Testing alternative ground-based cloud liquid water content measurement methods for estimating cloud water interception in tropical montane cloud forests

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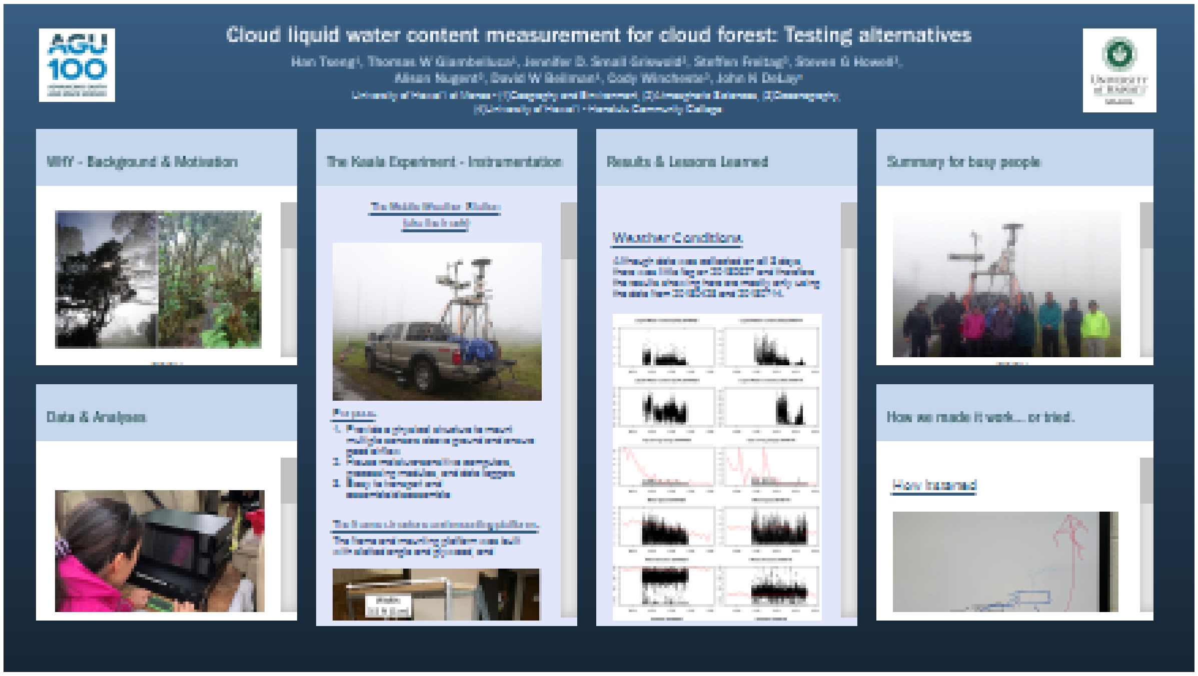
Abstract

Cloud water interception (CWI) is not captured by conventional rain gauges and not well characterized, but could have ecohydrological significance in systems such as tropical montane cloud forests. Quantifying CWI is necessary to assess the impacts of climate and land cover changes in places such as Hawai‘i. CWI can be estimated from wind speed, cloud liquid water content (LWC), and vegetation characteristics with an empirical model. Cloud microphysics sensors measure LWC accurately, but are expensive and often designed only for use on aircraft. LWC can be estimated by fog gauges, but poorly constrained catch efficiency and spurious rain catch can cause large errors. Visibility is related to LWC, but the relationship is non-linear and depends on the (usually unknown) drop size distribution. This study is part of a project aimed at mapping CWI across the Hawaiian Islands. Earlier analyses found disagreement between LWC estimated from fog gauge and visibility observations at the project field sites. In this study, we experimented with a novel in situ observation platform and cross disciplinary collaboration to compare cloud microphysics observations with those commonly used in cloud forest studies. Field missions took place from April to July 2018 at the summit of Mt. Ka‘ala (1,200 m) on O‘ahu Island. We built a pickup truck-mounted mobile weather station that can be assembled in the field, with weather-sensitive processing modules inside the cab. A total of 10 instruments were deployed: Phase Doppler Interferometer, Cloud Droplet Probe, fog gauge, visibility sensor, rain gauge, wind monitor, camera, water isotope sampler, UAV atmospheric sensor, and Aerosol Spectrometer. A nearby long-term station provides climate and canopy water balance data. Analyses found a strong relationship between visibility and LWC in dense fog. The fog gauge showed weak correlations due to coarse resolution and false rain catch, but had a reasonable catch efficiency. The start of fog catch lagged compared to the nearby station possibly due to screen surface wetting. Concurrent with other analyses, one goal is to calibrate the fog gauge and visibility sensor for long-term LWC monitoring. The mobile platform was effective for short-term deployment of airborne sensors. We hope to repeat the experiment in the future on O‘ahu and other islands.

Cloud liquid water content measurement for cloud forest: Testing alternatives



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PRESENTED AT:

WHY - BACKGROUND & MOTIVATION

Fog & Tropical Montane Cloud Forests

Fog is not measured by conventional rain gauges and often overlooked, but it can be a significant water source in places like the tropical montane cloud forests (TMCFs) in Hawaii. When fog passes along the mountain slope with the upslope wind, the cloud forest can capture the fog liquid water droplets by the forest canopy in a process called cloud water interception (CWI). The ability of TMCFs to gain extra water input from the fog, increase net precipitation under the forest canopy, enhance recharge, and improve freshwater resources is widely acknowledged and highly valued.

[VIDEO] https://www.youtube.com/embed/Sgp7K_S6o3s?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0

Cloud Water Interception

Despite its importance and the need for more studies, cloud water interception is not well characterized. Cloud water interception is hard to measure because it is a complex process between the vegetation canopy and the atmosphere, which both can be highly variable through space and time. Therefore, modeling is the only feasible way to estimate cloud water interception at larger scales relevant to most hydrological questions. Because CWI is mainly controlled by canopy characteristics, the wind condition, and the density of fog, it is possible to predict cloud water interception using an empirical model (cite Katata) if the canopy height, leaf area index, wind speed, and fog liquid water content are known.

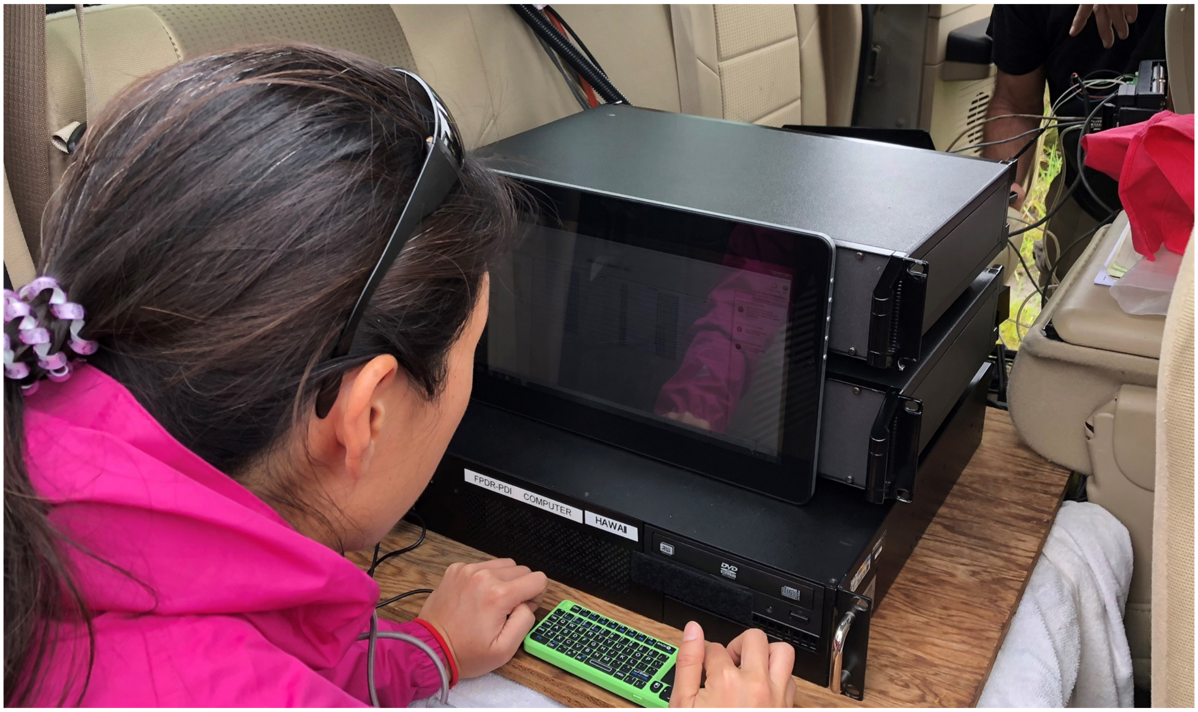
Liquid Water Content

Liquid water content (LWC) is a property of the atmosphere that is closely associated with processes and variables that determine cloud formation and structure. Many studies on cloud physics make observations during research flights with aircraft-mounted sensors, which typically measure the size and number density of cloud droplets. In contrast, most ecohydrological studies in tropical montane cloud forests do not measure fog liquid water content. Instead, the most common way of quantifying fog is by using a fog gauge, which measures the amount of fog water collected on an interception surface such as a screen or mesh. While few have examined the usage of fog gauges for measuring fog liquid water content, it is likely that calibration for the collection efficiency would be necessary.

The Kaala Experiment

This experiment is a part of the "Cloud Water Interception in Hawaii" project, which aims to map cloud water interception over the Hawaiian Islands through field observations and modeling. In this project, fog gauges were deployed to make fog liquid water content observations required for validating the output from an atmospheric model. The Kaala Experiment was initiated from the need of fog gauge calibration data; developed through conversations between researchers of different fields and focuses; and the resources and data shared between departments and labs across the campus.

DATA & ANALYSES



Experiment & Data

The experiment took place on the summit of Mt. Kaala, Oahu Island. Three field trips were made in April, June, and July 2018 (referred to as 20180428, 20180627, & 20180714 hereafter). Data was collected for a total of almost 18 hours.

Data were recorded at different time intervals depending on the sensor:

- 1-second: PDI, CDP, visibility (VIS), wind speed (WS) and direction (WD), Rain gauge (RF) and fog gauge (FOG_tip)
- 1-minute: time-lapse camera
- 15-minute: all data measured at the long-term climate station.

Analyses

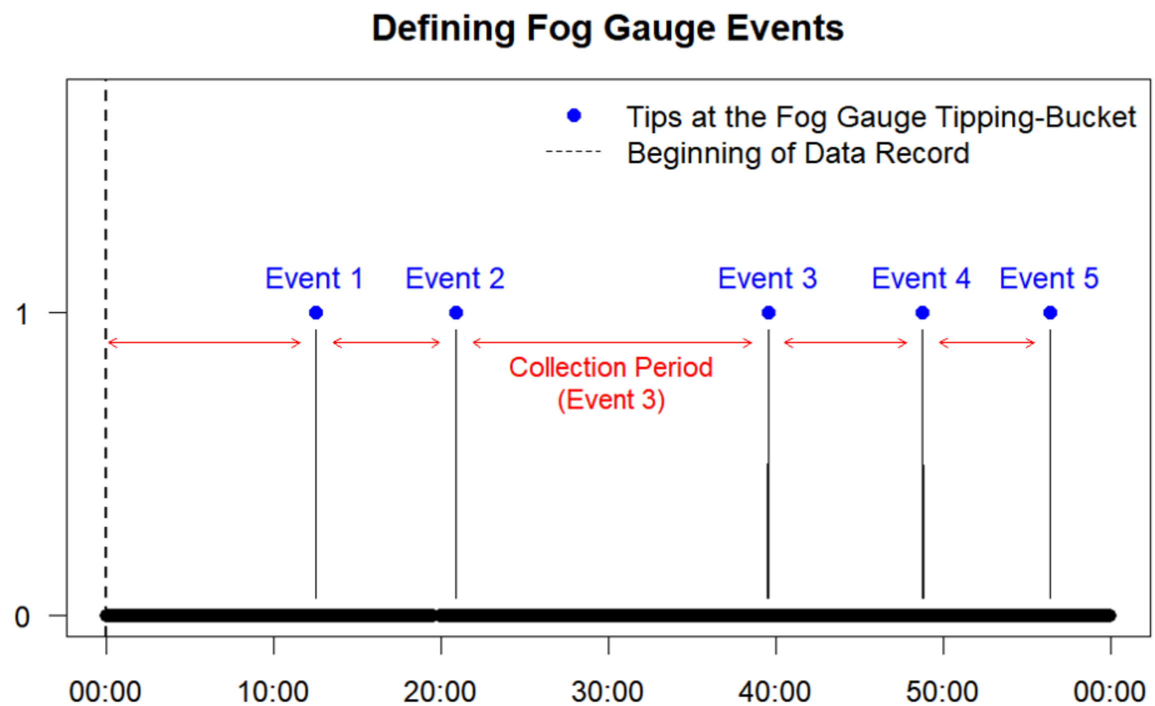
Droplet-based Liquid Water Content (drpLWC)

PDI and CDP data were processed and errors due to low wind speed were removed to produce 1-second LWC time series. The 1-second time series was then integrated to the mean LWC during each collection period (see section below) and at a 15-minute interval.

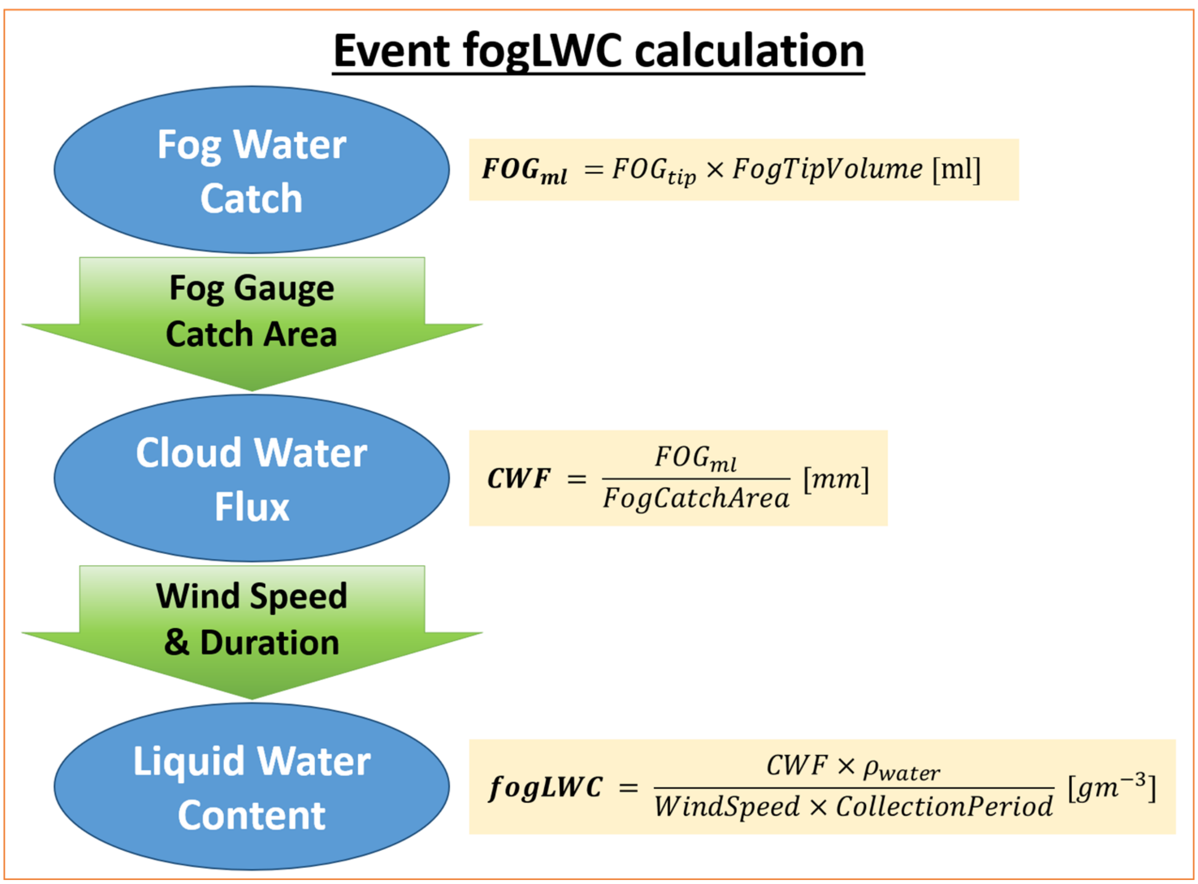
Fog gauge-derived Liquid Water Content (fogLWC)

- **Truck-mounted fog gauge (1-second)**

The 1-second tipping-bucket records of the truck-mounted fog gauge were calculated into liquid water content following the procedure below:



1. Defining the "fog gauge event" (FOG_id) as the time of each "tip" of the fog gauge tipping bucket, and calculate the "collection period" as the time between each tip.



2. Ignoring the gauge catch efficiency (assuming 100%), we calculated the fog LWC for each FOG_id from the volume of fog water collected (FOG_ml), the vertical projected area of the fog gauge interception screen (FogCatchArea), and the duration and wind speed of each collection period.

- **Climate station fog gauge (15-minute)**

The fogLWC was also calculated for the fog gauge installed at the long-term climate station with a procedure similar to above, except that the fog gauge event was not specifically defined, and the calculations were done on the regular data interval.

15-minute fogLWC calculation

$$\boldsymbol{total\ FOG_{ml}} = total\ FOG_{tip} \times FogTipVolume\ [ml]$$

$$\boldsymbol{CWF} = \frac{FOG_{ml}}{FogCatchArea}\ [mm]$$

$$\boldsymbol{fogLWC} = \frac{CWF \times \rho_{water}}{WindSpeed \times DataInterval}\ [gm^{-3}]$$

Fog Gauge Efficiency

We defined the fog gauge efficiency as:

$$\boldsymbol{Fog\ Gauge\ Efficiency} = \frac{fogLWC}{LWC}$$

The efficiency is calculated for each tipping-bucket event from the 1-second data of the truck-mounted fog gauge. We also examined the effects of wind speed and the data time resolution on the calculation of gauge efficiency.

THE KAALA EXPERIMENT - INSTRUMENTATION

The Mobile Weather Station

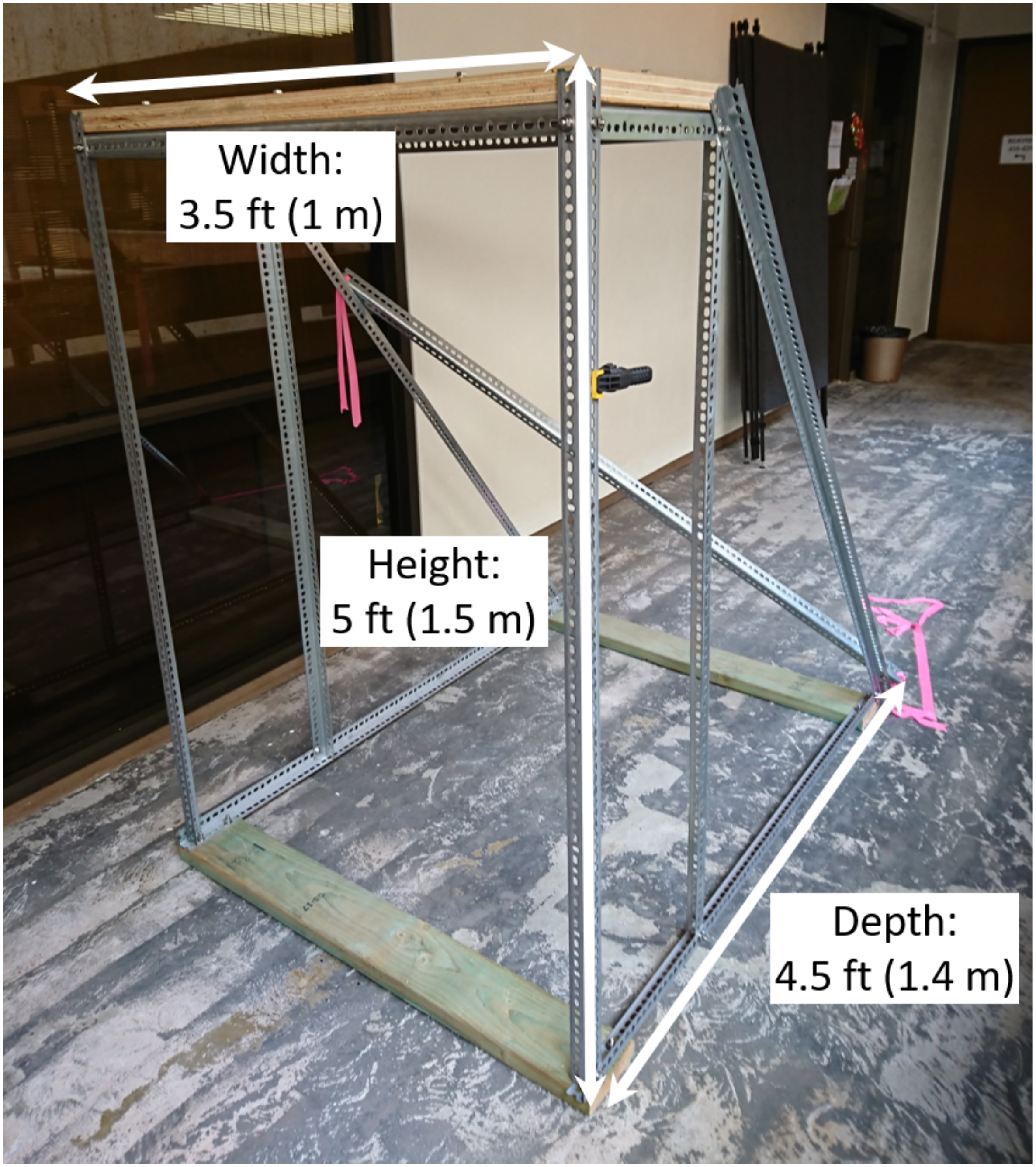
(aka the truck)

Purpose:

1. Provide a physical structure to mount multiple sensors above ground and ensure good airflow
2. House moisture-sensitive computers, processing modules, and data loggers
3. Easy to transport and assemble/disassemble

The frame structure and mounting platform:

The frame and mounting platform was built with slotted angle and plywood, and



- The frame

- The mounting platform with pre-drilled holes for mounting the PDI probe.

- The frame strapped down on the bed of a pickup truck.

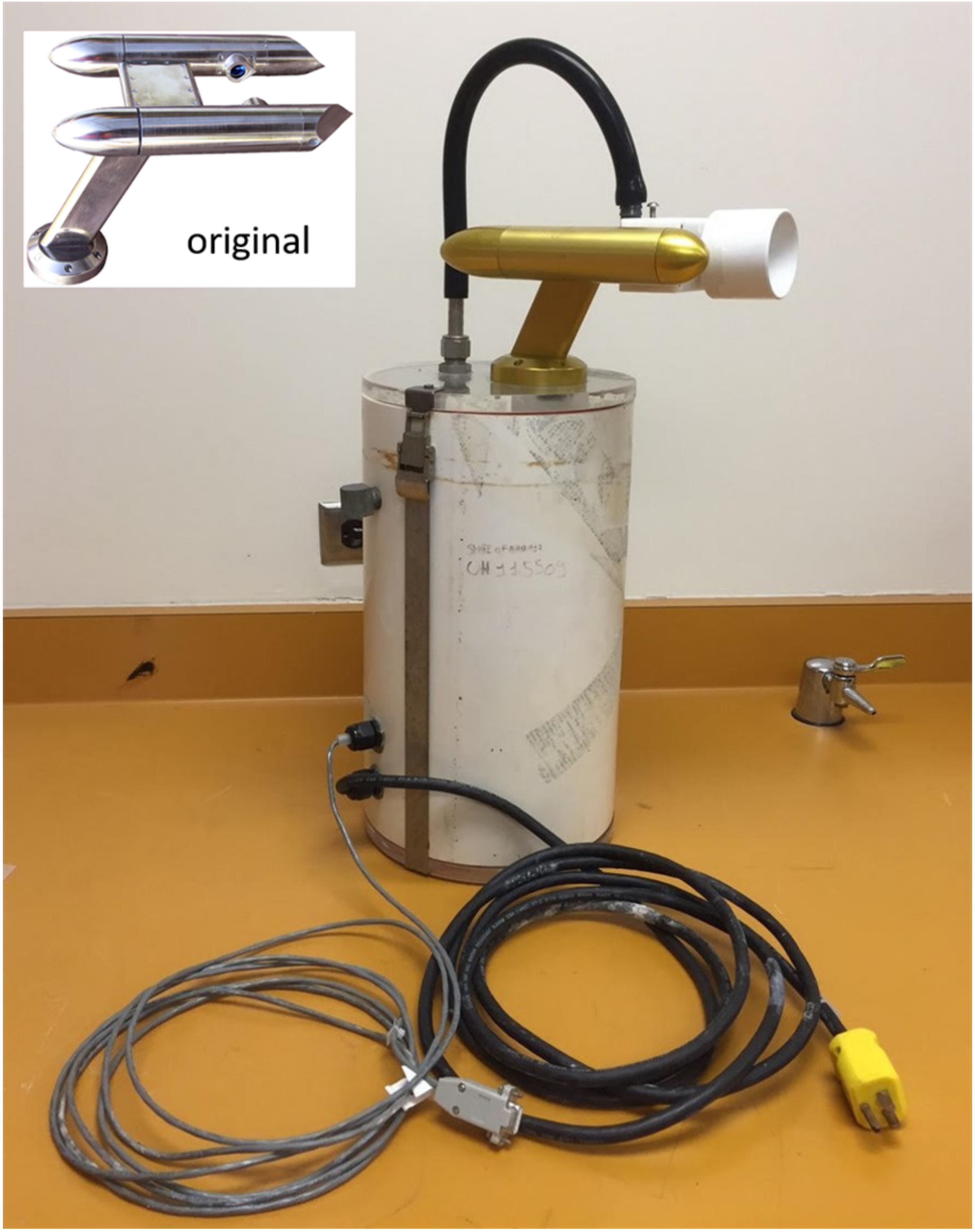
- Once in the field and the truck oriented with the tail pointing at the wind direction, instruments can be mounted on the platform.

Instrumentation: the mobile station

(Instrument listed by number in figure)

1. Phase Doppler Interferometer Flight Probe, Dual Range (PDI, Artium Technologies, Inc.)

[VIDEO] https://www.youtube.com/embed/xgcbXicYiy8?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0
2. Modified Cloud Droplet Probe (CDP-2, Droplet Measurement Technologies, Inc.)



3. Juvik-type Fog gauge

Close-up of the louvered aluminum screen

4. Visibility sensor (Belfort 6100)

5. Rain gauge (TE525)

6. Wind speed and direction monitor (RM Young 05106)

7. Time-lapse camera (Bushnell Trophy Cam HD Essential)

8. Isotope water sampler

9. UAV sensor: GPS, temperature, relative humidity, air pressure (InterMet iMetXQ)

10. Aerosol Spectrometer

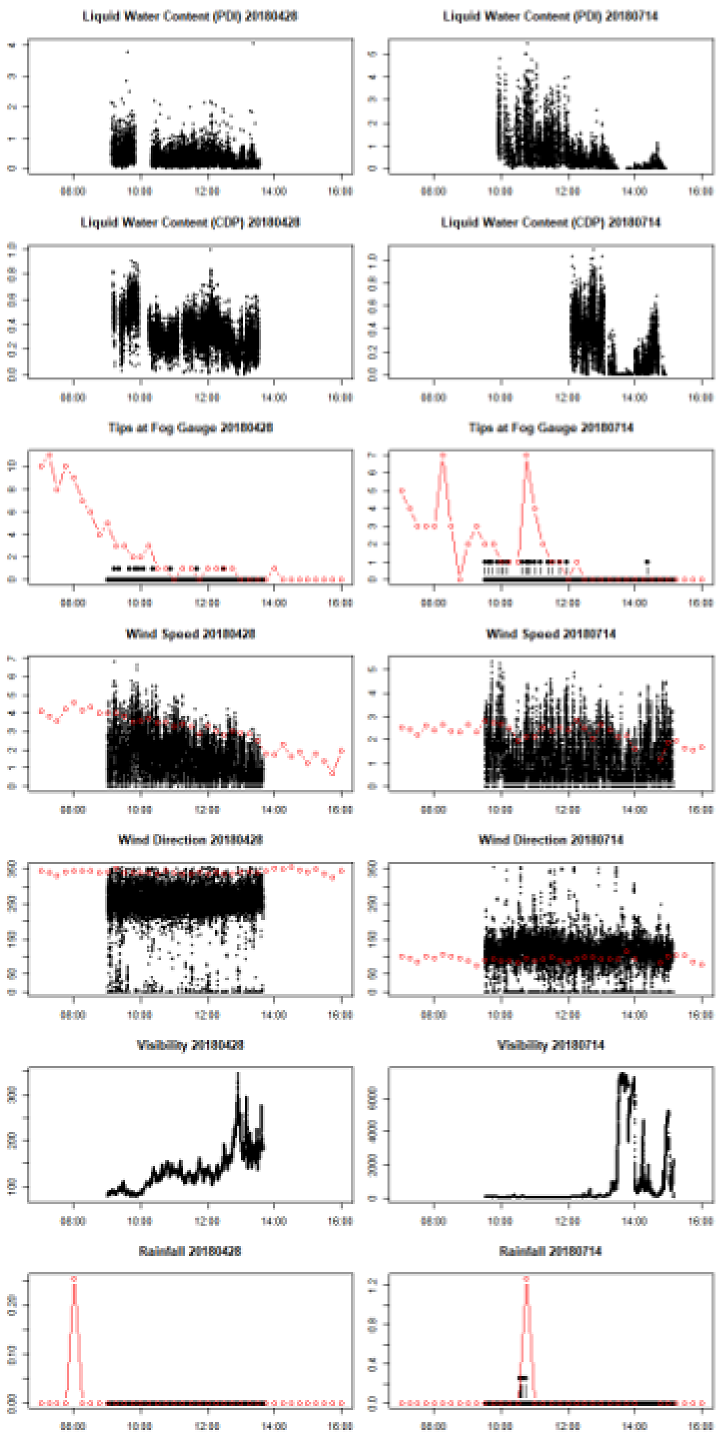
Instrumentation: long-term climate station

1. Net Radiometer (Kipp & Zonen, CNR1)
2. Wind sensor (Met One, 034B)
3. Temp/RH (Vaisala, HMP45C)
4. Soil Temperature (CSI, TCAV)
5. Soil moisture (CSI, CS616)
6. Soil heat flux (REBS, HFT-3)
7. Leaf wetness sensor (Decagon, LWS)
8. Rain gauge (Texas Electronics, TE525)
9. Juvik-type fog gauge

RESULTS & LESSONS LEARNED

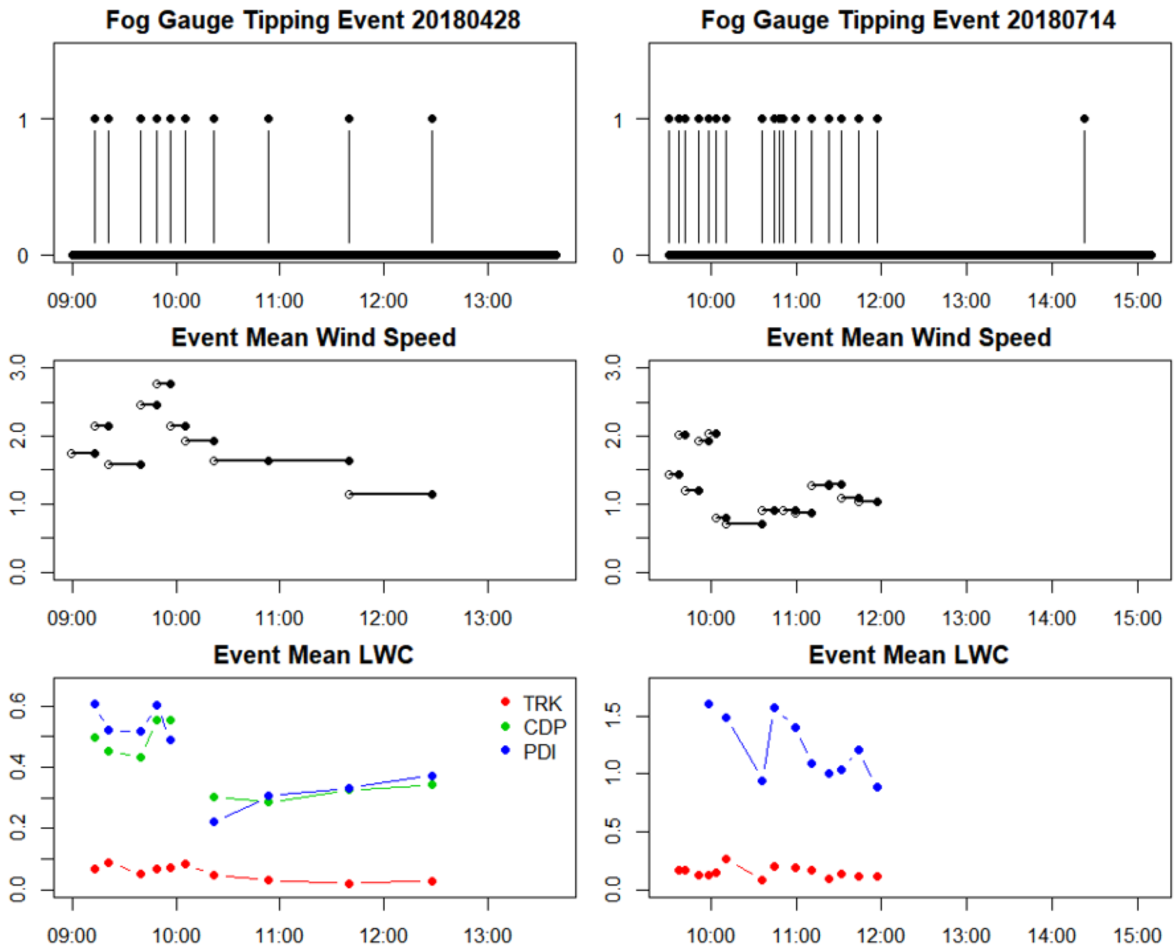
Weather Conditions

Although data was collected on all 3 days, there was little fog on 20180627 and therefore the results showing here are mostly only using the data from 20180428 and 20180714.

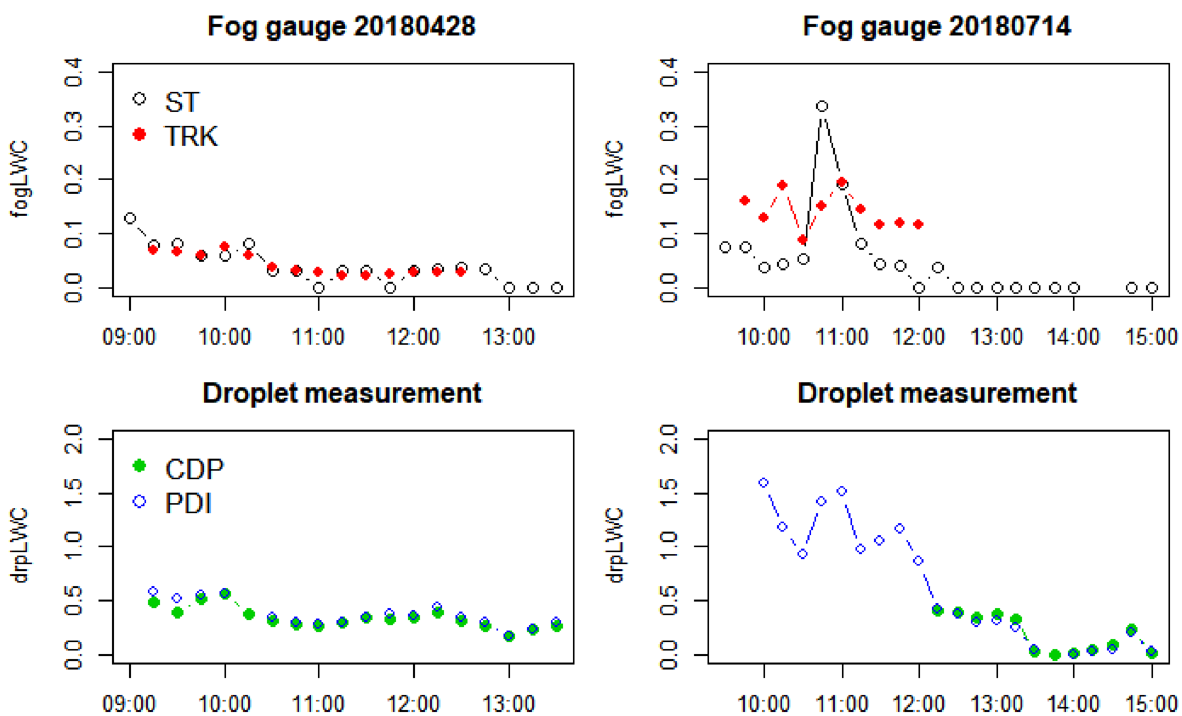


Liquid Water Content

Fog gauge tipping events

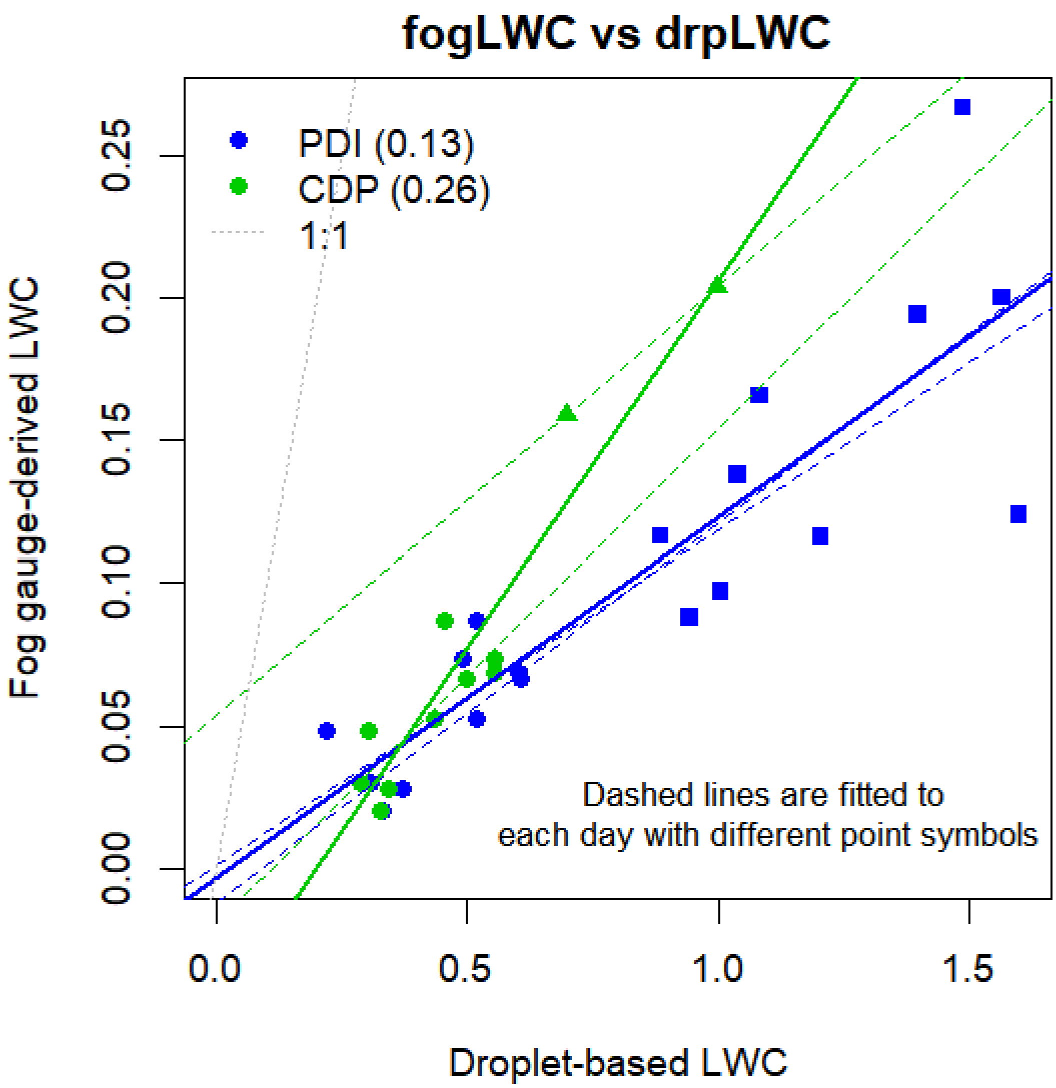


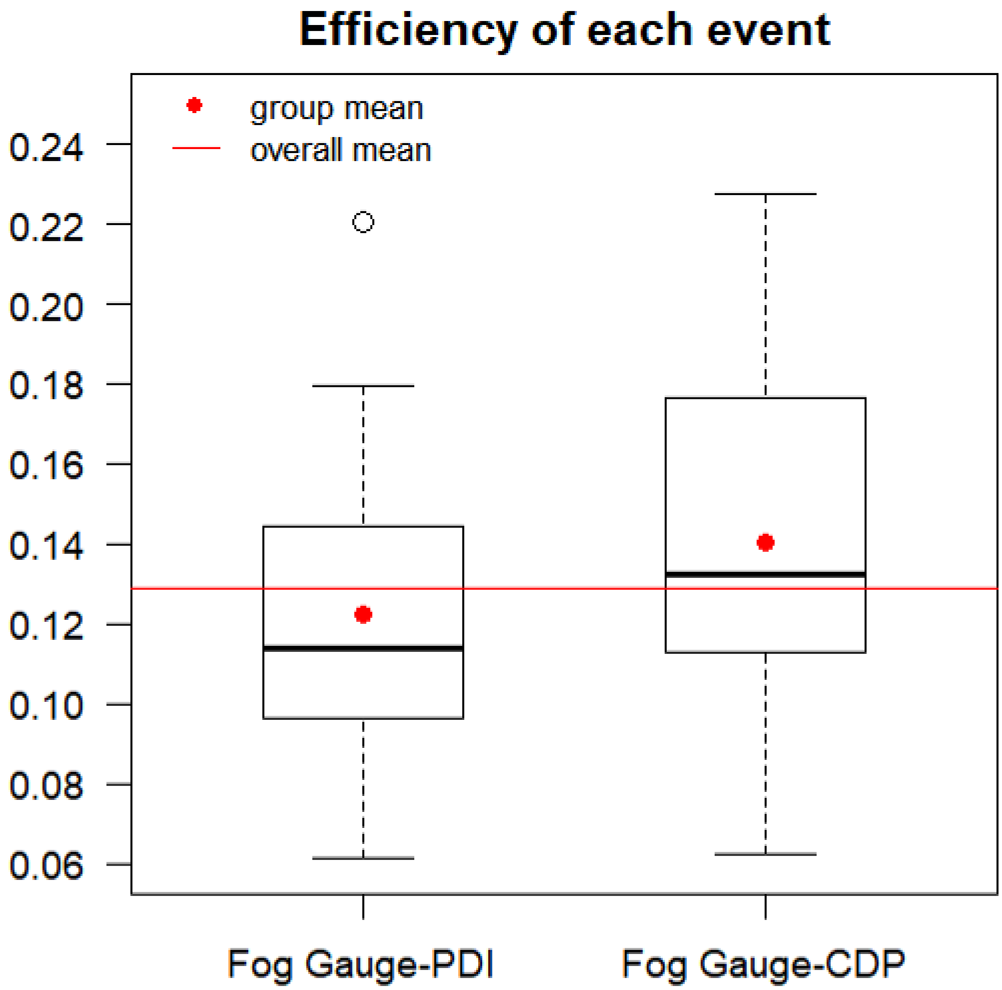
15-minute Interval



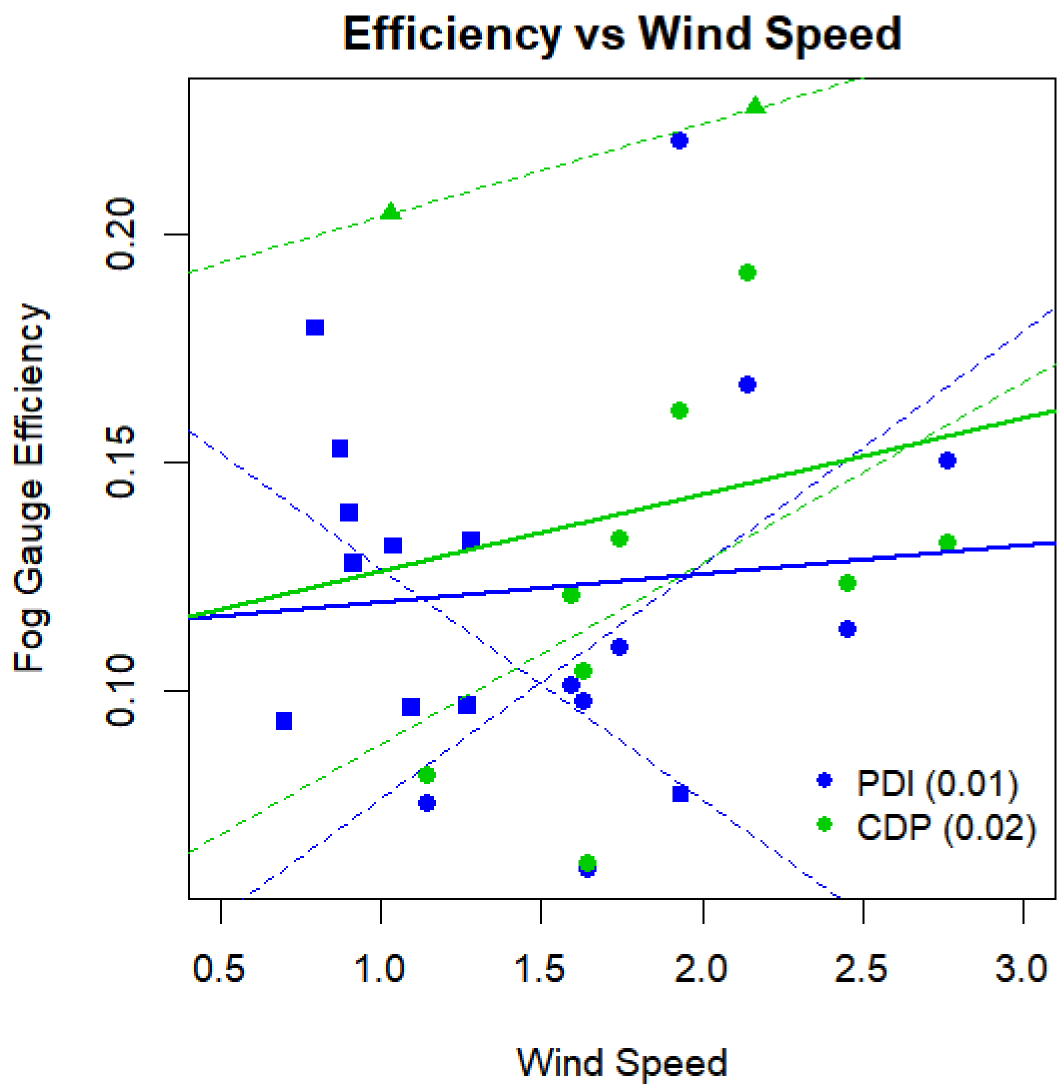
The LWC all follow the same temporal pattern closely despite the difference in values between the fog gauge and the droplet sensors.

Fog Gauge Efficiency





Compare to droplet measurements, the **fog gauge had an overall efficiency of 13%** when used to estimate LWC. Although this ratio somewhat varies from day to day and event to event, the two types of measurements correlate pretty well (0.87 for PDI, 0.95 for CDP).



Interesting and surprisingly, wind speed did not appear to affect the fog gauge efficiency,

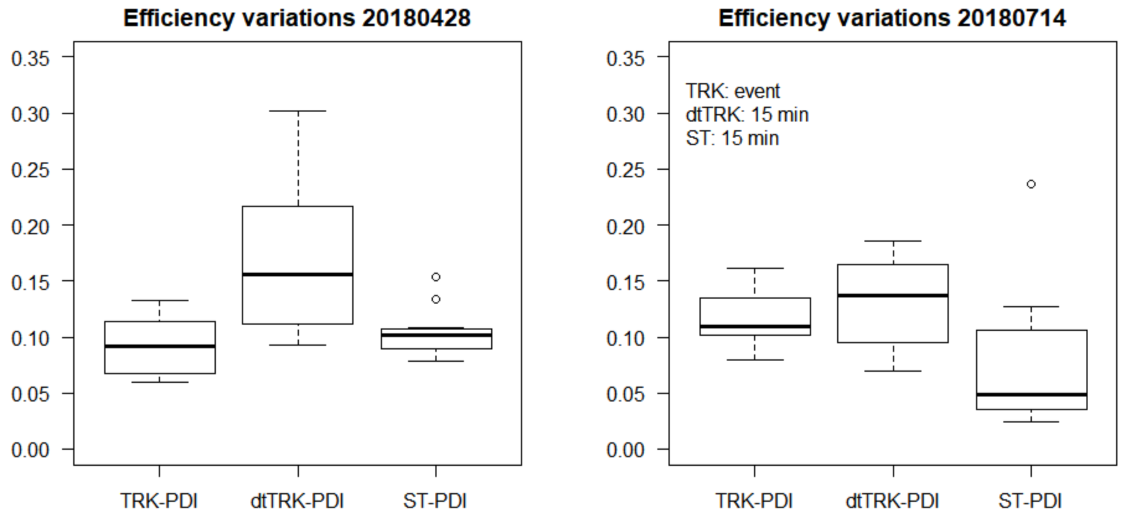
Effects of time scale

To compare with the fog gauge at the climate station, the truck fog gauge data was converted to 15-minute intervals with and without consideration of the collection period of each fog gauge tipping-bucket event.

Issues with Collection periods vs Regular intervals

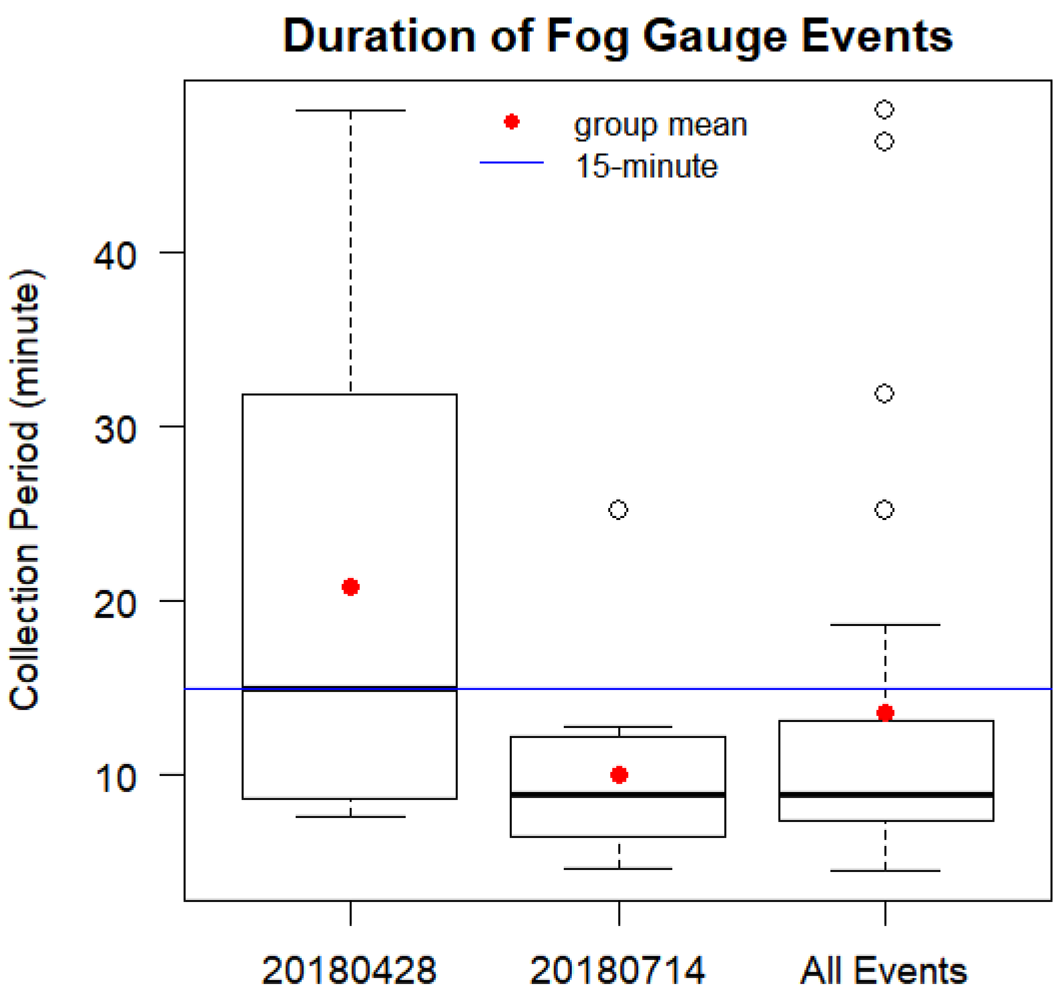
To compare with the fog gauge at the climate station (ST in figure below), the truck-mounted fog gauge data was converted to 15-minute regular time series by 2 ways:

1. With consideration of the collection period (TRK in figure below)
2. Ignore the collection periods of individual fog gauge tipping-bucket event, and use regular time intervals (the same way as the climate station data processing).(dtTRK in figure below)



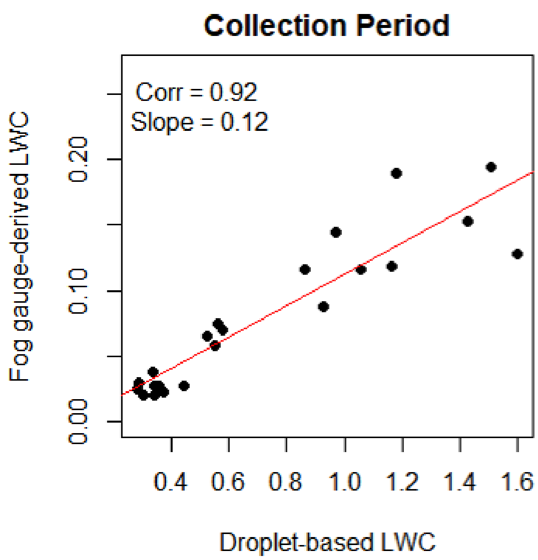
- TRK & dtTRK: same data, different calculation
- dfTRK & ST: different data, same calculation

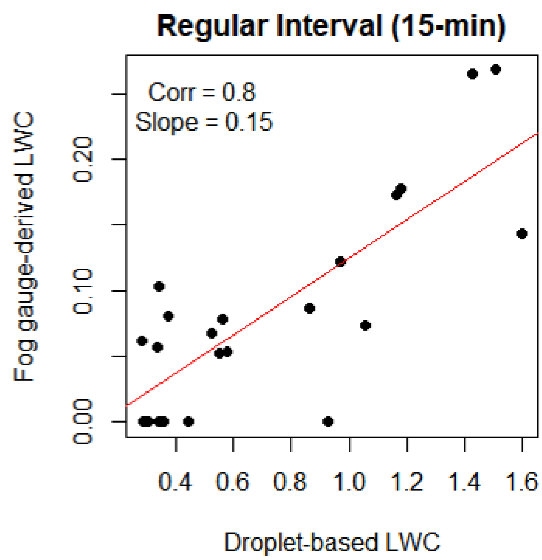
The dfTRK had overall higher efficiency in 20180428, but not in 20180726. This is likely due to the different length of collection periods on these two days.



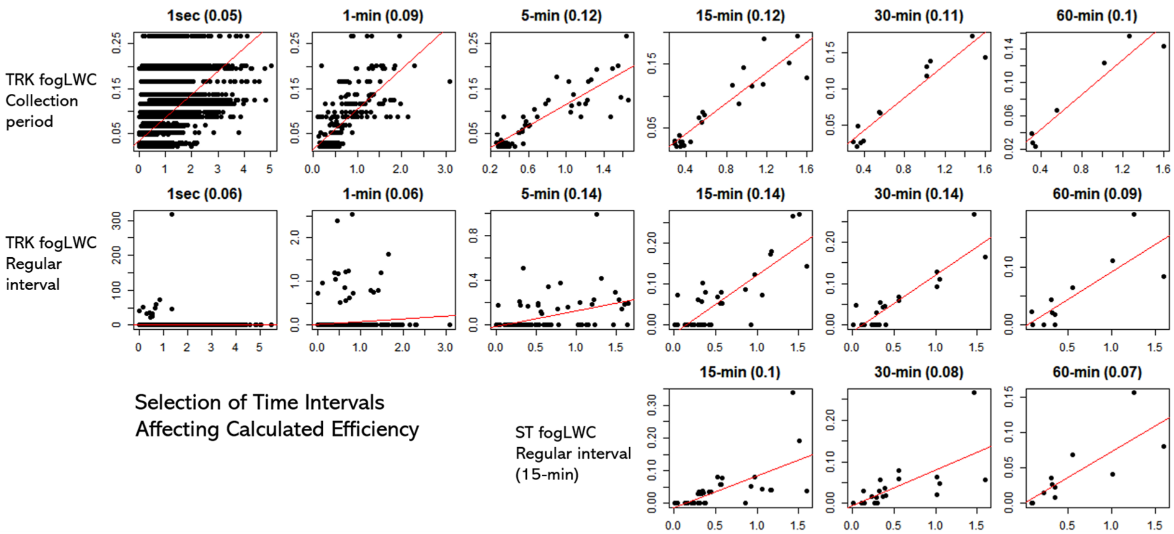
1. Collection period > data interval:
Overestimate fogLWC & efficiency

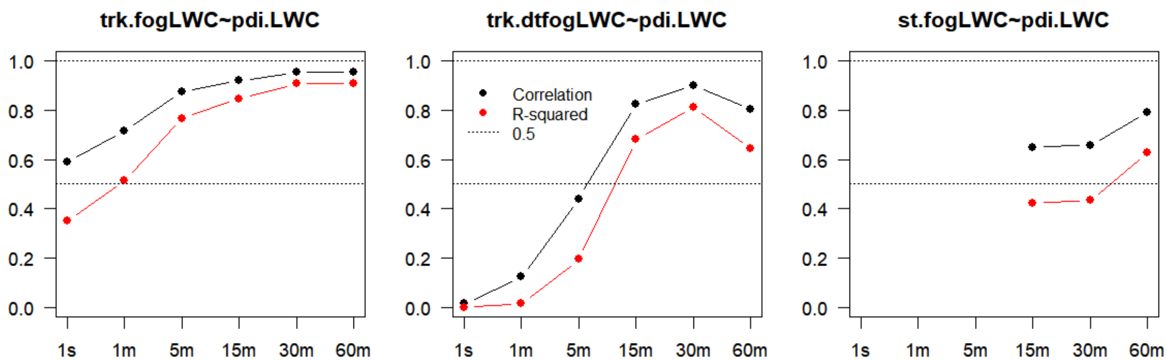
2. Collection period < data interval:
Does not affect mean LWC estimates, but reduce the data temporal resolution





Ignoring the variations in collection periods reduced correlation between drpLWC and fogLWC, and affects the resulting gauge efficiency.

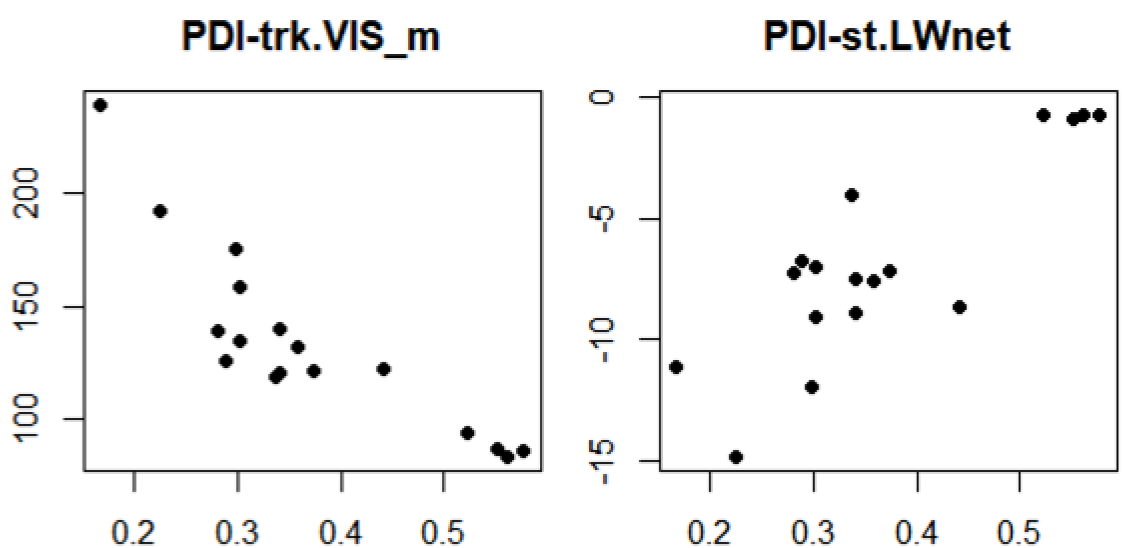




When aggregated over a longer time period, the correlations generally increases.

Other potentials

Analyses are on-going to explore more about the potential usage of other variables that may help improve the LWC estimates in addition to fog gauge.



Net longwave radiation and visibility also seem to correlate with drpLWC at 15-minute intervals.

Wind-Driven Rain

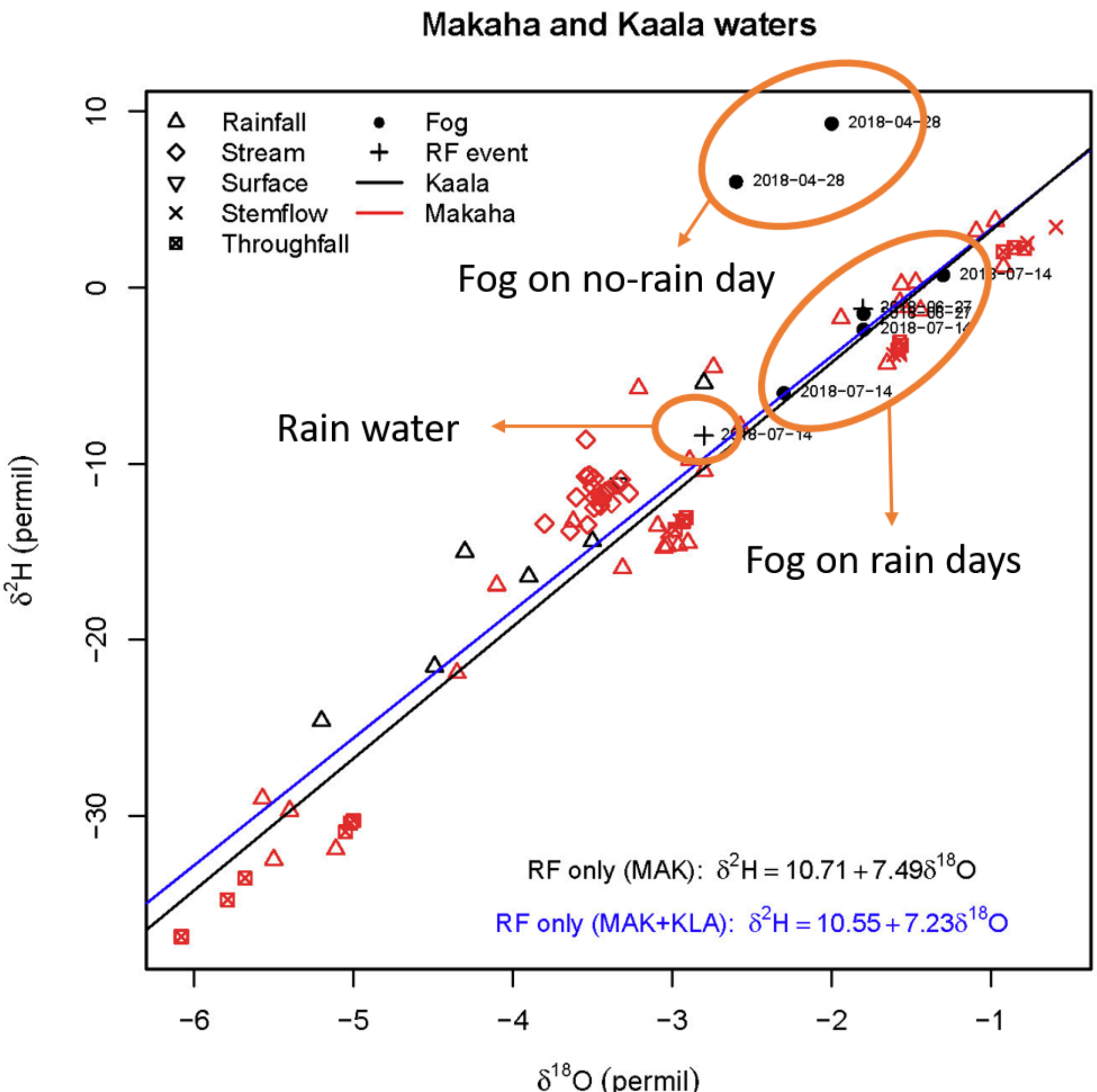
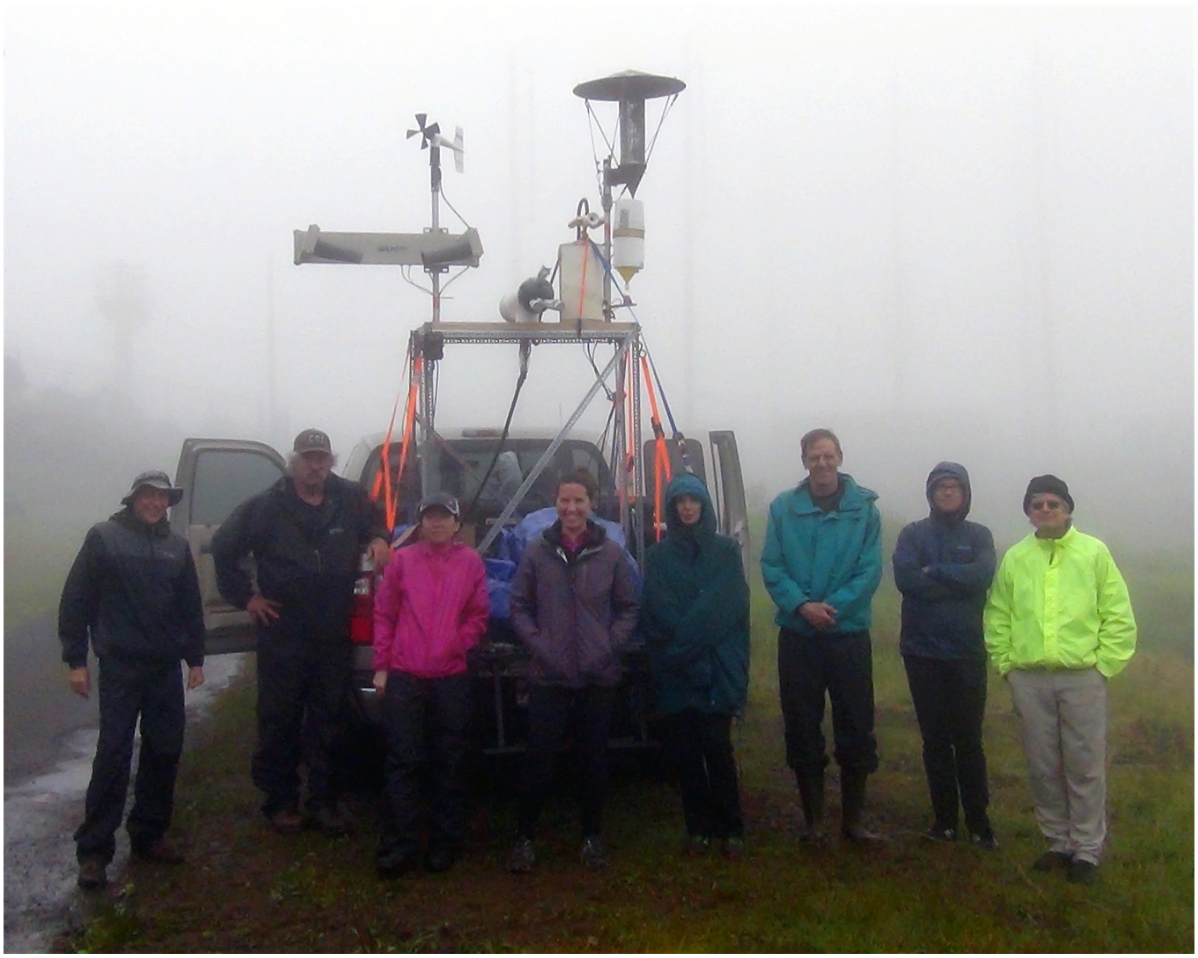


Figure made by Aurora Kagawa-Viviani

Stable isotope data may suggest the rainwater contamination in the fog catch, and highlight the need to account for wind-driven rain when using fog gauge.

Visually observing the false rainwater catch by the fog gauge.

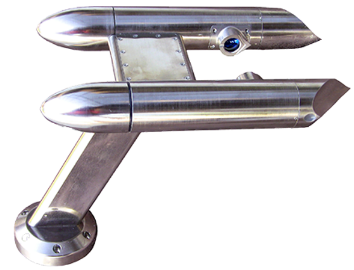
SUMMARY FOR BUSY PEOPLE



1. **Cloud water interception** is an ecohydrological process in tropical montane cloud forests that can increase total water input significantly. Estimating cloud water interception over large scales requires modeling, and observations of fog liquid water contents needed for model validation.

2. **Liquid water content (LWC)** can be measured accurately by cloud droplet sensors widely used in cloud physics studies, but most cloud forest studies measure **fog water catch** by a fog gauge. Few have tested fog gauges for determining LWC,

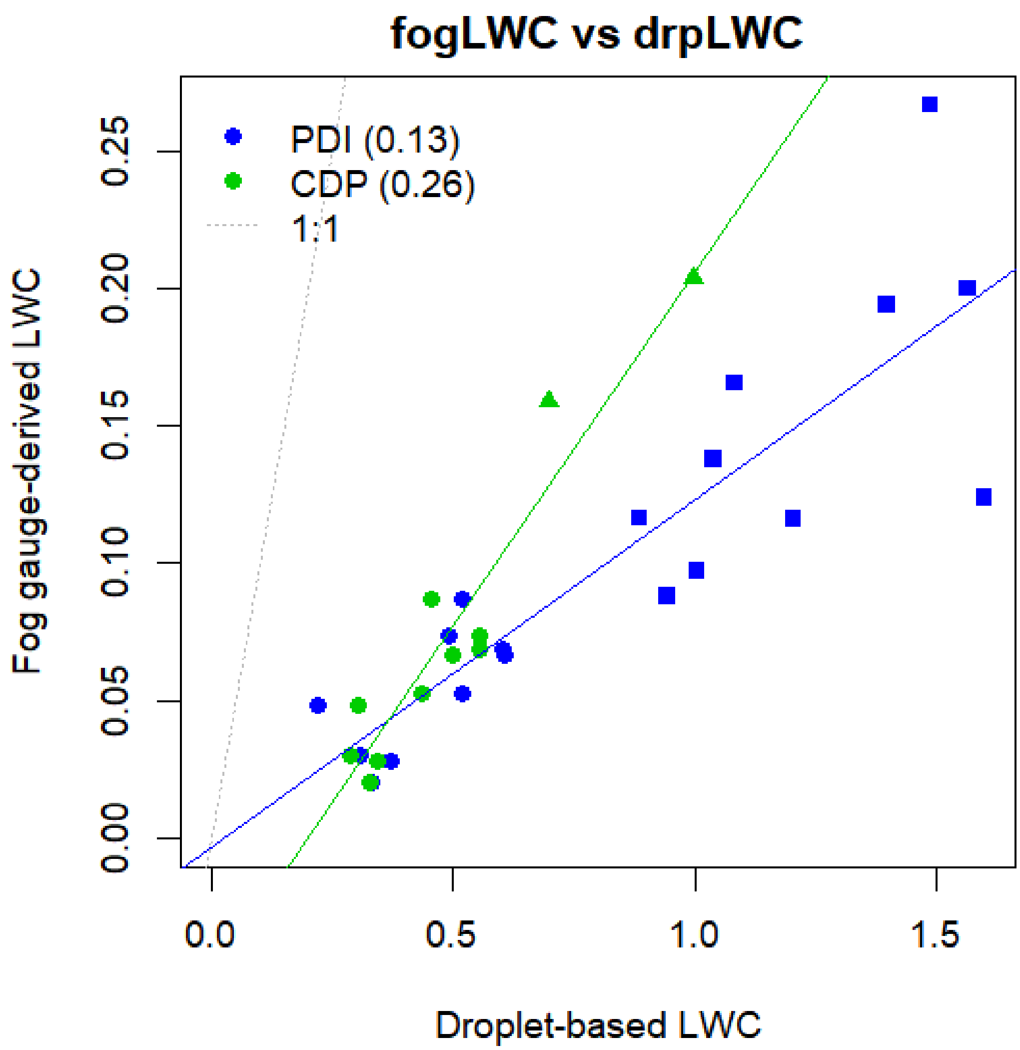
but calibration for the efficiency is likely required.



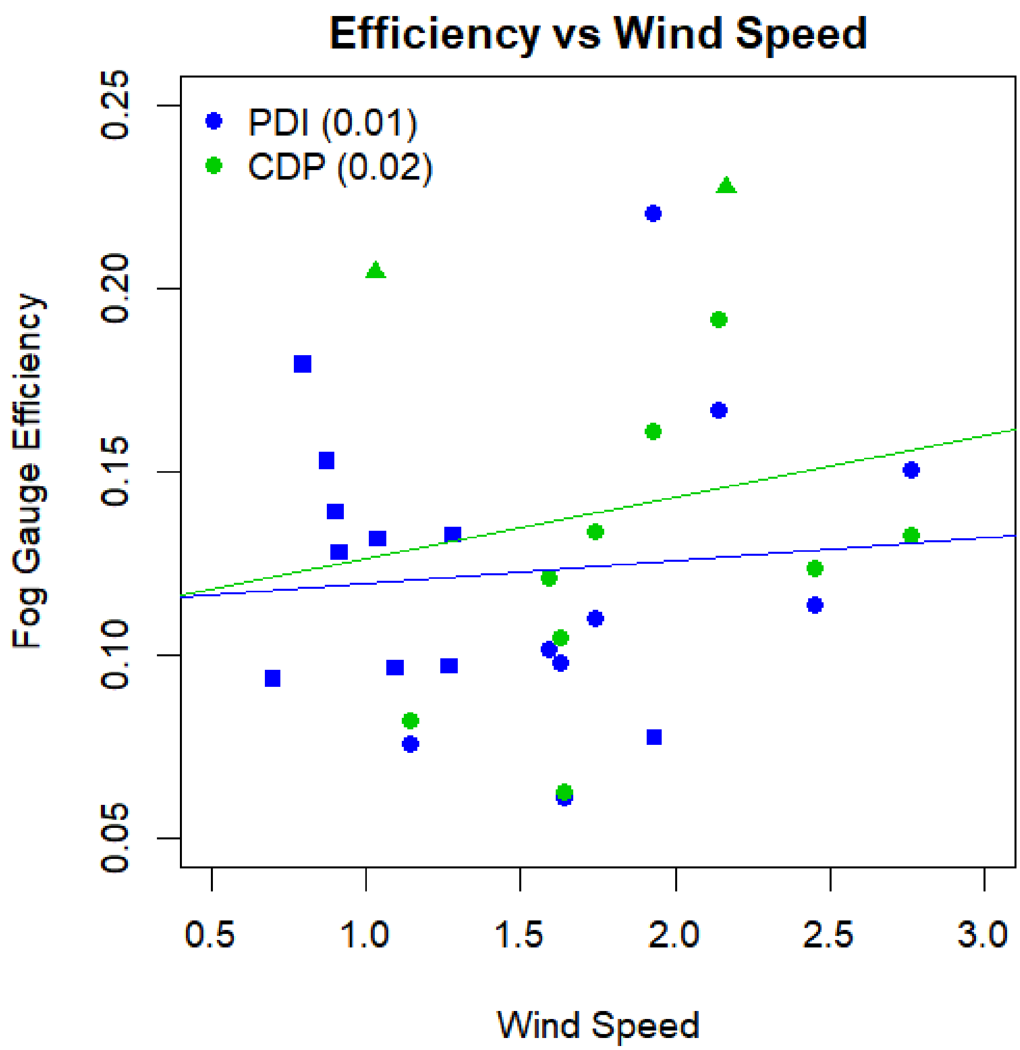
3. To **test the fog gauge and collect calibration data**, researchers across the UH campus teamed up, built a mobile station on a pick-up truck, and deployed 10 different instruments to measure fog and other climate variables on 3 field days at the summit of Mt. Kaala on Oahu Island, Hawaii.

10
3
6
9
4
2
8
5
1
7
On frame

4. The **fog gauge collection efficiency was 13%** compared to cloud droplet measurements.



5. Surprisingly, wind speed did not affect the efficiency significantly.



6. **Visibility** and **net longwave radiation** also appear to be potential predictors of cloud liquid water content. Potential **rainwater contamination** in the fog water catch was observed visually and might explain the **distinct isotopic signals** in fog water samples collected on days of rain vs no-rain.

The April 28 trip.

Acknowledgments

The project "Cloud Water Interception in Hawaii" is funded by Pacific Islands Climate Adaptation Science Center. Special Thanks to Aaron and Garima. And in particular Mike.

[VIDEO] https://www.youtube.com/embed/E4Vt0ZEQUAU?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0
The Zen moment.

ABSTRACT

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