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A Low Cost System for Detecting Fog Events and Triggering an Active Fog Water Collector

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ABSTRACT

A simple method of activating the Caltech Active Strand Cloud-water Collector (CASCC) is described. This system detected the onset of wet deposition events associated with the advection of marine stratus clouds using an optical rain sensor (ORS) and a standard passive fog collector (SFC) in combination with a relative humidity threshold. The system was deployed on a rooftop between May 10 and September 20, 2016 (134 days) at the University of California, Santa Cruz, six km from Pacific Ocean, at 240 m elevation. Twenty-nine fog water samples (daily mean volume = 174 ± 71 mL) were collected for the purposes of quantifying the concentration of monomethylmercury (MMHg) and its possible marine origins. For 20 days during the study, a visibility sensor (VS) was collocated with the ORS and both sensors detected 7 fog events. The ORS detected 2 additional marine stratus drizzle events missed by the VS. The start time of the events detected by the ORS was delayed relative to the onset of visibility reduction in 6 of 7 events by 4.5 ± 3.3 hours. Low wind speeds at night at this location limited the wet deposition to the SFC. Average CASCC sampling time during these events was 6.2 ± 2.8 hours and 4 liquid samples were obtained (80 to > 275 mL). As a comparison, fog water collections at UCSC during the fog seasons of 2014 and 2015 yielded 35 and 12 samples, respectively using a trigger based on relative humidity (RH) and sampling times of > 12 h per day. The main benefit of triggering with the ORS in 2016 was to cut in half the sampling time without loss of sample collection volume. Mean MMHg concentrations between the 3 years were not significantly different suggesting that the SFC/ORS triggering system is appropriate for use at multiple fog collection sites simultaneously.

Keywords: Fog water collector; Activation mechanism; Visibility; Moisture detection; Deposition; Mercury.

INTRODUCTION

Determining the chemical composition of fog water is important because it reveals processes taking place in the lowest levels of the atmosphere, where we are concerned about the transport of pollutants. Fog is a visible aggregation of liquid or solid aerosols that makes contact with the earth's surface. It is held aloft due to turbulent air movements and the small diameters (20–100 µm) of fog drops relative to rain drops (100–5000 µm) (Roman *et al.*, 2013). Scavenging of gases and impaction of dry aerosol particles during the fog event can lead to an enrichment of pollutants in fog and the potential for deposition of these pollutants to receptor locations as fog drip (Degefie *et al.*, 2015). Many studies have been carried out to investigate the influence of local and regional urban and industrial emissions on the chemical composition of fog and its potential impacts on human health and the environment (Watanabe *et al.*, 2011; Liu *et al.*, 2012; Yang *et al.*, 2012; Yue *et al.*, 2012; Giulianelli *et al.*, 2014; Wang *et al.*, 2015; Simon *et al.*, 2016).

The collection of fog water can be accomplished with either 1) a passive fog water collector, which relies on wind speed to impact droplets to a mesh (1.0 m^2 is standard) or a cylinder of thin strands, or 2) an active fog water collector which pulls air with a fan into a confined volume where impaction onto thin strands occurs. The latter method is preferred for chemical analysis of the fog water since the materials that make up the active fog water collector are chemically inert and are rigorously cleaned between fog events (Klemm *et al.*, 2008). In addition, active fog water collectors can be effective in places where wind speed is low, such as in forests or among buildings. The most commonly used design of active fog water collector is the Caltech Active Strand Cloudwater Collector (CASCC), originally described by Demoz *et al.* (1996). The strands in this active collector are made of Teflon as are the drip tray and tubing, in addition to a glass jar or Teflon bottle, which allows the sample to touch only inert materials. Ideally, the active collector is activated when fog is present to minimize the sampling of dry deposited particles and gases. The easiest way to activate is manually. However, fog often occurs just

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before dawn and thus it is necessary to have a fog sensor. Fog can be detected optically for the purposes of triggering the fan in the active collection with sensors such as the Present Weather Detector PWD-11 (Vaisala) (Simon *et al.*, 2016) and the Optical Fog Detector (OFD) (Carillo *et al.*, 2008; Straub *et al.*, 2012; Wang *et al.*, 2015). While these devices are capable of detecting the presence of reduced visibility, they are expensive in the case of the PWD and difficult to construct and maintain in the case of the OFD.

This paper describes a fog detector using a standard passive fog collector and an optical water droplet sensor in order to signal the presence of surface wetness combined with a micro-computer controlled data retrieval system that was used to trigger a CASCC to collect fog water for chemical analysis. The analyte of interest was monomethylmercury (MMHg), a contaminant in coastal fog of California believed to be originating from the coastal ocean (Weiss-Penzias *et al.*, 2016). The main question was: can a low-cost triggering system effectively allow for the collection of fog water samples so that multiple sites could collect fog water samples simultaneously in order to investigate spatial trends in MMHg concentrations in fog water, while keeping costs and maintenance time to a minimum? Performance of the low-cost triggering system during the summer fog season of 2016 at a site 6 km inland from the Pacific Ocean at the University of California, Santa Cruz (UCSC) is compared here to using both a crude triggering system of RH > cutoff and a more common trigger of reduction in visibility.

METHODS

Active fog collectors were built at UCSC and patterned after a CASCC from Colorado State University (Demoz *et al.*, 1996) (Fig. 1). The body was built of 0.953 cm Lexan held together with 316 stainless steel screws and airflow was generated by a 12 V automobile cooling fan located downstream of the strands. Air velocity at the strands was set at 8.0 m s^{-1}, slightly lower than the 8.5 m s^{-1} specified by Demoz *et al.* (1996) in order to mitigate excessive fan noise. Lexan doors on the inlet and exit of the collector were attached by a brass hinge at the bottom and a plastic latch and pull solenoid at the top. A silicone rubber gasket was used where the door met the collector opening to minimize air and particle entry during non-foggy periods. When activated, the system would engage the solenoids to lift the latches and allow the doors, which were set under tension with the hinges, to swing open and downward. At this time the fan would start pulling air through the strings to commence droplet coalescence. The doors needed to be manually closed between activation times. This collector was mounted on an aluminum surveyor's tripod, which was securely anchored.

The Standard Fog Collection (SFC) consists of copper and galvanized pipe supporting a double layer of 1.0 m^2 35% Coresa Rachel shade mesh mounted vertically (Schemenauer and Cereceda, 1994). The bottom of the collector is 2.0 m above the ground allowing sufficient airflow above, below, and around the collector. As wind and fog pass though the collector, water droplets gather on the mesh and they coalesce and fall to a collection tray. Water drains from the tray to a tipping bucket (TB) rain gauge (Fig. 2) connected to a data logger (115 Watchdog, Spectrum Technologies). Each tip of the TB represents a volume of 7.6 mL, providing an accuracy of within 2%. A data logger records sums of tips over 15-minute intervals and has a storage capacity of approximately 3 months.

Fig. 1. The UCSC–built active fog water collector shown at a rooftop location on the UC Santa Cruz campus. Three strand frames with 0.508 mm diameter Teflon strings were used to collect fog droplets. The front and back doors were set under tension and popped open when the solenoid pull was engaged, shown at the top of the collector under a weather-protecting dome. The front and back reed-switch door sensors are also visible which prevent the fan from operating if the doors fail to open.

Fig. 2. Optical rain sensor (ORS) (RG-11) positioned at the terminus of the drip tray of the standard passive fog collector, and above the tipping bucket (TB) rain gauge. The drip tray is slanted downward slightly to the right so each drop exits the drip tray at the right-most corner and rolls across the ORS. There is a gap on the right side of the base of the ORS so that all droplets rolling off the ORS are collected in the TB.

Water droplets were detected with an optical rain sensor (RG-11, Hydreon Corp.) that was attached to the terminus of the drip tray on the SFC (Fig. 2). The RG-11 detects water hitting its outside surface using beams of infrared light. The moving drops on the outside surface allow the beams to escape and pulses (contact closures) are generated based on the intensity of infrared light lost (http://rainsensor.com). A drop rolling across the surface is required for the RG-11 to send a pulse, even when the device is set to its most sensitive setting. A fog drop merely landing on the outside surface is not sufficient since the device is sensitive to changes in the scattering of the beams and requires drop movement (splashing, rolling). With the RG-11 positioned at the terminus of the drip tray, the first drop that finds its way down the Raschel mesh and rolls down the tray will trigger the RG-11. As long as the relative humidity was > 90%, a single pulse from the RG-11 would trigger activation of the active fog collector.

A schematic of the automated fog detection and collection system is shown in Fig. 3. All signals were controlled using a Raspberry Pi (RPi) model B 512 MB ram microcomputer and operating programs written in Python. The code (available at https://github.com/fogpi/FogPi) took readings every 6 s from a temperature (T) and relative humidity (RH) sensor (Honeywell HumidIcon™ HIH-6130) in addition to the RG-11 optical rain sensor and saved the data to a MySQL database. The RPi was connected with Ethernet cable to the internet through a static internet protocol address and this allowed for remote viewing of the collection bottle and door position with a webcam and real-time data and instrument status (Fig. 4). The connection allowed for direct communications with the RPi from any internet connected computer using port 22 for SSH, port 80 for HTTP, and a MySQL client (HeidiSQL). The HIH-6130 needed to be replaced every 60 days due to salt buildup.

The 12 V fan used in the active collector typically drew about 8A and was powered with a 10A AC/DC power supply. Power to the fan was controlled with a relay (Beefcake, Sparkfun.com) designed to handle larger loads than what are typically controlled by an RPi. When a pulse from the

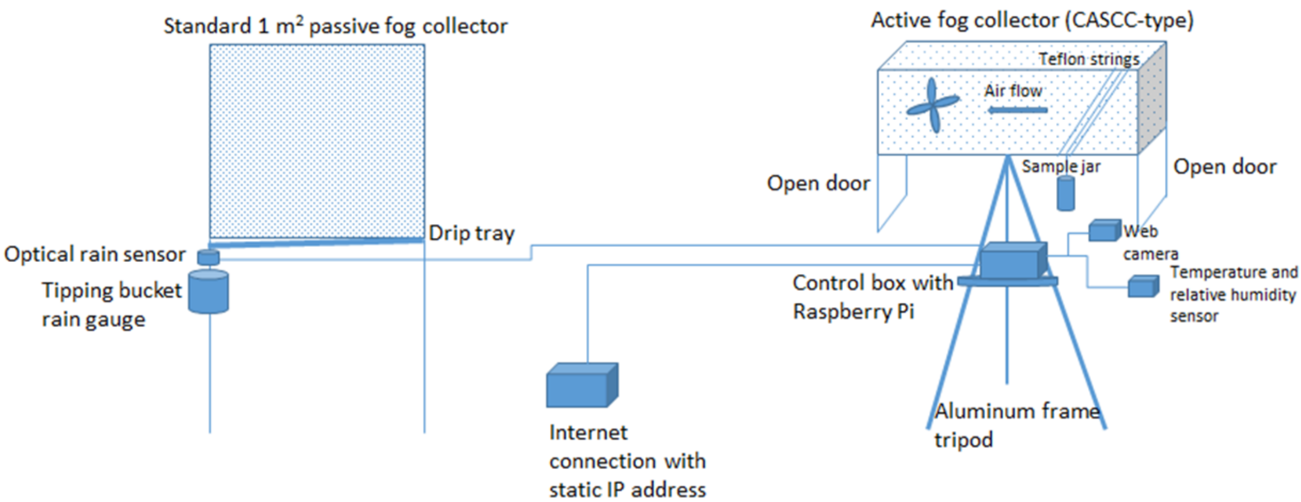

Fig. 3. Schematic of the fog detection, quantification, and sample collection system.

Fig. 4. Screenshot on August 17, 2016 at 9:50 showing the status of the active collector. The arrow shows the outline of the collector door indicating it is open. The text below the image reports the current conditions, time of activation, and current state (fan is on). An overflowing bottle (> 275 mL) of fog water was collected during the early morning hours.

RG-11 was detected and the relative humidity was > 90%, each of the solenoid pulls would engage. Door sensors in the form of reed switches (Adafruit, Inc.) were used to determine the door state, open or closed. If the door state was closed, the fan would not operate and the system would go into standby. This was to avoid damage to the fan by overheating, which would result from operating inside a closed box.

Images from the web camera were taken every 12 s and were accessible via the Internet along with the current time and system parameters (Fig. 4). Data posted to the web page included the time of activation and deactivation of the system, number of ORS signals in the last hour and the last 12 s, and whether the fan was on or off. With the image from the web camera, both the presence of liquid in the sample collection bottle and the position of the doors could be determined, greatly benefiting the field technician.

On August 31, 2016 a visibility sensor (VS) (MiniOFS, Optical Sensors, Inc.) was collocated with the passive and active collectors on the rooftop. The goal was to compare the signal of the ORS with a measurement of visibility to assess the efficacy of using the ORS for triggering the CASCC. The output of this device was connected to a PC computer with a terminal program capable of reading serial output every 30 s. The MiniOFS measures visibility up to 4 km.

Wind speed and direction were not measured at UCSC during this study. However, hourly data from a California Irrigation Management Information System (CIMIS) site Delaveaga, located 5.6 km due east of the UCSC site at a similar distance from the coastline (6 km), at an elevation of 100 m within a mixed oak, redwood, meadow landscape, were incorporated into this study. We suggest that the meteorology at this site is very similar to the UCSC site, especially during the consistent on-shore/off-shore flow pattern of the summertime. Sky condition information was also taken from the Watsonville Airport (KWVI), which is located in an open coastal plain ~22 km to the ESE of UCSC.

The system described here was operational from May 10 to September 21, 2016 and was located on the roof of the Interdisciplinary Sciences Building at UCSC (37.00°N, 122.06°W, 240 m elevation). The immediate environs are oak, redwood and Douglas fir forest and the collection was at an elevation of approximately 10 m below the tree tops.

Marine stratus clouds are a common nightly occurrence at this site during this season, but do not always form fog. From one night to the next, the cloud bank is variable in altitude, droplet density and rate of precipitation, from none to light drizzle. In this paper, the colloquial term “fog” is applied for all such marine stratus cloud events. Dew was not sampled during this study, as in our experience, its occurrence is uncommon during the fog season when nightly minimum temperatures are rarely cold enough with the presence of persistent marine stratus clouds to produce much dew.

RESULTS

Summary of 2016 Data and Comparison with Previous Years

A summary of the results from fog sampling during the summertime fog seasons of 2014, 2015, and 2016 at the UCSC site is shown in Table 1. The primary purpose in sampling the fog was to quantify the monomethylmercury (MMHg) concentrations contained therein. During 2014 and 2015, fog water was also sampled for MMHg at seven additional sites from Monterey in the south to Humboldt in the north of California (Weiss-Penzias *et al.*, 2016). Identical fog samplers (CASCC) were used at all sites with identical triggering means (RH > 87–94% depending on site). In 2016 an improved CASCC triggering method was used at one site (UCSC) and the performance of this triggering system is evaluated here. From May 10–September 20, (134 days) there were 29 fog water samples collected with volumes > 25 mL (Fig. 5). The daily mean sample volume was 174 ± 71 mL and only one sample per 24 h period was collected, always at night or early morning hours. The ORS produced a signal for 50 events, meaning that the CASCC was triggered for these 50 events but for 21 of these events, no sample was collected. Possible reasons for no sample collected are that the event did not deposit much more than a few drops of water (but enough to saturate the Raschel mesh and drip onto the ORS), the triggering happened near the end of the event, or the event was composed of drizzle (large drops) which were not efficiently sampled by the CASCC (Demoz *et al.*, 1996). These drizzle events, discussed further below, consisted of stronger than normal advection of marine stratus clouds. The TB located below the ORS produced a signal for 35 events (Table 1), all of which were sensed by the ORS. Fifteen events were evidently only wet enough to saturate the Raschel mesh of the SFC and cause a drip onto the ORS, but not wet enough to produce a tip in the TB (7.6 mL). The CASCC was triggered on all 35 events sensed by the TB, and a sample was collected on 25 events. The 10 TB-sensed events with no sample collected were probably of short duration and/or involved drizzle. In contrast, 4 events had liquid sample collection, but there was no signal recorded from the TB. These were probably very low wind speed fog events that were more effectively sampled by the fan powered CASCC compared to the passive SFC.

In the summers of 2014 and 2015 at UCSC, the CASCC was set to trigger on based on RH > 90%, which was most nights during fog season (Table 1), typically beginning around 20:00 local time and ending at 10:00 the next day for a total duration of > 12 hours per day. With the ORS triggering system, the mean duration of CASCC sampling was 7.9 ± 3.9 (1–24) hours per day and only on days when wetness due to fog drip was present. The sampling efficiency in 2014, 2015, and 2016, defined as number of CASCC-collected fog samples/days CASCC triggered on was 35% and 13%, 58%, respectively. 2015 was noticeable for its low number of fog events overall. The number of TB tips for a given fog event was variable with 2016 standing out as having almost twice as many fog events recorded by the TB as in previous years.

An example fog event for which our automated system provided pertinent information, occurred during the night of August 16 and early morning of August 17. According to the information shown on the screenshot in Fig. 4, water drops were first detected at 20:51 on August 16 and the collector was activated at this time. However, no further water counts were registered until 4:00 August 17, but then these continued until 8:00. The fan on the CASCC was shut off automatically at 10:00 on August 17 when the relative humidity fell below the cutoff value of 80%. The first and only tip registered by the tipping bucket rain gauge occurred at 6:00 on August 17. The single tip was indicative of very low wind speeds which limited the collection efficiency of the SFC. Average wind speed at Delaveaga was 0.76 m s^{-1} during the 4:00-8:00 hours on the 17th, and we assume these conditions applied to UCSC as well. An overflowing bottle of fog water (> 275 mL) was obtained (visible in photo in Fig. 4) and apparently filled during the 4-hour period when the optical rain sensor was registering water counts. In general, the capture efficiency of the Raschel mesh is dependent on wind speed (Fernandez *et al.*, in review) and we assume that low wind speed fog events would favor sample collection with the CASCC but limit tips by the TB.

Diurnal Cycles of Fog and Wet Deposition

Diurnal cycles (averages by hour of day) for parameters measured from May 10–September 20, 2016 reveal detailed information about the timing of wet deposition from fog and stratus, and the response of the fog sensors. The ORS and the TB had their maximum signals occur between 4:00 and 8:00 local time, corresponding to RH > ~95% and temperature < ~13°C. The maximum in TB signal was shifted one hour later than the ORS and continued to produce signal two hours after the ORS, owing to the time it takes to fill each tip (7.6 mL). On average, the TB registered its first tip 1.3 ± 0.7 hours after the first water count by the ORS. As wind speed and wind direction were not measured at UCSC, we incorporate these data from the CIMIS site at

Table 1. Summary of CASSC and TB sampling frequency, liquid sample volume and monomethyl mercury (MMHg) concentration in fog water samples collected in the summer season at UCSC three consecutive years. In 2016 the CASCC was triggered using the automated system described here, whereas in 2014 and 2015 RH > 90% used as trigger.

Time period	Total days	# days CASSC triggered on	# days TB tips > 0	# fog samples > 25 mL	Sample volume, mean (mL)	MMHg, mean (ng L^{-1})	MMHg, stdev (ng L^{-1})
June 2–Sept 14, 2014	108	100	18	35	163	1.8	2.1
May 31–Sept 28, 2015	120	90	18	12	101	1.2	1.3
May 10–Sept 20, 2016	134	50	35	29	174	1.9	1.3

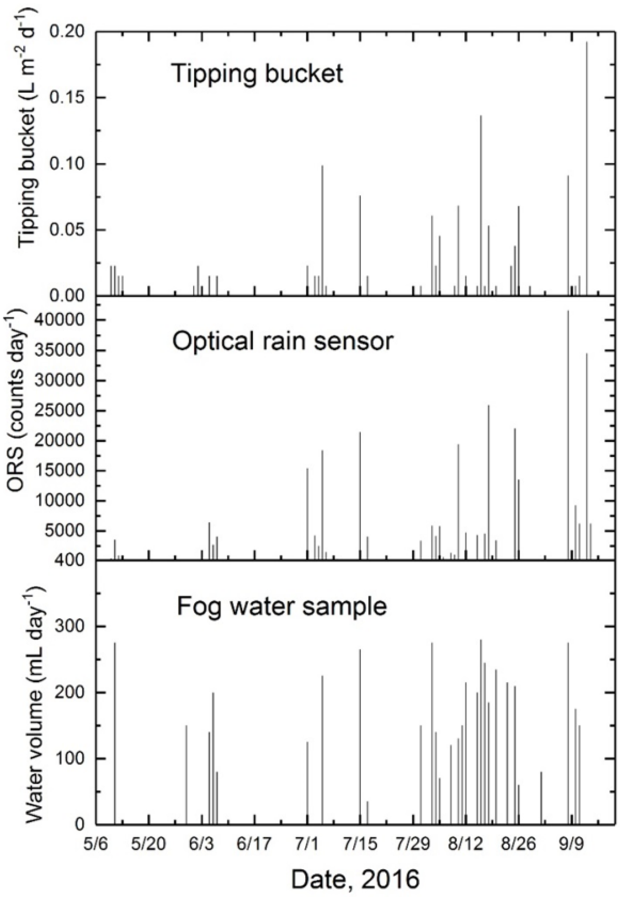

Fig. 5. Time-series data of total daily TB water volume from the SFC, total daily counts from the ORS, and daily volume of fog water sample collected from the CASCC.

Delaveaga. Note the overall low wind speeds at Delaveaga. During the wet deposition maximum at UCSC (4:00–8:00), wind speed at Delaveaga was at a minimum (< 0.75 m s^{-1}) and wind direction was from the north (off-shore flow) then shifting to a westerly direction at day break. Visibility at UCSC was measured during a shorter period than the other parameters (September 1–20), but is included in Fig. 5 for comparison. Its diurnal pattern shows that a 10% reduction in visibility occurred from 1:00–6:00 in the morning, 3–4 hours earlier than wet deposition was detected by the ORS. This offset in time indicates that the CASCC was not sampling fog for several hours at the onset of a fog event. However, this appears to not have sacrificed the volume of liquid sampled in 2016 relative to 2014 and 2015 (Table 1). Likewise, the mean MMHg concentrations from each year (Table 1) were not statistically different. Thus, while CASCC sampling time in 2016 was much less than in previous years, there was no loss in sampling performance in terms of numbers of samples and sample volume. This is discussed further below.

Comparison of Visibility and Optical Rain Sensors for Detecting Fog Events

An analysis of the time period (Sept 1–20) when a MiniOFS™ visibility sensor (VS) was co-located with the ORS, TB, and the CASCC at the UCSC site, is shown in Table 2 in order to assess the performance of the ORS triggering system against a more common approach (VS). A detail of the Sept 7–14 period is plotted in Fig. 7, including winds from Delaveaga. During the 20 d period, 16 marine stratus events were identified according to the weather condition description at the Watsonville Airport, which indicated "overcast" or "fog" for at least 4 h continuously during a 24 h period from 12:00–11:59 local time. The VS at UCSC identified 8 of these events as a reduction in visibility (> 10%) and these had a median duration of 195 minutes, but were variable from 15 minutes to over 13 h (Table 2). The ORS identified 9 events, 7 of which were in common with a reduction in visibility. For the 7 events in common between the two sensors, there was an average delay time between the onset of 10% reduction in visibility and the first signal from the ORS of 190 ± 285 minutes, or 272 ± 202 minutes if the event on Sept 9 is removed. This large spread in delay times is indicative of the variable nature of fog events and wind speeds during the events, with some events causing reduction in visibility with little wetness deposited and other events comprised of light drizzle with little or no visibility reduction. The two ORS events that were not detected by the visibility sensor and the one event in which the ORS detected 303 minutes before the VS (Sept 9, Table 2), all had occurrences of marine stratus drizzle. Drizzle in these circumstances can occur from an elevated cloud base which may not reduce visibility but is effective at wet deposition. The event on Sept 13, for example, produced significant wet deposition as indicated by 13 tips in the TB over a 6 h period, (Fig. 7, Event E) and the 0.4 mm of precipitation registered at nearby CIMIS Delaveaga weather station. Regional weather discussions imply that this phenomenon resulted from an occasional summertime weather pattern of short waves moving through the base of an upper level trough that is positioned over the west coast of the U.S., which lifts the marine layer clouds leading to increased drizzle (Mel Nordquist, National Weather Service, Personal Communication). For the purposes of this study, which was assessing the marine source of contaminants in fog, whether there was drizzle or true fog did not explicitly affect the chemical composition of the liquid sample.

The CASCC had a median sampling time of 359 minutes for the 9 events identified by the ORS during this 20 d period, and 4 fog water samples were obtained. The events on Sept 2, 9, 16, and 20 were not sufficiently long and did not produce enough moisture in order to collect a liquid sample in the CASCC, nor register a tip in the TB. During these events it may have been advantageous to trigger the CASCC earlier in the event in order to maximize sample volume. However, from our experience in 2014 and 2015 when the CASCC was sampling for > 12 h per night, these types of fog events rarely produced a sample. In contrast, the events on Sept 13 and 14 consisted of larger droplets (drizzle) that were not efficiently collected by the CASCC and also resulted in no sample. Additional sampling time under these conditions may not have improved sample volume, although an increase in fan speed may have helped. The ideal event for collecting a fog sample occurred on Sept 8

Table 2. Fog sampling details during period of comparison of the VS, ORS, TB, and CASCC at UCSC site. A marine stratus event was defined as > 4 hours of continuous "overcast" or "fog" weather condition description at night at the Watsonville Airport (KWVI). Wind speed and precipitation data were taken from CIMIS weather station at Delaveaga. Dates shown are the end of a 24-hr period beginning at 12:00 the previous day. All times are local (PDT).

End Date (12:00–11:59 Local time)	Marine stratus event (y/n)	Duration of > 10% reduction in vis (min)	Time of onset of > 10% reduced vis	ORS signal (counts 24 hr^{-1})	Time of 1st ORS signal	Delay time between reduced vis and 1st ORS signal (min)	TB signal (counts 24 hr^{-1})	Time of 1st tip	Vol collected in CASCC (mL)	Time on CASCC (min)	Mean wind speed 22:00–6:00 ($m\ s^{-1}$)	Precip (mm)
9/1/2016	y	255	2:15	38	3:55	100	0		80	317	0.8	0
9/2/2016	y	120	7:15	0			0		0	0	0.8	0
9/3/2016	y	0		0			0		0	0	0.7	0
9/4/2016	y	0		0			0		0	0	1.0	0
9/5/2016	y	0		0			0		0	0	0.9	0
9/6/2016	n	0		0			0		0	0	1.3	0
9/7/2016	n	0		0			0		0	0	1.0	0
9/8/2016	y	645	19:00 on 9/7	41564	1:01	361	12	2:30	> 275	706	0.8	0.2
9/9/2016	y	135	8:53	44	3:50	–303	0		0	465	1.2	0
9/10/2016	y	788	21:00 on 9/9	9172	6:42	582	1	8:15	175	243	0.6	0
9/11/2016	y	575	0:30	6168	5:27	297	2	6:30	150	349	0.5	0.1
9/12/2016	y	0		0			0		0	0	0.7	0
9/13/2016	y	0		34476	5:18		13	5:45	0	455	0.9	0.4
9/14/2016	y	0		6162	6:25		0		0	153	1.5	0.1
9/15/2016	n	0		0			0		0	0	1.3	0
9/16/2016	y	15	0:00	38	1:09	9	0		0	459	0.7	0
9/17/2016	y	0		0			0		0	0	0.6	0.1
9/18/2016	y	0		0			0		0	0	0.8	0
9/19/2016	n	0		0			0		0	0	1.4	0
9/20/2016	y	100	1:00	3	5:44	284	0		0	199	0.7	0

(Fig. 7, Event A), which produced > 10 h duration of visibility reduction, and the first ORS signal occurred at 1:01 local time resulting 11.7 hours of CASCC sampling time (Table 2). This event produced > 275 mL of sample (jar was overflowing in morning). The high ORS and TB signals, along with 0.2 mm of precipitation registered at Delaveaga indicate this event produced significant wet deposition from fog in this area.

The fog events A, B, C, and D in Fig. 7 and the diurnal cycles shown in Fig. 6 reveal an interesting pattern in visibility. This was characterized by an early visibility reduction before midnight co-occurring with the evening relaxation in wind speed, followed by an increase in visibility for 2–4 hours at around 2:00 followed by another more substantial and longer lasting reduction in visibility extending until sunrise. It was during the maximum of the second reduction in visibility that the ORS first registered a signal, also corresponding to the last 2–4 hours of RH maximum just before sunrise (see events C and D in Fig. 7). The early onset of reduced visibility may have resulted from onshore flow (winds from the south) that generally extended until 21:00 (Fig. 6), which could have brought the fog bank over land, but resulted in very little wet deposition, perhaps due to the time required for droplet growth and impaction on surfaces (like the SFC mesh). According to the diurnal cycles in Fig. 6, it is during periods of reduced visibility in conjunction with RH > 95% that significant wet deposition occurs, and this is the period when the CASSC was triggered on and collected a liquid sample. It is possible that if the CASCC had been on throughout the fog event, say starting closer to midnight, that more samples with greater volume may have been obtained. However, based on the results in 2014 and 2015 when no greater sample collections were obtained relative to 2016 even though sampling times were ~doubled, we suggest that the ideal fog collection time with the CASCC at this location may be the early morning period, beginning 2–4 hours before dawn. It is during the time that larger drops form and appear to be more effectively deposited to the SFC and to natural surfaces resulting in maximum impact on the ecosystem. Locations with higher nighttime wind speeds will probably exhibit less delay time between the onset of reduced visibility and the production of a signal from the ORS due to the faster rate of wet deposition to the Raschel mesh of the SFC.

CONCLUSIONS

For the purpose of triggering a CASCC during the presence of marine stratus events (fog and light drizzle) in a cost-effective manner with a minimum of maintenance required, a system using an ORS fitted to the drip tray of a passive SFC was built and tested over the period of May 10–September 20, 2016 at a rooftop site at UCSC on the central coast of California. The performance of the system in terms of numbers of fog water samples collected by the CASCC divided by number of days that the CASCC was

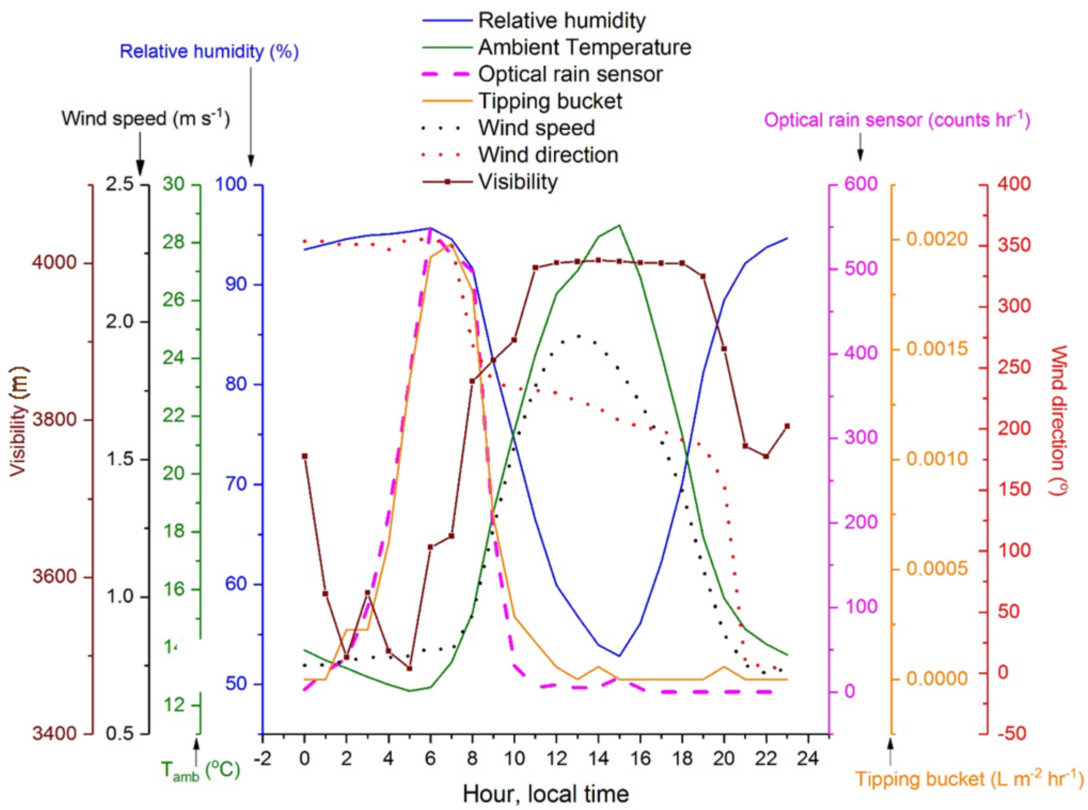

Fig. 6. Average diurnal cycles of relative humidity, temperature, ORS signal, TB volume, and visibility measured at the rooftop location at UCSC. Also shown are wind speed and direction measured at the CIMIS Delaveaga site. All data are for the time period May 10–Sept 21, 2016 except for visibility data which are Sept 1–20, 2016.

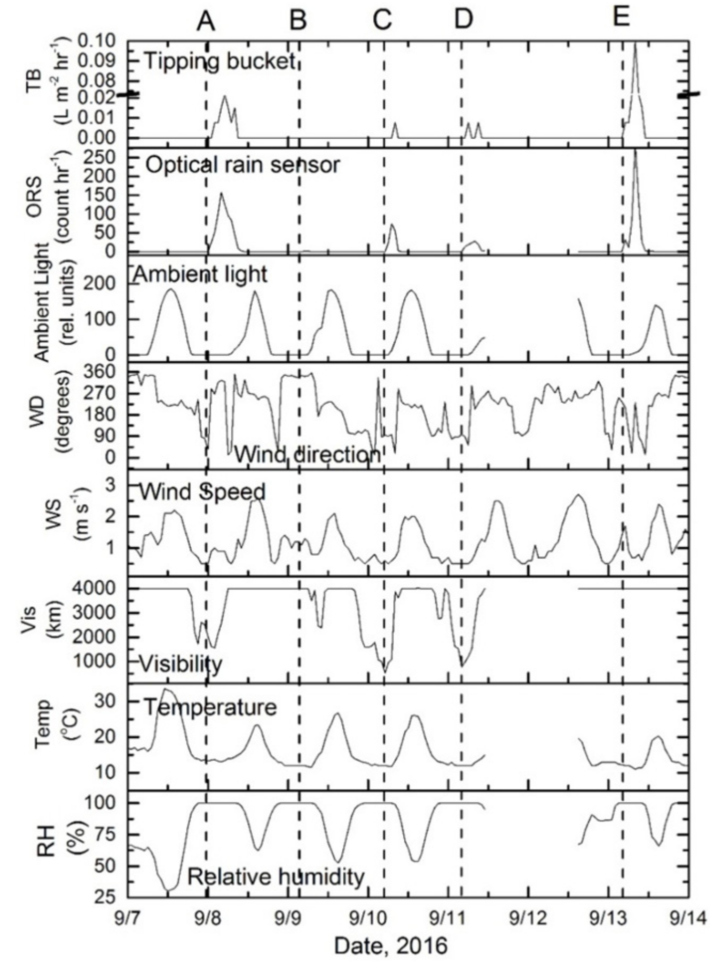

Fig. 7. Seven-day period showing data from the tipping bucket, optical rain sensor, ambient light sensor, visibility sensor, wind direction, wind speed, air temperature, and relative humidity. The wind data is from CIMIS Delaveaga weather station. The vertical dashed lines indicate first occurrence of signal from the ORS for each event (event B had < 5 ORS counts). Fog water samples were collected with the CASCC on events A (> 275 mL), C (175 mL), and D (150 mL).

triggered on, was compared in 2016 (58%) to what was observed in the summers of 2014 (35%) and 2015 (13%) when a crude triggering method was used based on RH exceeding a threshold of 90%. These results indicate a great improvement in sampling efficiency of the CASCC using the ORS-based triggering system. The mean MMHg concentration, a contaminant in marine fog due to oceanic emissions, was not significantly different between the 3 years indicating the change in triggering method in 2016 likely had little effect on the chemical composition of the fog water collected.

The average diurnal pattern of signal produced from the ORS due to water dripping off of the SFC mesh shows the first occurrence at about 1:00 and clear maximum between 4:00–8:00 local time. This maximum corresponded to weather conditions of RH > 95%, temperature < 13°C, very light wind speeds (< 0.75 m s^{-1}, as measured at a similar location 5.6 km away), and northerly wind directions (off-shore flow).

Installation of a standard visibility sensor was done on Sept 1 and thus only 20 days of direct comparison between the ORS signal and the VS could be made. Nonetheless, interesting patterns in visibility were revealed suggesting that 2 pulses of fog often occurred in a typical fog event. The first pulse happened just before midnight, and typically resulted in almost no wet deposition (no ORS signal produced, CASCC not triggered on), whereas the second fog pulse resulted in greater visibility reduction, was longer lasting, and typically occurred about 2 hours before sunrise. It was during this second pulse that wet deposition typically occurred and when the ORS signal was produced and CASCC sampling began. The delay time between the ORS signal and the occurrence of 10% reduction in visibility was substantial (3–5 hours) and this is a potential downside of using wetness instead of optical properties to trigger the CASSC, especially in low wind speed locations such as UCSC where more time is needed to saturate the Raschel mesh on the SFC. However, based on experiences with the CASCC sampling > 12 h per night in 2014 and 2015 with the RH-based trigger, sampling at the beginning of the time of significant wet deposition (~2 hours before sunrise) may result in no loss of sample volume collected, compared to sampling across the entire time of visibility reduction.

The main benefit to using the ORS trigger system is in its ease of use and relatively low cost, allowing this technique to be used on simultaneously operating fog collectors. For determining the spatial trends in contaminant concentrations, like monomethylmercury originating from the coastal ocean, the use of multiple CASCCs simultaneously is desired, and for this purpose, the ORS triggering system appears to be an important step forward. This system represents a simple add-on to the passive SFC/TB rain gauge system used to quantify fog wet deposition. It includes a web-camera to monitor sample collection, data storage and access, and can be constructed from readily available parts for less than $300 USD, which is an obvious advantage especially when multiple collectors are deployed simultaneously.

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REFERENCES

Carrillo, J.H., Emert, S.E., Sherman, D.E., Herckes, P. and Collett, J.L. (2008). An economical optical cloud/fog detector. *Atmos. Res.* 87: 259–267.

Degefie, D.T., El-Madany, T.S., Held, M., Hejkal, J., Hammer, E., Dupont, J.C., Haeffelin, M., Fleischer, E. and Klemm, O. (2015). Fog chemical composition and its feedback to fog water fluxes, water vapor fluxes, and microphysical evolution of two events near Paris. *Atmos. Res.* 164–165: 328–338.

Demoz, B.B., Collett, Jr. J.L., Daube, Jr. B.C. (1996). On the Caltech active strand cloudwater collectors. *Atmos. Res.* 41: 47–62.

Fernandez, D, Torregrosa, A, Weiss-Penzias, P, Cohen, R., Sorensen, D., Kleingartner, J., McKinley, G., Mairs, A., Wilson, S., Bowman, M., Barkley, T. and Gravelle, M. (2016). Inter-mesh Comparisons of Passive Fog Collectors, Papers from the 7th International Conference on Fog, Fog Collection and Dew.

Giulianelli, L., Gilardoni, S., Tarozzi, L., Rinaldi, M., Decesari, S., Carbone, C., Facchini, M.C. and Fuzzi, S. (2014). Fog occurrence and chemical composition in the Po valley over the last twenty years. *Atmos. Environ.* 98: 394–401.

Klemm, O., Wrzesinsky, T., Gerchau, J. and Grießbaum, F. (2008). A collector for fog water and interstitial aerosol. *J. Atmos. Oceanic Technol.* 25: 335–340.

Liu, X.,Wai, K.,Wang, Y., Zhou, J., Li, P., Guo, J., Xu, P. and Wang, W. (2012). Evaluation of trace elements contamination in cloud/fog water at an elevated mountain site in northern China. *Chemosphere* 88: 531–541.

Roman, P., Polkowska, Z. and Namieśnik, J. (2013). Sampling procedures in studies of cloud water composition: A review. *Crit. Rev. Env. Sci. Technol.* 43: 1517-1555.

Schemenauer, R.S. and Cereceda, P. (1994). A proposed standard fog collector for use in high-elevation regions. *J. Appl. Meteorol.* 33: 1313–1322.

Simon, S., Klemm, O., El-Madany, T., Walk, J., Amelung, K., Lin, P.H., Chang, S.C., Lin, N.H., Engling, G. and Hsu, S.C., Wey, T.H., Wang, Y.N. and Lee, Y.C. (2016). Chemical composition of fog water at four sites in Taiwan. *Aerosol Air Qual. Res.* 16: 618–631.

Straub, D.J., Hutchings, J.W. and Herckes, P. (2012). Measurements of fog composition at a rural site. *Atmos. Environ.* 47: 195–205.

Wang, Y., Zhang, J., Marcotte, A.R., Karl, M., Dye, C. and Herckes, P. (2015). Fog chemistry at three sites in Norway. *Atmos. Res.* 151: 72–81.

Watanabe, K., Honoki, H., Iwama, S., Iwatake, K., Mori, S., Nishimoto, D., Komori, S., Saito, Y., Yamada, H. and Uehara, Y. (2011). Chemical composition of fog water at Mt. Tateyama near the coast of the Japan Sea in Central Japan. *Erdkunde* 65: 233–245.

Weiss-Penzias, P., Coale, K., Heim, W., Fernandez, D., Oliphant, A., Dodge, C., Hoskins, D., Farlin, J., Moranville, R. and Olson, A. (2016). Total- and monomethyl-mercury and major ions in coastal California fog water: Results from two years of sampling on land and at sea. *Elem. Sci. Anth.* 4: 101.

Yang, J.Y., Xie, C.E., Shi, C.E., Liu, D.Y., Niu, S.J. and Li, Z.H. (2012). Ion composition of fog water and its relation to air pollutants during winter fog events in Nanjing, China. *Pure Appl. Geophys.* 169: 1037–1052.

Yue, Y., Niu, S., Zhao, L., Zhang, Y. and Xu, F. (2012). Chemical composition of sea fog water along the South China Sea. *Pure Appl. Geophys.* 169: 2231–2249.

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