A Hawaiian mountain climate cross-section

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ABSTRACT: This study analyzes 2 yr of surface climatological measurements at 6 sites forming a windward/leeward mountain cross-section on Hawai'i Island. Sites range in elevation from sea level to 2600 m and include wet, windward and dry, leeward slopes below the trade wind temperature inversion and a high elevation site located in the cool, dry air above the inversion. Climate contrasts between sites are emphasized using monthly average values. Data for the 670 m elevation leeward site represent some of the first climatological measurements of a unique leeward transition zone between areas of summer and winter rainfall maxima.

KEY WORDS: Hawaii · Mountain · Climate

INTRODUCTION

Only recently have climatologists begun detailed climate studies of Hawaiian mountains. While the general circulation and rainfall patterns have long been known, few meteorological stations had been emplaced and maintained in mountainous areas for any length of time, with the exception of Mauna Loa Observatory (MLO) at 3400 m on Hawai'i Island. Since 1980, however, the results of a number of climatological networks have been reported covering a wide variety of sensors. Ekern (1983) reported several years of data, including evaporation and solar radiation, for transects into the Ko'olau mountains on 'Ōahu. Giambelluca & Nullet (1991) maintained a transect between 950 and 3000 m on leeward Haleakalā, Maui, for several years, primarily to study the climate through the trade wind inversion. Nullet (1989) summarized several years of measurements between sea level and 1650 m that had been gathered for agricultural research on the northwest flank of Haleakalā. Chen & Nash (1994) and Chen & Wang (1994) analyzed 40 d of measurements at 50 sites on the island of Hawai'i giving a comprehensive picture of the island's surface airflow, rainfall, temperature, and humidity patterns under summer trade wind conditions. Juvik et al. (1993) and Juvik & Nullet (1994) reported the results of a climate transect through the wet windward rainforest and the climate of a high elevation dry forest on the island of Hawai'i. The current study expands the

data presented in the latter 2 articles and includes a new site at 670 m on leeward Hawai'i, a site representing 'the area between Mauna Loa and Hualālai (which) has little weather information (Schroeder 1993)', lying in a unique transition zone between areas of summer and winter rainfall maxima.

While the data presented here characterize the climate of mountains in Hawai'i, the results should have direct analogies on other high volcanic islands in the trade wind belts with little measured data, such as Tenerife (3718 m) in the Canary Islands, Fogo (2829 m) in the Cape Verde Islands, and La Reunion (3069 m) in the Mascarene Islands.

STUDY SITE AND MEASUREMENTS

The 6 meteorological stations are located between sea level and 2600 m on the island of Hawai'i (Fig. 1), which lies at the southeast end of the Hawaiian Island chain at approximately 19° to 20° N, 155° to 156° W. Over the open ocean, northeast trade winds prevail 80 to 95 % of the time in summer (May through September) but diminish in frequency during winter to as little as 50 % in January (Blumenstock & Price 1967). The trade wind inversion (a subsidence temperature inversion in the descending limb of the Hadley cell circulation present 70 % of the time at 1800 to 2400 m) suppresses cloud development and limits average annual open ocean rainfall to 500–600 mm. Three large shield
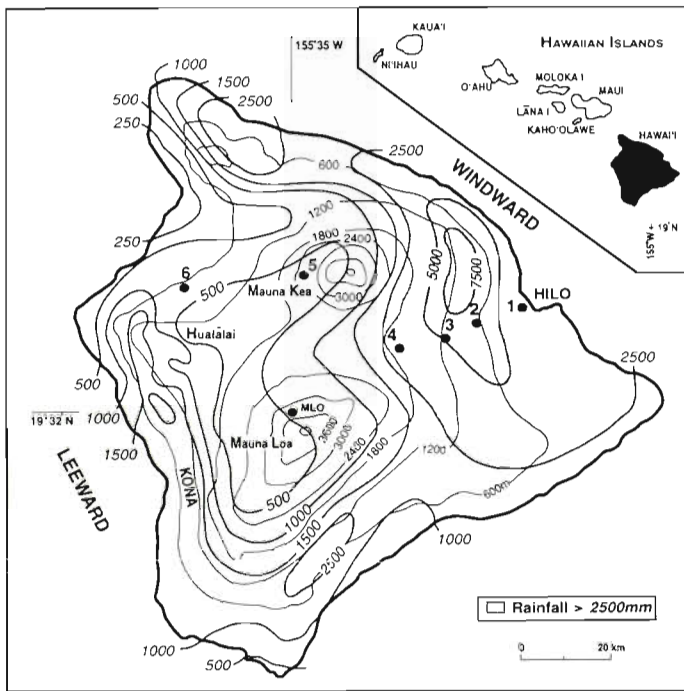
Fig. 1. Station locations, Hawai'i. Rainfall (mm; thick contour lines) from Giambelluca et al. (1986) and Armstrong (1983). 1: UH-Hilo (55 m); 2: Lower Saddle (710 m); 3: Middle Saddle (1130 m); 4: Upper Saddle (1650 m); 5: Pu'u La'u (2600 m); 6: Pu'uanahulu (670 m). MLO: Mauna Loa Observatory (3400 m). Elevations in m (thin contour lines)

volcanoes on Hawai'i rise well above the usual level of the inversion and thus host distinctly separate climates above (cool and dry) and below (warm and humid) that layer. In addition, the interaction of the mountains and prevailing trade wind flow generates wet windward slopes and a dry leeward rainshadow. The cross-section of stations included in this report includes measurements in the major climate zones: a wet, windward transect from sea level to the inversion level and dry, leeward sites above and below the inversion (see Fig. 1).

Each automated meteorological station (Campbell Scientific, Logan, UT, USA) recorded global solar radiation, photosynthetically active radiation, air temperature and relative humidity at 2 m, wind speed and direction at 3 m, soil temperature at 1 cm, leaf wetness, and rainfall. Net radiation was recorded at all but the Upper and Middle Saddle sites. Hourly maxima and minima were recorded as well as hourly totals for rainfall and hourly averages for all other variables. This report contains all data collected from 1 November 1992 through 31 October 1994. This provides the complete data record to date for the Pu'-

uanahulu and University of Hawai'i at Hilo (UH-Hilo) sites and continuity to previously reported data for the other stations. In this study, we analyze monthly total and average values summarized from the hourly measurements.

RESULTS

Climatological measurements during the 2 yr study are summarized in Table 1. Missing periods of record for individual instruments (due to site vandalism or faulty sensors) are also given in Table 1. Evaporation was estimated using the Penman-Monteith method (Monteith 1965). While the data are in general agreement with previously published results, there are several noteworthy features of the climate cross-section. These are discussed below.

Wind

Seemingly indifferent to the synoptic trade wind field, surface flow fluctuates in a diurnal rhythm as the mountain 'breathes' each day. Both land-sea and land-free atmosphere temperature differences drive the daily thermal circulation that controls surface winds. Under light synoptic wind conditions, this daytime convergence
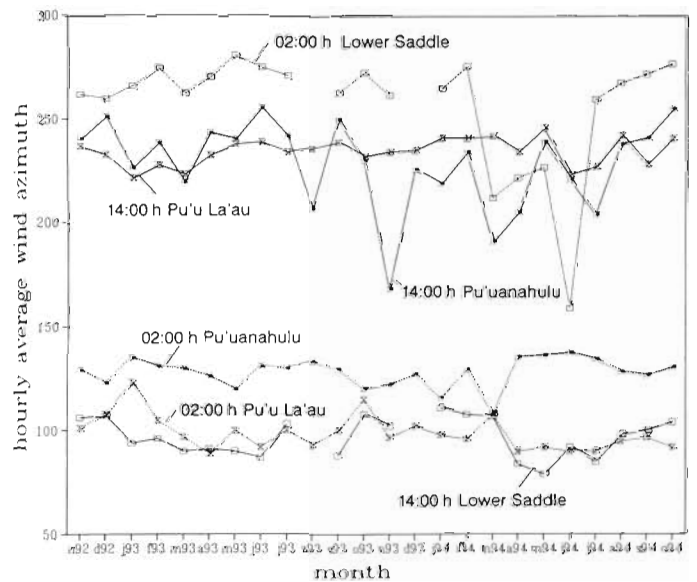

Fig. 2. Monthly average wind direction for the hours ending at 02:00 and 14:00 h HST (Hawaiian Standard Time) showing the consistency of the diurnal wind reversal at all locations. Mirror image wind direction patterns occur of opposing windward (Lower Saddle) and leeward (Pu'uanahulu and Pu'u La'au) slopes

of the winds toward the mountain summits can bring a torus of clouds and rain to the upper slopes. Fig. 2 shows the average wind direction for 02:00 and 14:00 h HST (Hawaiian Standard Time) for leeward and windward sites below the inversion and the leeward high elevation site. Daytime winds over our windward stations were almost due easterly, corresponding closely with results given by Chen & Nash (1994) based on 40 d of measurements between 11 July and 24 August 1990. The correspondence is good for the nighttime winds at leeward sites as well, with winds directly downslope as would be expected under gravity drainage of cool air.

Our measurements differ, however, for the daytime winds at the leeward sites. As shown in Fig. 2, the daytime surface wind azimuth converges for the 2 leeward sites to approximately 220 to 230°. This trajectory is consistent with the heavy, upslope fog that predominates between the 2 locations on the leeward slopes of Mauna Kea. During Chen & Nash's (1994) study, daytime winds near the Pu'uanahulu site averaged northwesterly (14:00 h HST), an upslope trajectory, rather than southwesterly, a parallel slope trajectory, as prevailed for all months except one during our study period.

Wind speed averaged less than 2 m s^{-1} for all sites except Pu'uanahulu (Table 1). At the leeward sites, maximum wind speeds at Pu'uanahulu (typically observed in early afternoon) nearly double those observed above the inversion at Pu'u La'au, despite virtually identical net radiation values (and by implication, identical surface air heating). This is presumably a consequence of a greater upslope area of heating for the lower site. The diurnal wind speed pattern is similar for all sites with daytime upslope wind speeds exceeding the nighttime drainage wind speed. As has been documented on Haleakalā, Maui (Giambelluca & Nullet 1991), a dip in wind speed accompanies the diurnal wind direction reversals in early morning and late afternoon.

Moisture

Diurnal wind patterns and the free atmosphere temperature and humidity profiles play major roles in the availability of water on the mountain slopes. The diurnal movement of air up and down slope carries with it a thin skin of source air. The cool, dry nighttime drainage winds [measured at 55 m depth by Mendonca (1969)] originate above the inversion while the daytime upslope winds bring a layer of moist, marine surface air (600 m depth; Mendonca 1969) through the inversion layer. This has the effect of creating opposing diurnal relative humidity patterns above and
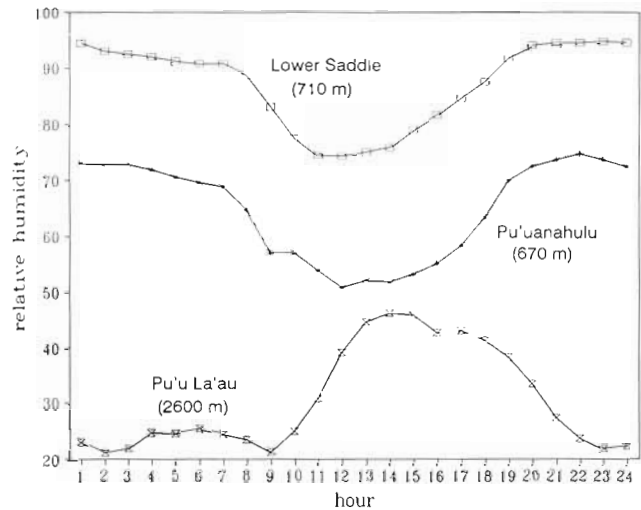
Fig. 3. Comparative diurnal relative humidity curves for February 1993. The humidity is lower on leeward slopes (Pu'uanahulu) than windward slopes (Lower Saddle) at similar elevations. Above the inversion (Pu'u La'au), the diurnal pattern reverses, with higher relative humidity values during daylight hours as moist air penetrates the inversion layer and increases the vapor pressure at the site

below the inversion as shown in Fig. 3 for February 1993.

The diurnal thermal circulations account for most of the variance (64 to 90%) in rainfall frequency over the island (Schroeder et al. 1977), producing afternoon maxima at most locations (associated with upslope winds and attendant cloud formation) and nocturnal maxima along windward coastlines as nighttime drainage winds converge with onshore trade wind flow. This pattern is interrupted during non-trade wind conditions and during periods when winter synoptic events, such as frontal passages and disturbances associated with upper-level troughs. In a comparison of rainfall totals at Pu'u La'au and Pu'uanahulu to test the association of rainfall-producing mechanisms above and below the inversion, winter rainfall (October through March, largely a consequence of synoptic events) was highly correlated (r = 0.80), while summer rainfall (April through September, a consequence of local circulations under strong trade wind inversion conditions) showed virtually no correlation at all, i.e. rainfall occurred on different days with no significant correlation in amount.

Other sources of moisture to the surface include cloud water and dew. Direct interception of cloud droplets can provide a significant source of moisture above the cloud base at 600 to 800 m. The ecological importance of cloud water interception increases as average rainfall decreases. At the Pu'u La'au site, for example, cloud water collection from a louvered fog

Table 1 Monthly summary data. Averages are given for all climate elements except rainfall, for which total values are given. Some months include incomplete data; details given under 'Missing data'. Abbreviations, where given, refer to 'Missing data'

Station	Elev (m)	1992 Nov	Dec	1993 Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	1994 Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Avg
Global solar radiation (W m⁻²) (GR)																										
UH-Hilo	55	–	–	–	–	–	–	–	–	–	–	–	–	137	101	137	115	160	175	188	200	194	176	155	173	159
Lower Saddle	710	97	97	115	130	163	166	155	155	132	–	113	115	109	–	106	97	152	–	–	–	142	153	128	141	130
Middle Saddle	1130	103	103	132	146	178	176	170	176	140	164	156	113	118	104	124	104	134	161	158	160	181	160	136	141	143
Upper Saddle	1650	125	126	175	201	233	228	222	230	176	–	183	139	141	145	157	133	167	204	208	201	232	211	171	172	182
Pu'u La'au	2600	153	163	198	255	265	278	272	270	229	250	221	186	199	194	197	163	226	268	269	261	238	243	211	218	226
Pu'uanahulu	670	125	139	176	214	240	198	227	203	221	244	208	172	192	164	167	157	210	236	233	226	230	237	209	201	201
Net allwave radiation (W m⁻²) (NR)																										
UH-Hilo	55	–	–	–	–	–	–	–	–	–	–	–	–	–	86	103	93	130	149	130	159	–	–	–	–	121
Lower Saddle	710	–	–	63	79	107	116	112	115	99	–	81	79	73	–	71	66	102	–	–	–	65	83	90	96	88
Middle Saddle	1130	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Upper Saddle	1650	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Pu'u La'au	2600	66	70	84	110	133	137	147	146	137	146	135	117	101	87	97	92	146	167	–	136	134	140	127	113	120
Pu'uanahulu	670	68	74	99	117	147	123	147	138	155	176	151	96	105	86	93	95	146	158	160	140	–	152	125	114	125
Photosynthetically active radiation (μEinsteins s⁻¹ m⁻²) (PAR)																										
UH-Hilo	55	–	–	–	–	–	–	–	–	–	–	–	–	255	202	247	204	228	248	329	359	349	302	230	270	269
Lower Saddle	710	206	201	229	260	326	321	300	311	265	–	207	216	199	–	186	170	261	–	–	–	249	265	249	274	247
Middle Saddle	1130	214	212	263	293	356	350	344	355	287	333	307	228	229	193	226	193	245	288	283	284	326	286	243	253	275
Upper Saddle	1650	238	237	340	391	444	432	410	433	310	–	330	244	236	240	286	232	284	324	345	321	394	343	262	278	320
Pu'u La'au	2600	265	286	341	438	458	479	476	473	410	444	396	333	348	334	340	291	390	460	463	451	418	426	372	378	395
Pu'uanahulu	670	267	295	–	–	491	410	469	421	463	507	433	361	396	337	342	327	364	480	457	465	476	489	434	414	414
Air temperature (°C) (Ta)																										
UH-Hilo	55	–	–	–	–	–	–	–	–	–	–	–	–	21.7	20.8	20.0	20.7	21.0	21.4	21.9	22.7	23.9	23.0	23.1	23.2	22.0
Lower Saddle	710	21.1	21.2	17.8	16.2	18.9	19.5	–	–	–	–	19.6	19.0	16.4	–	15.0	16.8	18.9	–	–	–	19.4	19.7	19.3	18.8	18.6
Middle Saddle	1130	16.3	15.1	13.7	12.6	13.8	14.7	14.7	16.2	16.8	17.6	17.2	16.6	14.2	13.7	13.2	12.4	13.9	14.5	15.1	16.0	17.3	17.5	17.3	16.4	15.3
Upper Saddle	1650	13.8	12.4	11.4	10.7	11.7	12.2	12.0	13.9	14.2	–	15.3	14.2	11.8	11.5	11.0	12.0	11.4	12.2	12.8	13.6	15.4	15.3	15.0	13.9	12.9
Pu'u La'au	2600	10.1	9.9	9.1	9.4	9.1	10.6	9.7	11.9	11.3	12.3	11.5	11.0	9.7	11.1	9.0	8.1	8.4	9.3	10.9	11.3	12.5	12.3	11.6	11.1	10.5
Pu'uanahulu	670	16.4	19.2	17.4	17.3	18.4	19.4	20.1	20.8	21.6	22.3	21.8	20.8	19.5	18.1	17.7	18.4	18.7	19.7	20.3	20.7	22.1	22.5	22.2	21.0	19.9
Soil temperature (°C at 1 cm) (Ts)																										
UH-Hilo	55	–	–	–	–	–	–	–	–	–	–	–	–	25.9	24.1	23.8	23.2	25.0	26.0	26.8	27.7	28.9	26.9	27.1	26.4	26.0
Lower Saddle	710	19.6	18.6	16.9	16.6	18.5	19.5	19.5	20.6	20.5	–	21.1	20.6	18.4	–	16.8	17.9	18.5	–	–	–	21.4	21.5	21.1	20.5	19.4
Middle Saddle	1130	17.4	16.1	14.3	14.2	15.7	16.7	16.9	18.4	18.1	19.2	18.6	18.0	15.7	15.2	14.4	15.3	15.9	16.5	17.1	18.0	19.2	19.2	18.7	17.8	16.9
Upper Saddle	1650	14.0	13.0	10.9	12.4	13.4	14.1	13.3	15.2	14.9	–	15.9	14.6	12.2	11.5	10.8	12.1	12.1	13.2	13.7	14.3	15.6	16.0	15.6	14.5	13.6
Pu'u La'au	2600	10.7	9.5	8.2	13.9	15.5	14.7	17.9	20.8	17.3	19.3	16.6	12.3	11.0	11.7	10.5	8.9	12.0	14.7	–	16.1	15.4	16.4	13.8	14.6	14.2
Pu'uanahulu	670	17.2	20.0	18.6	20.8	22.6	23.3	25.2	24.3	25.4	27.1	24.4	22.5	22.0	19.9	19.5	20.1	21.8	24.7	25.0	24.3	26.1	26.7	25.6	24.0	23.0
Wind speed (m s⁻¹)																										
UH-Hilo	55	–	–	–	–	–	–	–	–	–	–	–	–	1.2	1.0	1.1	0.9	1.4	1.2	1.1	1.1	1.1	1.0	1.0	1.2	1.1
Lower Saddle	710	1.0	1.1	1.3	1.2	1.2	1.2	1.1	1.1	1.1	–	1.0	1.0	0.9	–	1.0	1.0	1.1	–	–	–	1.1	1.1	1.1	1.2	1.1
Middle Saddle	1130	0.9	0.9	1.3	1.1	1.0	1.1	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.9	1.0	0.9	0.9	0.9	1.0	0.9	0.9	0.9	1.0
Upper Saddle	1650	1.2	1.2	1.3	1.3	1.5	1.6	1.3	1.4	1.5	1.2	1.2	1.2	1.3	1.2	1.3	1.2	1.6	1.6	1.5	1.5	1.5	1.4	1.3	1.3	1.4
Pu'u La'au	2600	1.4	1.5	2.3	1.7	1.8	1.6	1.4	1.5	1.3	1.4	1.3	1.6	1.4	1.6	1.5	1.4	1.5	1.5	1.5	1.5	1.5	1.3	1.3	1.4	1.5
Pu'uanahulu	670	–	1.9	2.3	2.3	2.4	2.2	2.3	2.1	2.3	2.4	2.1	2.0	2.6	2.2	2.2	1.8	2.1	2.4	2.3	2.4	2.4	2.3	2.2	2.1	2.3

Relative humidity (%) (RH)

Station	Elev.																						
UH-Hilo	55	–	95	–	–	–	–	–	–	–	–	–	83	84	86	87	88	88	90	91	86	87
Lower Saddle	710	–	87	94	88	88	87	91	93	89	92	80	81	84	93	90	94	93	95	94	96	90
Middle Saddle	1130	–	87	88	80	88	89	93	94	89	92	93	93	93	89	91	92	94	94	93	92	91
Upper Saddle	1650	–	90	80	86	80	76	94	94	92	93	90	95	93	92	93	90	95	95	94	93	90
Pu'u La'au	2600	–	52	61	58	43	31	59	57	50	66	54	58	55	55	63	67	69	73	69	62	56
Pu'uanahulu	670	60	60	77	80	69	65	66	66	72	71	68	71	73	70	78	75	76	70	74	73	71

Leaf wetness (% of time wet)

Station	Elev.																					
UH-Hilo	55	–	41	45	20	35	18	35	49	43	53	46	56	58	58	48	59	53	43	52
Lower Saddle	710	–	61	57	34	50	38	55	63	58	54	33	39	35	–	42	49	49	39	40
Middle Saddle	1130	–	58	57	34	46	36	53	65	48	61	47	63	58	69	52	60	60	48	54
Upper Saddle	1650	–	12	10	9	5	0	9	13	42	66	59	60	59	68	48	56	67	60	54
Pu'u La'au	2600	–	12	10	13	6	9	2	11	9	8	16	8	10	10	10	12	17	10	9
Pu'uanahulu	670	–	6	14	4	2	4	6	6	8	6	3	6	4	5	8	3	7	5	8

Rainfall (mm)

Station	Elev.																					
UH-Hilo	55	–	808	762	–	485	243	293	362	1019	94.0	291	–	–	487	–	635	396	–	445	273	438	719	233	412
Lower Saddle	710	–	611	552	84.9	336	139	215	205	762	178	317	–	289	829	557	635	396	664	652	951	885	336	520
Middle Saddle	1130	–	364	305	60.5	181	69.3	–	101	506	306	312	438	230	561	317	402	266	415	519	633	539	244	354
Upper Saddle	1650	–	117	148	23.6	2.0	69.3	36.1	12.7	36.6	14.2	152	252	165	308	189	182	118	181	334	338	261	118	206
Pu'u La'au	2600	–	13.5	74.5	2.5	10.7	13.6	2.3	21.0	15.5	17.9	6.9	7.1	65.0	110	–	10.2	13.2	45.2	80.5	–	88.9	17.0	42
Pu'uanahulu	670	–	21.4	101	3.4	13.6	5.9	36.1	21.0	65.1	66.2	0.2	1.4	62.8	42.4	0.0	13.9	27.5	20.2	–	4.1	21.3	40.2	28

Climatic average rainfall (mm)[a]

Station	Elev.																					
UH-Hilo	55	350	370	300	350	410	250	170	240	230	270	350	370	410	250	350	250	170	240	300	230	300	270	296
Lower Saddle	710	530	520	400	600	650	500	280	480	320	400	530	520	650	500	600	500	280	480	550	320	550	400	479
Middle Saddle	1130	430	490	330	480	470	300	200	330	240	270	430	490	470	300	480	300	200	330	410	240	410	270	360
Upper Saddle	1650	250	300	220	250	270	190	130	210	150	170	250	300	270	190	250	190	130	210	280	150	280	170	218
Pu'u La'au	2600	40	40	50	50	50	30	20	25	40	40	40	40	50	30	50	30	20	25	50	40	50	40	42
Pu'uanahulu	670	40	40	50	60	65	50	35	25	30	55	40	40	65	50	60	50	35	25	30	30	30	55	46

Estimated evaporation (mm d^{-1})

Station	Elev.																					
UH-Hilo	55	1.8	1.4	2.1	3.1	2.9	3.1	3.2	2.7	2.4	2.1	3.1	2.5	3.6	4.1	3.6	4.5	4.5	3.6	3.9	3.4	3.9	3.6
Lower Saddle	710	1.5	1.4	2.2	3.0	2.9	3.0	3.2	2.6	2.5	1.9	1.9	–	2.9	–	–	1.8	–	–	2.2	2.4	2.5	2.3
Middle Saddle	1130	1.6	1.8	3.1	3.8	3.8	3.0	2.6	3.0	1.9	1.8	1.6	1.5	2.2	2.7	2.8	3.2	2.8	2.7	2.2	2.3	2.3	2.4
Upper Saddle	1650	1.8	1.8	3.1	3.6	3.8	3.7	3.1	3.1	2.1	1.9	1.9	1.9	2.4	3.0	3.1	3.7	3.1	3.2	3.3	2.6	3.3	2.5	2.8
Pu'u La'au	2600	1.9	1.9	2.5	3.1	3.4	3.6	3.8	3.4	2.9	2.7	2.7	2.7	3.5	4.0	3.7	3.5	3.4	3.7	3.5	3.1	3.5	2.9	3.1
Pu'uanahulu	670	2.2	2.2	2.9	3.4	3.6	4.3	4.0	4.6	2.9	2.9	3.2	2.6	4.1	4.6	4.1	4.3	4.6	4.6	4.6	3.8	4.6	3.4	3.7

[a]From Giambelluca et al. (1986)

Missing data

UH-Hilo — 14 Apr to 16 May 1994 (all); 20 Jun to 31 Jul 1994 (Ts); 2 Jul to 9 Jul 1994 (all)

Lower Saddle — 1 Nov to 31 Dec 1992 (NR); 31 Dec 1992 to 16 Jan 1993 (rainfall); 25 to 30 Apr 1993 (RH, Ta); 1 to 17 May 1993 (Ta); 18 May to 31 Jul 1993 (RH, Ta); 1 Aug to 19 Sep 1993 (all); 1 to 14 Nov 1993 (all); 1 Dec 1993 to 16 Jan 1994 (all); 15 Mar to 30 Jun 1994 (Ta, Ts, NR, GR, PAR); 2 Jul 1994 (all)

Middle Saddle — 17 to 18 Apr 1994 (all); 2 to 3 Jul 1994 (all)

Upper Saddle — 28 Nov to 6 Dec 1992 (RH, Ta); 1 Aug to 12 Sep 1993 (all); 17 to 18 Apr 1994 (all); 2 to 3 Jul 1994 (all)

Pu'uanahulu — 26 to 30 Nov 1992 (all); 29 Jul to 3 Aug 1993 (all); 17 Apr 1994 (all); 2 Jul 1994 (all); 10 to 24 Aug 1994 (all)

Pu'u La'au — 1 to 9 Jan 1993 (Ta); 7, 9, 15, and 20 Jan 1994 (Ts); 7, 9, 15 to 18, and 20 Jan 1994 (Ta); 16 Jan 1994 (all); 13 Feb to 13 Mar 1994 (all); 10 to 28 Aug 1994 (all)
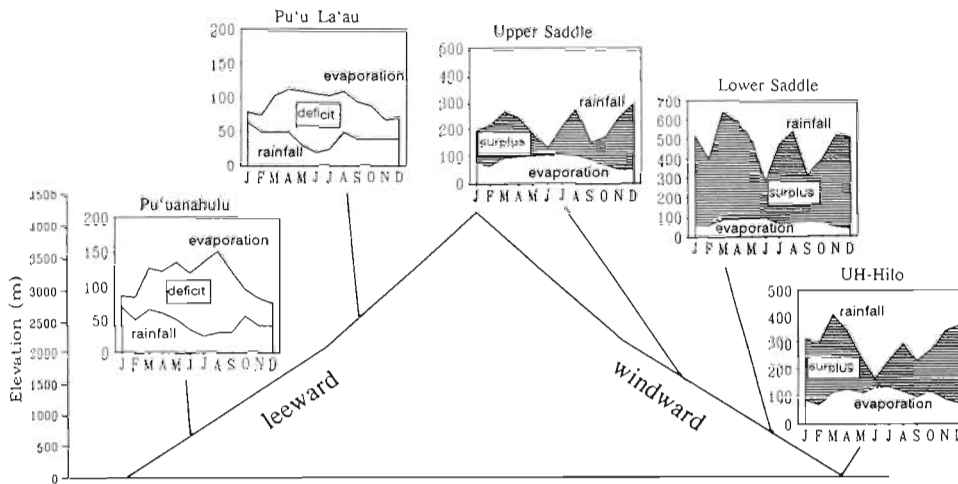
Fig. 4. Climate diagrams for the mountain cross-section. On average, rainfall greatly exceeds evaporation on windward slopes, while the reverse is true of leeward areas

gauge (25.8 mm) exceeded rainfall (17.5 mm) during an exceptionally dry 5 mo period, February through June 1992 (Juvik & Nullet 1995). Dew does not appear to be an ecologically significant source of moisture at the dry leeward sites in this study, as suggested by negligible nighttime leaf wetness frequencies. High nighttime relative humidity values suggest dew formation at the wet windward sites, although at these high rainfall locations, vegetation seldom experiences moisture deficits and thus would not necessarily benefit by added moisture from dew and cloud water.

The atmospheric evaporative demand determines, in part, moisture availability and stress on vegetation. On windward slopes, rainfall exceeded estimated evaporative demand for all months except January and February 1993, and March 1993 at 1650 m. For leeward locations, estimated evaporative demand exceeded rainfall during 21 of the 24 months at the 2600 m elevation site, and 22 of 24 months at the 670 m elevation site. Consistent with implied high moisture stress, both areas support dryland vegetation: open forest with bunch grass ground cover. The relationship between rainfall and estimated evaporation under normal climatic conditions is illustrated in Fig. 4. This figure compares only the magnitudes of rainfall and evaporation and generally sets an upper limit on the average moisture availability to plants as a complete water balance would show that much of the rainfall input quickly infiltrates into the porous substrate and is not available to meet the evaporative demand.

Radiation

Fig. 5 shows elevation profiles of measured solar radiation as a percentage of modeled clear day values

(Bird & Riordan 1986). On windward slopes, maximum attenuation of solar radiation occurs at 700 m, near the rainfall maximum (and, by inference, the cloud cover maximum). Results correspond well with similar measurements reported for Maui, although attenuation at 2600 m exceeds that for a comparable exposure and elevation on Haleakalā (Giambelluca & Nullet 1991), suggesting greater cloudiness on the larger mountain. The contrast between the attenuation of solar radiation on upper and lower mountain slopes is much greater on windward than leeward exposures.

At Pu'uanahulu, net radiation exceeded the average value at Pu'u La'au despite receiving about 11% less
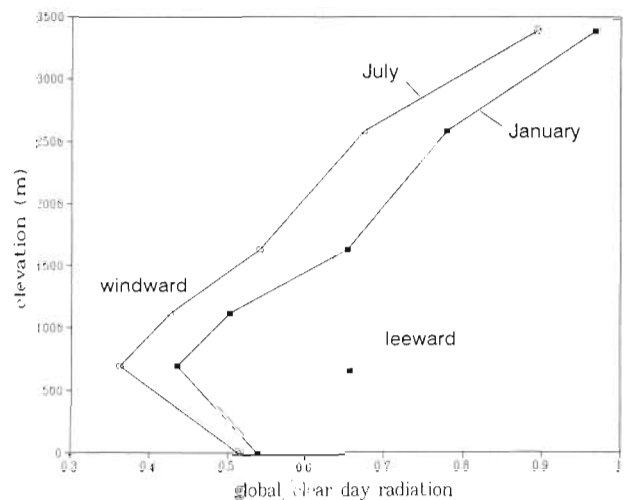
Fig. 5. Measured solar radiation as a percentage of clear-day radiation for January and July showing the reduction by cloud cover. Data for 3400 m are long-term averages for Mauna Loa Observatory (see Fig. 1) for comparison. Annually, clear skies occur more frequently during the cooler winter months, while in summer convective heating and stronger trade winds lead to increased cloud cover

solar radiation, a consequence of generally clearer skies and less far infrared absorption in the dry air above the inversion. For example, nighttime longwave radiation loss at Pu'u La'au averaged about 20 W m^{-2} higher than at Pu'uanahulu. At comparable elevations, net radiation averaged a higher fraction of solar radiation at the windward Lower Saddle site than at the leeward Pu'uanahulu site. The photosynthetically active component generally decreased as a percentage of solar radiation with elevation within the range of 35 to 45%.

Temperature

The annual range in average monthly air temperature was similar (less than 6°C) at all sites, although the soil temperature range stratifies by elevation and exposure. At the wet windward sites, average air and soil temperatures are nearly equal, indicating that the air layer near the ground is in thermal equilibrium with the surface. On leeward slopes, however, soil temperature greatly exceeds air temperature as a consequence of lower soil moisture and less canopy shading of the surface. For the 2 leeward sites, despite receiving lower net radiation and higher rainfall during the study period, the soil-air temperature difference was greater at the Pu'u La'au (2600 m) than at Pu'uanahulu (670 m). Presumably, the flow of cool, free atmosphere air greatly retards air temperatures near the surface at Pu'u La'au.

CONCLUSION

This study has presented the results of 2 yr of surface meteorological observations transecting Hawai'i Island including stations on wet windward slopes, and dry, leeward sites above and below the trade wind inversion. The data illustrate the striking climate gradients found in Hawaiian mountains. The data has expanded on previously reported results for the wet windward sites and the high elevation Pu'u La'au site. These are the first complete climatic average data reported for the dry leeward slopes of Mauna Loa.

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