Appendix F

EC Tower Data Processing for 2020 Season

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Data Analyses Performed for Each Eddy Covariance Station

Here, we outline the stages of processing raw data acquired from each eddy covariance station, in order to produce a final set of hourly flux values, including ET. With a 20 Hz sampling rate (20 observations every second), each site produces over 1.7 million records of data each day (nearly 7 million records/day for all four sites). Hence, this set of analyses requires a large portion of the total time and effort at USU.

Documenting and Removing Finite Sections of Bad Data

The QA/QC process begins with a manual analysis of the daily graphs of the 20 Hz time series data to identify and remove any observed coarse sections of clearly bad data. Such data are 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 computed fluxes and time series analyses. They are identified and replaced using a supervised algorithm written in Fortran. In order to identify spikes and suspicious sections of data, windows of various time lengths are passed over the time series. Experience indicates that the optimal window sizes under our conditions range from about 5 – 30 seconds. Two distinct calculations are made to identify the credibility of each point. First, the number of standard deviations the data point differs from the window and the computed hourly value is compared to the user-defined threshold. Usually three or four standard deviations are chosen. Because some data regions have very low variability, the previous methodology can result in false flags, as a difference of a large number of standard deviations is still very small in physical terms. So a second approach looks at the difference of each variable at each point compared to the average in the window and hour. The changes are compared to assigned limits that represent changes that are physically unlikely.

When a data point is flagged, that record in addition to the 60 values before and after are listed on the screen. The user decides whether that point (and perhaps a series of them) warrant replacement by linear interpolation. The user decision is based on values knowledge of micrometeorology, turbulence and energy balance processes. Again, these are short term periods of usually seconds, and always under a minute. Longer sections of bad data are treated as explained above.

Flux Calculations

The two sets of procedures described above constitute the vast majority of time and effort involved in the data analyses. 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. Briefly, these 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. In addition, the legitimacy of the averaging period is periodically checked by analyzing the cospectra of the vertical velocity & temperature pairs, as well as those of vertical velocity and humidity. In simple terms, a cospectrum quantifies the proportion of the total flux contributed by any scale of time. It can clearly show that the averaging period used was long enough to recover realistic fluxes.

Hourly and Daily Gap Filling

Data removed during earlier coarse QA/QC will necessarily lead to extended gaps in the computed fluxes. These gaps can range from an hour to more than a day, and can also result from extended time periods in which the winds blow from a ‘forbidden’ direction. In most cases this is simply a 30° window behind the sensor (i.e. hours with winds from 75°-105° would be gap filled for a sensor oriented 270°).

Gap filling of 2019 data followed a different procedure than was used for 2018 data. In 2018, daylight hours (Rn > 50 W m^{-2}) were filled by determining the evaporative fraction, or ratio of water evaporated to available energy.

$$EF = \frac{LE}{R_n - G} \tag{1}$$

LE is latent heat flux (energy equivalent of the ET), R_n is net radiation, and G is soil heat flux.

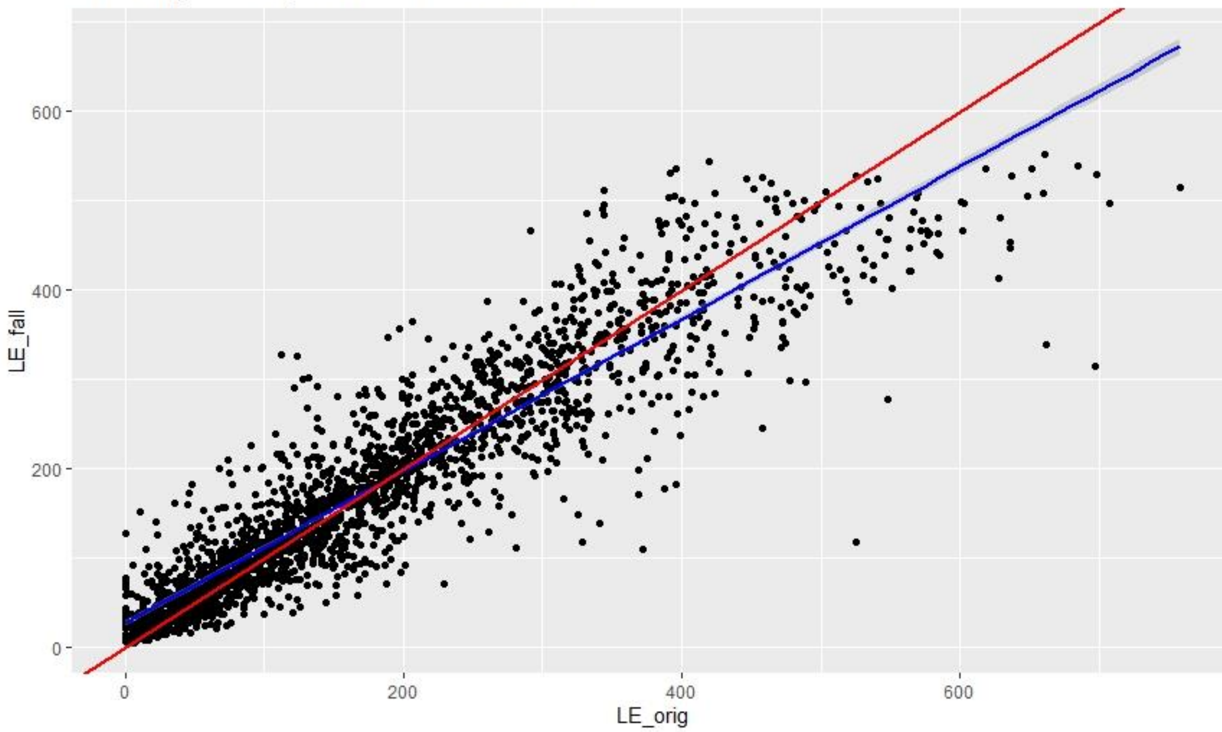
Values of EF were determined for periods with similar environmental conditions before and after the gap. Since available energy was usually available for the gap periods, the LE values could be filled in using the EF values.

For 2019 data, we used a new gap filling algorithm developed and hosted 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 auto-correlation of the fluxes (Reichstein et al. 2005).

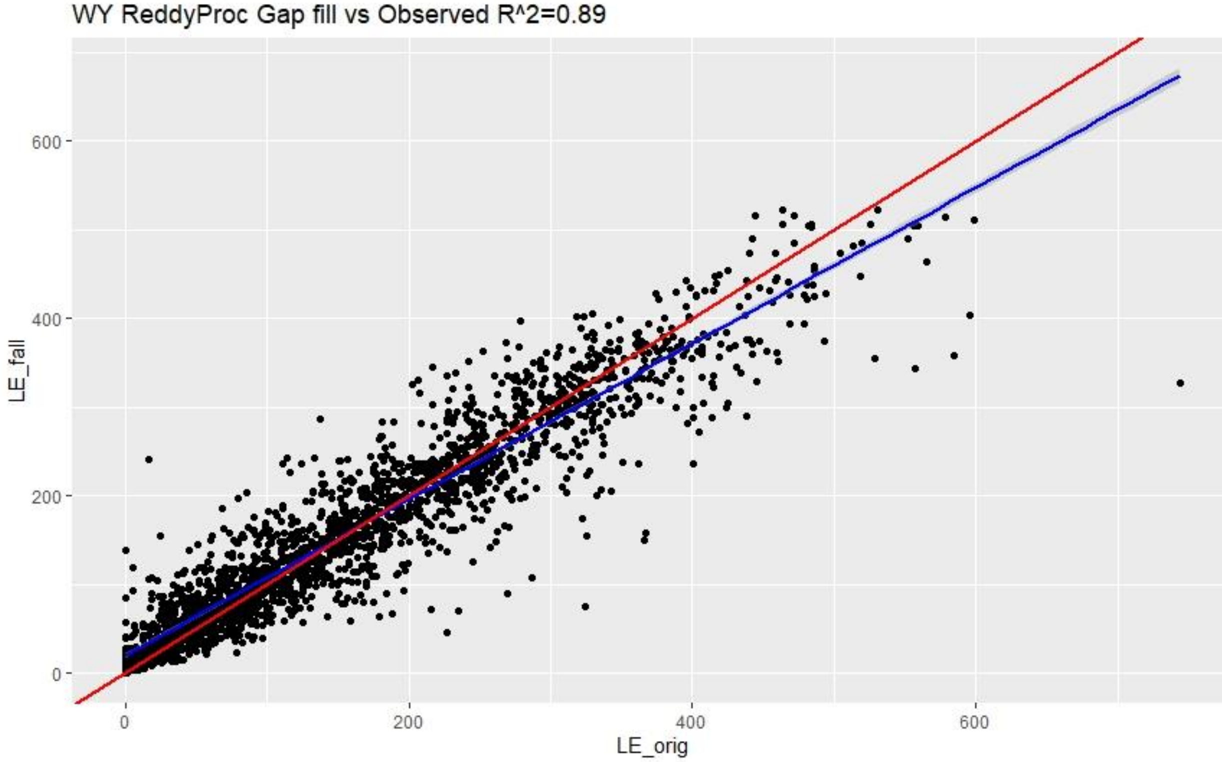
In our use of this algorithm we only have two direct fields of interest (H and LE). With a dataset including fields of radiation (R_s), air temperature (T_{air}), and vapor pressure deficit (VPD), the gap filling algorithm has optimal input conditions. All missing values of H and LE within the seasonal dataset are replaced by the average value for nearby periods under similar meteorological conditions, i.e. with a look-up table (LUT), within a certain time window. Similar meteorological conditions are assumed when R_s does not deviate by more than 50 W m^{-2}, T_{air} by 2.5°C, and VPD by 5.0 hPa. If no similar meteorological conditions are present within the time window of 7 days, the windows size is increased to 14 days.

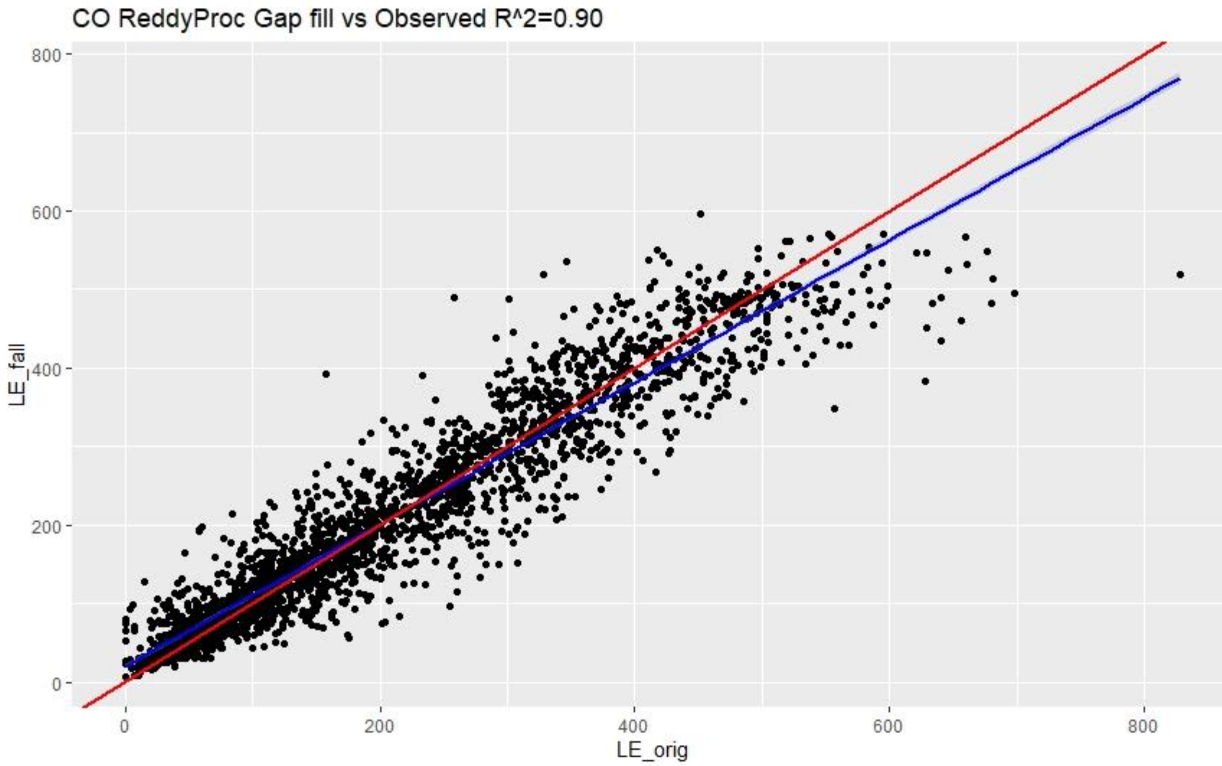
To verify the accuracy of the procedure, a dataset of daytime values was generated for all times where no gaps were present. . Model derived LE values were compared to the actual measured values for daytime hours (R_s>50 W m^{-2}) at each location through the growing season. Plots showing these comparisons are in Figures 1 – 4. Both the 1:1 lines and fitted linear regression lines are depicted. It is apparent that in general the algorithm performed adequately, with r^2 values at each site of ~0.90.

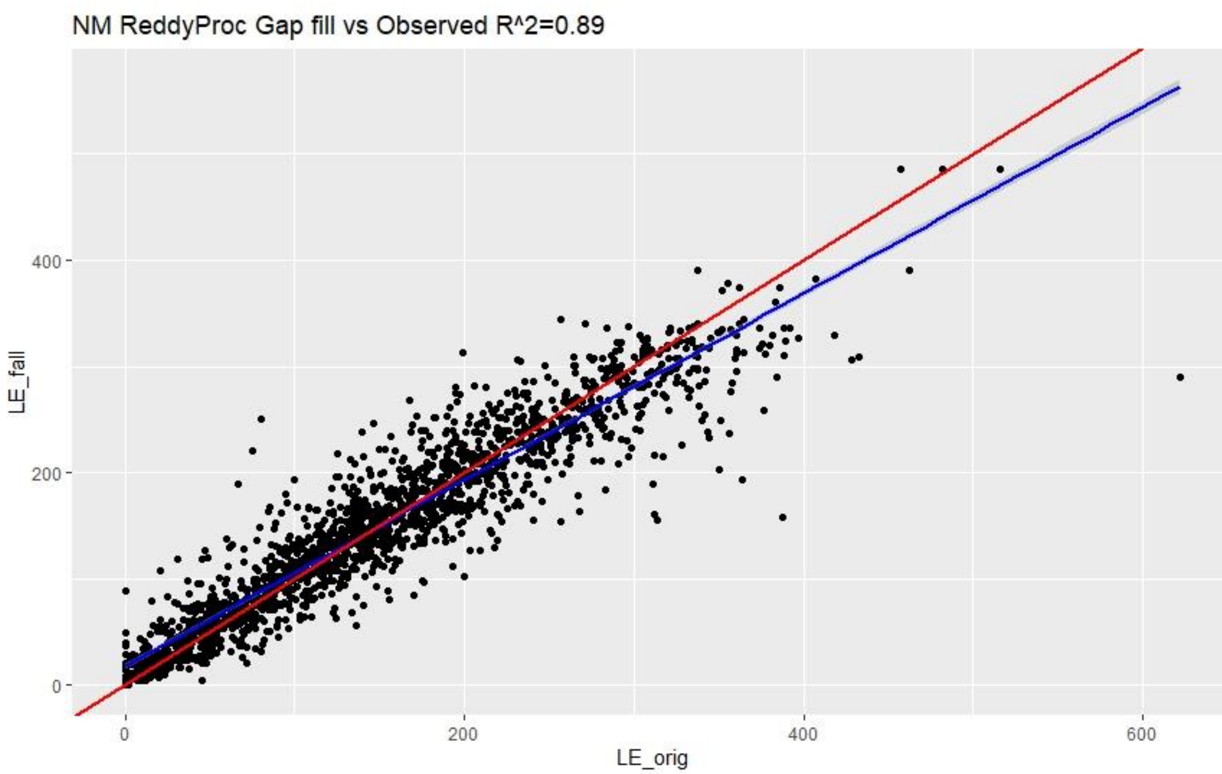
UT ReddyProc Gap fill vs Observed R^2=0.85



WY ReddyProc Gap fill vs Observed R^2=0.89







Figures 1 - 4: Daytime comparison plots of ReddyProc derived LE and actual measured LE. Red line = 1:1 line, Blue line = linear regression.

Data Completeness Ratings

In past years, a relative output flux completeness rating was applied to each day of flux data. Note that output flux completeness **is not the same as data quality**. The proportion of flux values for ET that resulted from gap gilling determines how complete are the results. Data quality on the other hand, represents the confidence in the accuracy of the raw data measured, which later is used to calculate the fluxes. As an example, low signal strength values for the water vapor sensor, make the data more suspect, but not necessarily unreliable. These **completeness** ratings are a simplistic definition, based on the number of hours in which measured fluxes have been replaced by gap filled hours. The designations corresponded to hourly count thresholds are as follows:

Good: 0 - 2 hours gap filled

Fair: 3 - 5 hours gap filled

Poor: 6 or more hours gap filled

None: Entire day has been gap filled

Note that the complete daily values for energy balance, including ET, were provided in all cases. The "completeness" ratings only indicate the proportion of the results that had to be interpolated and are **not a reflection of data quality**. As outlined in the gap filling section, under most circumstances, the gap filling estimates are quite reasonable. For the 2019 dataset, we merely provide the number of gap filled hours and leave any analysis from these fields up to the user.

Forcing Energy Balance Closure When Appropriate

Note that the **two sets** of reported daily ET values are reported:

- **original final calculations from the fully analyzed eddy covariance data**
- **results if H and LE are increased to force their sum to equal available energy (R_n – G); "forcing energy balance closure"**

Daily energy balance was determined by computing hourly fluxes for net radiation (R_n , soil heat flux (G), sensible heat flux (H), and latent heat flux (LE). The occasional very small negative LE values at night are lower than the ability of the methodology to calculate credible numbers, and were set to zero. Hourly fluxes were summed for 24 hours, resulting in daily fluxes, which were converted to mm hr^{-1} using latent heat of vaporization corrected for temperature. Energy balance closure was forced on each daytime (Rn > 50 W m^{-2}) hourly total according to the ratio of the H and LE measured by the eddy covariance sensors by applying the equations below:

$$LE_{new} = \frac{(Rn - G)}{\left(1 + \frac{H}{LE}\right)} \tag{2}$$

$$H_{new} = Rn - G - LE_{new} \tag{3}$$

Closure was only forced on hours that were not gap filled and that had reliable net radiation and soil heat flux measurements. The later caveat was an issue for the Big Piney, Wyoming site. Agricultural fields in this area are flood irrigated to the point that they are essentially a "wetland" for much of the year, with significant standing water. It is not possible to use our measurements in the soil to recover soil heat flux when the soil is under water. First of all, the plate transducers are not calibrated for such conditions. Also, the standing water can store a significant amount of energy, which cannot be quantified over short periods. In this case, the energy balance would be:

$$Rnet = H + LE + G + energy\ stored\ in\ water \tag{4}$$

Since we cannot confidently measure G, nor estimate any value for the storage term in the standing water at the Wyoming site, the complete energy balance could not be quantified there. Therefore, trying to force closure of the energy balance by adding to the H and LE values was not scientifically credible and ET values were not adjusted to force closure at the Wyoming site.

Closure Issues When Winds From NE in Vernal, UT

Most of the daily energy balance closure values at the Vernal, UT location were near 0.80. However, it was observed that when winds were from the NE, the closure values were consistently lower than this value. The upwind conditions to the NE are not representative of the rest of the site. Fortunately this wind direction is not common during the growing season. However, to address this issue, we assumed that if the upwind surface NE of the tower were the same as other directions, the closure would also have been 0,80. So when the "forced closure" values for ET were determined as in equations (2) and (3), they were forced to a closure of 0.80 instead of 1.0.

Creating Fetch/Footprint Rasters

For all reliable daytime hours (i.e. hours not gap-filled), an hourly footprint dataset was created for each of the four validation sites using the Kljun model:

http://footprint.kljun.net/index.php

This is a published model, based on sound scientific processes, that has been shown to be of good accuracy. It quantifies the proportion of the total calculated fluxes of H and LE that come from any distance upwind. Such results are needed for two reasons. First, the analyses show that the upwind distance of the crop in question was large enough to allow the measurements to represent the crop at that location. Second, the relative contribution of any section of the upwind surface to the total ET determined at the tower can be quantified. These results are needed by the groups analyzing the remote sensing-based ET models, so that the relative weight of each pixel in the image contributing to the ET can be assigned.

References

Falge E, Baldocchi D et al. (2001). Gap filling strategies for long term energy flux data sets. *Agric. Forest Meteorol*. 107 (2001): 71-77.

Reichstein M, Falge E, Baldocchi D et al. (2005). On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. *Global Change Biology*, 11, 1424-1439.

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