Title

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Journal
Water Resources Research, 43

ISSN
0043-1397

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Publication Date
2007-04-01

DOI
10.1029/2006WR005124

Peer reviewed

Evaluating patterns of fog water deposition and isotopic composition on the California Channel Islands.

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Abstract

Fog deposition is an important water source for endemic conifer species during the annual summer drought along the California coast (and in other coastal and montane areas). We present a new design for a passive fog collector that is useful both for characterizing fog regimes (timing and quantity of deposition), and for collecting fog water for subsequent isotopic analysis. The new collector both mimics vegetation collection efficiency and minimizes isotopic fractionation under a range of fog conditions. Low construction cost and collector durability allow widely distributed installation and greater insight into spatially heterogeneous fog patterns. We installed 21 fog collectors throughout a stand of Bishop Pines (*Pinus muricata* D. Don) on Santa Cruz Island. In general there was greater fog deposition with increasing elevation, and decreasing frequency farther inland. Within these broad patterns, there was large spatial and temporal variability in fog deposition. Monthly samples of fog and rain waters reveal differences in stable isotope composition ($\delta^{18}O$ and δD) large enough to serve as tracers of different water sources moving through the ecosystem.

Index terms

1813 – Eco-hydrology
1840 - Hydrometeorology
0454 - Isotopic composition and chemistry (1041, 4870)
1895 - Instruments and techniques: monitoring
0426 - Biosphere/atmosphere interactions (0315)

Keywords: fog, fog drip, fog collection, Pinus muricata, Santa Cruz Island, Channel Islands

1. Introduction

1.1. Ecosystem importance of fog and motivation for new collector design

Fog has been recognized as an important hydrological input in many regions, including coastal areas, tropical montane cloud forests, and in other areas worldwide (e.g., Marloth 1905, Parsons 1960, Kerfoot 1968, Leyton and Armitage 1968; Azevedo and Morgan 1974; Schlesinger and Reiners 1974, Goodman 1985, Bruijnzeel 1990, Bruijnzeel and Proctor 1995; Walmsley et al. 1996, Dawson 1998; Weathers 1999, Corbin et al. 2005). Rising interest in fog's ecological and chemical impacts (Schemenauer and Cereceda 1992, Weathers et al. 2000) has fueled the development of increasingly sophisticated methods for evaluating fog water inputs and distributions. Some of the most informative studies of fog's ecosystem impacts use stable isotopes as tracers of water inputs from different sources (e.g., Ingraham and Mathews 1995; Dawson 1998, Scholl et al. 2002, Scholl et al. 2005). Provided that isotopic signatures of two water sources such as fog and rain are sufficiently distinct, their relative contributions to any water pool (e.g., soil water or plant xylem water) can be calculated with a simple mixing model (Dawson 1993, Phillips and Gregg 2001, Corbin et al. 2005). All of these studies rely on fog and rain collectors that reliably sample fog water and rain water without altering its original isotopic composition. Collecting rain water without alteration of its isotopic composition is frequently and easily accomplished, but much less work has been done to assess fog collector designs for reliable sampling of fog water isotopic signatures (Scholl et al. 2007).

1.2. Fog collector design considerations

The broader goal of our study is to assess the contribution of fog drip to water budgets of a fog-belt endemic pine species, Bishop Pine (*Pinus muricata* D. Don), on Santa Cruz Island in

Channel Islands National Park. Anecdotal evidence suggests that this species relies in part on summer fog drip to survive the annual summer drought throughout its range along the coast of California. To accomplish this goal we designed a new type of fog collector that could be used in remote locations and could quantify fog water inputs and stable isotope composition of the fog water for our plant ecological investigations. The quantity and isotopic composition of fog water can vary over relatively short distances (Scholl et al. 2007). We were therefore interested in characterizing spatial and temporal variability in fog inputs and isotopic composition for a 25 km^2 study area, and planned to deploy a relatively dense network of 21 fog collectors dispersed across 12 sites. This large number of collectors raised the priority of reducing collector cost and complexity. Specifically we desired a fog collector meeting, to the extent feasible, the following design criteria:

A) Collect fog water in proportion to that collected by the vegetation under study (Bishop pines) under a variety of fog conditions (e.g., changing fog intensity, duration, and wind speed), including low-intensity, short-duration fog events.

B) Collect fog water relatively consistently regardless of wind direction.

C) Collect fog water with minimal isotopic fractionation.

In this paper, we compare the performance of a new fog collector design to that of previous collectors based on these three design criteria. Then, we report on how the data obtained from these new collectors provided new insights about fog deposition on the southern California Channel Islands and the implications for our ongoing plant-based investigations.

1.3. Previous fog collector designs

Previously published fog collector designs fall into two main categories. “Active collectors” sample known volumes of air per unit time using a fan to pull air past collection surfaces (e.g., Daube et al. 1987a, Collett et al. 1989; Figure 1A), and have been applied extensively in fog chemical analyses (e.g., Collett et al. 1989, Weathers and Likens 1997, Collett et al. 2002, Burkard et al. 2003). “Passive collectors” rely on wind to move air past collection surfaces (e.g., Schemenauer and Cereceda 1991), and almost all studies of fog water isotopic composition have been conducted with such collectors. Active collectors can be very complex (e.g., self-cleaning, computer-controlled, with closing doors and autosamplers to subsample individual fog events) and cost many thousands of dollars (e.g., Collett et al. 1990, Demoz et al. 1996, Fuzzi et al. 1997, Burkard et al. 2003). In contrast, the simplest passive collectors can be built for only tens of dollars (e.g., Schemenauer and Cereceda 1994; Figure 1B), can be deployed in remote environments lacking electrical power, are easily replaced or repaired, and have a comparatively low failure rate under harsh environmental conditions.

Both passive and active fog collectors can be further subdivided based on the type of collection surfaces used. The most common two types are “mesh collectors,” with horizontal and vertical strands, and “harp collectors,” with only vertical strands (Figure 1C, 1D). Mesh collectors are generally simpler to construct, utilizing a mass-manufactured mesh that can be fastened to a simple frame (e.g., Schemenauer and Joe 1989, Schemenauer and Cereceda 1994, Juvik and Nullet 1995). Harp collectors are generally more time-consuming to build, requiring manual stringing (e.g., Falconer and Falconer 1980). For simplicity, the passive collector designs will be referred to in the remainder of the paper by the first author’s name (i.e., Schemenauer, Falconer, and Juvik collectors respectively).

1.4. Mesh vs. harp

While mesh collectors are simpler than harps, one drawback is that they tend to store more water on the collector strands than a harp of similar collection area. This increased “canopy storage” on the collector is caused by water drops adhering in the corners of the mesh where strands cross. Thus, mesh collectors generally take more time to reach saturation and begin dripping at the beginning of a fog event. This effect was consistently observed in side-by-side comparison of harp, Juvik, and Schemenauer fog collectors (Frumau 2006, A. Frumau pers. comm. 2006). The degree to which this delay matches vegetation collection performance depends on the nature of the canopy under study. Needle-leaved trees, for instance, tend to collect fog much more efficiently and shed fog drip more quickly than broader-leaved trees (Goodman 1985). The increased “canopy storage” of water on the collector means that mesh collectors generally do not react as quickly to fog events, and may entirely miss low-intensity, short-duration fog events that often produce measurable fog drip from pines at our sites. In initial testing, a prototype mesh style collector (a modified Juvik, after T.E. Dawson, pers. comm. 2003) failed to record many fog events that were heavy enough to generate substantial fog drip from adjacent pine trees. This finding dictated the use of a harp collector for our study.

An additional consideration supported our choice of a harp collector: for studies of the isotopic composition of fog, increased canopy storage also allows more chance for isotopic enrichment by evaporation during intermittent fog events. Water molecules containing lighter isotopes of hydrogen and oxygen evaporate preferentially, so that any liquid water remaining after evaporation is enriched in heavier isotopes (Craig 1961, Gat 1996, Mook and deVries 2001).

Thus, at the end of a fog event, any water left on the collector starts to evaporate and become isotopically enriched. Should fog deposition begin again before it has evaporated completely, that enriched water would be collected and contaminate the previously stored sample. The less water that is remaining on a collector at the end of a fog event, the less time it will be around in a partially evaporated (isotopically enriched) state, available to contaminate the collected sample if fog returns. We tested the amount of water retained on our harp collector versus a mesh collector similar to that described by Schemenauer and Cereceda (1994) by weighing both collectors before and after simulated fog events. After initial weighing, we simulated a heavy fog event by misting both collectors heavily with an atomizer until water ran freely off them at a steady rate. We stopped the mist, waited five minutes for the collectors to drain, and weighed them again. We then compared the amount of water retained as a function of collection area, which differs by a factor of 6 (1-sided silhouette area of collecting strands is 0.093 m^2 for our harp, 0.6 m^2 for the Schemenauer mesh collector). The new harp collector retained 40% less water than the mesh collector per area (300 g/m^2 vs. 500 g/m^2).

1.5. Sensitivity to wind direction

The simplest passive fog collector, a flat mesh Schemenauer collector, is sensitive to wind direction—it collects more water when winds are perpendicular to the collector than when winds are more nearly parallel (Juvik and Nullet 1995, Schemenauer and Cereceda 1995). This means that one needs to know the prevailing wind directions during fog events (and not just the overall prevailing wind direction) prior to installation in order to collect representative volumes. In many areas such knowledge is readily available, but in other areas lack of a priori knowledge and/or large variability in wind direction make strong directional sensitivity undesirable. Two solutions to wind sensitivity have been proposed: mounting collectors to pivot into the wind, or making "omni-directional" collectors that are the same from all sides. Pivots add significantly to complexity of construction, deployment, and maintenance; omni-directional collectors are a more elegant solution. Existing omni-directional fog collectors are cylindrical mesh (Juvik) or harp (Falconer) collectors.

We considered the cylindrical harp collector designed by Falconer and Falconer (1980). It is a cylindrical harp of Teflon strands strung between two horizontal polypropylene disks (Figure 1C). Unlike the simplest planar fog collectors, it is not sensitive to wind direction. It is, however, time-consuming and expensive to build (as discussed by Schemenauer and Cereceda, 1994). In the interests of simplicity we opted to slightly relax the requirement that the collector be strictly omni-directional (i.e., collecting fog consistently regardless of wind direction) and built one that is essentially two flat harps perpendicularly bisecting each other. This design reduces cost and complexity, allowing much greater spatial coverage of our field site, and the departure from strict omni-directionality is minimal (see section 2.4 below).

2. New design

2.1. System description

Our fog collector is a passive, harp-style collector. It consists of two perpendicular panels intersecting on a vertical center post (Figure 2A). The panels consist of two layers of monofilament fishing line stretched taut vertically between two stainless steel threaded rods. Water dripping off the collecting strings collects in a small trough and drains to a central funnel (Figure 2B), and from there the water is routed either to a sampling bottle (designed to minimize isotopic enrichment from subsequent evaporation) or to a tipping bucket rain gauge (to log timing and quantity of collection). A plastic drum lid fits over the top of the collector to somewhat reduce the amount of rain collected.

This collector was designed from readily available, off-the-shelf components in U.S. industry-standard sizes and is relatively simple to construct. Several collectors can easily be built in 2-3 days with materials cost of around $50 each. The central column is 3/4" PVC pipe (2.7 cm O.D.). Threaded rods inserted horizontally through the column are 3/8" (0.95 cm O.D.) stainless steel. Our collectors measure 61 cm (2 ft) between top and bottom threaded rods. The collector is strung with 122 m (400 ft) of monofilament fishing line with a diameter of 0.76 mm spaced 9 mm apart. While fishing line is inappropriate for atmospheric contaminant sampling (especially for nitrogen compounds), it is perfectly suitable for assessing fog water quantity and isotopic composition. It is also less expensive, more readily available and easier to work with than Teflon strands.

Collection troughs are made of 1/2" PVC pipe (2.1 cm O.D.) cut in half lengthwise. Once cut in half, the pipe is heated in the middle and shaped to a slight “V”, so that water drains to the center. A drain hole is drilled in the center, and attachment holes drilled at each end. The ends are heated and folded up to fit over the ends of the lower threaded rod. The narrower 1/2" pipe was used for troughs to reduce “by-catch” of rain. Even in relatively strong winds, the drops of fog coming off the threaded rod are large enough to drip straight down into the troughs.

Installation is simple. We simply hose clamp a collector to a T fence post (adding guy wires for those posts with tipping buckets). The collector is durable. Stainless steel and gray PVC hold up in the harshest environments. After two years of UV exposure, the fishing line has remained strong and flexible. On monthly sampling trips, maintenance has consisted primarily of dusting off the collector strands. More detailed construction information can be obtained from the authors.

2.2. Deployment on Santa Cruz Island

Paired fog collectors were deployed at 7 sites on Santa Cruz Island, the largest of the California Channel Islands, located approximately 40 km south of Santa Barbara (Figure 3). At each site, one fog collector was plumbed into a collection bottle to collect water samples for subsequent isotopic analysis. We used amber plastic bottles for collection, with long vent tubes to minimize evaporation (see discussion in Scholl et al. 2005 of different methods of protecting collected water from evaporation). This design was tested for evaporation effects in northern California and found to be satisfactory (T Dawson pers. comm. 2003). When subsamples were taken from these bottles each month, fog water volumes were also recorded (up to a maximum volume of 4.4 L). The other fog collector was plumbed to a tipping bucket rain gauge in order to record timing and quantity of fog water inputs. Differences in monthly collection volumes between the two collectors at each site were noted (only possible when less than 4.4 L). These differences were sometimes large initially as a result of clogged collection tubing. Clogs (primarily due to invertebrates) were largely eliminated by the addition of a filter screen in the central funnel.

In the following sections, we address the performance of the collector with respect to the design criteria from section 1 above based on field experience.

2.3. Collecting volumes of fog water representative of vegetation under study

For hydrologic studies, the volume of water from a fog collector is a proxy for the amount of fog drip potentially generated by vegetation. The key measurement is whether, under a range of conditions, the fog collector generates fog drip in some consistent proportion to fog drip generated by the vegetation under study. The Falconer harp has been shown to collect fog in linear proportion to conifer canopies and so we expected our similar design also to correlate strongly with fog drip from pines (DeFelice and Saxena 1990, Joslin et al. 1990). That assumption was tested during the 2005 dry season by comparing daily fog collection totals at Site 10 to throughfall collected by a rain gauge deployed under the canopy of adjacent pines (Figure 3). Daily fog drip throughfall totals (noon to noon) from that gauge are linearly correlated with fog water volumes from the fog collector (Figure 4, $R^2=0.74$ for 80 foggy days out of 164 total days, excluding 4 days with rain > 1 mm). The fog collector appears to have a slight bias toward recording small events that do not generate sufficient fog drip from the canopy to register on the rain gauge. This oversensitivity bias can be filtered out of volumetric data (by setting a minimum daily threshold) and is preferable to under-sensitivity. Furthermore, it is possible that the pine canopy absorbs some of the fog it collects via foliar absorption (Leyton and Armitage 1968, Boucher et al. 1995, Munne-Bosch et al. 1999, Burgess and Dawson 2004), and such inputs would not be recorded by the throughfall collector but would be recorded by our more sensitive collectors. The linear correlation supports our deployment of standard collectors across the study area as a way to measure fog water availability in areas both with and without tree canopies.

2.4. Sensitivity to wind direction

Prior to this study, we knew that fog occurred primarily from late afternoon through early morning at our sites. Mesoscale circulation around the Northern Channel Islands in summer tends to show west-northwesterly flow in the p.m. but (weaker) easterly flow in the a.m. (Dorman and Winant 2000). Further, winter rain clouds are generally associated with winds from the southwest. Local topography of course modifies these wind directions at any given site. We wanted to be able to collect fog / cloud water from each of these directions, not knowing in advance how large their respective contributions might be.

While our collector is not strictly omni-directional, in theory the strands on our collector are spaced far enough apart (0.9 cm ± .05) to not interfere significantly with the airflow around each other (Demoz et al. 1996). The orientation of the collector to the wind therefore becomes largely unimportant. The collection rate becomes not a function of collector cross-sectional area; rather, it is a function of the 1-sided area (silhouette area) of all 200 individual strands. Accounting for reduced water content of fog impacting downwind portions of the fog collector yields only a small theoretical difference in collection rates between wind blowing at 90 degrees to one of the collector arms versus wind blowing at 45 degrees (using equations derived from Demoz et al. 1996). To test this calculation, we used an atomizer to simulate heavy fog on a collector mounted at different angles in a wind-tunnel (wind speed =~2 m/s). After allowing flow off the collector to stabilize (at ~30 ml/min) we observed a roughly linear 9% decrease (± 2%, n=5 replicates) in collection rates as the collector was rotated from 45 degrees through 67.5 degrees to 90 degrees.

The assumption of strand independence only holds at low wind speeds. At our sites, wind speeds rarely exceed 4 m/s during fog events, and so this assumption seems valid. At sites with higher wind speeds during fog events, the spacing of strands would need to be evaluated (along with other fog collection concerns (Frumau et al. 2006)).

2.5. Collect unfractionated water samples for isotopic analysis

The main challenge for a fog collector for isotope studies is to collect fog water while minimizing the potential for evaporation. Evaporation fractionates isotopologues of water, as molecules with lighter isotopes ($H_2{}^{16}O$) evaporate and diffuse more quickly, leaving behind liquid water that is enriched in heavier isotopes (primarily HDO or $H_2{}^{18}O$). As described in section 1.4 above, the harp design of the new collector is superior to mesh designs for minimizing evaporation by minimizing the amount of water left on the collector at the end of fog events. It is this stored water that has the potential to become enriched, and then contaminate the collected sample if fog deposition begins again before it has completely evaporated.

A second potential source of error in fog collection is by biased collection of isotopically differing size classes of fog droplets. Distinguishing the sizes of droplets collected can be very important for cloud chemistry studies, as pollution concentrations can vary widely across a spectrum of droplet sizes (e.g., Hindman et al. 1992, Collett et al. 1994, Demoz et al. 1996, Collett et al. 2002). For isotopic studies, droplet size distribution has never been shown to be important, as even larger cloud droplets (~50 µm) are small enough to come into isotopic equilibrium with atmospheric water vapor within seconds (Lee and Fung 2006). Fog droplets are typically much smaller (~10 µm) (Goodman 1977, Meyer et al. 1980, Hudson and Svensson 1995), and thus have even faster equilibration times (Lee and Fung 2006). Therefore, isotopic composition of collected fog water should not be overly dependent on droplet sizes collected, although to our knowledge this has never been examined experimentally.

2.6. Exclusion of rain water

Finally, we wanted to exclude enough rain water to be able to detect isotopic differences between fog and rain since they can occur simultaneously in the winter rainy season at our sites. We compared the new design to a modified Juvik collector of similar size with a similar 60 cm diameter rain cap (T. Dawson, pers. comm. 2003). In side-by-side deployments for five winter rain storms, the new collector collected on average only 10% (range 5-20%) as much rain water as the adjacent modified Juvik collector. We attribute this reduced rain contamination to the smaller collection troughs and funnel. Extending the rain cap farther out beyond the strands could further reduce rain contamination, but larger caps increasingly disturb airflow over the collector (Schemenauer and Cereceda 1995), and present structural problems. With the current design, the water sampled from the collectors during months with winter storm events was almost always isotopically enriched compared to rain water collected at the same site, implying a substantial percentage of water was from fog (and had not all been diluted out by unimpeded rain collection).

3. Fog regime case study: Santa Cruz Island

3.1. General observations

This collector was developed as part of a larger study examining the role that fog and persistent stratus clouds play in ecological processes and plant distributions in the California Channel Islands and along the California coast. Previous studies along the California Coast have used a diversity of fog collectors in different locales. Goodman (1985) used a planar harp (and a cylindrical harp) on Montara Mountain (450 km NNW) in the Bay Area. Estberg (2001) used a planar harp on the consistently cloudier / foggier San Miguel Island (50 km W), and at the sunnier Torrey Pines State Park (260 km ESE) near San Diego. Ruiz (2005) used a Schemenauer collector at two locations near California State University Monterey Bay (345 km NNW). We present summer fog collection data from these studies (Table 1) normalized for collector silhouette area (as the collectors differed by a factor of six in this regard). The collection rates from the current study on Santa Cruz Island were qualitatively similar, though lower than at the other sites, with the exception of Torrey Pines State Park. This fits the established positive correlation of summer fog / overcast intensity with latitude along the California coast (Filonczuk et al. 1995).

Our primary study area is a stand of Bishop Pines (*Pinus muricata* D. Don) on Santa Cruz Island. The study area is subject to frequent short-duration, low-intensity nighttime fog events. Dry season (May-September) fog water deposition on western Santa Cruz Island comes mainly overnight in 5-15 events per month, generally with relatively light NW winds (typified at Site 7, Figure 5). During these events, pines collect sufficient fog to produce drip that regularly wets the upper soil profile to 15 cm or deeper, raising soil water potentials for significant periods of time (Fischer et al. *in prep.*). Within this broad pattern, there is substantial local variation in timing and quantity of fog water inputs, which we sought to characterize.

3.2. Effects of elevation

Fog water collection was positively correlated with elevation at our sites. Figure 6 shows the cumulative fog water volumes collected during the summer dry season at five sites in 2004 (17 Mar. – 16 Oct.), and seven sites in 2005 (9 May – 16 Oct.). The stations are listed in order progressing from West to East, with higher elevation stations (300-440m) shown with bold lines and lower elevation stations (60-200m) shown with thinner lines. Steep sections of the curves indicate significant fog events where large volumes of fog water were collected in a short period of time. Note that higher elevation stations (bold lines) intercept consistently greater amounts of fog. This pattern is expected for three reasons. First, low stratus clouds over the Santa Barbara Channel frequently form a solid layer overnight with cloud bases around 100-200m and cloud tops around 600-900 m elevation (based on pilot reports and ceilometer data from Santa Barbara Airport). After dawn, the clouds begin to thin, evaporating from both top and bottom. The result is that our higher elevation stations (300 - 440 m) spend many more hours inundated by clouds than lower elevation stations. Other points on the island at still higher elevations, however, are usually well above the stratus clouds and so this positive correlation between fog collection and elevation is presumably limited to below the typical stratus tops. Second, the prevailing summertime NW winds encounter sharply rising terrain on the western part of the island, leading to orographic cloud formation on and above the ridges on the western part of the island, including our sites. Since higher ridges provide more orographic lifting, they are more likely to receive thicker orographic fogs for longer duration than lower elevation stations. Third, wind speeds at higher elevation stations tend to be slightly higher. Higher wind speeds will, all else being equal, push a greater volume of fog past a collection surface in the same time period, resulting in higher rates of fog collection.

3.3. Spatial variability

At seven sites on Santa Cruz Island, we recorded wind speed and direction at 15-minute intervals (hourly at Sites 1 and 10) to determine wind conditions during fog events. At most of our sites, wind direction during dry season fog events is sufficiently consistent that it is less important that fog collectors be omni-directional (Figure 7). It worth noting, however, that it is often difficult to know for certain what wind direction will prevail during fog events prior to monitoring, especially in remote areas. We were surprised, for instance, at the variability of incoming fog direction at Site 11, and at the dominance of fogs from the east at Site 12. It appears that even though prevailing winds at Sites 11 and 12 are from the NW, they are far enough inland (from that direction) that fog banks from the NW do not as reliably make it across intervening topography.

For all but two sites, winds were consistently out of the northwest during dry-season fog events (Figure 7). While there were periods with winds from the southeast quadrant, the total amount of fog collected during those periods was minimal. At the eastern two sites, an increasing fraction of collected fog water came from the east. This change in prevailing wind direction for the eastern stations suggests that fog deposition at those stations results from different mesoscale weather patterns than the prevailing patterns farther west. Further evidence of decoupling between eastern and western sites is that daily fog totals at the easternmost site are not significantly correlated with daily totals at any of the five western sites (each $R^2 < 0.06$, and $p > 0.01$ using pairwise t tests). In contrast, daily fog totals at four of the five western sites (excluding the lowest one that received almost no fog) are all significantly correlated ($p < .0001$) if weakly so ($R^2 = 0.18 – 0.48$). An important implication of the observed decoupling between east and west is that fog water input is likely to be subject to different climatic controls between east and west, and so respond differently to climatic variability. Also, the eastern range boundary of pines in this stand borders the two easternmost fog stations, so it is possible that the differing fog regime affects the distribution of these pines.

3.4. Temporal variability

Note that some of the larger fog events are contemporaneous at several stations, but absent at others (e.g., 7/15/05, Figure 6). This small-scale spatial pattern illustrates the importance of spatially-distributed sampling of fog water inputs. Most of the ridge-top stations in the stand receive similar amounts of fog drip over the course of the summer dry season (Figure 6). Despite this similarity, there is only weak day-to-day correlation in the amount of fog water deposited at different ridge-top stations (with pairwise R^2 values from 0 to 0.59, median 0.15). This low correlation reflects both temporal and spatial patchiness in fog deposition and should not be overlooked by focusing solely on total inputs. The temporal distribution of fog inputs at a given site can significantly affect the ecosystem availability of fog water. Comparing two ridge-top stations in the 2005 dry season, for instance, revealed that site 10 (near the middle of the study area) received 22% less fog water than site 12 (farthest east). But, despite receiving less total water, site 10 had 22% more nights with measurable fog deposition (73 nights versus 60 Table 2). Site 12 received fully 30% of its total seasonal fog water in just three foggy nights, while site 10 received only 17% in its three foggiest nights. Overall, fog deposition is much less frequent, and less evenly distributed in time in the eastern part of the study area, and this difference in the fog regime at this site is reflected in the difference in dominant wind direction of fog events (Figure 7).

Frequent light fog events (as at site 10) provide consistent small amounts of moisture that may be important for certain ecosystem functions. Certainly there is a much higher density of lichen around site 10 (growing on all exposed surfaces) than site 12. On the other hand, fog drip from light events is unlikely to penetrate deeply into the soil, and so a greater percentage may be lost to rapid re-evaporation the next morning than would be the case with heavier fog events. This also implies that understory grasses, herbs, and shrubs might not benefit as much from fog drip following such light events. Depending on the organisms of interest (e.g., lichens, grasses, pines) and processes under study (e.g., foliar absorption of water, litter decomposition, root uptake, etc.), temporal distribution of fog water inputs could be quite important.

4. Fog water isotopic patterns

4.1. Observations

Fog and rain samples were collected from the amber bottles attached to fog collectors at each site on a monthly basis. These 15-ml subsamples were then frozen until being analyzed for isotopic composition at UC Santa Barbara and/or UC Berkeley using an isotope ratio mass spectrometer. Correlation between δD and $\delta^{18}O$ was high and so for simplicity only δD data are discussed. The local meteoric water line (including both fog and rain) is $\delta D = 6.7\ \delta^{18}O + 6.6$, $R^2 = 0.92$. This line deviates from the global meteoric water line (Gat 1996, Mook and deVries 2001); the deviation is expected, since the line includes both fog and rain (Gonfiantini and Longinelli 1962).

Figure 8 shows two years of isotopic values for fog and rain at the Site 7, which is near the middle of the study area. We have collected and analyzed fog and rain samples for isotopic composition at other sites as well, but this site is fairly representative of the entire study area. Rain samples (generally winter and spring) were depleted isotopically compared to fog samples collected in the same months. Rainy season fog was markedly depleted compared to dry season (summertime) fog, reflecting both temperature differences and rain water contamination. These findings are discussed in the following three sections, as is their relevance to the collector's performance.

4.2. Dry season fog

Dry season fog in the study area forms from water vapor in the lower atmosphere that is largely in isotopic equilibrium with the relatively warm sea surface immediately below, although marine vapor is always several ‰ depleted from a strict temperature-dependent equilibrium offset from sea water (Craig and Gordon 1965). Isotopic composition is reported using delta notation versus Standard Mean Ocean Water (VSMOW). Sea water, by definition (Mook and deVries 2001), has an isotopic composition close to 0 ‰ for both δD and δ^{18}O on the VSMOW scale. The formula is $\delta D = (\text{conc. } D_{sample} - \text{conc. } D_{standard}) / (\text{conc. } D_{standard}) * 1000$ ‰ (Mook and de Vries 2001). Sea surface temperatures northwest of Santa Cruz Island are relatively consistent over the summer months (Dorman and Winant 2000) and so it is not surprising that fog water isotopes are relatively consistent as well during these rain-free months (see Gonfiantini and Longinelli 1962; Ingraham and Matthews 1995, Dawson 1998, Scholl et al. 2005).

4.3. Winter rain

The depleted signatures of winter rains are primarily due to two processes. First, winter rains in the study area are generally from frontal storms coming down from high latitudes, and so contain moisture evaporated off much colder ocean surfaces, which would lead to greater isotopic depletion in rain water derived from this vapor. Second, air masses become progressively depleted in heavier isotopes over time by preferential condensation and rain-out of the heavier isotopes (Gat 1996, Mook and deVries 2001).

The isotopic composition of rainfall did not vary much spatially for a given month across the study area. Only once (of seven monthly samples from winter 2004-2005) did rainfall among the three stations analyzed (sites 2,7,8) differ by more than 7‰ in δD. The one large difference was in the mid-February 2005 samples. These samples are a mixture of water from two storms in the preceding month 26-28 Jan. and 12-Feb. Tipping bucket data show that the percentage of the total sample from the latter storm varied among stations (from 51% to 63%), as did the sample's isotopic composition (δD -77‰ to -111‰). We used a linear mixing model between station pairs to infer that the 26 Jan. storm was around δD -32‰ (close to the volume-weighted seasonal rainfall mean δD of -36‰ for Site 7), but the 12 Feb. storm was extremely depleted in heavy isotopes, with an inferred δD value lower than -120‰. It appears that the spatial differences in isotopes for that month are related to different amounts of rain water contamination from the 12 Feb. storm that was strikingly depleted in heavier isotopes.

As noted above differences in isotopic composition between storms are largely due to air mass source regions and history. While most winter storms in the area form as isotopically depleted low pressure systems tracking down from Alaska, they also usually entrain a certain amount of moisture from the warmer, and therefore isotopically enriched, subtropical jet, east of Hawaii (e.g., National Weather Service 2005). Differences in dominance of the polar jet versus the relatively enriched subtropical jets in supplying storm moisture can lead to large differences in rain water isotopic composition.

4.4. Rainy season fog

Rainy season fog is more isotopically depleted than dry season fog for at least three reasons. First, sea surface temperatures are lower, so local water vapor in equilibrium with the ocean is more depleted. In practice, however, the seasonal cycle in local sea surface temperatures generally varies between ~10°C and ~20°C (Dorman and Winant 2000). The expected difference in liquid-vapor fractionation for δD over this range is < 5 ‰ (Majoube 1971, Horita and Wesolowski 1994).

The second, and more important, cause of depletion is rain water contamination. This is always an issue with collection of fog during rainy seasons (see discussion in Scholl et al. 2005). While the new collector collects less rain than the modified Juvik collector, it certainly does not prevent all rain water contamination. All of the isotopic values listed for "fog" during the rainy season are therefore inevitably a combination of fog and rain. We calculated the amount of fog water collected within an hour of recorded rainfall (i.e., potential rain contamination) as a percentage of the total monthly collection. For the seven months of the 2004-2005 rainy season this was 50%-98% of each monthly cumulative fog water sample (volume-weighted mean of 71% at Site 7). This might lead to the assumption that the collector is merely collecting rain water and that fog is not an important hydrologic input in the wet season. Isotopic analysis, however, suggests otherwise. If we assume that the “fog” water collected during rain events is all rain water (and is therefore isotopically identical to collected rain water), then we can mathematically un-mix the collected “mixed fog” water into a rain component and a “true fog” component.

For example, assume that in a given month that half of the "mixed fog" water was collected during rain events, and half not during rain. Further assume that the collected “mixed fog” water had a δD value of -30‰. If the sampled rain water had a δD value of -40‰, we could then assume that the “true fog” water must have had a δD value of -20‰ (in order for a 50-50 mixture to end up with δD -30‰). In practice, this un-mixing approach does not work. The predicted, un-mixed values for “true fog” (calculated with our actual measured values for “mixed fog” and rain) are all unreasonably enriched, with δD values well above 0‰, including some months in the hundreds. (Observed values for meteoric water are generally negative as they are reported vs. standard mean ocean water, and water vapor is always depleted compared to the liquid it is evaporating from. Furthermore, the δD values of fog water in the compendium of Scholl et al. (2005) rarely exceed -1 ‰). Our interpretation is that, while rain does enter the collector, a significant proportion of the water collected during rain events is actually fog water, both from low clouds, and from shallow ground fogs.

The third reason for isotopic depletion of winter fog is that fog water associated with rain events is likely to be modified by interaction with rain. The two types of rain-modified fog water are from low rain clouds and from ground fogs. When rain droplets are collected within the base of a cloud, the isotopic composition of the rain and cloud droplets should be generally similar due to rapid isotopic equilibration with vapor (Lee and Fung 2006). Where these low clouds intersect the ground, the fog water thus collected will be similar to rain and thus quite depleted compared to summer fog. The other rain-modified fog water is from ground fogs that commonly form locally during and following rain events. They are typically just a few meters thick. The ground fogs have the potential to be quite enriched compared to rain. They are forming from ambient atmospheric vapor at low elevation. Ambient vapor should contain a large component of (relatively enriched) water vapor that is in isotopic equilibrium with the sea surface. However, ambient vapor will also contain some portion of (relatively depleted) vapor from evaporated rain water. These ground fogs will therefore be more depleted than fog that is not associated with rain, but significantly enriched in heavy isotopes compared to the rain itself. The observed difficulty in un-mixing of “mixed fog” water into rain and believable “true fog” components is explained by rejecting the assumption that all collected water during a rain event is rain water with the isotopic composition of rain water. Instead, much of that water is probably actual fog water, enriched in heavy isotopes compared to rain.

Determining relative proportions of fog and rain water when they occur simultaneously is recognized as a difficult problem (e.g., Frumau et al. 2006, Rhodes et al. 2006, Scholl et al., 2006). To address this issue quantitatively requires the use of more complex collectors (e.g., Daube et al. 1987b). Even with its limited ability to exclude rain, the new collector has allowed us to collect samples suggesting that fog water may contribute significantly to local wet-season hydrology through deposition, even during rain events. This phenomenon merits further study, given the different implications of fog versus rain sources for aerosol deposition (e.g., Weathers et al. 2000) as well as hydrologic studies (e.g., Hutley et al. 1997, Holwerda et al. 2006) and isotopic studies (e.g., Dawson 1998, Corbin et al. 2005).

4.5. Isotopic differentiation between dry season fog and winter rain

A primary goal of the larger study is to determine the ecological importance of dry-season fog water inputs. Stable isotopes provide natural abundance tracers to address this question. The stable isotope approach relies on having substantial differences between the isotopic signatures of different water inputs, in this case dry-season (fog) and wet-season (primarily rain) precipitation. The isotopic results presented here show that dry season fog is sufficiently distinct to allow the use of isotopes to partition plant water uptake (e.g., Ingraham and Matthews 1995; Dawson 1998), and adds to the small number of studies examining the isotopic composition of fog water (reviewed in Scholl et al. 2005). Indeed, the isotopic offset between summer fog and winter rain is at least an order of magnitude greater than the measurement precision, providing further confidence in a water tracing study. As shown by Scholl et al. (2005), the northern California coast has the largest isotopic offset between fog and rain of any systems studied to date, primarily because the fog and rain seasons are distinct (summer versus winter).

5. Conclusion

Fog has long been recognized as an important water source along many coasts and on mountains around the globe. Quantifying the ecological importance of fog remains a challenging problem, both in terms of estimating total fog water inputs and in tracing these inputs through ecosystem components. Recent studies have focused on developing isotopic techniques to trace fog water through vegetation and soils, but this requires an unambiguous estimate of the original fog water isotopic composition. The collection of fog for isotopic analysis requires developing collectors with an appropriate set of design tradeoffs. The fog collector described here has proven useful in capturing fog water samples for isotopic and fog regime analyses. Ease of construction and maintenance allows mass deployments to characterize spatial as well as temporal dynamics of fog regimes. The new design has reduced rain water contamination compared to other designs examined. The reduced storage of fog water on the collection surface (compared to mesh collectors) also minimizes the risk of isotopic enrichment from evaporation of samples during prolonged, intermittent fog events.

The collector has been successfully deployed for two and a half years along a 7 km east-west transect on Santa Cruz Island, revealing spatial and temporal patterns in fog deposition. Higher elevation sites received much more fog deposition than lower sites. Western sites (near the coast) received most summer fog from the northwest and were correlated in timing and quantity. Sites farther east (inland) collected similar overall amounts of fog but from the east, and in fewer, larger events. These results demonstrate the spatial and temporal patchiness of fog and support the importance of spatially distributed sampling for ecological or hydrological fog studies.

The stable isotope composition of local fog water is shown to differ significantly from local rain water, allowing the use of isotopes as natural abundance tracers of the two source waters through the ecosystem (Dawson 1993, Dawson et al. 2002, Fischer et al. in prep).

Acknowledgements

This work was supported by the Andrew W. Mellon Foundation and UCSB. The fieldwork was performed at the University of California Natural Reserve System's Santa Cruz Island Reserve, on property owned and managed by The Nature Conservancy. Throughfall data were generously provided by J. Baker at UC Davis. We are grateful to J.B. Wall at CSU Northridge for long-term weather data, and to L. Laughrin and staff at the Reserve for weather records and field support. The manuscript was much improved with helpful comments from T.E. Dawson, O. Chadwick, A.P. Williams, T. Eckmann, and two anonymous reviewers. W.M. Fischer helped prepare the figures. We thank all the following for their assistance with fieldwork: C. Ebert, E. Thorsos, A.P. Williams, T. Eckmann , R. Richardson, M. Kelly, S. Battersby, J. Bernstein, A. Hartshorn, K. Cover, W. Amselem, E. Mason, R. Roff, N. Wilson, E. Edwards, J. Rumbly, J. Hecht, N. Nagle, P. Dennison, J. Baker, K. Hertel, Tim Laverne, and all the Geography 194 students.

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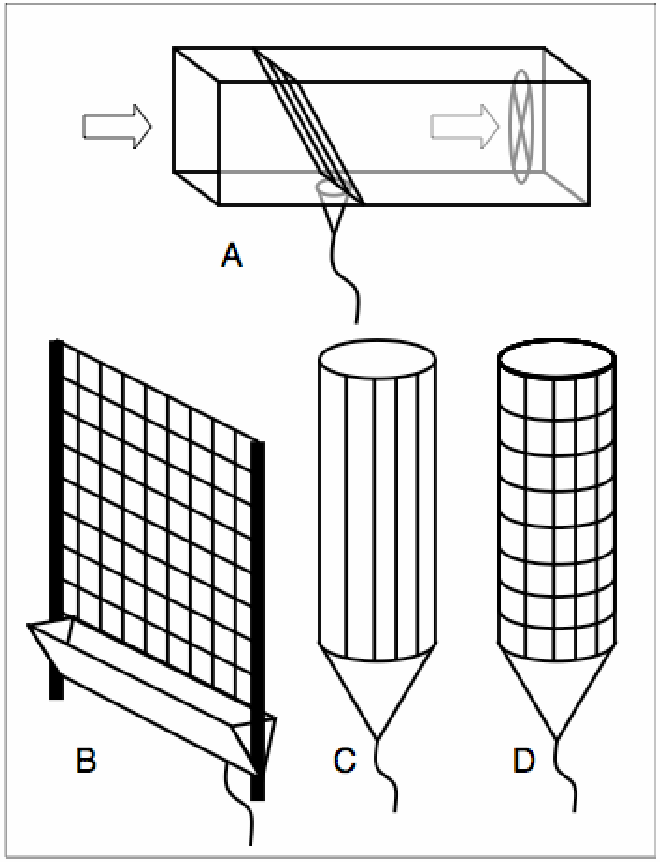

Fig. 1. Schematics of selected fog collector designs. CASCC active collector (A) draws air across a harp with a fan (Daube et al. 1987, Collett et al. 1989). Schemenauer passive mesh collector (B) is nursery shade cloth stretched between posts and oriented orthogonal to prevailing wind flows (Schemenauer and Cereceda 1994). Falconer passive harp collector (C) is cylindrical with wires/strings as collection surfaces (Falconer and Falconer 1980). Juvik passive mesh collector (D) is metal mesh wrapped in a cylinder (Juvik and Nullet, 1995).

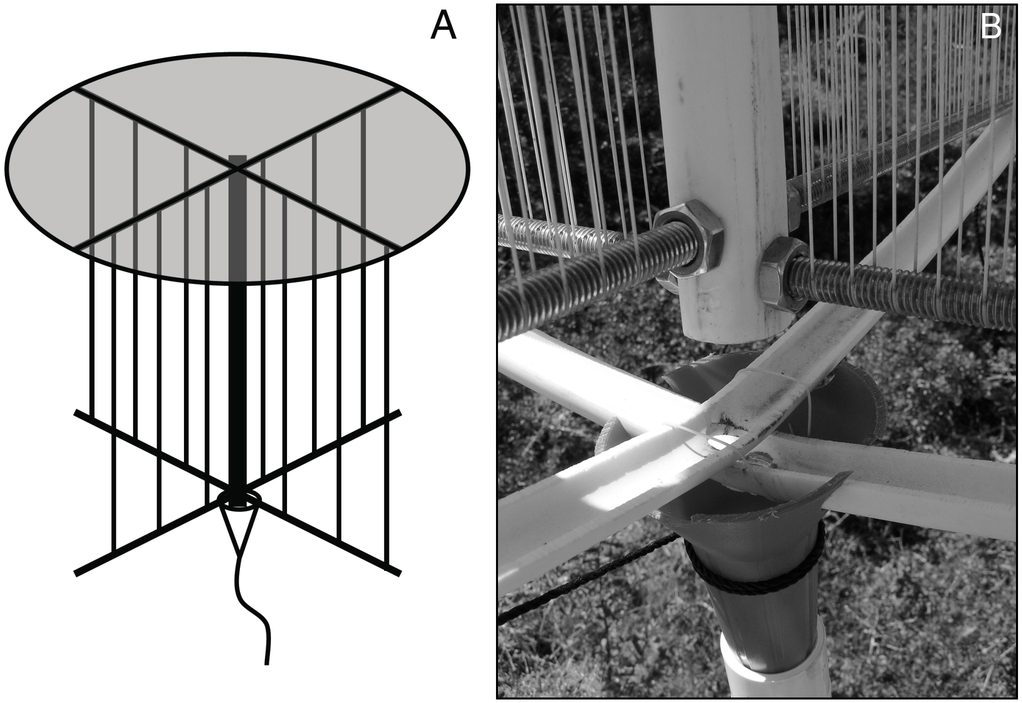

Fig. 2. Schematic of new fog collector design. Central column of PVC pipe supports cross arms of stainless steel threaded rod (***A***). Fog droplets collect on fishing line strung vertically between the cross arms. Fog water drips off the lower cross arms into troughs that drain into a central funnel (which has a screen to exclude debris) (***B***). From there, fog water can be metered through a rain gage or collected for isotopic analysis.

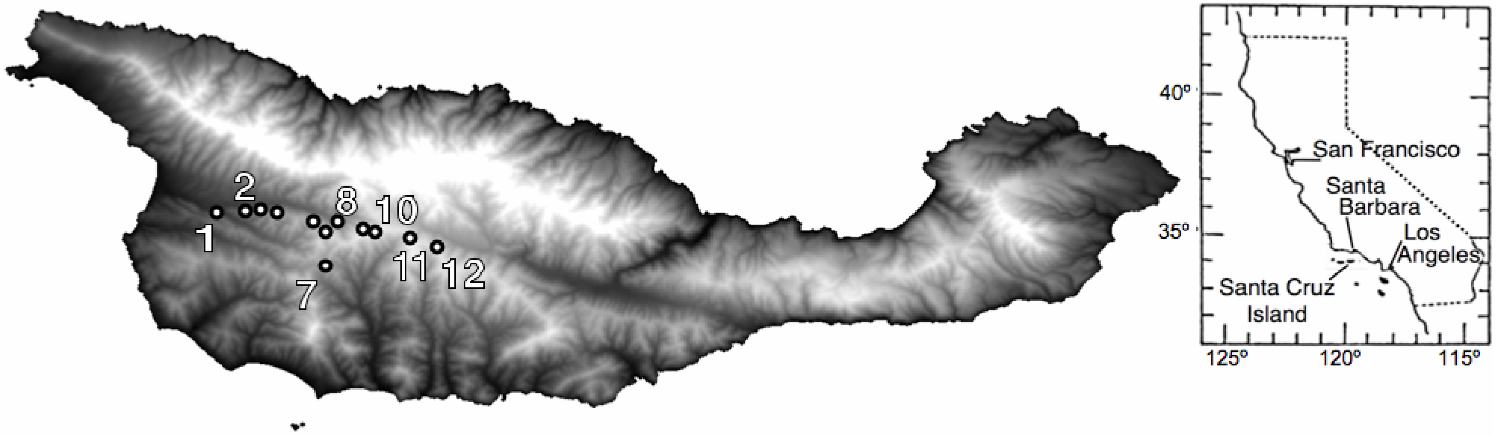

Fig. 3. Elevation map of Santa Cruz Island showing fog collector sites deployed on an E-W transect throughout the island's main stand of Bishop pines (*Pinus muricata* D. Don). Stations are numbered one to twelve, west to east (numbers shown for sites where dataloggers and paired fog collectors were installed). The island lies about 30 km off the coast of Southern California, is 38km long, and reaches 753m elevation. (Locator map redrawn with permission from Agenbroad et al. 2005.)

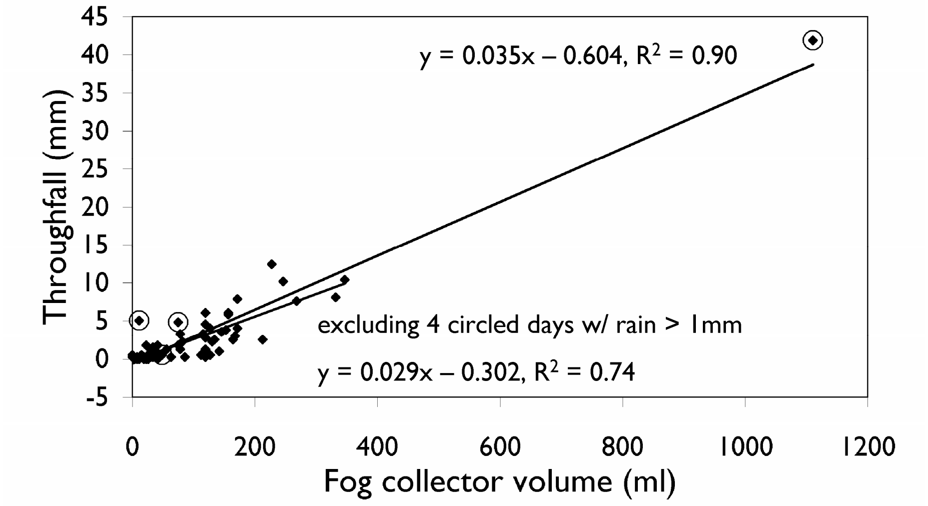

Fig. 4. Daily (noon to noon) throughfall at Site 10 versus collected fog water for 6/2 - 11/19/05. Throughfall is from a rain gauge placed under an adjacent tree canopy. The 164-day available record includes 4 days (circled) with rainfall > 1mm, and 80 days with measurable fog water collection.

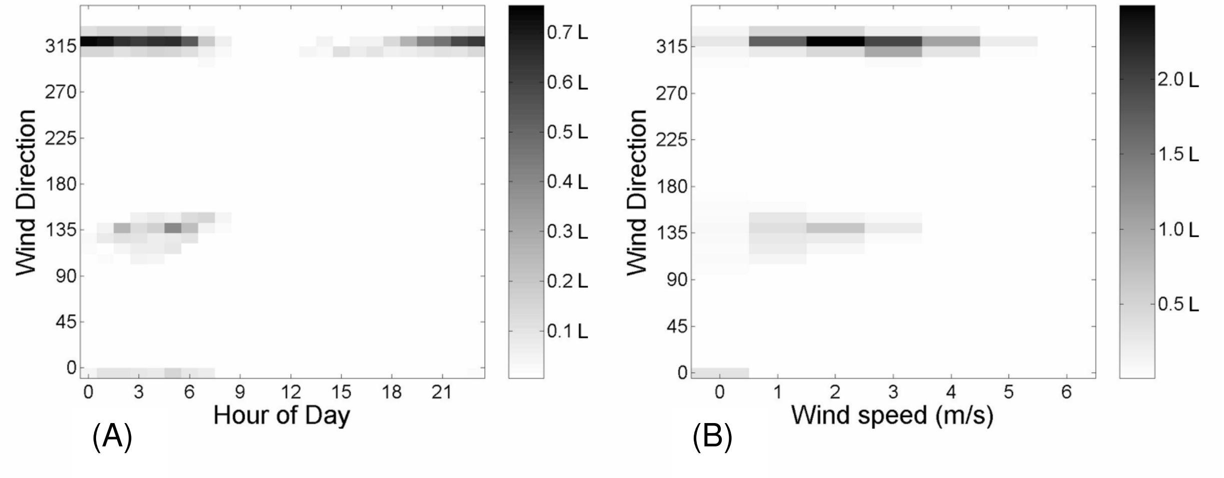

Fig 5. Total volumes of fog water collected (liters) as a function of wind direction at Site 7. The general summer pattern is of fog rolling in from the northwest in the evening, intensifying overnight, and then burning off in the morning (A). A second pattern is for fog to come from the southeast in the early morning. When winds are less than 0.25 m/s, fog is plotted as coming from 000 degrees. (B) shows total fog volume as a function of wind speed. Almost all fog water is collected with northwest winds at 2-3 m/s. Fog deposited from the southeast is associated with lower wind speeds. The fog regime shown for this site is typical of all but the easternmost two sites.

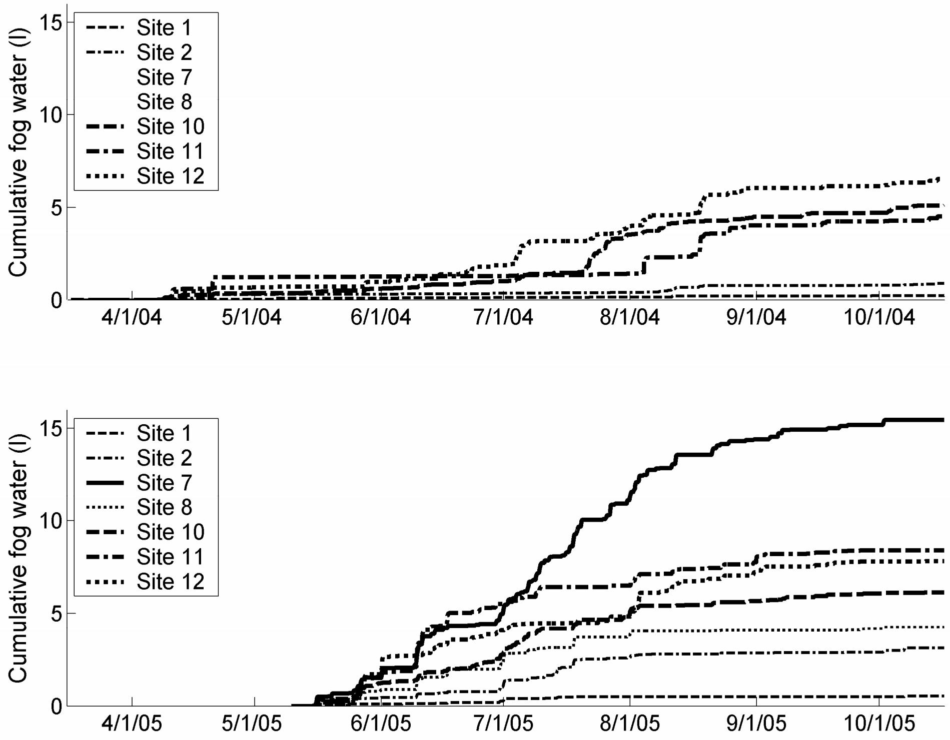

Fig. 6. Cumulative fog water (liters per site) collected during annual summer dry season on Santa Cruz Island. Five stations for 2004 (3/17-10/16) and seven stations for 2005 (5/9-10/16). Stations are listed West to East (1-12). Higher elevation stations (296-437m) are plotted with thicker lines and consistently record higher fog volumes than lower stations (61-200m). Occasional clogs by invertebrates during 2004 mean these values are lower limits on actual fog deposition.

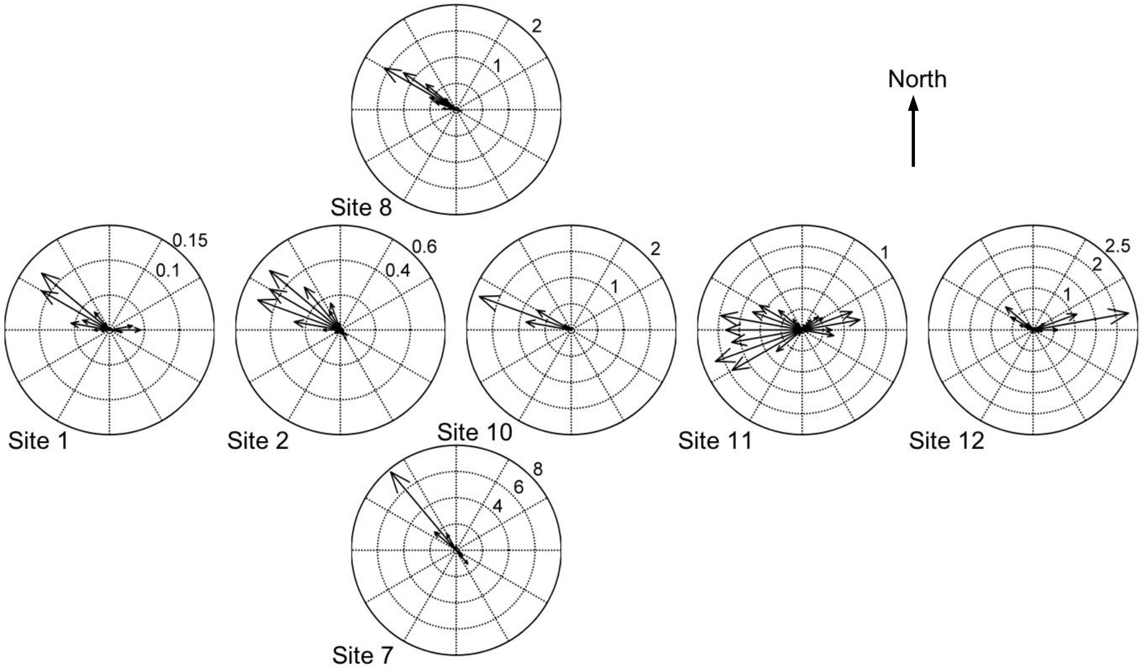

Fig 7. Fog deposition as a function of wind direction at seven weather stations on western Santa Cruz Island. Plots are arranged to represent relative station locations from west to east. Sites are numbered west to east along the main ridge. Sites 7 and 8 are south and north of the main ridge respectively. Lengths of arrows indicate the volume of fog water (liters) collected from each wind direction during the 2005 dry season (5/10/05-10/16/05). Note that the scale differs between plots to clearly show relative proportions. The western five stations all receive almost all fog water from the NW (with slight variation due to local topography). The eastern two stations, however, show increasing importance of fog from the east.

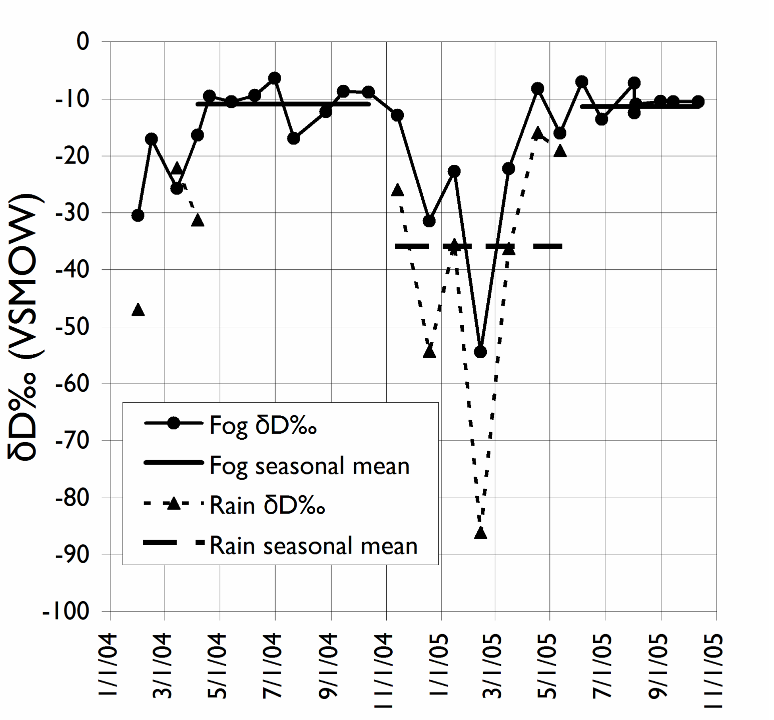

Fig. 8. Isotopic composition of fog and rain water at Site 7. "Fog" values for rainy months are a mixture of fog and rain water. Dry season fog water is consistently enriched compared to rainy season fog/rain water. Horizontal lines are seasonal means (volume-weighted after 11/1/04).

Location	Latitude (deg N)	Long. (deg W)	Elevation (m)	Collection surface area (m^2)	Fog volume (L/m^2)				Year	Reference
					Jun	Jul	Aug	Sep		
Montara Mtn.	37.5		550	0.4	293	235	166	-	1982	*Goodman, 1985*
CSUMB 3	36.7		76	"	-	7	27	3	2005	*Ruiz, 2005*
Glen Deven 1	36.4		292	0.6	-	-	108	12	2005	
Glen Deven 2	"		271	"	-	-	79	21	2005	
Site 1 (coastal)	34.0		61	0.093	2	2	0.04	0	2005	Current study
Site 2	"		147	"	8	16	3	0.4	2005	
Site 7	"		296	"	38	66	33	8	2005	
Site 8	"		200	"	18	14	2	1	2005	
Site 10	"		437	"	17	24	6	5	2005	
Site 11	"		402	"	43	11	17	4	2005	
Site 12 (inland)	"		387	"	25	8	26	6	2005	
San Miguel Is.	34.0		152	.35-.43	39-48	81-99	111-136	51-62	1995	*Estberg, 2001*
Torrey Pines	32.9		101	"	0.1	0.4	0.3	0.1	1995	

Table 1. Volume of fog water collected during summer dry season for several Coastal California studies. Collection volumes are normalized by one-sided collection surface area (silhouette area). Sites 1-12 are on a 7 km east-west transect on western Santa Cruz Island (Figure 3). Collection surface area for the current collector is 200 strands * 610 mm * 0.76 mm diameter. The planar harp used by Goodman had 500 strands, 0.8 mm diameter, strung vertically in a 1m by 1m frame. The planar harp used by Estberg had 1066 strands, 0.41mm diameter, strung on a rectangular frame with an area of 0.59 m^2. The dimensions of the rectangle are not given, hence the uncertainty of the collection surface area. The fog collector used by Ruiz has two layers of mesh with a combined estimated 40% void space on a 1m by 1m frame. While there is much interannual variability in fogginess (Leipper 1994), these data support generally increased fogginess with altitude, latitude along California (Filonczuk et al. 1995), and farther west in the Channel Islands.

	Elevation (m)	**Nights with fog (of 160)**	**Total collected L/m^2**	**Avg. nightly L/m^2**	**Avg. for foggy nights**	**Max nightly L/m^2**	**Max rate L/hr/m^2**
	(A)	(B)	(C)	(D)	(E)	(F)	(G)
Site 1	61	24	5.7	0.04	0.24	1.32	0.48
Site 2	147	48	33.5	0.21	0.70	4.13	1.12
Site 7	296	83	166.2	1.04	2.00	11.35	0.96
Site 8	200	32	45.6	0.28	1.42	6.33	2.08
Site 10	437	73	65.9	0.41	0.90	3.73	2.73
Site 11	402	64	90.2	0.56	1.41	13.91	1.92
Site 12	387	60	83.9	0.52	1.40	9.86	2.03

Table 2. Volumes of fog water collected on Santa Cruz Island during summer dry season of 2005 (160 nights: 5/10-10/16/05). All volumes are normalized to the collector silhouette area of 0.093m^2. "Nights" for this table are 24 hours from noon to noon – so that individual overnight fog events are not split at midnight into separate days. Column D = Column C / 160, while Column E = Column C / Column B. Column G is maximum 15-minute collection rate, reported in the more common units of liters/hour. Site 7, which received the most fog, is slightly south of the main West (Site 1) to East (Site 12) transect. Site 7 not only has the greatest volume, but also the most nights with fog, and the highest volume of water collected per foggy night. Note Site 10 received 22% less fog than the lower elevation Site 12 farther east/inland. But Site 10 actually had 22% more nights with fog than Site 12. Despite relatively low average collection rates, Site 10 had the highest instantaneous collection rate.