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Canopy water balance of windward and leeward Hawaiian cloud forests on Haleakalā, Maui, Hawai'i†,‡

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Abstract:

The contribution of intercepted cloud water to precipitation at windward and leeward cloud forest sites on the slopes of Haleakalā, Maui was assessed using two approaches. Canopy water balance estimates based on meteorological monitoring were compared with interpretations of fog screen measurements collected over a 2-year period at each location. The annual incident rainfall was 973 mm at the leeward site (Auwahi) and 2550 mm at the windward site (Waikamoi). At the leeward, dry forest site, throughfall was less than rainfall (87%), and, at the windward, wet forest site, throughfall exceeded rainfall (122%). Cloud water interception estimated from canopy water balance was 166 mm year^{-1} at Auwahi and 1212 mm year^{-1} at Waikamoi. Annual fog screen measurements of cloud water flux, corrected for wind-blown rainfall, were 132 and 3017 mm for the dry and wet sites respectively. Event totals of cloud water flux based on fog screen measurements were poorly correlated with event cloud water interception totals derived from the canopy water balance. Hence, the use of fixed planar fog screens to estimate cloud water interception is not recommended. At the wet windward site, cloud water interception made up 32% of the total precipitation, adding to the already substantial amount of rainfall. At the leeward dry site, cloud water interception was 15% of the total precipitation. Vegetation at the dry site, where trees are more exposed and isolated, was more efficient at intercepting the available cloud water than at the rainy site, but events were less frequent, shorter in duration and lower in intensity. A large proportion of intercepted cloud water, 74% and 83%, respectively for the two sites, was estimated to become throughfall, thus adding significantly to soil water at both sites. Published in 2010 by John Wiley & Sons, Ltd.

KEY WORDS tropical montane cloud forest; cloud water interception; fog

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INTRODUCTION

Trade-wind-driven orographic uplift on windward slopes, and thermal slope winds in leeward areas, subject Hawaiian mountain forests to frequent direct cloud contact. Some of this water is intercepted by the canopy and may serve important hydrological and ecological functions. The elevations most often exposed to fog are determined by the vertical extent of the cloud layer, which is limited at its lower boundary by the lifting condensation level at about 600 m.a.s.l. and at its upper boundary by the trade-wind inversion (Cao *et al.*, 2007) at about 2200 m (DeLay and Giambelluca, 2010). Distinct spatial patterns of clouds, fog, and rainfall result from orographic and thermal circulations, while synoptic-scale storms generate widespread clouds and rain and produce most of the rainfall in leeward areas.

Several approaches have been used to estimate the amount of cloud water intercepted by vegetation. Many prior studies have been carried out using measurements of water collected by passive fog gauges, vertically oriented obstacles mounted atop a collection device, as an estimate of fog and wind-driven precipitation interception by vegetation (Bruijnzeel *et al.*, 2005; Holwerda *et al.*, 2011). Many examples of the use of this technique can be found in the literature (e.g. Grunow, 1952; Ekern, 1964; Schemenauer and Cereceda, 1994; Juvik and Nullet, 1995a,b). Marloth (1904) pioneered this measurement technique using grass from the site mounted on the perimeter of a rain gauge and found that it intercepted more moisture than did a standard rain gauge. Although this design also intercepted rainfall in addition to fog, it was more representative of the natural vegetation structure than subsequent screen-type designs often used to assess cloud water flux. The two basic forms most often used are the cylindrical design (Grunow,1952; Juvik and Nullet, 1995a) and the vertically mounted planar screen (Twomey, 1956; Schemenauer and Cereceda, 1994). DeLay and Giambelluca (2010) provide a synthesis of previous cloud water research in Hawai'i, most of

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which was done using cylindrical fog gauges (Juvik and Ekern, 1978; Juvik and Nullet, 1995a,b).

Difficulties in interpreting fog gauge measurements include the addition of wind-blown rainfall, the effect of relative wind direction on interception by flat screen designs, comparing estimates of cloud water between designs, and the collection efficiency of the mechanical collector in relation to that of the vegetation (Frumau *et al*., 2011). The canopy water balance approach is a more direct method of estimating the interception of fog by vegetation (Juvik and Nullet, 1995b; Holwerda *et al*., 2006). By measuring gross precipitation (measured above the vegetation canopy or in a clearing), throughfall (water falling through or dripping from the canopy), and stemflow (water reaching the ground by flowing down the stems of plants), and by estimating evaporation of water from the wet canopy, the additional water added by cloud water interception can be quantified. Alternatively, some have used the stable isotopes of water to estimate the proportion of water derived from fog in various parts of the local hydrological cycle (Liu *et al*., 2007; Scholl *et al*., 2007, 2011).

In a previous paper (Giambelluca *et al*., 2010), we developed a technique to separate the intercepted rainfall from cloud water caught by a planar fog screen of the Schemenauer and Cereceda (1994) type, and compared the results at two cloud forest sites in Hawai'i with estimates derived from a canopy water balance model using several months of data. This paper presents results for estimates derived from fog screen measurements and from a slightly modified canopy water balance approach for observations over a 2-year period at each of the same two field sites as the previous paper.

METHODS

Meteorological monitoring was carried out at windward and leeward forest sites on the slopes of Haleakalā, a 3055-m shield volcano that forms the larger, eastern portion of the island of Maui, Hawai'i. Sites were chosen to represent the extremes of dry and wet cloud forest environments. The dry leeward field site was monitored from February 2002 to March 2004, and the collection period extended from October 2001 to August 2003 at the wet windward site. Field measurements were aimed at evaluating fog water inputs to the respective ecosystems based on fog gauge measurements, the canopy water balance approach, and the use of stable isotopes of water to identify the proportions of fog and rain in surface water, soil water, groundwater, and plant tissue. The use of stable isotopes to assess fog water inputs at these two sites is presented by Scholl *et al*. (2007).

Field sites

Field instrumentation was set up at a leeward dry forest site at 1219 m.a.s.l. in Ulupalakua Ranch, called 'Auwahi', and at a wet windward site at 1951 m.a.s.l. within the Nature Conservancy's Waikamoi Forest Reserve, called 'Waikamoi'. Both Waikamoi (Medeiros *et al*., 1995) and Auwahi (Wagner *et al*., 1999) have been identified as 'hot spots' of endemic biodiversity. Hawaiian dry forests were the most diverse of Hawaiian ecosystems and Auwahi is the most diverse dry forest location left in Hawai'i with more than 40 genera present. At Auwahi, instruments for canopy water balance measurements were placed in low shrubs and trees of up to $\sim$2·5 m in height (estimated leaf area index LAI = 0·82), located just upslope of a pasture. Wind direction is often upslope; hence, the vegetation is exposed to air moving across the open pasture land. Because of this exposure, interception of fog and wind-blown rainfall is much higher than would be the case with continuous vegetation of the same height (e.g. Weathers *et al*., 1995). However, the study site is typical of the shrub and tree cover in the area, which occurs exclusively in small isolated patches. The wet windward forest site at Waikamoi is more typical of other Hawaiian cloud forests (estimated LAI 2·0), with the dominant tree genera including *Metrosideros, Acacia, Cheirodendron, Hedyotis, Meliocope*, and *Ilex* (A. Medeiros, personal communication; Medeiros *et al*., 1998). Here, the site was at the boundary between continuous 4–6-m-high forest and 0·5–1·5-m-high shrub, with the predominant wind direction bringing air from low to high vegetation at night and from high to low vegetation during the day. Hence, there may be some edge-related enhancement of fog and wind-blown rain interception at this site. Wind speeds as measured at approximately 2 m above the ground averaged $2{\cdot}8 \pm 1{\cdot}3$ m s^{-1} at Auwahi and $2{\cdot}7 \pm 0{\cdot}9$ m s^{-1} at Waikamoi. Epiphytes, including alien 'Spanish Moss' (*Tillandsia usneoides*), are found at both sites, adding to the above-ground water storage capacity.

Field measurements

Meteorological variables were monitored to estimate wet-canopy evaporation at the two sites. The net radiation was measured with a Radiation and Energy Balance Systems (REBS Model Q × 7·1, Seattle, WA, USA) at each site. Air temperature and humidity were sampled with Vaisala (model HMP45C, Helsinki, Finland) sensors. Wind speed and direction were measured with a MetOne (Grants Pass, OR, USA) model 014A anemometer and model 024A vane respectively. The soil heat flux was recorded at 8 cm depth with 2 REBS (HFT3·1 and HFT1) heat flux plates at each site. Two soil temperature sensors, each Campbell Scientific (Logan, UT, USA) TCAV averaging thermocouple probes, were also installed at each site at 2 and 6 cm depths. Soil moisture was measured from the surface to 30 cm with a water content reflectometer (model CS615, Campbell Scientific) at both locations. Rainfall was measured with a tipping bucket rain gauge (model TE525, Texas Electronics, Dallas, TX, USA).

Throughfall at each site was measured using four trough-type gauges (Ziegler *et al*., 2009) deployed beneath the canopy near the meteorological station. Each consisted of three inclined troughs, 6 m × 0·04 m, draining into a large capacity tipping bucket set to tip at approximately 150 ml. The total horizontal collection area of each system was about 0·7 m^2, yielding an equivalent resolution of about 0·21 mm. Hobo event loggers (Onset Computer, Pocasset, MA, USA) were used to record tips of the throughfall gages.

Cloud water flux

Cloud water was collected using 1-m^2 screen as described by Schemenauer and Cereceda (1994). The vertical screen surface intercepts a variable amount of wind-blown rainfall in addition to cloud water. This paper reports the fog screen catch (FS) as a depth by normalizing the measured volume by the screen area. The FS time series were used to estimate the amount of cloud water passing through a unit area perpendicular to the wind, or cloud water flux (CWF), by estimating and removing the amount of wind-blown rainfall caught by the screen, adjusting for wind direction relative to the screen orientation, and applying a fog catch efficiency of 0·66 (recommended by Schemenauer and Cereceda 1994) to the screen (Giambelluca *et al.*, 2010). Catch efficiency is probably sensitive to wind direction relative to screen orientation, and possibly also to wind speed (Holwerda *et al.*, 2010; 2011). However, insufficient data were available to test this quantitatively and therefore the assumed catch efficiency was held constant. Methods of estimating CWF, based on rainfall intensity, predicted drop size distribution, wind speed and direction, slope, and screen orientation, are given by Giambelluca *et al.* (2010).

Canopy water balance

Canopy water balance calculations were performed at the event scale. Events were defined as periods separated by three or more hours with no recorded precipitation, throughfall, or fog screen input. Cloud water interception (CWI) was calculated for periods during which fog data was available using a mass balance approach as

$$\mathrm{CWI} = E_\mathrm{e} + E_\mathrm{a} + \mathrm{TF_c} - R_\mathrm{slope} \quad (1)$$

where E_e is evaporation from the wet canopy during events. E_a is the evaporation after rainfall and cloud water input cease, $\mathrm{TF_c}$ is the corrected throughfall ($\mathrm{TF_c} = f\mathrm{TF}$, where f is a factor to adjust throughfall for splash loss and to account for stemflow), and R_slope is rainfall adjusted for the rainfall catch on a slope under wind-driven conditions. Measured rainfall values were first corrected for wind-related underestimation by the rain gauge (Førland *et al.*, 1996) as

$$R_\mathrm{c} = kR \quad (2)$$

where R_c is rainfall corrected for wind effects, R is measured rainfall, and the aerodynamic disturbance coefficient k is given by:

$$k = -0.001 \ln I - 0.0122 U_\mathrm{g} \ln I + 0.0343 U_\mathrm{g} + 0.0077 \quad (3)$$

where I is rainfall intensity (mm d^{-1}) and U_g is the wind speed at rain gage height (m s^{-1}) estimated as (Rosenberg *et al.*, 1983):

$$U_\mathrm{g} = U \frac{\ln(z_\mathrm{g} - d) - \ln z_0}{\ln(z_\mathrm{u} - d) - \ln z_0} \quad (4)$$

where U is the measured wind speed, z_g the rain gauge height, z_u the anemometer height, z_o the roughness parameter (set equal to $0.1h$, where h = vegetation height in m), and d is the zero displacement plane (set equal to 0.65h).

The effects of slope are addressed by calculating the incident rainfall R_slope relative to measured, wind-corrected rainfall R_c as

$$\frac{R_\mathrm{slope}}{R_\mathrm{c}} = \frac{\cos(\beta)}{\cos(\gamma)} \text{ for } \cos(\beta) \geq 0 \quad (5)$$

$$\frac{R_\mathrm{slope}}{R_c} = 0 \quad \text{for } \cos(\beta) < 0 \quad (6)$$

where γ = rainfall zenith angle and β = angle of incidence of rainfall on slope:

$$\cos(\beta) = \cos(\delta)\cos(\gamma) + \sin(\delta)\sin(\gamma)\cos(\theta - \alpha) \quad (7)$$

where δ = slope, θ = wind direction, and α = slope aspect (Sharon, 1980).

Reported throughfall values are the average of the four gauges at each site. At the Auwahi site, all four collectors remained operational throughout the study period but at Waikamoi there were several periods during which one or more gauges malfunctioned. To provide a consistent average, the values for malfunctioning gauges were filled for the period of gauge malfunction using the best-fit regression from the remaining, functioning units. For all relationships between gauges r^2 exceeded 95%. Throughfall measurements conducted with trough-type systems can be expected to reflect some loss due to rain splash. Some loss is also incurred through wetting of the trough surface and by evaporation. In an attempt to account for these losses and to reconcile the lack of stemflow measurements, a throughfall adjustment factor (f) was derived by obtaining the slope of the regression line (through the origin) between $R_\mathrm{slope} - E_\mathrm{e} - E_\mathrm{a}$ and TF for events with zero cloud water flux.

Maximum canopy storage (S_max) was determined as the x-intercept obtained from a regression of $\mathrm{TF_c}$ versus R_slope using events with zero cloud water flux and rainfall sufficient to fully wet the canopy, but low enough that throughfall would be significantly influenced by canopy storage (4 mm < $R_\mathrm{slope} - E_\mathrm{e} - E_\mathrm{a}$ < 15 mm). The use of rainfall-only events to determine maximum canopy storage capacity was necessitated by the uncertainty in CWI, requiring the assumption that maximum canopy storage for rainfall and CWI were equal.

The evaporation of stored water in the canopy after the end of each event (E_a) was estimated as

$$E_\mathrm{a} = S_\mathrm{max} \quad \text{if TF} > 0 \quad (8)$$

$$E_a = R_{slope} - PE \text{ if } TF = 0 \text{ and } R_{slope} > PE \quad (9)$$

$$E_a = 0 \text{ if } TF = 0 \text{ and } R_{slope} < PE \quad (10)$$

Wet-canopy evaporation was calculated using the Penman–Monteith equation (Monteith, 1973):

$$PE = \frac{\Delta(Q_n - G) + \rho_a C_p (e_s - e_a)/r_a}{\lambda(\Delta + \gamma)} \quad (11)$$

where PE is the potential evapotranspiration (mm d^{-1}), Δ is the slope of the saturation vapour pressure versus temperature curve (mb K^{-1}), Q_n is the net radiation (W m^{-2}), G is the soil heat flux (W m^{-2}), ρ_a is the density of moist air (kg m^{-3}), C_p is the specific heat of air at constant pressure (J kg^{-1} K^{-1}), e_s is the saturation water vapour pressure (mb), e_a is the partial pressure of water vapour in air (mb), γ is the psychrometric constant (mb K^{-1}), λ is the latent heat of vapourization (W m^{-2} mm^{-1} d), and r_a is the aerodynamic resistance to water vapour diffusion (s m^{-1}) as

$$r_a = \frac{\left[\ln \frac{(z_a - d)}{z_0}\right]\left[\ln \frac{(z_t - d)}{z_{0h}}\right]}{\kappa^2 U} \quad (12)$$

where z_a is the wind measurement height (m), d is the zero plane displacement, estimated as $0{\cdot}65h$, where h is the vegetation height (m), z_t is the temperature measurement height (m), z_0 is the roughness length for momentum transfer, estimated as $0{\cdot}1h$ (m), z_{0h} is the roughness length for sensible heat transfer, estimated as $0{\cdot}1z_0$ (m), κ is the von Kármán constant (0·4), and U is the wind velocity (m s^{-1}).

RESULTS

Table I gives site and study period characteristics for the two stations. Equipment malfunction resulted in some data gaps at both stations. For the Auwahi site, where only the fog collector malfunctioned, results are presented for the whole period, and separately for only the events with good fog screen data. At Waikamoi, malfunctions involved variables needed for the canopy water balance, which required that these periods be excluded from the analysis. It should be noted that the period when all the instruments were functioning at Auwahi was characterized by somewhat drier conditions than those represented by the study period as a whole.

Using the methods described previously (Giambelluca *et al*., 2010), the quantity of rainfall caught by the fog screen was estimated for hourly periods at the two sites, and subtracted from the total amount of water captured by the screen (FS). Subsequently, the amount of cloud water flux through a vertical plane normal to the wind direction (CWF) was estimated. Events were identified and totals summed for each event period. Table II gives the frequency and duration of water input (rain and/or fog) events, raw observations of rainfall R, throughfall TF, and FS, and calculated CWF. For comparison, annual totals were derived by multiplying the per-day values by 365·25. Annual rainfall totals given in Table II were somewhat lower than the long-term mean annual rainfall for the two sites (Giambelluca *et al*., 1986); annualized study-period rainfall at Auwahi was 962 mm compared to the long-term mean of 1011 mm; at Waikamoi, the annualized study-period rainfall was 2389 mm compared to 2702 mm for the long-term mean. Canopy water balance results are also summarized in Table II and discussed below. Note that the throughfall adjustment factor (f) to correct for splash loss, wetting, evaporation, and stemflow was determined to be 1·134 and 1·126 respectively for Auwahi and Waikamoi. The maximum canopy storage (S_{max}) was estimated to be 1·04 and 1·64 mm, respectively, for the two sites.

DISCUSSION

Correcting the fog screen values attributable to cloud water for wind-driven rainfall resulted in significantly lower amounts than measured values (FS). However, subsequent correction for wind direction resulted in a significant increase. The net effect of the two corrections was to produce cloud water flux values (CWF) that were 28% lower and 22% higher than FS at Auwahi and Waikamoi respectively (Table II). The amounts by which FS is inflated by wind-driven rainfall, and reduced by changing the wind direction relative to the fixed

Table I. Study site and study period characteristics

	Auwahi	Waikamoi
Elevation (m)	1219	1951
Aspect	Leeward	Windward
Start of study period	12 February 2002	6 October 2001
End of study period	4 March 2004	11 August 2003
Period total (days)	751	673
Observation period excluding missing canopy water balance data		
Missing data (days)	0	109
Observation period total (days)	751	564
Observation period excluding missing canopy water balance data and missing fog screen data		
Missing data (days)[a]	291	109
Observation period total (days)	461	564

[a] Discrepancy between missing plus observation and total period due to rounding.

Table II. Event statistics and observation totals for Auwahi and Waikamoi

	Auwahi				Waikamoi			
	Study period	Per day	Per rain/fog day	Annual	Study period	Per day	Per rain/fog day	Annual
A. Excluding periods with missing canopy water balance data								
N: Sample period (days)	751				564			
No. of days with rain and/or fog	370	0·49	1·00	180	367	0·65	1·00	238
No. of rain and/or fog events	464	0·62	1·25	226	438	0·78	1·19	284
Event duration (h)	2139	2·85	5·78	1040	3553	6·30	9·68	2300
Mean event duration (hh : mm)	4 : 37				8 : 07			
R: Rainfall (mm)	1979	2·63	5·35	962	3690	6·54	10·05	2389
R_{slope}: Incident rainfall (mm)	2001	2·66	5·41	973	3939	6·98	10·73	2550
TF_c: Throughfall (mm)	1736	2·31	4·69	844	4817	8·54	13·13	3118
FS: Fog screen (mm)	NA	NA	NA	NA	3810	6·75	10·38	2466
CWF: Cloud water flux (mm)	NA	NA	NA	NA	4661	8·26	12·70	3017
E_{event}: Evap. dur. events (mm)	316	0·42	0·85	153	441	0·78	1·20	285
E_{after}: Evap. After events (mm)	292	0·39	0·79	142	553	0·98	1·51	358
CWI: Cloud water intercept (mm)	342	0·46	0·92	166	1872	3·32	5·10	1212
R_{slope} + CWI: Total water input (mm)	2343	3·12	6·33	1139	5811	10·30	15·83	3761
Number of CWI events	348	0·46	0·94	169	382	0·68	1·04	247
B. Excluding periods with missing canopy water balance data or missing fog screen data								
N: Sample period (days)	461				564			
No. of days with rain and/or fog	219	0·48	1·00	174	367	0·65	1·00	238
No. of rain and/or fog events	273	0·59	1·25	216	438	0·78	1·19	284
Event duration (h)	932	2·02	4·26	739	3553	6·30	9·68	2300
Mean event duration (hh : mm)	3 : 25				8 : 07			
R: Rainfall (mm)	753	1·64	3·44	597	3690	6·54	10·05	2389
R_{slope}: Incident rainfall (mm)	700	1·52	3·20	555	3939	6·98	10·73	2550
TF_c: Throughfall (mm)	611	1·33	2·79	485	4817	8·54	13·13	3118
FS: Fog screen (mm)	232	0·50	1·06	184	3810	6·75	10·38	2466
CWF: Cloud water flux (mm)	167	0·36	0·76	132	4661	8·26	12·70	3017
E_{event}: Evap. dur. events (mm)	139	0·30	0·63	110	441	0·78	1·20	285
E_{after}: Evap. after events (mm)	185	0·40	0·84	147	553	0·98	1·51	358
CWI: Cloud water intercept (mm)	198	0·43	0·90	157	1872	3·32	5·10	1212
R_{slope} + CWI: Total water input (mm)	897	1·95	4·10	712	5811	10·30	15·83	3761
Number of CWI events	209	0·45	0·95	166	382	0·68	1·04	247

screen orientation, are dependent on numerous site- and installation-specific variables. One can reasonably expect FS to diverge from CWF by larger amounts at other sites. For example, García-Santos and Bruijnzeel (2011) derived an underestimation of 63% for CWF based on a small planar fog gauge at a windy site on La Gomera (Canary Islands). Hence, as an estimate of CWF, it is not recommended to use uncorrected FS values from a planar fog screen such as the Schemenauer and Cereceda (1994) gauge (cf. Juvik and Nullet, 1995a).

Comparison of the per-day R, TF, and CWF values for the two sites (Table II) underscores the extreme contrast between windward and leeward exposures on mountain slopes in Hawai'i, although some of the difference may be explained by the difference in elevation (1219 m at Auwahi and 1951 m at Waikamoi). Water input events were 26% more frequent, mean event duration was 76% longer, and intensities of R, TF, and CWF were much higher at Waikamoi as compared to those at Auwahi. The contrast is most striking in terms of CWF, which was nearly 23 times greater, on average, at Waikamoi than at Auwahi. Even as a percentage of incident rainfall, CWF was much greater at Waikamoi (118%) than at Auwahi (24%). The CWF values at Waikamoi suggest that interception of cloud water adds significantly to the already high amount derived from rainfall (Table II).

Accounting for the effects of wind-driven rainfall in sloping terrain can reduce or increase the estimate of incident rainfall compared to uncorrected measured rainfall, depending on wind direction and slope aspect. When rain occurs with upslope winds, incident rainfall is greater than the measured rainfall, and the opposite is true for rain during downslope winds. For both stations, the estimated incident rainfall was lower than the measured rainfall at times, but was higher on average, indicating a predominance of upslope wind during periods of rain at both sites. Rain catch by the vegetation above the throughfall gauges at both sites was, undoubtedly, also enhanced at times and reduced at other times as changing wind direction and speed either improved or reduced the exposure of parts of the canopy to wind-driven rainfall (cf. Schmid *et al.*, 2011). No attempt was made to account for these effects in this analysis.

Measured TF (after adjustment for splash loss from the collection troughs, wetting, evaporation, and stemflow) was about 87% of R_{slope} at Auwahi, and 122% of R_{slope} at Waikamoi (Table II). This difference is indicative of the much greater amount of CWF at Waikamoi.

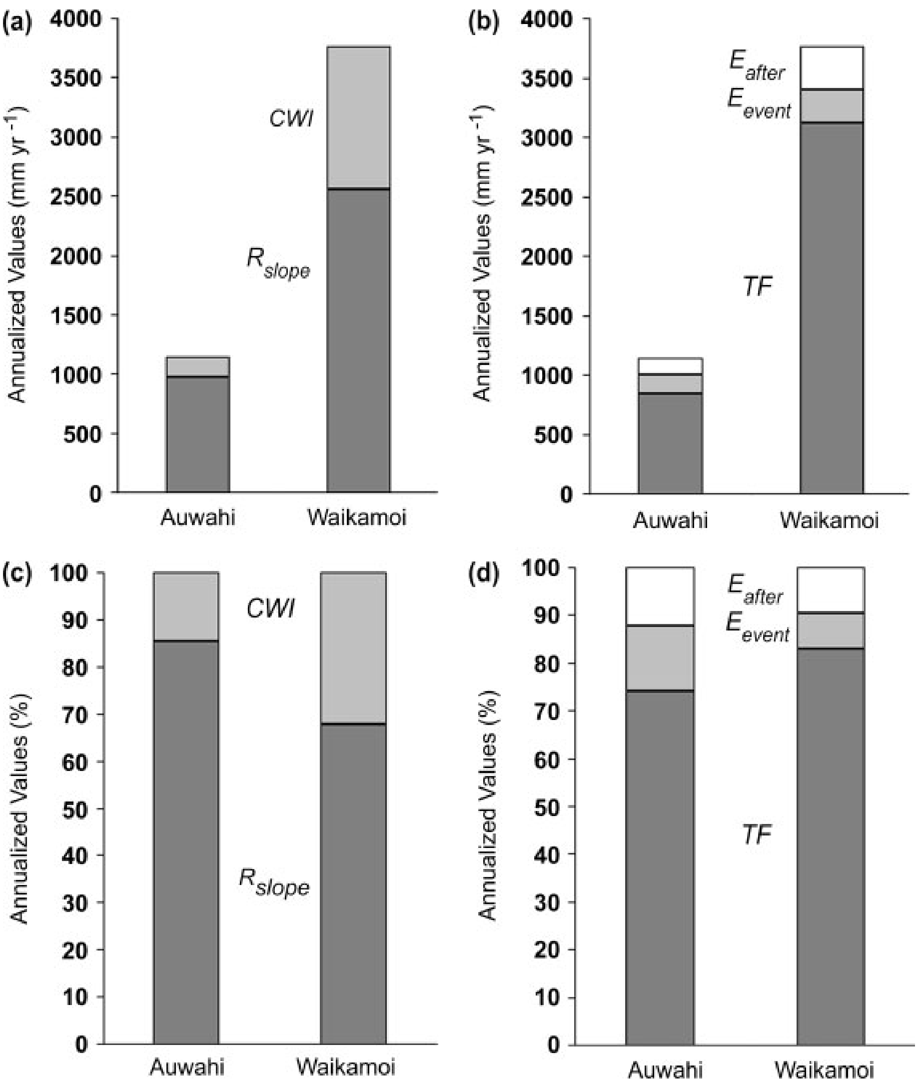

Figure 1. Annualized canopy water balance totals for Auwahi and Waikamoi, Haleakalā, Maui, Hawai'i; (a) water input equal to incident rainfall (R_{slope}) plus cloud water interception (CWI); (b) disposition of water input equal to the sum of throughfall (TF), evaporation of intercepted water during events (E_{event}), and evaporation of storage water following events (E_{after}); (c) same as (a), but expressed in relative units; (d) same as (b), but expressed in relative units

On the basis of the wet-canopy water balance estimates, fog contributed to water input events at an average frequency of 169 and 247 times per year respectively at Auwahi and Waikamoi. Derived estimates of CWI were equivalent to 166 mm year^{-1} (adding 17% to the water input derived from R_{slope}) at Auwahi and 1212 mm year^{-1} (adding 48% to R_{slope}) at Waikamoi (Table II). Isotope mixing models gave estimates for a cloud water component of 46% of the total precipitation at Auwahi and 37% of the total precipitation at Waikamoi (Scholl *et al*., 2007), compared with the estimates given here that indicate 15% and 32% of the total precipitation are derived from CWI at Auwahi and Waikamoi respectively. These estimates differ, in part, because stable isotopes are a marker for precipitation source rather than droplet size, and rain and fog in locally generated clouds often had similar isotopic compositions (cf. Scholl *et al*., 2011).

The total water input at the two sites is shown in Figure 1 (left panels). The bottom left panel gives the percentage contributions of R_{slope} and CWI at each site. It is clear that both in absolute and relative terms CWI is a larger contributor to the total water input at the wet, windward site. At Auwahi, CWI, although much smaller in absolute terms, is significant in relation to rainfall. The disposition of water input at the two sites is illustrated in the right panels of Figure 1. Evaporation accounts for a larger proportion of the canopy water budget at the dry, leeward site.

As a rough estimate of the contribution of CWI to TF, assume that total wet-canopy evaporation ($E_{event} + E_{after}$) would be the same proportion of the total water input regardless of the amount of CWI. On the basis of the present observations, evaporation is 26% of the total water input at Auwahi and 17% at Waikamoi. Using these percentages, one can estimate how much wet-canopy evaporation would occur at each site without CWI: 252 and 436 mm year^{-1} at the two sites, respectively. Subtracting these estimates from R_{slope} yields estimates of TF in the absence of CWI. The amount of observed TF in excess of these estimates suggests that 123 mm year^{-1}

Table III. Percentage of each water balance component and event occurrence for rain-only, fog-only, and rain-and-fog events at Auwahi and Waikamoi

	Auwahi				Waikamoi			
	Rain only	Fog only	Rain and fog only	No rain[a] and no fog	Rain only	Fog only	Rain and fog only	No rain[a] and no fog
Fog/no fog based on CWF								
R: rainfall	1	0	99	0	1	0	99	0
R_{slope}: Incident rainfall	1	0	99	0	1	0	99	0
TF: Throughfall	0	0	99	0·25	0	0	100	0·08
E_{event}: Evaporation during events	3	26	69	2	2	9	87	2
E_{after}: Evaporation after events	7	4	79	10	8	6	74	12
CWI: Cloud water interception	4	15	73	8	2	4	90	4
R_{slope} + CWI: Total water input	2	3	93	2	1	1	96	1
Percentage of CWI events	5	38	47	10	7	18	64	11
Fog/no fog based on CWI								
R: rainfall	50	0	50	0	19	0	81	0
R_{slope}: Incident rainfall	59	0	41	0	19	0	81	0
TF: Throughfall	47	0	53	0	14	0	86	0
E_{event}: Evaporation during events	20	28	53	0	3	11	86	0
E_{after}: Evaporation after events	25	14	61	0	3	18	78	0
CWI: Cloud water interception	0	23	77	0	0	8	92	0
R_{slope} + CWI: Total water input	45	6	49	0	13	3	84	0
Percentage of CWI events	0	47	53	0	0	29	71	0

[a] Note that a small number of events at both Auwahi and Waikamoi had recorded throughfall with no recorded rainfall or fog.

(74%) of CWI becomes TF at Auwahi and 1004 mm (83%) of CWI becomes TF at Waikamoi. The frequent presence of fog also enhances the net hydrological input to the ecosystem by reducing transpiration. During fog, transpiration is lower because of reduced solar radiation (Fischer *et al.*, 2009) and because water on the leaf surfaces can cover stomata, blocking gas exchange (cf. Smith and McClean, 1989).

CWF is an estimate of the horizontal throughput of liquid water, which, in part, controls the amount of cloud water interception. Comparing the two cloud water variables, CWI was 119% of CWF at Auwahi and only 40% of CWF at Waikamoi. Taken at face value, this implies that the vegetation at the Auwahi site is more efficient at catching cloud water than the vegetation at Waikamoi, which is reasonable given the exposure of the Auwahi site to unimpeded flow of fog across the adjacent pasture. For this same reason, however, the Auwahi site may be more susceptible to error from unaccounted enhancement of incident rainfall. It should also be emphasized that both sites, but especially Auwahi, are exposed such that cloud water and rain deposition are enhanced by air entering the vegetation from the side. Measurements made further away from the edge are likely to have given much lower values (Weathers *et al.*, 1995). However, in the case of Auwahi, the present-day vegetation distribution is characterized by small patches of shrubs surrounded by much larger areas of short vegetation. It is important to recognize that the results presented here pertain only to the patches of shrubs.

If fog occurrence is identified using the CWF variable, the occurrence of rain without fog appears to be very infrequent at both sites (Table III, upper portion). Using the CWI variable to determine fog occurrence, however, indicates that rain-only events occur frequently and account for significant portions of water input and throughfall (Table III, lower portion). The discrepancy between CWF and CWI in the determination of fog occurrence underscores the ineffectiveness of fog screen observations in distinguishing between fog and wind-driven rain, even after removing rainfall effects. This is especially true at the Auwahi station. Regardless of which variable is used to determine fog occurrence, it is clear that rain-and-fog events are the predominant TF source at both sites.

In Figure 2, the presently derived CWI estimates have been plotted against elevation along with previous cloud water deposition estimates from Hawai'i, obtained mostly from fog screens (i.e. FS). The exceptionally high estimates given by Juvik and Nullet (1995b) for Kohala, which were based on only 100 days of observation, have been left out from the diagram. The zone of frequent cloud contact is also shown by shading. The Auwahi estimate appears somewhat below the average for its elevation, while Waikamoi exceeds all previous estimates. Overall, the maximum values as a function of elevation (Figure 2, grey line) match reasonably well with the qualitative fog zones, with the highest values observed between about 600 and 2600 m.a.s.l. However, the range of values is almost certainly indicative of more than the true variability. Hence, there is still work to do in quantifying cloud water interception in Hawai'i's montane forests.

Table IV gives the results of regression analysis to elucidate the relationships among some of the measured and calculated variables based on event totals. TF was almost fully explained by rainfall at both sites. Adjustments made to R observations to estimate R_{slope} resulted

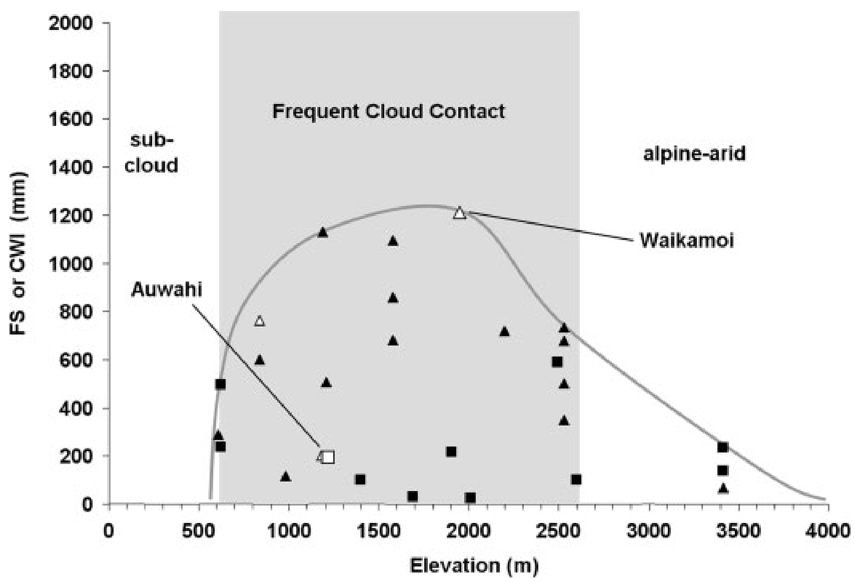

Figure 2. Current and prior estimates of cloudwater interception in Hawai'i shown as a function of elevation; prior studies summarized by DeLay and Giambelluca (2010). Shading corresponds to vertical cloud water zones as depicted DeLay and Giambelluca (2010). Grey line shows approximate maximum value of CWI versus elevation

Table IV. Results of linear regressions between various measured and derived variables (all regression significant at $p = 0.0001$)

	Auwahi				Waikamoi			
	a	B	r^2	N	a	b	r^2	N
TF $= a + b(R)$	−0·499	0·994	0·984	464	0·795	1·211	0·946	438
TF $= a + b(R_{slope})$	−0·124	0·896	0·962	464	0·959	1·116	0·951	438
TF $= a + b$(FS)	−0·934	3·734	0·804	273	0·604	1·334	0·890	438
TF $= a + b$(CWF)	−0·289	4·131	0·490	273	2·905	1·307	0·854	438
TF $= a + b$(CWI)	1·656	2·463	0·115	464	−0·903	2·784	0·494	438
TF $= a + b(R_{slope} +$ CWI)	−0·767	0·874	0·978	464	−1·862	0·969	0·998	438
CWI $= a + b$(FS)	0·170	0·845	0·421	272†	0·797	0·457	0·781	437[a]
CWI $= a + b$(CWF)	0·546	0·503	0·069	272†	0·152	0·428	0·796	437[a]

Note: $a = y$-intercept of regression line; $b =$ slope of regression line; $r^2 =$ coefficient of determination; $N =$ sample size; TF = throughfall; $R =$ rainfall; $R_{slope} =$ rainfall incident on sloping surface; FS = fog screen capture; CWF = cloud water flux; CWI = cloud water interception.
[a] One outlier removed.

in slightly lower explanation of TF at Auwahi and slightly improved explanation of TF at Waikamoi. TF was also well correlated with FS, which responds to both rainfall and fog interception, but less so than for R_{slope}. Conversion of FS to CWF resulted in a substantial reduction in correlation with TF at Auwahi and a slight reduction at Waikamoi. This result is probably related to the strong controlling influence of rainfall, which is removed in the estimation of CWF, on TF. CWI has even less explanatory power for TF. TF is very strongly correlated with the total water input (R_{slope} + CWI), a result that is guaranteed by the use of R_{slope} and TF to estimate CWI. Use of fog screen variables (FS or CWF) as predictors of CWI produced better results at Waikamoi than at Auwahi, although present efforts to improve the utility of fog screen measurements by removing effects of wind-driven rainfall and varying wind direction did not result in improved prediction of CWI at either station. In particular, CWF is a good predictive variable for CWI at Waikamoi ($r^2 = 0{\cdot}80$), but, at Auwahi, CWF is a very poor predictor ($r^2 = 0{\cdot}07$), and is less correlated with *CWI* than FS ($r^2 = 0{\cdot}42$). The slopes of best-fit lines forced through the origin (not shown) indicate that CWI is 59% of CWF at Auwahi and 43% of CWF at Waikamoi. As previously mentioned, this implies that cloud water is more efficiently caught by the vegetation at Auwahi site than the vegetation at Waikamoi. However, it should be noted that this observation may result, in part, from uncertainty in CWF, rather than a real difference between the sites in catch efficiency by the vegetation.

The results of the present efforts to make use of fog screen measurements to estimate CWF, and ultimately to have an index of CWI, have not yielded satisfactory results. Whilst it is not clear why the estimates of CWF failed to improve prediction of CWI, it seems likely that errors both in the measurements and the assumptions inherent in the methods led to this result. It is noted that FS and CWF were much better predictors of CWI at the wet site, and that CWF was slightly better than FS as a predictor of CWI there. This suggests that errors may be more significant for the relatively small fog events at the drier site. To test this, a subset of the Waikamoi sample including only small events, in the same range as those at Auwahi, was analysed. The results show that, whilst the predictive power of FS ($r^2 = 0{\cdot}53$) and CWF ($r^2 = 0{\cdot}54$) are lower for the small events, prediction of CWI by either variable remains much better for Waikamoi than for Auwahi. The reason for the poor relationship between CWF and CWI at Auwahi remains as yet unresolved.

CONCLUSION

The results presented here indicate that cloud water interception adds significantly to rainfall inputs at both dry and wet cloud forest sites in Hawai'i. Direct interception of cloud water added 166 mm year^{-1} (17% of annual rainfall) and 1212 mm year^{-1} (48% of annual rainfall) to the dry leeward and wet windward sites respectively. A large proportion of intercepted cloud water, 74% and 83%, respectively for the two sites, was estimated to become throughfall, thus adding significantly to soil water. The Auwahi site and, to a lesser extent, the Waikamoi site probably received cloud water inputs that were enhanced by the transition from low to high stature of vegetation. Cloud water input is probably lower for comparable locations within continuous vegetation of the same height.

Methods developed and applied to improve the utility of planar fog screen observations by removing the effects of wind-driven rainfall and varying wind direction, did not agree with estimates of cloud water interception derived from the wet canopy water balance. At the dry site, screen-based calculated cloud water flux had very little predictive value for cloud water interception by the vegetation. These results suggest that planar fog screens are not useful for estimating cloud water interception, and are therefore not recommended for that purpose.

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