THE ECOLOGY OF AN ELFIN FOREST IN PUERTO RICO, 2. THE MICROCLIMATE OF PICO DEL OESTE

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MOUNTAINS PENETRATE the base of trade-wind cumulus on many Caribbean Islands. Topping these mountains is a mossy, bushlike, elfin forest. One such forest is situated on 1050-meter Pico del Oeste in the Luquillo Mountains of eastern Puerto Rico. This forest has recently been the subject of a joint ecological investigation by the Arnold Arboretum and the National Center for Atmospheric Research (NCAR). The objective was to determine the environmental factors responsible for the dwarfed nature of the forest.

One year of meteorological data collected on Pico del Oeste is summarized in this report. In the tropics, as elsewhere, the variability of weather is such that one year does not define a climate. Nevertheless, the microclimate associated with the cloud forest is sufficiently unique that even a single year's data suggest many characteristic weather features. Moreover, more extensive climatologies of Puerto Rico (Briscoe, 1966; Picó, 1950; Wadsworth, 1948) provide a useful standard for evaluating the representativeness of the year reported herein.

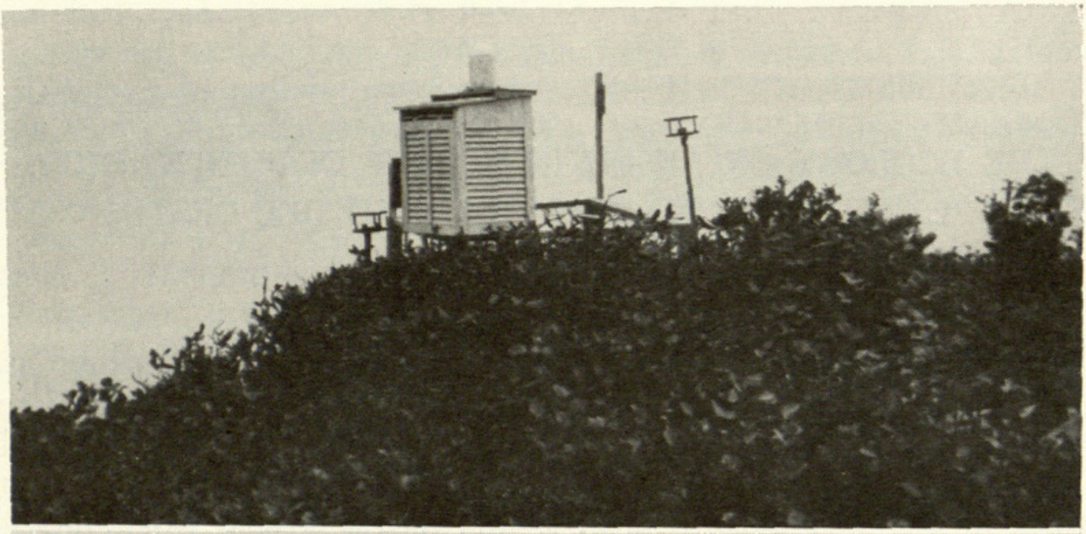
Pico del Oeste is at the eastern (i.e. windward) end of Puerto Rico. It is far enough inland to be affected by convective showers produced by the sun's heating of the ground, yet near enough to the coast to receive the full influence of the moist tropical trade winds. Rising to 1050 meters, Pico del Oeste naturally owes much of its rain to the upslope effect. The *Glossary of Meteorology* (1959) specifies 600 to 750 meters as the characteristic base of trade-wind cumulus. It is not surprising that Pico del Oeste is shrouded in cloud most of the time.

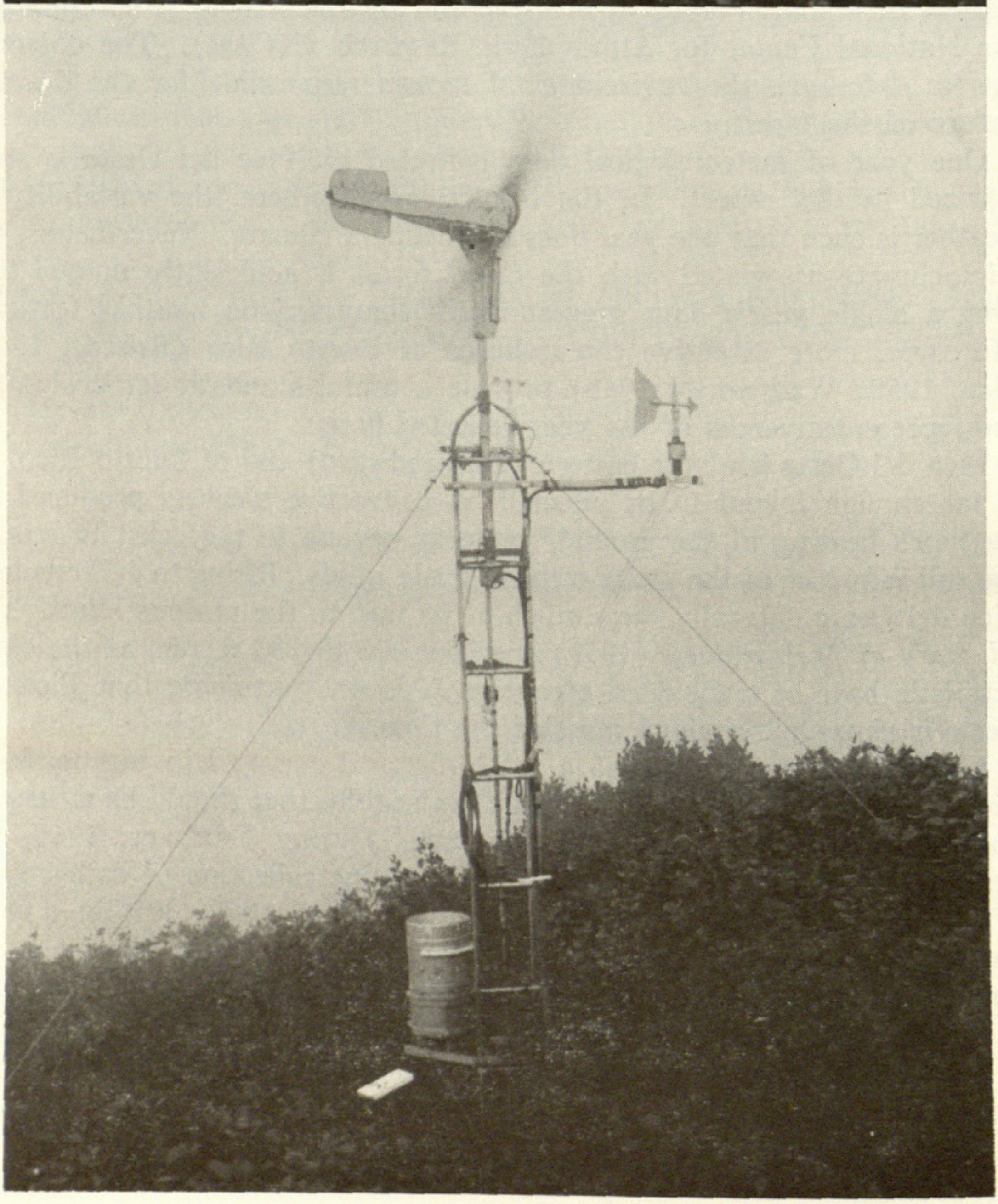
Late in September of 1965 a meteorological survey trip was made to Pico del Oeste to aid in determining the variables that should be measured and the instruments that should be used. During February, 1966, the first of the equipment was installed and routine collection of data began. Wind sensors were added during the summer of 1966. Within a year corrosion and electrical failure of equipment had become a chronic problem and later data were too intermittent and unreliable to be included in a climatological survey.

In the following sections the meteorological instruments are described and weather data observed immediately above the canopy are tabulated.

INSTRUMENTATION

The variables that were measured include temperature, humidity, solar radiation, rainfall, wind speed and direction, and soil temperature. A





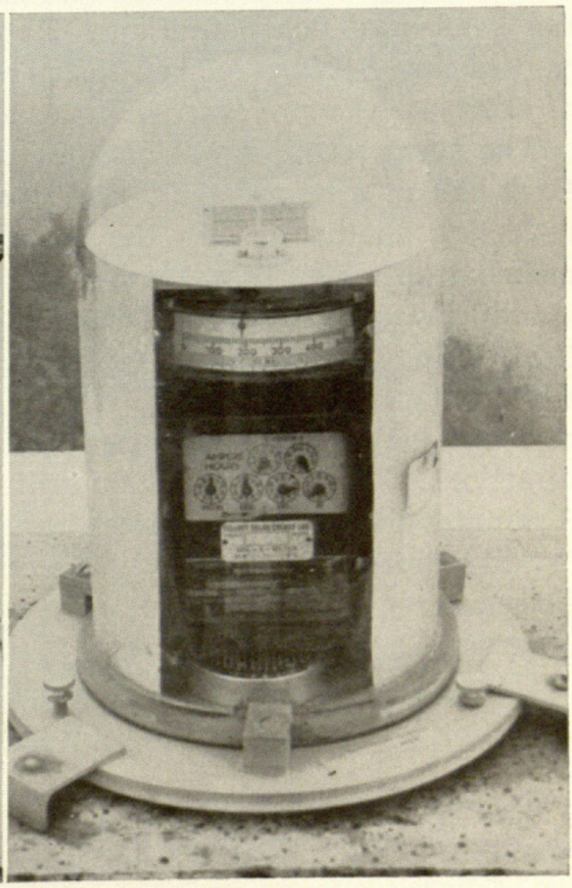
ABOVE: FIG. 1. Thermometer shelter just above canopy.
BELOW: FIG. 2. The 20-foot tower showing tipping-bucket rain gage, 3-cup anemometer, wind vane, and wind-powered generator on top.

relative measure of the amount of water extracted from the impinging cloud was also made. However, since the interpretation to be placed on this measurement is not self evident, the subject will be deferred to a later report.

Temperature and humidity were measured inside a thermometer shelter designed to protect the instrument from direct rain and sun, while assuring adequate ventilation by its louvered structure. The shelter was mounted just above the canopy on the roof of the hut as shown in Fig. 1. Solar radiation was measured on top of the thermometer shelter. Rainfall was measured just at the top of the canopy on a 20-foot tower shown in Fig. 2 and below the canopy. Wind speed and direction were measured at the top of the tower about 8 feet above the canopy, and wind speed was measured below the canopy also.

Because of the lack of commercial electric power, instruments that required little or no power were used. A limited amount of 12-volt direct current was supplied by a wind-powered generator shown atop the tower in Fig. 2.

A standard hygrothermograph, which requires no power, provided continuous records of temperature and relative humidity. The instrument is shown inside the thermometer shelter in Fig. 3. A Bourdon tube and a bundle of hairs were the sensing elements for temperature and humidity



Left: Fig. 3. Hygrothermograph inside thermometer shelter. Cloud-water collector in background, Sol-a-meter on roof.

Right: Fig. 4. Close-up of Sol-a-meter.

respectively. Periodically the calibration of the instrument was checked by a wet and dry bulb psychrometer. A spring-wound 8-day clock permitted weekly chart changes. FIG. 5 is an example of a typical chart. These charts gave daily values of the maximum and minimum temperature, the minimum relative humidity and the duration of less-than-100 percent relative humidity. Experience showed that the latter humidity condition was diagnostic of an absence of cloud on the peak.

Solar radiation was measured by a Sol-a-meter shown in FIG. 4. Four parallel-connected silicon cells generate a current proportional to the incident solar radiation. The output of the cells is connected through a milliammeter that indicates the instantaneous insolation rate, and to an ampere-hour meter that gives a readout of the total solar radiation during any desired period of time. A dessicant of silica gel is changed when a change in its color indicates an accumulation of moisture inside the glass cover. Readings near the beginning and end of the month were used to give an average value of the daily accumulation of solar radiation. The Sol-a-meter also required no power.

The rainfall detector was a tipping-bucket gage, shown in FIG. 2; rain from the collector is funnelled to the tipping-bucket mechanism shown in FIG. 6. Each bucket-tip, resulting from 1/100 inch of rain, closed a magnetic reed switch connected to the 12-volt supply. The switch-closure deflected a pen in an Esterline Angus 20-pen event recorder. Thus the amount of rain in hundredths of an inch is equal to the number of pen deflections. Rate of rainfall was obtained from the elapsed time between bucket-tips as read from the chart, on which 6 inches of chart-travel represented 1 hour.

The event recorder was also used to record wind speed and direction. Each mile of wind passage closed a reed-switch inside a 3-cup anemometer, deflecting another pen in the recorder. FIG. 7 shows the below-canopy anemometer. Hourly average winds and the fastest mile of wind were readily obtained. The wind vane, shown in FIG. 8, is attached to a vertical shaft that activates a contacting assembly consisting of eight wiper-type contacts spaced at 22.5 degree intervals. Only one contact is closed at a time. A separate event pen was assigned to each of the eight cardinal directions. By means of a cam switch built into the recorder, once every 3 minutes the circuit was closed and a wind direction was recorded.

Soil temperature at a depth of 8 centimeters was measured by a mercury thermometer. The thermometer was read during the regular visits of the observer.

RESULTS

TABLE 1 contains a summary of mean monthly temperatures, winds, humidity, solar radiation, and total rainfall. Gaps in the record occur when equipment was not operating.

The dominance of the northeast trade winds was almost complete. For the seven months of record the frequency of winds from the north, north-

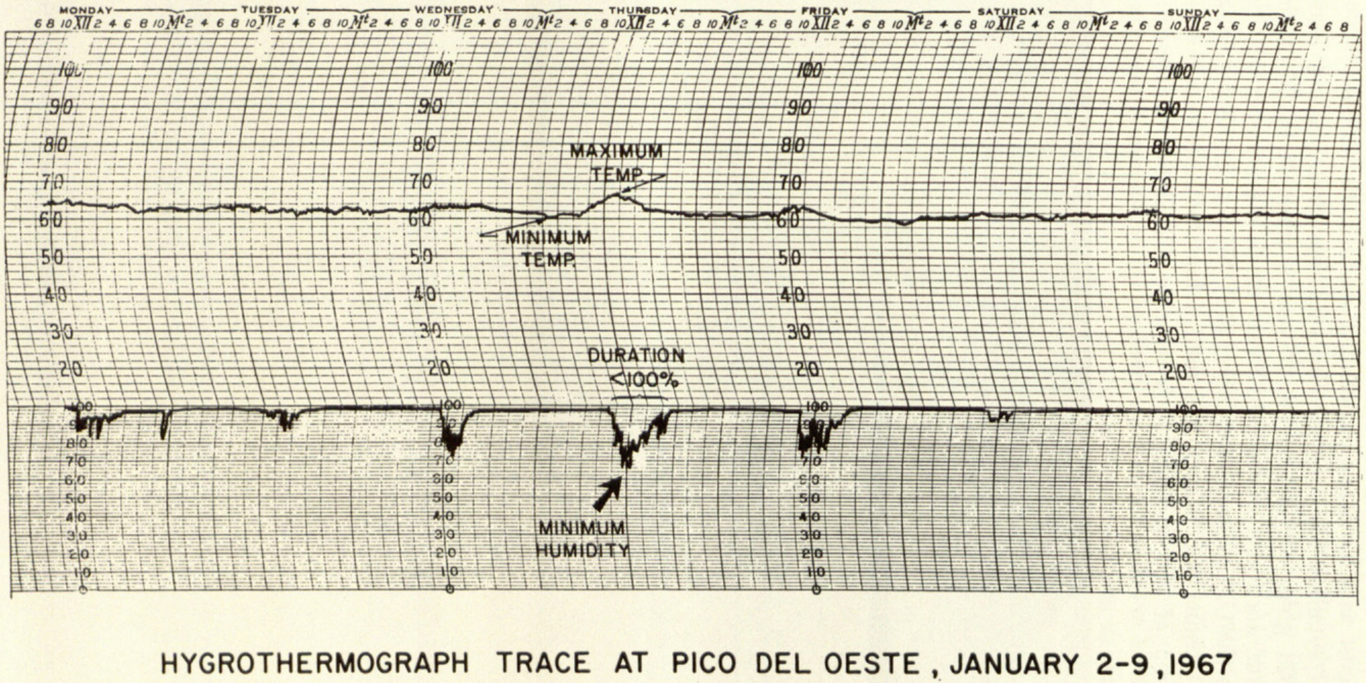


FIG. 5. Hygrothermograph chart for Pico del Oeste, January 2–9, 1967.

east, and east totalled 81 percent. The fastest mile of wind was 32 mi./hr. on 26 August as a hurricane passed just south of the island.

Rainfall totalling 453 cm. for the year was probably not abnormal. Picó (1950) gives 478 cm. as the 10-year average at La Mina, located about 5 km. northwest of Pico del Oeste at an elevation of 700 m. According to the U.S. Weather Bureau (1965) 402 cm. is the normal annual rainfall at Upper Rio Blanco less than 3 km. southwest of the peak at an elevation of 450 m. The heaviest rate of rainfall during the year

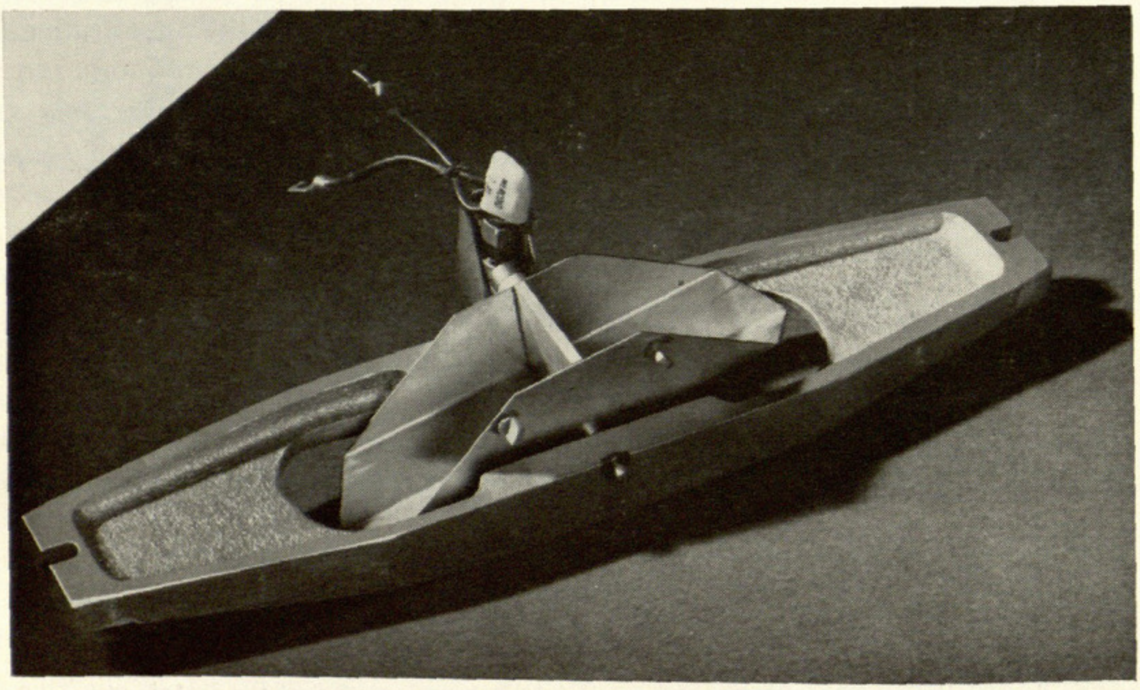


FIG. 6. Tipping bucket mechanism housed inside rain-gage directly under funnel from collector. When one compartment fills bucket tips, closing switch and simultaneously positioning other compartment under funnel.

occurred in the forenoon of 15 April 1966 when 2.5 mm. fell in just under a minute, a rate of just over 15 cm./hr.

Solar radiation at Pico del Oeste was compared to Tampa, Florida, and Swan Island, the two nearest stations for which radiation data are available. Normally Swan Island gets about 130 cm. of rainfall annually compared to 153 cm. at San Juan, and since it is at nearly the same latitude as Pico del Oeste it is comparable to the coastal plains of eastern Puerto Rico. Tampa probably gets somewhat less radiation than the coastal plains of Puerto Rico because it is further north. For similar (although not identical) periods in 1966 solar radiation averaged 478 Langleys/day at Tampa and 518 at Swan Island compared to 262 at Pico del Oeste.

This suggests that over 40 percent of the incident radiation is attenuated by the cloud, a plausible value since the peak is enveloped in cloud for about 60 percent of the daylight hours. Based on two years data Briscoe (op. cit.) found that solar radiation on a nearby mountain, 1065-meter El Yunque, was 60 percent of that measured at Cape San Juan on the coastal plain.

Moreover, as pointed out by Szeicz (1966), since the spectral composition of light changes very little with cloudiness, the light energy available for photosynthesis is also attenuated by over 40 percent.

TABLE 2 compares temperatures and rainfall at Pico del Oeste with those for the same period at Roosevelt Roads on the coast about 14 km. to the east southeast and about 1000 meters lower. The differences are readily accounted for by their 1 kilometer (1000 m.) difference in height. During the warmest part of the day temperatures in the first few hundred meters above ground usually decrease at the rate 9.8° C/km. (the dry adiabatic lapse rate). Maximum temperatures were observed to differ by just about this amount. Rainfall at the peak includes a substantial contribution from the orographic process, namely the forced rising, cooling, and resultant condensation within the moist northeast trade winds.

The climate on Pico del Oeste is described further in TABLE 3 in terms of occurrences of meteorological events. The first two columns are events or attributes of unpleasant weather. The last three columns are favorable weather attributes. There are two seasons of favorable weather and two seasons of unfavorable weather. Favorable weather in March and April coincides with the normal dry season over the Caribbean; the favorable weather of October and November may have been an anomaly since these are normally among the wettest months. It is noteworthy that measurable rain fell during 350 days in the year.

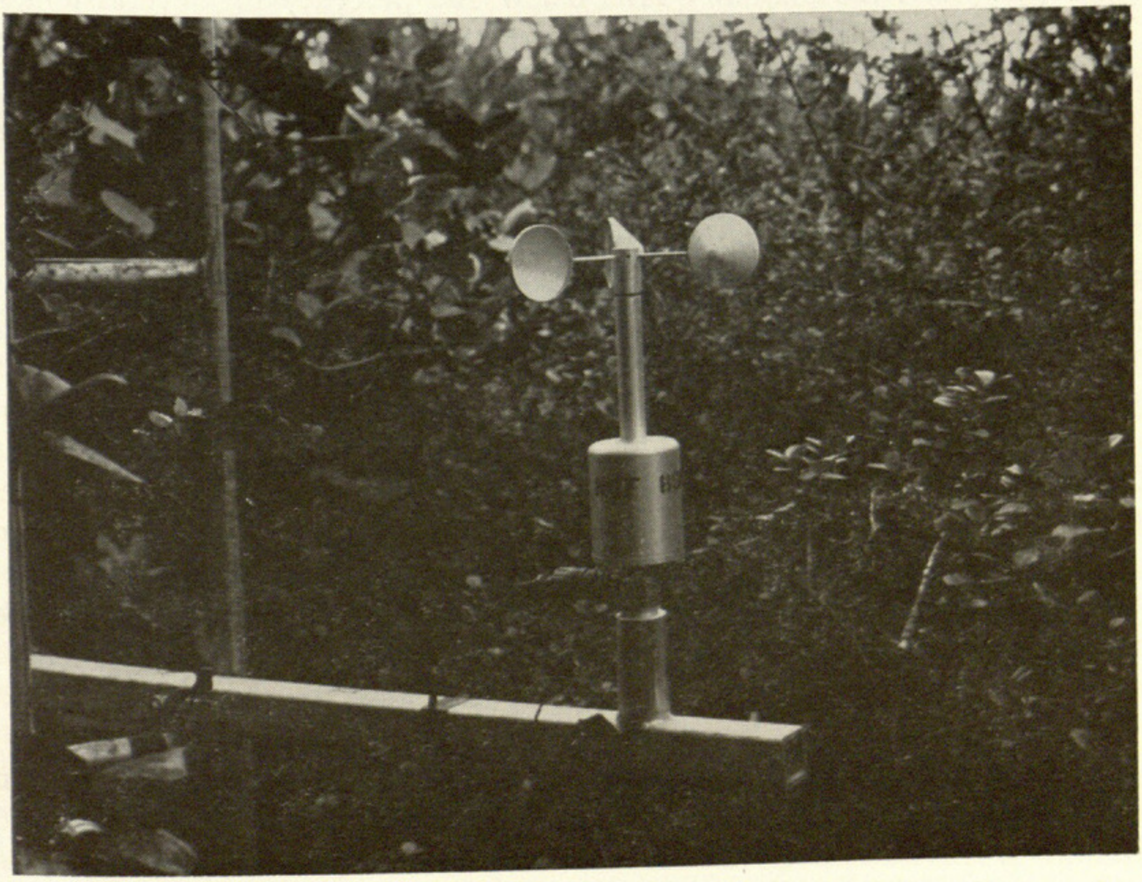


FIG. 7. 3-cup anemometer used for measuring wind speed below the canopy.

The longest spell of fine weather extended from November 8 to 28 or a total of 3 weeks. During this remarkable period there was an average of 15 hours per day of cloud-free weather and radiation averaged 305 Langleys/day. Maximum temperatures averaged 21°C and relative humidity averaged 91 percent. Even so, rain totalled 20 cm.

There were also spells distinguished by their lack of rain. The best example occurred during the normal dry season that generally includes February, March, and April. In the 23 days from March 20 to April 11, 1966, the total rainfall was 6.5 cm., there was an average of 9 hours/day of cloud-free conditions, humidity averaged 95 percent, maximum temperatures averaged 20.5° C, and radiation averaged 360 Langley/day.

There were also two notable spells during which cloud enveloped the peak almost continuously. In the 16 days from June 10 to 25, 1966, there were only 6 hours in which the cloud broke from the peak. On 12 of the days the relative humidity never fell below 100 percent. Maximum temperatures averaged 20.5° C and rainfall totalled 24 cm.

In the 15 days from January 14 to 28, 1967, there were only 7 hours in which the cloud cleared from the peak and on 12 of the days it did not clear at all. This was a cool spell in which maximum temperatures averaged 17.2° C and rainfall totalled 19 cm.

Some additional noteworthy features may be mentioned. The highest and lowest observed screen temperatures during the year were 26° C and 13° C. The diurnal temperature variation is very small. As shown in FIG. 5, it is well defined only on days when the cloud lifts from the peak (i.e. when the humidity falls below 100 percent) for several hours. The peak was enveloped in cloud close to 100 percent of the night hours and 60 percent of the day hours.

SUMMARY

Garnier (1961) defines the humid tropics as "the area where (1) the mean monthly temperature for at least eight months of the year equals or exceeds 68° F (20° C); (2) the vapor pressure and relative humidity for at least six months of the year average at least 20 millibars and 65 percent respectively; and (3) the mean annual rainfall totals at least 40 inches (1000 millimeters), and for at least six months precipitation is 3 inches (75 millimeters) each month." By this definition, Pico del Oeste is clearly not in the humid tropics. During the year reported herein rainfall met the criterion. Although relative humidity more than met the criterion, average vapor pressure exceeded 20 mb. in only 6 of the months. Temperatures were clearly too cold. However the presence of an elfin forest rather than a rain forest tells even more eloquently that Pico del Oeste is not in the humid tropics.

There has been much speculation as to the causes of elfin forests. In discussing this region in Puerto Rico, Cook and Gleason (1928) asserted that high wind exposure is the most important environmental factor in differentiating the mossy forest from the palm forest, although low temperature, water-soaked soil, and high humidity were also considered important. They added that on rocky summits of peaks the trees are bush-like on account of the strong winds and thin and rocky soils. Grubb and Whitmore (1966) suggest that the most important factor in the development of tropical montane forests is the frequency of fog, although they concede that additional exposure to winds and leaching of soils on ridges may contribute to stunting. The first year of data on Pico del Oeste offers little support to the belief that strong winds account for the stunting. Leaching of soils is probably important. The most unusual features of the weather appear to be the high fog incidence and the 40 percent attenuation of solar radiation, tending to support the suggestions of Grubb and Whitmore.

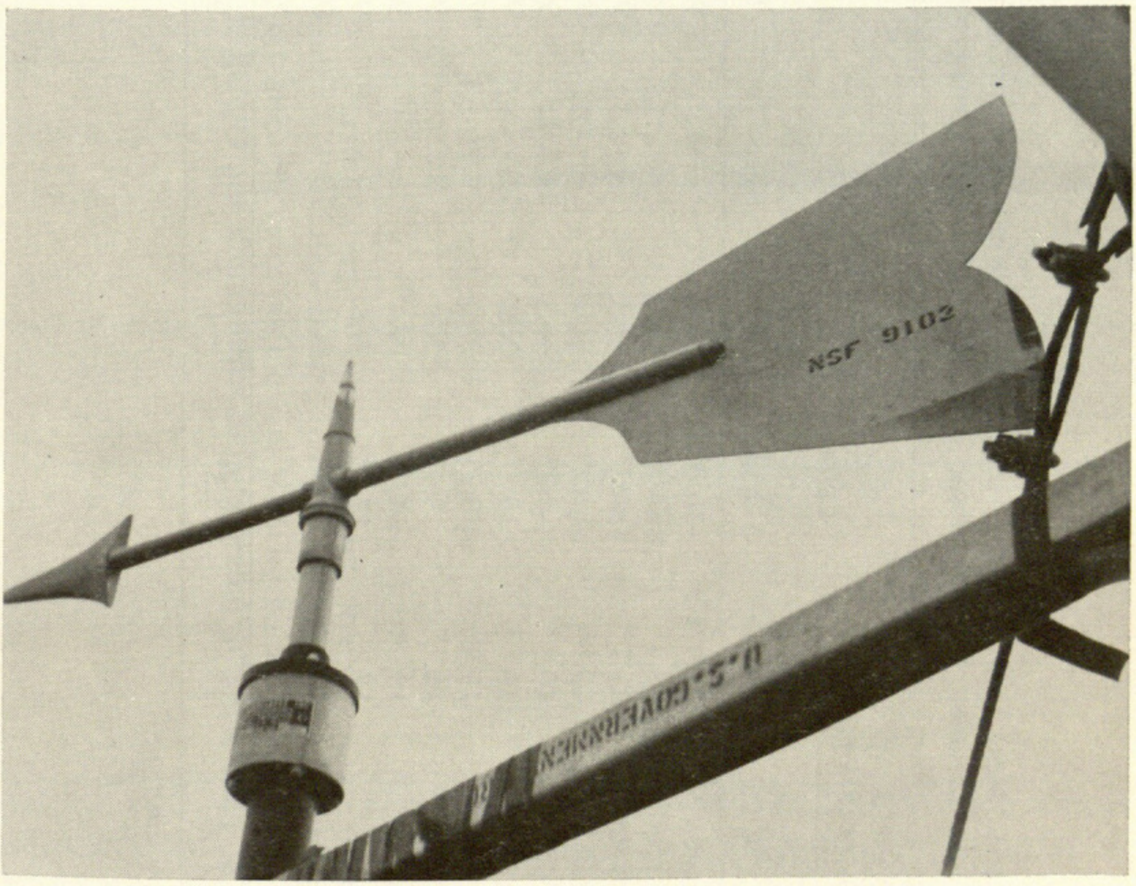


FIG. 8. Wind vane on top of tower.

ACKNOWLEDGMENTS

The contributions of the following individuals are gratefully acknowledged. Mr. Donald Eklund made the original installation of meteorological equipment including the tower and wind-powered generator, and designed and assembled the trough rain-gage for measuring rainfall under the canopy. Later in the year special maintenance and further refinements to the installations were carried out by Dr. Julian Pike. Various members of the staff of the Arnold Arboretum performed the regular chart changes and other routine duties that are essential to a program of continuous data collection.

TABLE 1. **Mean monthly values of temperature, wind, humidity, rainfall and solar radiation, Pico del Oeste, 1 March 1966 to 28 February 1967**

	AVERAGE AIR TEMPERATURE			SOIL TEMP.	WIND				
	Daily Max.	Daily Min.	Daily Mean	8 cm. Depth	Prev. Dir.	Mean Speed	Rel. Hum.	Rain-fall	Solar Radiation Langleys[1] per day
MARCH '66	19.2°C	16.5°C	17.9°C	16.9°C	—	—	98 %	34.8 cm.	245
APRIL	20.0°	16.7°	18.4°	17.0°	—	—	96	38.5	322
MAY	20.0°	18.4°	19.2°	18.3°	—	—	99.9	45.1	203
JUNE	20.4°	18.8°	19.6°	18.9°	—	—	99.8	36.4	260
JULY	20.7°	18.9°	19.8°	19.2°	—	11.0 kt	99.7	43.9	249
AUGUST	20.7°	18.5°	19.6°	19.3°	NE	11.1	99.8	41.8	266
SEPTEMBER	21.1°	18.4°	19.8°	19.7°	NE	9.6	98	39.9	290
OCTOBER	21.6°	18.6°	20.1°	19.4°	NE	8.0	97	25.6	271
NOVEMBER	21.0°	16.8°	19.0°	18.7°	N	—	94	27.4	297
DECEMBER	18.3°	16.3°	17.3°	17.8°	NE	9.3	99	62.0	212
JANUARY '67	17.5°	15.6°	16.6°	17.0°	NE	10.9	99.4	30.3	—
FEBRUARY	17.6°	15.6°	16.6°	17.0°	NE	9.2	99.3	27.6	—
ANNUAL	19.9°	17.4°	18.6°	18.3°	—	—	98.5	453.3	262

[1] One Langley is 1 calorie/square cm.

TABLE 2. **Comparison of monthly mean temperatures and rainfall at Pico del Oeste and Roosevelt Roads, 1 March 1966 to 28 February 1967**

	MAX. TEMP.		MIN. TEMP.		MEAN TEMP.		RAINFALL	
MONTH	Pico	RR	Pico	RR	Pico	RR	Pico	RR
MARCH '66	19.2°C	29.2°C	16.5°C	23.0°C	17.9°C	26.1°C	34.8 cm.	7.5 cm.
APRIL	20.0°	29.6°	16.7°	23.0°	18.4°	26.4°	38.5	11.0
MAY	20.0°	29.8°	18.4°	24.1°	19.2°	26.9°	45.1	9.3
JUNE	20.4°	30.9°	18.8°	25.1°	19.6°	28.0°	36.4	10.0
JULY	20.7°	31.3°	18.9°	25.3°	19.8°	28.3°	43.9	10.5
AUGUST	20.7°	31.1°	18.5°	25.4°	19.6°	28.2°	41.8	10.8
SEPTEMBER	21.1°	31.3°	18.4°	25.1°	19.8°	28.2°	39.9	17.0
OCTOBER	21.6°	31.1°	18.6°	23.9°	20.1°	27.5°	25.6	18.2
NOVEMBER	21.0°	30.0°	16.8°	21.8°	19.0°	25.9°	27.4	17.7
DECEMBER	18.3°	28.4°	16.3°	22.4°	17.3°	25.4°	62.0	12.9
JANUARY '67	17.5°	27.8°	15.6°	21.5°	16.6°	24.7°	30.2	10.0
FEBRUARY	17.6°	28.3°	15.6°	21.8°	16.6°	25.0°	27.6	3.9

Particular mention must be made of the kindness of Mr. J. B. Martinson in providing excellent accommodation close to Pico del Oeste. Both the scope and quality of the research have benefited greatly from this generous support.

TABLE 3. **Occurrences of significant meteorological events by months, Pico del Oeste, 1 March 1966 to 28 February 1967**

	NUMBER OF DAYS				
	In cloud for 24 hrs.	Rain 1 or more cm.	Max. temp. 22°C or more	8 or more hours with Rel. Humid. less than 100%	No Rain
MARCH '66	9	12	3	7	3
APRIL	3	9	4	12	5
MAY	20	17	0	1	0
JUNE	17	14	0	1	0
JULY	14	12	1	2	0
AUGUST	18	13	3	2	0
SEPTEMBER	8	12	4	7	1
OCTOBER	8	7	7	11	1
NOVEMBER	3	9	7	19	4
DECEMBER	10	16	2	8	1
JANUARY '67	15	9	0	3	0
FEBRUARY	13	7	0	6	0
ANNUAL	138	137	31	79	15

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