of ET between original and forced closure are not too different.

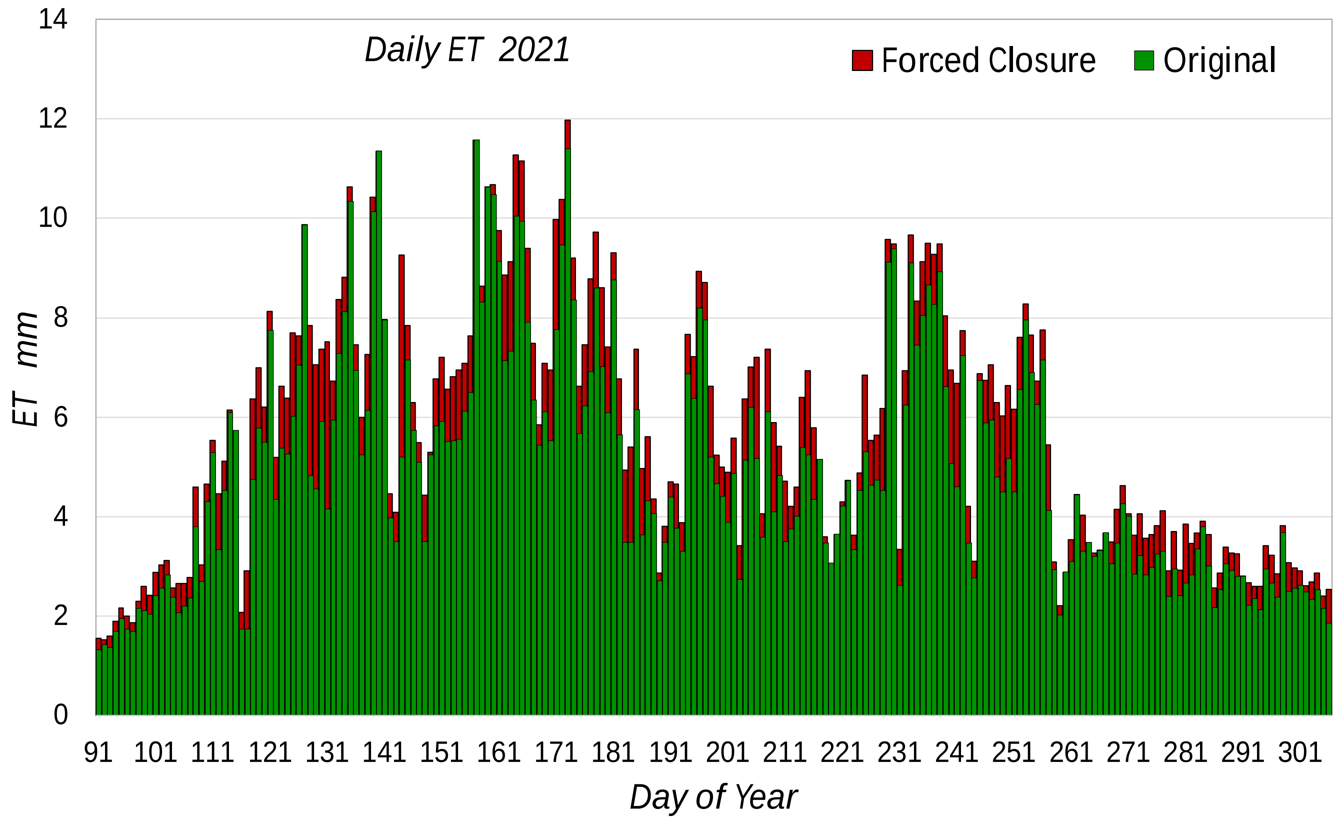


Figure 1. Daily ET values from the eddy covariance station in 2021.

Importance of Advection at Site

The transport of warm and dry air from upwind surfaces adds to the ET of the irrigated surface as the flow of sensible heat (H) will be directed towards the surface and acts to supply additional energy. In simple terms, this process mixes warm and dry air to replace the air above the crop that would otherwise humidify from the ET. This process is termed advection. The Modena study site consisted of irrigated fields located in an arid landscape with moderate winds. So, this was a situation where significant advection might be expected. The remote sensing-based ET models do not account directly for advection. Hence, knowledge of the contribution of advection to the ET at the site is important in interpreting the validation of these ET models against the measured eddy covariance ET values.

By summing the values of negative H over daytime hours, the contribution to ET can be estimated by converting the totals from energy units to depth of water. Figure 2 shows the daily values of the total ET from the original eddy covariance results along with an estimate of the contribution of advected energy from the surroundings. One can see that advection is significant at the site during a number of days. It could explain up to 30% of the observed ET.

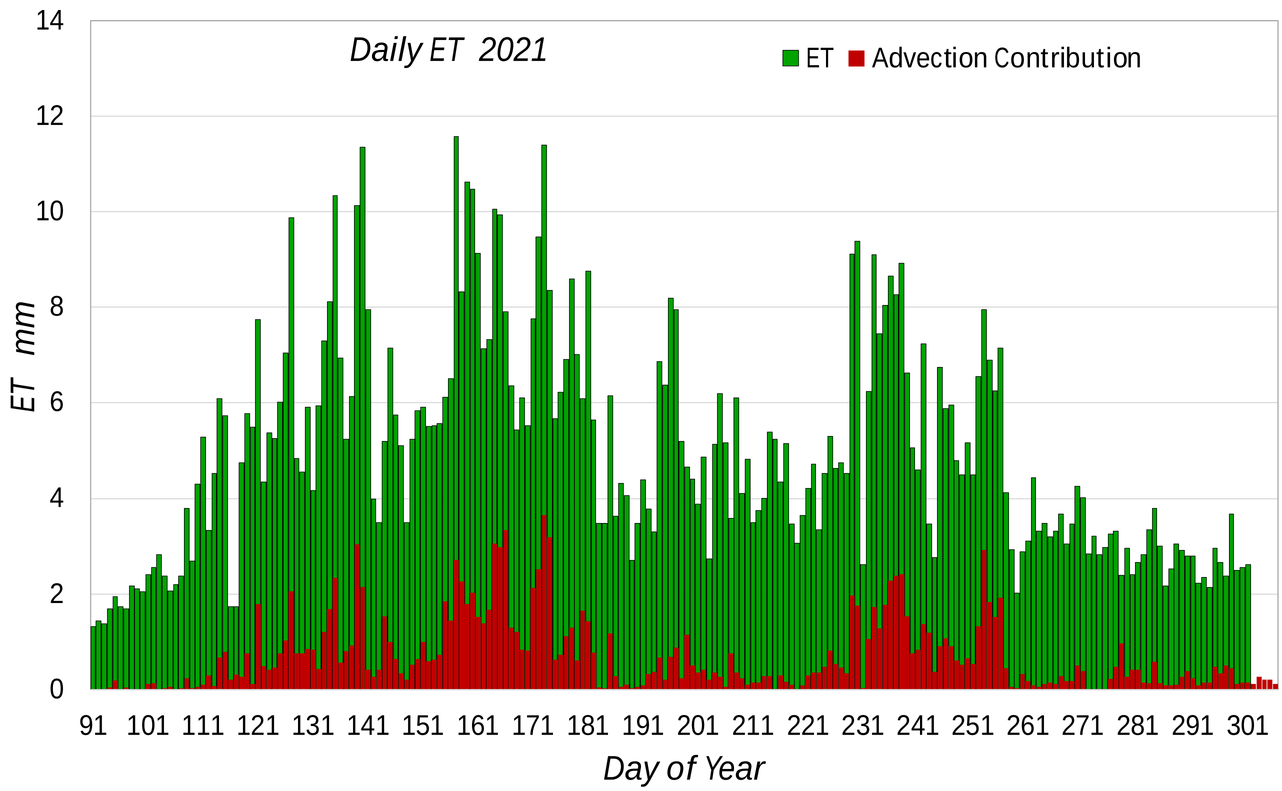


Figure 2. Daily ET values along with estimate of the contribution of advection

Uncertainty of Eddy Covariance Results

Estimating the uncertainty of eddy covariance estimates of fluxes, including ET, is difficult, as there is no other direct measurement that would be considered an absolute. Note, that lysimeters directly measure mass loss, but they have their own set of issues such as restricted rooting depth and vegetation growing on them that does not adequately represent that of the general surface around them. In addition, some of the sources of uncertainty will act in opposite directions and cancel out some of the effects.

However, there have been studies that attempt to address sources of uncertainty. Unfortunately, these do not provide simple answers such as percent uncertainty. One useful approach is to run a number of eddy covariances side by side in the same field. In a perfect world, they would all measure the same fluxes. Observed deviation from this mythical result, provides useful information in the inherent uncertainty of the fluxes calculated by the approach.

Alfieri et al. (2011) ran nine stations adjacent to each other and examined various statistics from the outputs. The variations of flux values among the stations were reported in energy units of W m^{-2}. When translated to a percentage of the average fluxes the value of about 7% is obtained (personal communication, lead author Joseph Alfieri). This is a minimum uncertainty inherent to the variations among identical sets of sensors. Under very optimal situations with the best quality sensors, idealized vegetation surfaces that are near uniform in space, steady state atmospheric conditions, and rigorous approaches to analyzing the time series data, an uncertainty of 10% is the best that most micrometeorologists would accept as possible.

Results of Surface Renewal Method for Estimating ET

The methodology for surface renewal was described above in section 2. Recall that surface renewal actually calculates the sensible heat flux, H. The water vapor flux, LE, is then calculated as a residual using equation 3. As noted, the fast response air temperature data from the fine wire thermocouples, along with measurements of net radiation and soil heat flux were provided to UC-Davis, where the actual technique was first proposed. They used their algorithm to generate estimates of ET. Since actual measurements of net radiation and soil heat flux were made in this case, they did not have to be estimated with less accurate methods. This provided the best possible situation for the surface renewal approach.

As described earlier, the unexpected wind directions at the Modena site created problems where the sensors did not measure the flux from the actual irrigated field.. As noted, when directions were unacceptable eddy covariance results had to be gap filled. To provide the most credible evaluation of the surface renewal methodology, only data from periods where winds were from acceptable directions were used as input for the surface renewal.

Comparison of Results with Eddy Covariance

Hourly Results

There were two sets or duplicates of fine wire temperature measurements, since these often break due to their very small size. Results are shown for one set, as both are similar. Since ET is near zero at night, only results during daytime hours are shown. Figure 3 shows the direct calculation of hourly values of sensible heat flux (H) by the surface renewal compared to the eddy covariance.

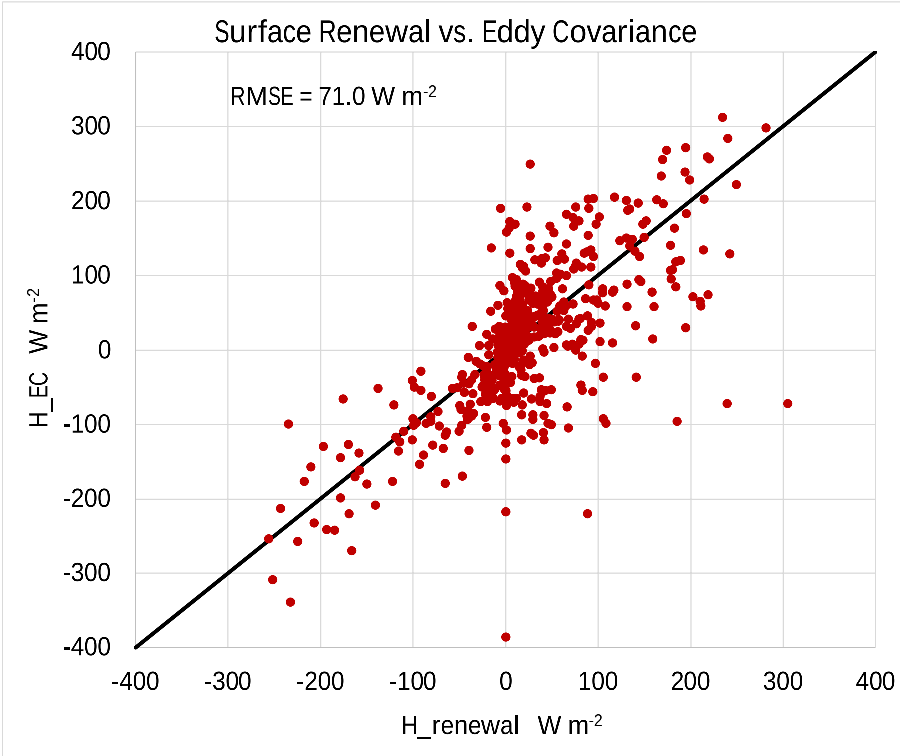


Figure 3. Comparison of hourly H from surface renewal to the eddy covariance standard.

Note the negative values of H happen when there is advection of warm dry air over the irrigated crop, which is common during afternoon hours. Although the two estimates are related to one another, the agreement is only moderate, with a root mean square difference of 71 W m^{-2}.

The results for the water vapor flux or LE are shown in Figure 4. Recall this is determined using the earlier results for H and determining LE from the residual of the energy balance. The root mean square difference is about 99 W m^2, while mean LE from the eddy covariance was about 230 W m^{-2} The agreement is similar to that of H, which might be considered moderate.

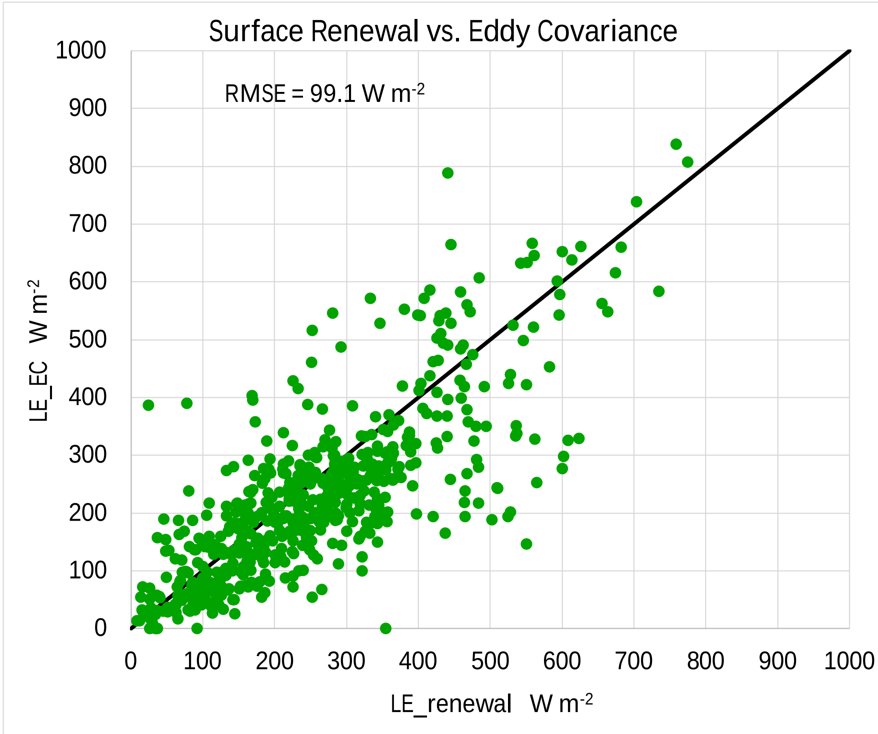


Figure 4. Comparison of hourly LE from surface renewal to the eddy covariance standard.

Daily ET Values Surface Renewal vs. Eddy Covariance

A more practical comparison would be to examine the total daily ET values for surface renewal and compare them to the eddy covariance standard. The results are shown in Figure 5.

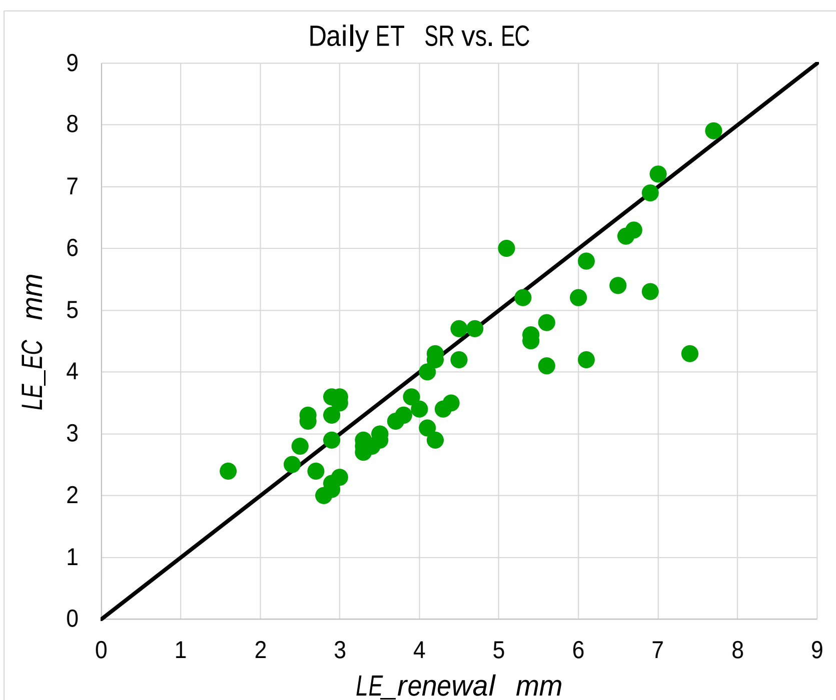


Figure 5. Comparison of daily ET from surface renewal to the eddy covariance standard

Here the daily totals of ET in mm of water are compared. Again, only data from periods where winds were from acceptable directions were used as input for the surface renewal estimates. This way they could be compared to direct EC measurements rather than the gap filled ones done during bad wind directions.

The agreement is rather good, with a root mean square difference of about 0. 8 mm day^{-1}. However, there is a bias, with the surface renewal estimating values that generally exceeded those of the eddy covariance. The mean of all daily values was 3.9 mm for the eddy covariance and 4.3 mm for the surface renewal.

The better agreement for daily values compared to hourly resulted because the hourly surface renewal estimates were sometimes lower and other times higher than eddy covariance. Hence, the daily total agreed better. Whys this is the case is not clear.

In summary, the surface renewal produced daily ET estimates that are in rather good agreement with the eddy covariance. But is bears noting that this was a very ideal situation to test the surface renewal, due to the very expert and experiences people doing the analyses, and high-quality direct measurements of the available energy were provided.

Summary -- Fluxes of ET

The study site turned out to be somewhat problematic, due to wind directions not conforming to the record of a weather station only 5 miles away and evidence of overirrigation during the latter part of the season. Although the results were adequate to meet the goals of the project, this was not the ideal situation to conduct this study.

Eddy covariance measurements had to be gap filled a significant portion of time due to the unfavorable wind directions where the air reached the sensors from only the upwind lands, and not the irrigated field. The energy balance closure which expresses the ability to match the fluxes of energy to available energy reached a good value for the season. This may have been somewhat biased by the gap filling methodology that assumes the energy balance is achieved..

Daily ET values during the summer season were generally about 5 mm, but could reach as high as 11 mm. There was a great deal of advection of heat from the dry upwind lands, which acted to significantly increase the ET.

The surface renewal methodology was tested under the best possible scenario and expertise of analyses. The daily ET was somewhat biased high by surface renewal, but overall daily estimates were fairly close to those of the eddy covariance.

The results are certainly scientifically credible, given the due diligence to cutting edge research measurements and methodologies. However, additional studies at a more desirable location would produce findings with much less gap filling and add more data to the findings making them more robust.

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