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The QCECOR Value-Added Product: Quality-Controlled Eddy Correlation Flux Measurements

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August 2024

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Acronyms and Abbreviations

ANL	Argonne National Laboratory
ARM	Atmospheric Radiation Measurement
BAEBBR	Bulk Aerodynamic Technique EBBR value-added product
EBBR	energy balance Bowen ratio
ECOR	eddy correlation flux measurement system
LH	latent heat
LLNL	Lawrence Livermore National Laboratory
MAO	ARM's Mobile Facility site at Manacapuru, Brazil during GoAmazon 2014/15
MASRAD	Marine Stratus Radiation Aerosol and Drizzle field campaign
netCDF	Network Common Data Form
NSA	North Slope of Alaska
PYE	ARM's Mobile Facility site at Point Reyes, California during MASRAD (2005)
QC	quality control
QCECOR	Quality-Controlled ECOR value-added product
SEBS	surface energy balance system
SGP	Southern Great Plains
SH	sensible heat
TWP	Tropical Western Pacific
UTC	Coordinated Universal Time
VAP	value-added product
WPL	Webb-Pearman-Leuning

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1.0 Overview

Eddy correlation flux (ECOR) measurement systems are used by the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility to measure near-surface turbulent fluxes (Cook and Sullivan 2020). For over a decade, ARM has deployed ECORs at all its primary research observatories and mobile facilities. However, the original ECOR data, 30ecor, were not corrected through common eddy covariance corrections and contain suspicious data due to instrument and measurement uncertainties. Such uncertainties in the ECOR near-surface turbulent fluxes hamper their use by the user community. To improve the ECOR data, we develop a value-added product (VAP) — **the Quality-Controlled Eddy Correlation Flux (QCECOR)** — by applying the following necessary corrections and quality control (QC) procedures:

1. Eddy correlation corrections.
2. Determination of the quality-controlled energy fluxes from the corrected ECOR fluxes.
3. Stringent QC checks.

The QCECOR VAP contains three primary measurements: corrected surface latent heat flux (LH), corrected surface sensible heat flux (SH), and corrected carbon dioxide (CO_2) flux, together with their QC flags. The uncorrected surface turbulent fluxes of LH, SH, and CO_2 from the original ECOR data are included as well for the user's reference. The QCECOR VAP also includes the wetness measurements from the surface energy balance system (SEBS; Cook and Sullivan 2024). The SEBS's wetness sensors are collocated with the ECOR systems, mounted on the same boom arm as the sonic anemometers and infrared gas analyzers, and return an analog voltage output from 1 to 3 V corresponding to wet and dry conditions, respectively. The SEBS wetness measurements are useful for identifying periods during which the ECOR sensors are potentially impacted by precipitation or dew/frost and are included in the QCECOR VAP for users' reference but not applied for any QC procedures.

2.0 Corrections and QC Procedures

The protocol for the QCECOR VAP workflow is shown in Figure 1. It includes the following flux corrections and QC procedures:

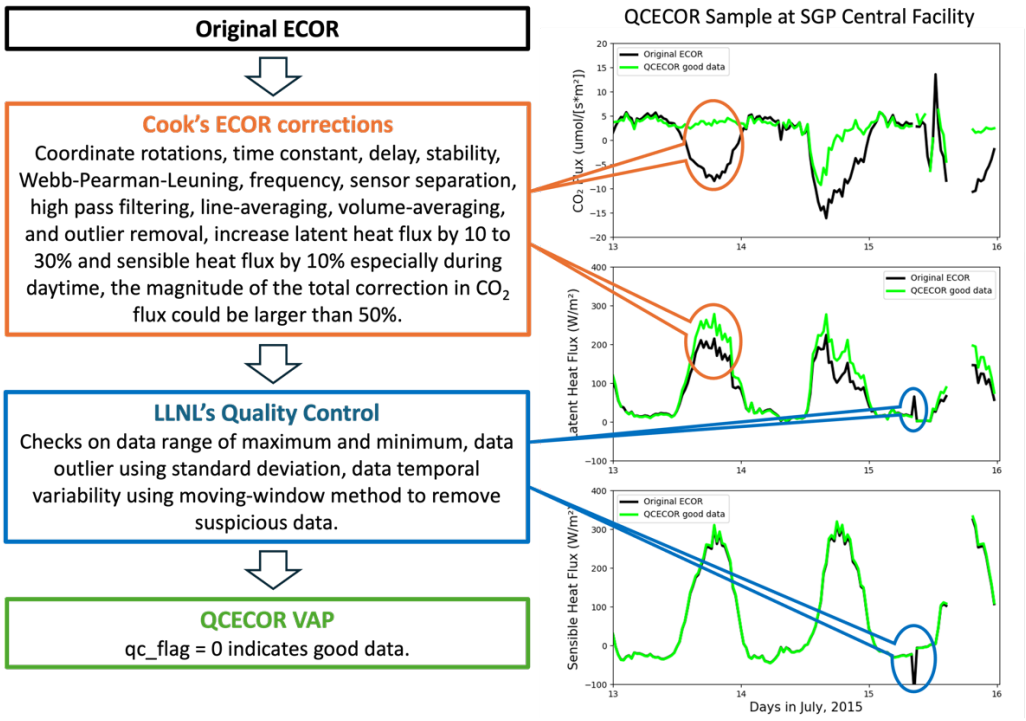

Figure 1. The protocol for the QCECOR VAP workflow.

Eddy correlation corrections include stability correction, Webb-Pearman-Leuning (WPL) correction, frequency correction, sensor separation correction, filtering correction, line-averaging correction, and volume-averaging correction (Cook et al. 2008, Fuehrer and Friehe 2002).

LLNL further quality controls include:

1. Data range check on maximum and minimum values. The original ECOR data were further filtered to remove surface sensible and latent heat fluxes when they were > 150 W/m^2 or < -150 W/m^2 during the night; and when they were < -100 W/m^2 when solar insolation is > 300 W/m^2.
2. Outlier check using standard deviation. If data departures from the mean, averaged during the day or during the night separately, are larger than four standard deviations, the data are flagged as bad.
3. Temporal variability check using moving window method. This method is applied with a moving window of ± 3 hours centered at the data point. In the time window, two temporal variabilities, with and without the data point, are calculated. If the absolute value of the difference between the two temporal variabilities is larger than a threshold (i.e., 25 W/m^2 for surface sensible and latent heat fluxes, 1.0 µmol/m^2/s for CO_2 flux), the data are considered as an outlier and flagged as bad.

Based on our initial analysis (Figure 1), these corrections generally increase the latent heat flux by 10 to 30 % and the sensible heat flux by 10 % from the original data, especially during the daytime, while a much smaller increase is noticed during nighttime. CO_2 flux corrections can be 0 to 50 % from the WPL correction alone, and when all corrections are considered, the total correction to CO_2 flux can be larger than 50 % (Burba and Anderson 2010).

QC flag setting: Two QC flags are set for corrected surface turbulent flux: qc_flag = 0 represents good data while qc_flag = 1 represents bad data. The data are flagged as bad if they were identified as bad data

from the original ECOR data or they failed any of the above-noted LLNL's quality controls. The value of corrected surface turbulent flux is set to missing when qc_flag = 1.

3.0 Comparison of Turbulent Fluxes between QCECOR and BAEBBR

In addition to the ECOR, the energy balance Bowen ratio system (EBBR) was installed across the ARM Southern Great Plains (SGP) site in Oklahoma to measure sensible and latent heat fluxes (with a VAP available, the Bulk Aerodynamic Technique EBBR (BAEBBR), that corrects non-sensical fluxes near sunrise and sunset when the Bowen ratio is near -1). Most of the ECOR and EBBR instruments are located at different facilities within the SGP extended site, except two collocated facilities: the Central Facility (E13 and E14 for EBBR and ECOR, respectively; 2003-2023) and Extended Facility 39 (E39, 2015-2023). At the SGP Central Facility, the two instruments were a few hundred meters apart but had fetch footprints over vegetation cover that varied between the two instrument systems, depending on wind direction. Tang et al. (2019) found sensible and latent heat fluxes measured from ECOR and EBBR to have quite significant differences (Figure 2). Overall, BAEBBR had similar LH and larger SH compared to QCECOR during spring, but it had much larger LH and smaller SH during summer.

The differences between ECOR and EBBR were, in part, attributed to the different upwind surface vegetation types. At the Central Facility, ECOR is located at the edge of cropland and grassland, measuring fluxes over cropland under prevailing southerly winds, while EBBR was located within grassland. Apart from E39, all EBBR stations were located over grassland, while ECOR stations are located over a variety of vegetation types including cropland, grassland, and forest, depending on site and prevailing wind direction. Users should be aware of the surface type representation when using the turbulent flux measurements from ECOR and EBBR. More information about site-specific vegetation type can be found in Cook and Sullivan (2019, 2020) and the comparison of ECOR and EBBR at SGP can be found in Tang et al. (2019).

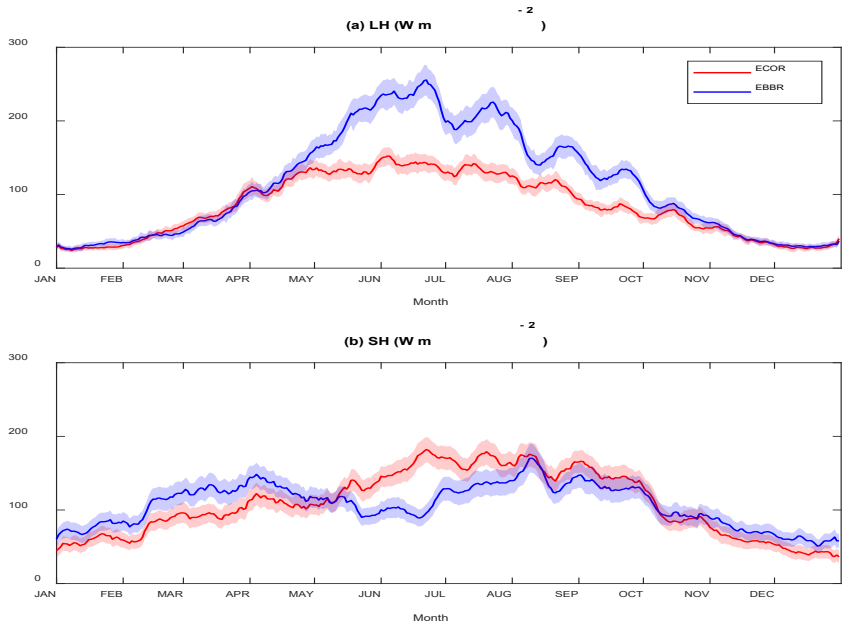

Figure 2. The seasonal variation of daytime (06–18 local time, UTC-6) mean (a) LH and (b) SH from QCECOR (red) and BAEBBR (blue) at the SGP Central Facility from 2004 to 2015.

4.0 Output Data

The primary variables in QCECOR are corrected surface latent heat flux, corrected surface sensible heat flux, corrected CO_2 flux and their QC flags. A detailed list of the output variables is given in Appendix A. The VAP produces a single output file per day, named with the following convention:

XXX30qcecorFF.c1.YYYYMMDD.hhmmss.nc

where:

XXX = the location of the instrument (e.g., nsa, sgp, twp, pye, etc.)
30qcecor = identifies the datastream name: QCECOR VAP with 30-min time resolution
FF = facility (e.g., C1, M1, S1, etc.)
c1 = identifies the data level: derived or calculated value-added data product (VAP) using one or more measured or modeled data (a0 to c1) as input
YYYYMMDD = year, month, and day
hhmmss = hour, minute, second

Currently we do not have quick plots for this VAP. Figure 3 gives an example of the final QCECOR products with QC flag.

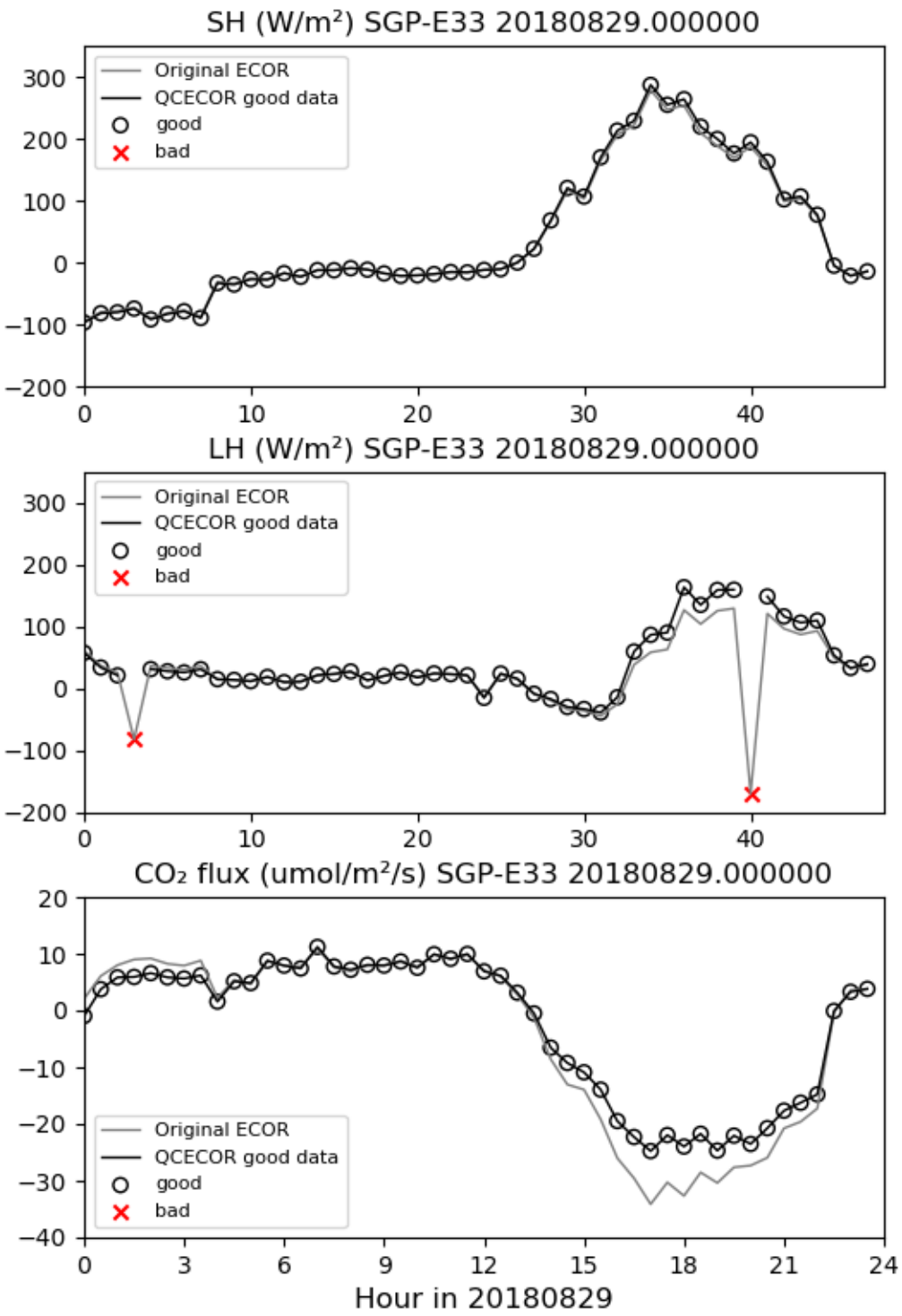

Figure 3. Time series of SH, LH, and CO_2 fluxes from ECOR and QCECOR VAP at SGP E33 on August 29, 2018. The gray line is original ECOR data. The black line represents corrected QCECOR data, with circles indicating good data. Red crosses indicate bad data and are set as a missing value (-9999) in QCECOR.

5.0 References

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Webb EK, GI Pearman, and R Leuning. 1980. "Correction of flux measurements for density effects due to heat and water vapour transfer." *Quarterly Journal of the Royal Meteorological Society* 106(447), 85-100, https://doi.org/10.1002/qj.49710644707

Appendix A

Example of File Head of QCECOR

```
netcdf hou30qcecorM1.c1.20220901.000000 {
dimensions:
      time = UNLIMITED ; // (48 currently)
      bound = 2 ;
variables:
      int base_time ;
            base_time:string = "2022-09-01 00:00:00 0:00" ;
            base_time:long_name = "Base time in Epoch" ;
            base_time:units = "seconds since 1970-1-1 0:00:00 0:00" ;
            base_time:ancillary_variables = "time_offset" ;
      double time_offset(time) ;
            time_offset:long_name = "Time offset from base_time" ;
            time_offset:units = "seconds since 2022-09-01 00:00:00
0:00" ;
            time_offset:ancillary_variables = "base_time" ;
      double time(time) ;
            time:long_name = "Time offset from midnight" ;
            time:units = "seconds since 2022-09-01 00:00:00 0:00" ;
            time:bounds = "time_bounds" ;
            time:axis = "T" ;
            time:standard_name = "time" ;
      double time_bounds(time, bound) ;
            time_bounds:long_name = "Time cell bounds" ;
            time_bounds:bound_offsets = -1800., 0. ;
      float corrected_sensible_heat_flux(time) ;
            corrected_sensible_heat_flux:long_name = "Corrected
sensible heat flux at surface" ;
            corrected_sensible_heat_flux:units = "W/m^2" ;
            corrected_sensible_heat_flux:standard_name =
"surface_upward_sensible_heat_flux" ;
            corrected_sensible_heat_flux:positive = "up" ;
            corrected_sensible_heat_flux:missing_value = -9999.f ;
            corrected_sensible_heat_flux:_FillValue = -9999.f ;
            corrected_sensible_heat_flux:valid_max = 1100.f ;
            corrected_sensible_heat_flux:valid_min = -300.f ;
            corrected_sensible_heat_flux:ancillary_variables =
"qc_corrected_sensible_heat_flux" ;
      int qc_corrected_sensible_heat_flux(time) ;
```

```
          qc_corrected_sensible_heat_flux:long_name = "Quality check
results on variable: Corrected sensible heat flux at surface" ;
          qc_corrected_sensible_heat_flux:units = "1" ;
          qc_corrected_sensible_heat_flux:description = "This
variable contains integer values indicating the results of a QC test
on the data. Non-zero integers indicate the QC condition given in the
description for those integers; a value of 0 indicates the data has
not failed any QC tests." ;
          qc_corrected_sensible_heat_flux:flag_method = "integer" ;
          qc_corrected_sensible_heat_flux:flag_1_description = "Value
not available or failed one or more quality control tests, value set
to missing_value." ;
          qc_corrected_sensible_heat_flux:flag_1_assessment = "Bad" ;
          qc_corrected_sensible_heat_flux:standard_name =
"quality_flag" ;
     float corrected_latent_heat_flux(time) ;
          corrected_latent_heat_flux:long_name = "Corrected latent
heat flux at surface" ;
          corrected_latent_heat_flux:units = "W/m^2" ;
          corrected_latent_heat_flux:standard_name =
"surface_upward_latent_heat_flux" ;
          corrected_latent_heat_flux:positive = "up" ;
          corrected_latent_heat_flux:missing_value = -9999.f ;
          corrected_latent_heat_flux:_FillValue = -9999.f ;
          corrected_latent_heat_flux:valid_max = 1100.f ;
          corrected_latent_heat_flux:valid_min = -300.f ;
          corrected_latent_heat_flux:ancillary_variables =
"qc_corrected_latent_heat_flux" ;
     int qc_corrected_latent_heat_flux(time) ;
          qc_corrected_latent_heat_flux:long_name = "Quality check
results on variable: Corrected latent heat flux at surface" ;
          qc_corrected_latent_heat_flux:units = "1" ;
          qc_corrected_latent_heat_flux:description = "This variable
contains integer values indicating the results of a QC test on the
data. Non-zero integers indicate the QC condition given in the
description for those integers; a value of 0 indicates the data has
not failed any QC tests." ;
          qc_corrected_latent_heat_flux:flag_method = "integer" ;
          qc_corrected_latent_heat_flux:flag_1_description = "Value
not available or failed one or more quality control tests, value set
to missing_value." ;
          qc_corrected_latent_heat_flux:flag_1_assessment = "Bad" ;
          qc_corrected_latent_heat_flux:standard_name =
"quality_flag" ;
     float corrected_co2_flux(time) ;
          corrected_co2_flux:long_name = "Corrected CO2 flux" ;
          corrected_co2_flux:units = "umol/(s m^2)" ;
          corrected_co2_flux:standard_name =
"surface_upward_mole_flux_of_carbon_dioxide" ;
          corrected_co2_flux:missing_value = -9999.f ;
          corrected_co2_flux:_FillValue = -9999.f ;
          corrected_co2_flux:valid_max = 35.f ;
```

```
           corrected_co2_flux:valid_min = -50.f ;
           corrected_co2_flux:ancillary_variables =
"qc_corrected_co2_flux" ;
     int qc_corrected_co2_flux(time) ;
           qc_corrected_co2_flux:long_name = "Quality check results on
variable: Corrected CO2 flux" ;
           qc_corrected_co2_flux:units = "1" ;
           qc_corrected_co2_flux:description = "This variable contains
integer values indicating the results of a QC test on the data. Non-
zero integers indicate the QC condition given in the description for
those integers; a value of 0 indicates the data has not failed any QC
tests." ;
           qc_corrected_co2_flux:flag_method = "integer" ;
           qc_corrected_co2_flux:flag_1_description = "Value not
available or failed one or more quality control tests, value set to
missing_value." ;
           qc_corrected_co2_flux:flag_1_assessment = "Bad" ;
           qc_corrected_co2_flux:standard_name = "quality_flag" ;
      float uncorrected_sensible_heat_flux(time) ;
           uncorrected_sensible_heat_flux:long_name = "Uncorrected
sensible heat flux at surface" ;
           uncorrected_sensible_heat_flux:units = "W/m^2" ;
           uncorrected_sensible_heat_flux:standard_name =
"surface_upward_sensible_heat_flux" ;
           uncorrected_sensible_heat_flux:positive = "up" ;
           uncorrected_sensible_heat_flux:source = "hou30ecorM1.b1:h"
;
           uncorrected_sensible_heat_flux:missing_value = -9999.f ;
           uncorrected_sensible_heat_flux:_FillValue = -9999.f ;
           uncorrected_sensible_heat_flux:valid_max = 1100.f ;
           uncorrected_sensible_heat_flux:valid_min = -300.f ;
           uncorrected_sensible_heat_flux:ancillary_variables =
"qc_uncorrected_sensible_heat_flux" ;
      int qc_uncorrected_sensible_heat_flux(time) ;
           qc_uncorrected_sensible_heat_flux:long_name = "Quality
check results on variable: Uncorrected sensible heat flux at surface"
;
           qc_uncorrected_sensible_heat_flux:units = "1" ;
           qc_uncorrected_sensible_heat_flux:standard_name =
"quality_flag" ;
           qc_uncorrected_sensible_heat_flux:description = "This
variable contains bit-packed integer values, where each bit represents
a QC test on the data. Non-zero bits indicate the QC condition given
in the description for those bits; a value of 0 (no bits set)
indicates the data has not failed any QC tests." ;
           qc_uncorrected_sensible_heat_flux:flag_method = "bit" ;
           qc_uncorrected_sensible_heat_flux:bit_1_description =
"Value is equal to missing_value." ;
           qc_uncorrected_sensible_heat_flux:bit_1_assessment = "Bad"
;
           qc_uncorrected_sensible_heat_flux:bit_2_description =
"Value is less than the valid_min." ;
```

```
           qc_uncorrected_sensible_heat_flux:bit_2_assessment = "Bad"
;
           qc_uncorrected_sensible_heat_flux:bit_3_description =
"Value is greater than the valid_max." ;
           qc_uncorrected_sensible_heat_flux:bit_3_assessment = "Bad"
;
      float uncorrected_latent_heat_flux(time) ;
           uncorrected_latent_heat_flux:long_name = "Uncorrected
latent heat flux at surface" ;
           uncorrected_latent_heat_flux:units = "W/m^2" ;
           uncorrected_latent_heat_flux:standard_name =
"surface_upward_latent_heat_flux" ;
           uncorrected_latent_heat_flux:positive = "up" ;
           uncorrected_latent_heat_flux:source = "hou30ecorM1.b1:lv_e"
;
           uncorrected_latent_heat_flux:missing_value = -9999.f ;
           uncorrected_latent_heat_flux:_FillValue = -9999.f ;
           uncorrected_latent_heat_flux:valid_min = -300.f ;
           uncorrected_latent_heat_flux:valid_max = 1500.f ;
           uncorrected_latent_heat_flux:ancillary_variables =
"qc_uncorrected_latent_heat_flux" ;
      int qc_uncorrected_latent_heat_flux(time) ;
           qc_uncorrected_latent_heat_flux:long_name = "Quality check
results on variable: Uncorrected latent heat flux at surface" ;
           qc_uncorrected_latent_heat_flux:units = "1" ;
           qc_uncorrected_latent_heat_flux:standard_name =
"quality_flag" ;
           qc_uncorrected_latent_heat_flux:description = "This
variable contains bit-packed integer values, where each bit represents
a QC test on the data. Non-zero bits indicate the QC condition given
in the description for those bits; a value of 0 (no bits set)
indicates the data has not failed any QC tests." ;
           qc_uncorrected_latent_heat_flux:flag_method = "bit" ;
           qc_uncorrected_latent_heat_flux:bit_1_description = "Value
is equal to missing_value." ;
           qc_uncorrected_latent_heat_flux:bit_1_assessment = "Bad" ;
           qc_uncorrected_latent_heat_flux:bit_2_description = "Value
is less than the valid_min." ;
           qc_uncorrected_latent_heat_flux:bit_2_assessment = "Bad" ;
           qc_uncorrected_latent_heat_flux:bit_3_description = "Value
is greater than the valid_max." ;
           qc_uncorrected_latent_heat_flux:bit_3_assessment = "Bad" ;
      float uncorrected_co2_flux(time) ;
           uncorrected_co2_flux:long_name = "Uncorrected CO2 flux" ;
           uncorrected_co2_flux:units = "umol/(s m^2)" ;
           uncorrected_co2_flux:standard_name =
"surface_upward_mole_flux_of_carbon_dioxide" ;
           uncorrected_co2_flux:source = "hou30ecorM1.b1:fc" ;
           uncorrected_co2_flux:missing_value = -9999.f ;
           uncorrected_co2_flux:_FillValue = -9999.f ;
           uncorrected_co2_flux:valid_min = -50.f ;
```

```
           uncorrected_co2_flux:ancillary_variables =
"qc_uncorrected_co2_flux" ;
      int qc_uncorrected_co2_flux(time) ;
           qc_uncorrected_co2_flux:long_name = "Quality check results
on variable: Uncorrected CO2 flux" ;
           qc_uncorrected_co2_flux:units = "1" ;
           qc_uncorrected_co2_flux:standard_name = "quality_flag" ;
           qc_uncorrected_co2_flux:description = "This variable
contains bit-packed integer values, where each bit represents a QC
test on the data. Non-zero bits indicate the QC condition given in the
description for those bits; a value of 0 (no bits set) indicates the
data has not failed any QC tests." ;
           qc_uncorrected_co2_flux:fail_max = 35.f ;
           qc_uncorrected_co2_flux:flag_method = "bit" ;
           qc_uncorrected_co2_flux:bit_1_description = "Value is equal
to missing_value." ;
           qc_uncorrected_co2_flux:bit_1_assessment = "Bad" ;
           qc_uncorrected_co2_flux:bit_2_description = "Value is less
than the valid_min." ;
           qc_uncorrected_co2_flux:bit_2_assessment = "Bad" ;
           qc_uncorrected_co2_flux:bit_3_description = "Value is
greater than fail_max" ;
           qc_uncorrected_co2_flux:bit_3_assessment = "Bad" ;
      float wetness(time) ;
           wetness:long_name = "Wetness, rain detector" ;
           wetness:units = "V" ;
           wetness:resolution = 0.01f ;
           wetness:ancillary_variables = "qc_wetness" ;
           wetness:missing_value = -9999.f ;
           wetness:comment = "3 V indicates sensor is dry, 1 V
indicates sensor is fully wetted" ;
      int qc_wetness(time) ;
           qc_wetness:long_name = "Quality check results on variable:
Wetness, rain detector" ;
           qc_wetness:units = "1" ;
           qc_wetness:standard_name = "quality_flag" ;
           qc_wetness:description = "This variable contains bit-packed
integer values, where each bit represents a QC test on the data. Non-
zero bits indicate the QC condition given in the description for those
bits; a value of 0 (no bits set) indicates the data has not failed any
QC tests." ;
           qc_wetness:flag_method = "bit" ;
           qc_wetness:bit_1_description = "Value not available or
failed one or more quality control tests, value set to missing_value."
;
           qc_wetness:bit_1_assessment = "Bad" ;
      float lat ;
           lat:long_name = "North latitude" ;
           lat:units = "degree_N" ;
           lat:standard_name = "latitude" ;
           lat:valid_min = -90.f ;
           lat:valid_max = 90.f ;
```

```
      float lon ;
            lon:long_name = "East longitude" ;
            lon:units = "degree_E" ;
            lon:standard_name = "longitude" ;
            lon:valid_min = -180.f ;
            lon:valid_max = 180.f ;
      float alt ;
            alt:long_name = "Altitude above mean sea level" ;
            alt:units = "m" ;
            alt:standard_name = "altitude" ;


// global attributes:
            :command_line = "idl -R -n qcecor -s hou -f M1 -b 20201116
-e 20221002 -D 2 --max-runtime 0 -R --filter-overlaps" ;
            :Conventions = "ARM-1.3" ;
            :process_version = "vap-qcecor-1.6-0.el7" ;
            :dod_version = "30qcecor-c1-1.2" ;
            :input_datastreams = "hou30ecorM1.b1 : 13.6 :
20220901.000000\n",
                  "housebsM1.b1 : 1.6 : 20220901.000000" ;
            :site_id = "hou" ;
            :platform_id = "30qcecor" ;
            :facility_id = "M1" ;
            :data_level = "c1" ;
            :location_description = "Tracking Aerosol Convection
Interactions Experiment (TRACER), La Porte, Texas" ;
            :datastream = "hou30qcecorM1.c1" ;
            :title = "Quality Controlled Eddy Correlation Flux
Measurement (QCECOR) for surface sensible and latent fluxes, and CO2
flux." ;
            :institution = "U.S. Department of Energy Atmospheric
Radiation Measurement (ARM) Climate Research Facility" ;
            :doi = "10.5439/1097546" ;
            :description1 = "This VAP of surface latent and sensible
heat flux, and CO2 flux is generated based on original ECOR data by
Cheng Tao, Yunyan Zhang and Shaocheng Xie (LLNL) with help from ARM
ECOR instrument mentor David R. Cook and Ryan Sullivan (ANL)." ;
            :description2 = "Eddy correlation corrections applied
include Webb-Pearman correction, frequency correction, sensor
separation correction, stability corrections, filtering correction,
and line-averaging and volume-averaging corrections. Sonic and IRGA
sensor heads are mounted on a small tower at 3 m above ground level,
except for SGP E21 where the ECOR system is installed on a tall tower
at 15 m above ground (Cook and Sullivan, 2020)." ;
            :description3 = "LLNL added QC includes data range check,
outlier check, standard deviation check,  and temporal variability
check. Value is set to missing if it fails LLNL QC, qc_flag value is
set to 1." ;
            :description4 = "Users are suggested to use the corrected
surface latent and sensible heat flux and CO2 flux. The surface latent
```

```
and sensible heat flux, and CO2 flux from 30ecor*.b1 are also included
for users\' reference." ;
           :description5 = "The corrected CO2 flux is validated via
comparison with that corrected using a community vetted code, EddyPro.
The magnitude of the WPL correction is generally 0-50% of the original
measured flux. Thus, in combination with the other corrections, the
magnitude of the total correction in CO2 flux could be larger than 50%
(Burda 2022, Webb et al. 1980)." ;
           :authors = "Cheng Tao (tao4@llnl.gov); Yunyan Zhang
(zhang25@llnl.gov)" ;
           :qc_date = "Thu Jan 28 21:54:10 UTC 2016" ;
           :history = "created by user gaustad on machine prod-
proc5.adc.arm.gov at 2024-07-08 06:33:44, using vap-qcecor-1.6-0.el7"
;
}
```

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