

Salt Spray: Its Directional Stress on Plants on the Island of Oahu, Hawaii

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Abstracts

The effect of air-borne salt spray on plants was studied on the Island of Oahu, Hawaii. The analysis of wind data, observations of salt spray damage on plants by exceptionally strong winds and the study of salt deposition on plant leaves suggest that deformation of tree canopies in Hawaii has developed at least by the salt spray damage under strong, but infrequent NE wind conditions in winter.

1. Introduction

Wind is an important controlling factor for plant growth owing to mechanical and physiological stresses on plants. In wind-exposed areas in mountains and on coasts wind-related factors such as ice particles, sand, and salt spray add complexity to the wind-plant relationship.

One of the remarkable characteristics of the wind factor, particularly in windy areas, is that the effect on plants is usually from one or a few limited directions. On ocean islands and in coastal areas plants often show these directional stresses in their morphological and physiognomic appearance.

On the island of Oahu deformation of tree crowns and vegetative differences on opposing slopes of valleys and gullies are easily spotted. Since the Hawaiian Islands, located in the southern sector of the mean subtropical high, are exposed to the persistent NE tradewinds throughout the year, the individual plants and vegetation seem to be affected by these winds and tend to develop particular shapes and patterns. These features are intriguing ecological and biogeographical subjects by themselves, but at the same time, suggest the possibility of their use as indicators of wind force and direction after rigorous evaluation of the causal relationship.

Noguchi (1979) discussed the use of wind-deformed trees for the con-

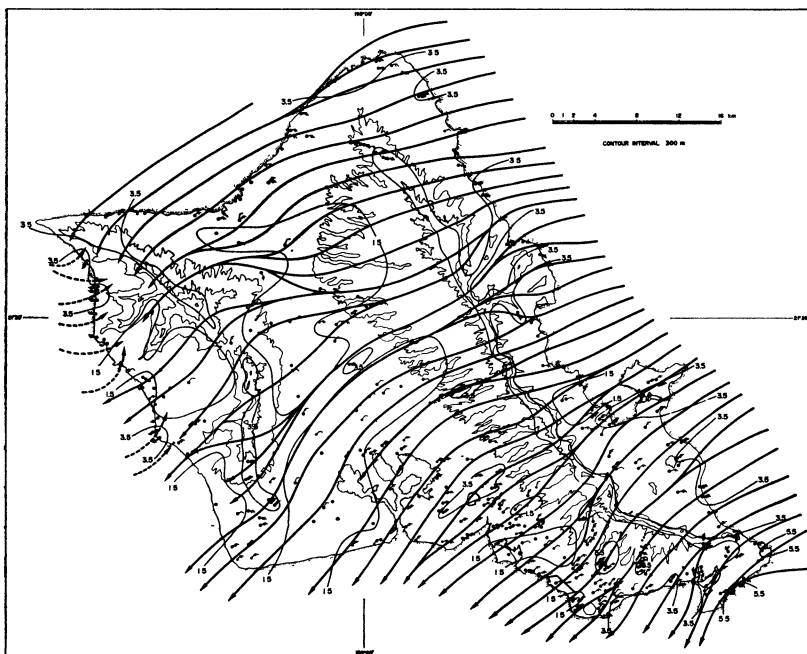


Fig. 1: Estimated surface flowlines of prevailing winds on Oahu based on observations of wind-deformed trees and isolines of grades of tree deformation.

Source: Noguchi (1979).

struction of maps of wind patterns over Oahu (Fig. 1) and Maui. Although the prepared wind maps clearly depicted the interaction between the steady NE tradewinds and terrain features over the islands, it has not been made clear which winds, normal tradewinds or unusually strong winds, the maps indicated, i.e., which winds contributed to the deformation of tree crowns.

Unclear at the same time was the relative importance of the effect of salt spray on plants under rare but unusually strong wind conditions. Salt spray has been the subject of intensive discussion in relation to the development of the coastal ecosystem. The effect of salt spray on the physiognomic development of coastal vegetation is well documented (Boyce 1954; Karschon 1958).

The objective of this study is, therefore, to obtain the frequency and direction of winds at various wind speed intensities for Honolulu for the better understanding of the characteristics of salt spray carrying winds; to prepare a distribution map of the salt spray damage on Oahu after a strong wind event for a comparison with the wind pattern over the island based on the wind-deformed tree method; and to delineate

the relationship between terrain exposure and salt spray deposition, as a first step for the understanding of the causal relationship between the wind or wind-related factors and asymmetrical vegetation distribution on slopes in Hawaii.

This study was performed as a part of the intensive investigation of vegetation which was continued at Punaluu, Oahu for three years from 1978 to 1980 and temporarily in 1983.

2. Review

There are several arguments in the study of the salt spray effect on vegetation which still need further clarification. At least one argument comes from the ambiguity in separating the chemical effects of air-borne salt from wind damage on vegetation. Boodle (1920) already pointed out this problem and concluded that most damage in coastal areas was caused by the wind. The same view was shared by Osborn (1922) and Smith (1957). Sauer (1962) considered the high mortality of medium-sized *Casuarina* on coastal Mauritius after tropical cyclones to be solely the result of wind effects. However, Wells and Shunk (1938), Oosting (1945), Boyce (1954), Karschon (1958), and Parsons and Gill (1968) see salt spray as the main cause of damage to coastal vegetation. Reitz (1978) maintains that wind-deformed trees in coastal areas are all to be attributed to salt spray and not to wind.

A second problem may be found in the relationship between the wind speed and the transportation and deposition of air-borne salt. Many reports showed a rapid drop in the amount of salt deposit in the first few hundred meters from the sea and a slower and more irregular decrease further inland (Fujiwara and Umejima 1962; Edwards and Claxton 1964; Malloch 1972). Hama and Takagi (1970) expressed the total mass and number of giant air-borne salt particles as a function of distance inland from the beach. Semonin (1972) found the concentration of chloride particles at Mauna Loa Observatory 68 km inland to be about 1% of that near the coast at Hilo. However, under some extreme conditions, salt particles in sufficient quantity to damage vegetation are carried as far as 45 to 50 km inland from the coast (Moss 1940; Edlin 1957).

Edwards and Claxton (1964) analyzed two years of data and pointed out that highly significant differences in salt deposition were found between sites classified according to their estimated degree of exposure to the wind (i.e., the greater the exposure to the wind, the more the salt

deposition). Similar results were reported from the same site by Rutter and Edwards (1968) and from the Netherlands by Sloet van Oldruitenborgh and Heeres (1969) and from Barbados in the northeast tradewind region by Randall (1970). Rutter and Edwards (1968) showed a high correlation between the on-shore wind speed and salt deposition, and a sharp decrease of more than 80% in salt deposition from an exposed ridge site to a nearby leeward slope. The effectiveness of windbreaks to prevent salt spray damage on crop plants was discussed by Sideris (1955) in Hawaii and by Lomas and Gat (1967) in Israel.

A third problem may be that there is, among plant species, a wide range in tolerance to salt spray as shown by the experiment of spraying sea water on coastal dune plants by Oosting and Billings (1942) and Oosting (1945). Other studies also showed different responses to salt spray by plants of different species and life forms (Moss 1940; Tagami 1976). Sideris (1955) and Sideris and Young (1954) showed experimentally that young pineapple leaves are far more tolerant to salt spray than are old leaves and that tolerance could be increased by ample application of soil nutrients.

A fourth problem lies in the absence of any standard instrument or guidelines for the measurement of salt aerosols and deposits (e.g., guidelines for the location and height of an instrument above ground), which

Table 1 Material Used for the Collection of Air-borne Salt

<u>Material</u>	<u>Remarks</u>	<u>Source</u>
• Windvane, raingauge (A)	"Halatometer"	Sideris (1942)
• 8 in. cheezecloth (B)	Stretched, wooden frame	Oosting & Billings (1942)
• Unspecified	"Wet candle"	Ambler & Bain (1955)
• Double muslin (B)	Stretched, 20×20 cm metal frame	Lomas & Gat (1962)
• Blotting paper, jam bottle, 20 cm-long pillar (B)	None	Sloet van Oldruitenborgh & Heeres (1964)
• Filter paper, tube, vane (A)(B)	1×1 cm filter paper in a tube	Edwards & Claxton (1964)
• Wash towel (B)	30 cm ² , suspended	Randall (1970)
• Polythene tube, acid-washed sand (C)	Tube 4.4 cm dia. ×40 cm	Malloch (1972)
• Plastic beakers (C)	7.3 cm dia., 10.7 cm deep	Goldsmith (1973)
• Vacuum pump, membrane filter (B)	None	Rossknecht et al. (1973)

makes it difficult to compare data from various studies. There are as many methods to measure air-borne salt as there are the number of investigators. However, they are classified into three major groups according to the material used for the collection of salt spray (Table 1)

For the determination of the absolute or relative amount of salt (Sodium) in the samples, Edwards and Claxton (1964) and Malloch (1972) used flame photometry and expressed the salt content in micrograms of NaCl/cm² of filter paper. Oosting and Billings (1942), Lomas and Gat (1967), and Sloet van Oldruitenborgh and Heeres (1969) employed a titration method with silver nitrate, using potassium chromate as an indicator, and expressed the salt content in mg. Randall (1970) and Parsons and Gill (1968) used electrical conductivity (micromhos/cm) as a measure of salt content.

3. Study Areas and Methods

3.1. Wind Analysis

Daily mean and fastest 1 minute ("fastest mile") wind data of the Honolulu International Airport for the period of 20 years (1959-1978, NOAA) were analyzed for the frequency, intensity and direction of winds.

3.2. Oahu Island Observations

As shown in Fig. 2, the island of Oahu consists of two parallel mountain ranges, the Koolau and the Waianae, which run at right angles to the NE tradewinds. This arrangement of mountains has a significant orographic effect on the distribution of climatological factors on the island, particularly rainfall.

From late December 1978 to early January 1979, the effect of salt spray on plants was studied for the entire island of Oahu after an exceptionally strong NE wind (Fig. 3) which lasted for 12 days in the middle of December, 1978 (hereafter called the Holoholo wind after the name of the University of Hawaii research vessel Holoholo which left Honolulu on December 9 and disappeared with seven scientists and three crewmen on board).

When the wind returned to the normal trade wind intensity, it left many scars of salt spray damage on plants and vegetation. The damage was particularly noticeable on exposed canopies of shrub and tree species. All damaged leaves showed necrosis with a stain pattern on the leaf surface as if burned by chemicals. Necrosis on leaf tips and margins

by the salt spray, as described by Boyce (1954) and Sideris (1955), was also typical in the Holoholo wind event.

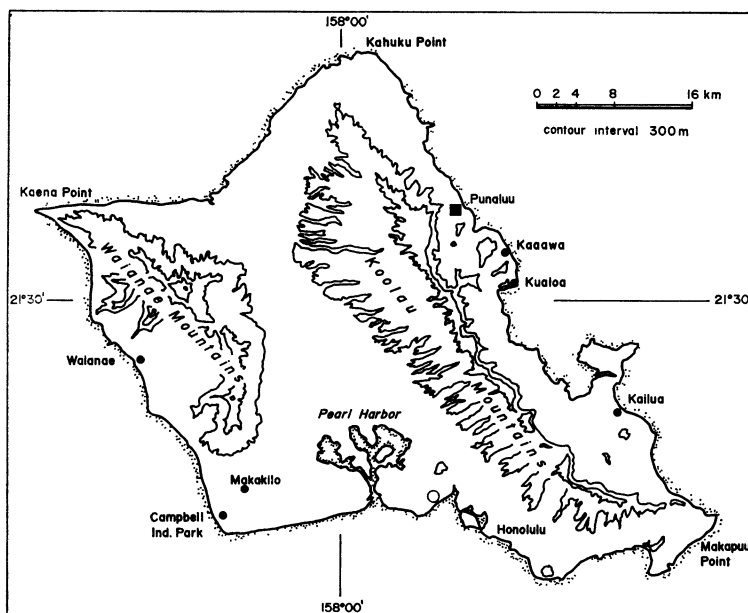


Fig. 2: General outline of the Island of Oahu.

Note: Square: Punaluu study site; circle: Honolulu International Airport.

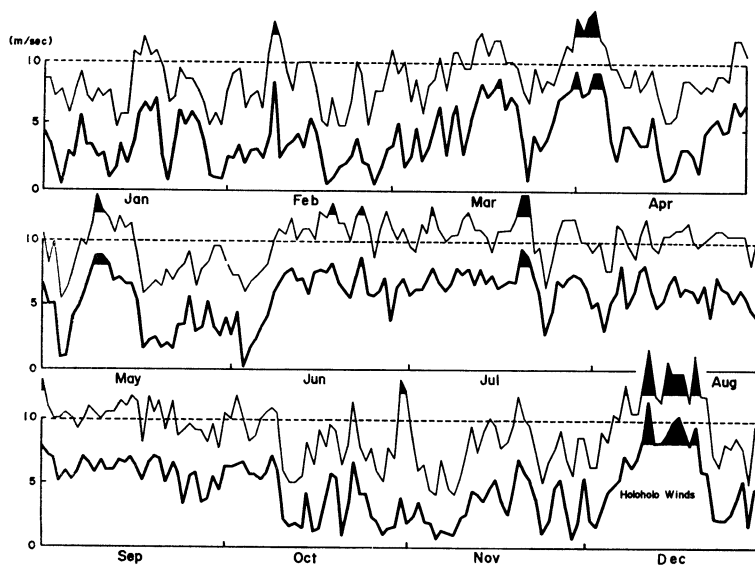


Fig. 3: Daily mean and fastest 1 minute wind speeds at Honolulu International Airport, 1978.

Note 1: Thick line: daily mean; thin line: fastest 1 minute.

Note 2: Wind speeds greater than 8 m/sec for daily mean and 12 m/sec for fastest 1 min. winds were darkened.

Observations of damaged plants started immediately after the strong winds ended, and completed within ten days from December 24 to January 4, 1979, covering both the coastal and inland areas of Oahu. However, mountains, sugarcane and pineapple plantations had to be eliminated from the observation routes due to the inaccessibility or absence of trees.

The distribution map of the salt spray damage was constructed for Oahu by the following procedure: (1) the average area of necrosis on damaged leaves was estimated in percentage of a leaf area; (2) the damaged area of the entire canopy was estimated in percentage; (3) the total damaged area of a single tree was calculated by multiplying the values of (1) and (2) above; and (4) the percent value of total damage was plotted.

No single tree species was present which could be used as an indicator of salt spray damage for the entire island because of the diversity of the island in moisture conditions and, therefore, uneven distribution of arboreal species. There was also no experimental data to differentiate species based on their resistance to salt spray damage.

However, an effort was made in the observations to eliminate those species found in the previous study (Noguchi 1979) to be wind-resistant in Hawaii. The exclusion of certain resistant species (e.g., *Casuarina equisetifolia*, *Prosopis pallida*, *Rhizophora mangle*) was a necessary, although not sufficient, first step in constructing a map of air-borne salt deposits based on the degree of salt spray damage.

3.3. Punaluu Valley Observations

To examine the effect of topography on the distribution of air-borne salt deposits, leaf samples were collected at 10 sites set up across a tributary valley 1 km inland in the Punaluu Valley on the NE-facing windward side of Oahu (Fig. 4).

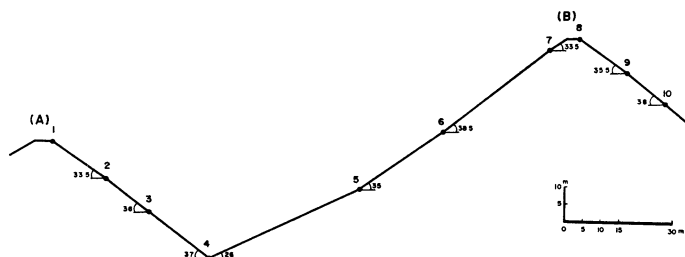


Fig. 4: Locations of sampling sites across the study valley, Punaluu, Oahu.
Note: NE tradewinds are from right to left.

Leaves were sampled from a shrub (*Schinus terebinthifolius*), a grass (*Andropogon virginicus*), and a fern (*Sphenomeris chinensis*) which are representative of Punaluu Valley. Samples were taken four times after strong wind events from exposed plants of less than 2 m in height. On one occasion (Dec. 5, 1979) the sampling was made from both the windward and the leeward sides of shrub canopies.

The leaves from each sample site were weighed and a unit weight of leaves (2 g) was immersed in a unit volume (50 ml) of deionized water. This procedure was based on the finding that a unit weight of leaves represents a unit leaf area accurately (Fig. 5). Although soluble salt in either soils or salt spray is known to enter plants and induce succulence (Boyce 1954) and a large difference in leaf thickness was reported between the samples taken from exposed and protected sites (Parsons and Gill 1968), sample leaves taken at Punaluu did not show any measurable difference in leaf thickness between the exposed and the protected sites or between the windward and the leeward sides of a canopy.

The electrical conductivity of deionized water was measured in micromhos at a certain time interval for several days until conductivity

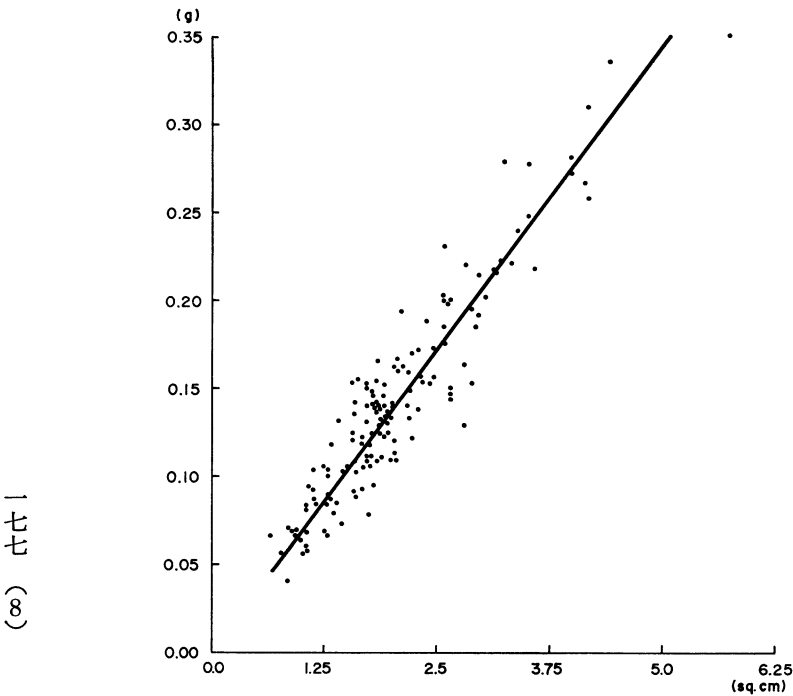


Fig. 5: Relationship between leaf weight and leaf area for *Schinus terebinthifolius*, Punaluu, Oahu.

no longer increased. The evaporation of deionized water from containers was kept minimal by putting lids on them.

4. Results

4.1. Wind Analysis

Tables 2 and 3 show the frequency distribution of daily mean and fastest 1 min. wind speed and direction based on the NOAA data for the period of 20 years (1959–1978).

According to these tables:

1) Both daily mean and fastest 1 min. wind speeds are steadier and stronger in summer and more variable in winter

Table 2 Frequency distribution of daily mean wind speed and direction, 1959–1978, Honolulu International Airport

	Daily Mean Wind speed (m/sec)							
	0*-2	2*-4	4*-6	6*-8	8*-10	10*-12	12*-14	14*-16
20 years	71	1853	2895	2065	357	28	2	2
Jan	19	276	219	82	20	3	0	1
Feb	11	216	197	97	38	6	1	0
Mar	7	184	210	146	40	2	0	0
Apr	5	139	224	186	42	4	0	0
May	6	140	254	200	22	2	0	0
Jun	2	62	282	230	22	0	0	0
Jul	0	33	255	289	42	1	0	0
Aug	0	45	268	281	23	0	1	0
Sep	0	134	273	177	15	0	0	0
Oct	4	196	270	136	14	0	0	0
Nov	11	189	237	126	35	1	0	0
Dec	6	239	206	115	44	9	0	1
0*-30	6	229	124	10	2	0	0	0
30*-60	0	246	785	563	97	13	0	0
60*-90	2	320	1616	1413	242	11	1	1
90*-120	3	130	68	6	2	0	1	0
120*-150	5	151	35	9	3	0	0	0
150*-180	13	161	54	16	4	1	0	0
180*-210	12	169	46	22	4	2	0	1
210*-240	17	101	44	8	1	0	0	0
240*-270	3	86	33	10	2	1	0	0
270*-300	3	86	18	2	0	0	0	0
300*-330	2	74	18	4	0	0	0	0
330*-360	1	100	55	1	0	0	0	0

Note: * means inclusive.

Data source: Local Climatological data, NOAA, 1959–1978

Table 3 Frequency distribution of fastest 1 minute wind speed and direction, 1959—1978, Honolulu International Airport

	0*-2	2*-4	4*-6	6*-8	8*-10	10*-12	12*-14	14*-16	16*-18	18*-
20 years	1	7	657	1407	2319	2069	641	125	35	12
Jan	0	3	117	185	162	93	36	14	4	6
Feb	0	1	92	145	141	108	51	18	10	0
Mar	0	0	66	130	167	145	62	15	4	0
Apr	0	0	44	101	163	185	85	19	3	0
May	0	0	47	117	202	199	54	5	0	0
Jun	1	0	22	74	237	217	40	7	0	0
Jul	0	0	6	34	214	288	71	7	0	0
Aug	0	0	8	48	238	266	53	3	1	1
Sep	0	0	37	95	248	182	33	3	1	0
Oct	0	0	61	143	240	142	28	4	2	0
Nov	0	2	68	150	162	129	70	12	4	2
Dec	0	1	89	185	145	115	58	18	6	3
N	0	0	38	79	56	42	8	1	1	1
NE	1	1	72	547	1589	1633	491	90	22	2
E	0	0	34	153	321	274	104	20	3	1
SE	0	0	90	263	174	28	16	2	4	4
S	0	6	262	166	79	25	4	2	1	2
SW	0	0	125	121	36	27	8	6	3	2
W	0	0	19	43	30	18	7	1	1	0
NW	0	0	17	36	33	22	3	3	0	0

Note: * means inclusive.

Data source: Local climatological data, NOAA, 1959—1978

2) If we assume that the minimum intensities of the daily mean and the fastest 1 min. Holoholo winds were 8 m/sec and 12 m/sec, respectively (Fig. 3), the percentage of winds at the intensity greater than the Holoholo winds at the airport in 20 years is 5% (18 days/year) for the daily mean and 11% (40 days/year) for the fastest 1 min. winds.

However, the author's experience in Hawaii for six years show that the winds at the intensity and duration of the Holoholo winds are much rarer than 18 days/year. If we use 10 m/sec (daily mean) and 14 m/sec (fastest 1 min.) for the minimum intensity of the Holoholo wind, we obtain more reasonable values, i.e., 0.4% (1.5 days/year) and 2.4% (8.6 days/year), respectively.

3) Of the daily mean wind speeds equal to or greater than 8 m/sec and of the fastest 1 min. wind speeds equal to or greater than 12 m/sec, 63% and 62% respectively occur in half a year between November and April, whereas of the daily mean wind speeds equal to or greater than

10 m/sec and of the fastest 1 min. wind speeds equal to or greater than 14 m/sec, 88% and 80% respectively occur in the same period. This means that very strong daily mean and fastest 1 min. winds tend to occur more often in winter than in summer.

4) Wind direction is very consistent, with 73% of the daily mean winds occurring in the range between N30E and E and 50% between N60E and E, whereas 74% of the fastest 1 min winds from the NE and E direction combined and 61% from the NE direction alone.

5) Of the daily mean wind speeds equal to or greater than 8 m/sec, 94% occurs in the range between N30E and E and 66% in the range between N60E and E. Of the fastest 1 min. wind speeds equal to or greater than 12 m/sec, 90% occurs in the NE and E directions. Similar but a little lower percent values apply to winds greater than 10 m/sec for the daily mean and 14 m/sec for the fastest 1 min. winds.

6) Wind direction is more variable in lower wind speed classes and more consistent in higher wind speed classes for both types of wind data. The wind direction becomes more concentrated in NE or ENE with stronger winds.

4.2. Oahu in General

The salt spray damage on plants by the Holoholo wind was enormous. But a survey of the entire island after the wind showed a rather irregular distribution of damage (Fig. 6):

1) The damaged areas were mainly concentrated on the windward coast of the island and promontories, such as Kaena, Kahuku and Makapuu Points.

2) Even within the heavily damaged areas on the coast, many plants escaped fatal damage if they were protected by other plants or shelters.

3) Trees and shrubs in the leeward coastal areas between Kaena Point and Waianae were also badly damaged. The damage on the leeward ocean side of canopies suggest that the wind took a form of vortex behind protruded Kaena Point.

4) The interior region between the Koolau and the Waianae Ranges and topographically protected areas on the leeward side of the island showed no salt spray damage by the Honoholo wind.

5) The areas of small damage are scattered on the leeward side of the island (e.g., the southern tip of the Waianae Range around Makakilo City, parts of Pearl Harbor and Honolulu). Even in Campbell

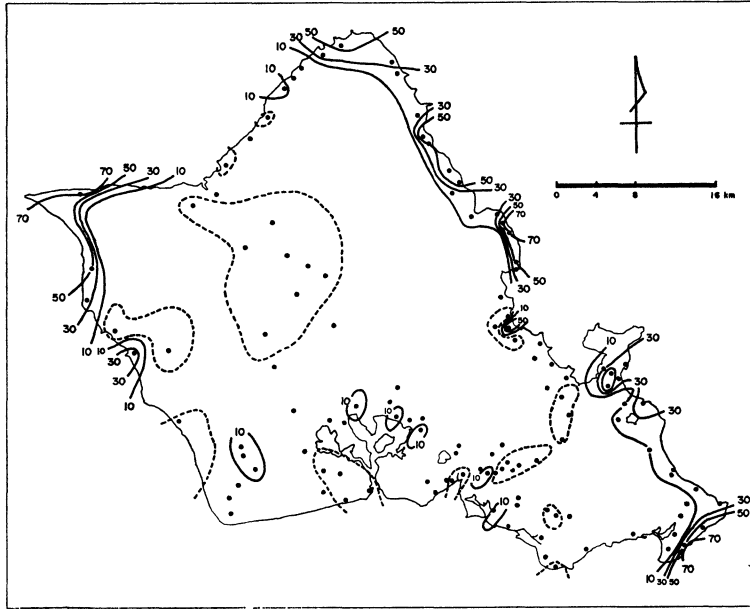


Fig. 6: Salt spray damage on shrubs and trees by the Holoholo wind in the middle of December 1978, Oahu, expressed in percentage of the entire canopy.

Note: Areas encircled by broken lines show no salt spray damage.

Industrial Park, which is located at the leeward end of the longest trajectory of the NE tradewinds over the island (40 km), the windward NE-facing sides of tree canopies showed necrosis

4.3. Punaluu Site

Figs. 7-10 show the measurements of electrical conductivity of leaf samples taken at sites 1 through 10 on four occasions after strong NE tradewind days. These figures show some characteristics in common:

1) The conductivity distribution reflects the degree of exposure, i.e., the deposition of wind-borne salt, at each station. Site 7 on the upper leeward slope (Fig. 4), with consistently low values of conductivity, presents a striking difference from the other sites.

2) Different species indicated different values of conductivity probably because of the difference, from species to species, in leaf surface morphology and surface area per unit weight of 2 g. However, all species showed a similar trend in the spatial change in conductivity across the valley (Fig. 7). For example, a unit weight of *Andropogon virginicus* (grass species) gave low values of conductivity, although the relative magnitude of conductivity for each site is similar to the

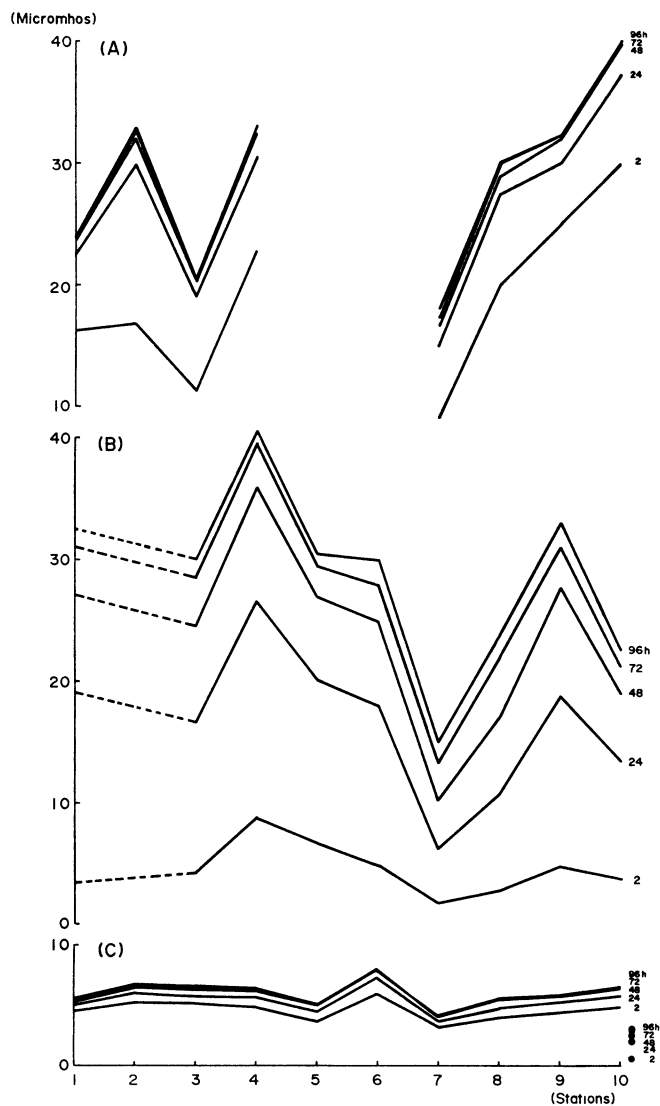


Fig. 7: Electrical conductivity of leaves sampled across the study valley, Punaluu, Oahu (Samples taken on Nov. 23, 1979).

Notes: A: *Sphenomeris chinensis*

B: *Schinus terebinthifolius*

C: *Andropogon virginicus*

Dots: *Schinus terebinthifolius* sampled in a protected valley bottom and used as a control

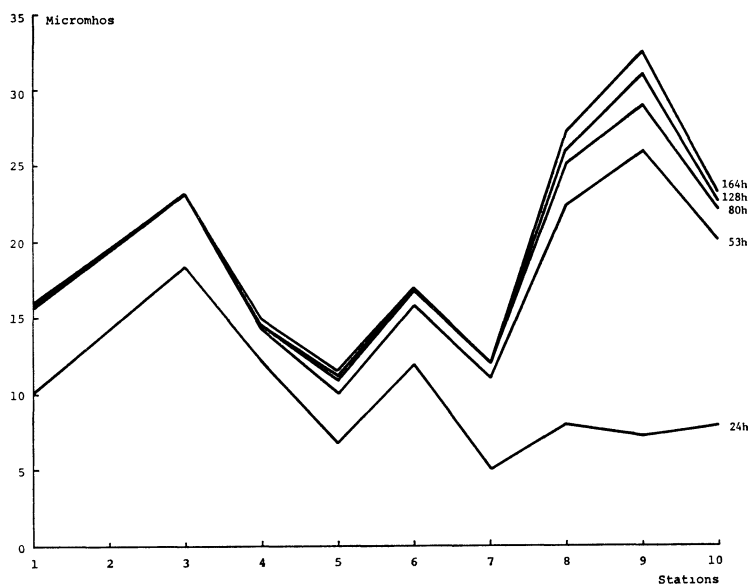


Fig. 8: Same as Fig. 7 except for samples taken from *Schinus terebinthifolius* on Nov. 28, 1979.

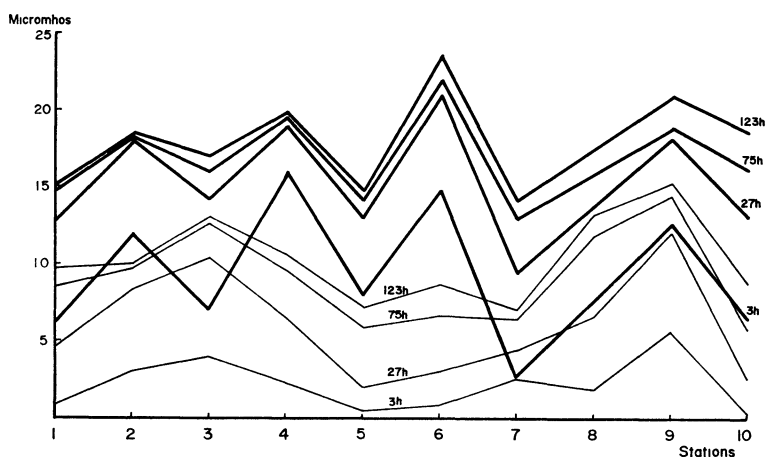


Fig. 9: Same as Fig. 7 except for samples taken from windward and leeward sides of *Schinus terebinthifolius* canopies on Dec. 5, 1979.

Note: Thick lines: windward samples

Thin lines: leeward samples

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ones for other species, with low values at site 7 in all cases.

3) Conductivity observations at certain time intervals showed that at all sites the conductivity increased at a relatively slow rate at first, then at a faster rate, and finally at a slower rate again with increasing

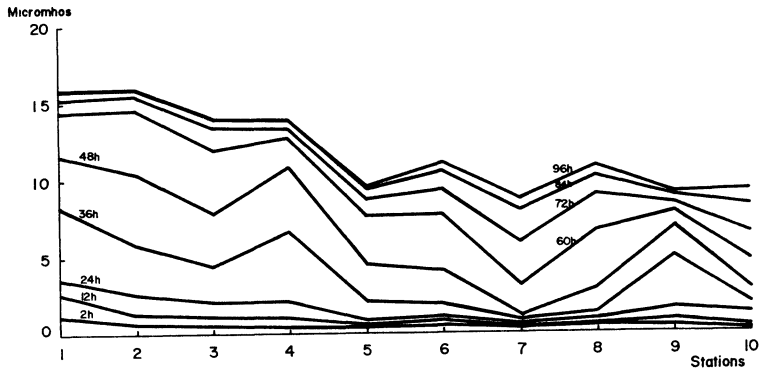


Fig. 10: Same as Fig. 7 except for samples taken from *Schinus terebinthifolius* on Mar. 8, 1980.

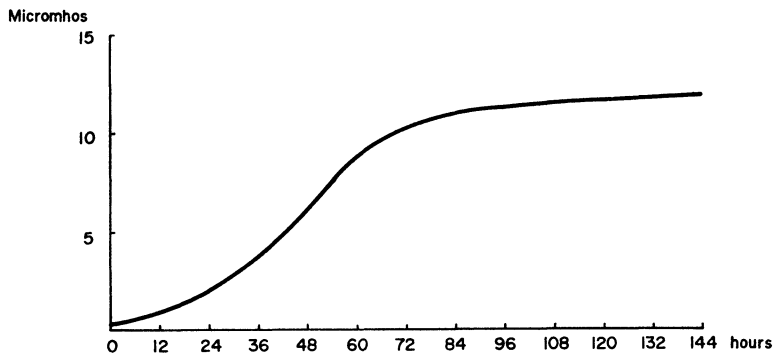


Fig. 11: Temporal change in electrical conductivity of deionized water after immersion of 2g of *Schinus terebinthifolius* leaves sampled on Mar. 8, 1980, Punaluu, Oahu.

time of immersion and finally showed no increase at all. Fig. 11 shows a typical temporal change in conductivity (average of 10 sites) for every 12-hr increment calculated from Fig. 10.

4) Leaves taken at a well-protected area in the study valley were used as a control (Fig. 7). These leaves showed the smallest value of conductivity. The value did not increase much during the course of the conductivity measurement, suggesting again that the electrical conductivity increases with the degree of exposure of leaves to the wind at the Punaluu site

5) On one occasion leaf samples were taken from both the wind-exposed (windward) and the protected (leeward) sides of the canopy of a shrub (*Schinus terebinthifolius*) at each site. The conductivity of leaves from the protected sides was consistently lower than that from

the exposed sides (Fig. 9), implying that the effect of the directional air-borne salt is more important than that of salt in the soil.

5. Discussion

5.1. Wind Speed, Salt Spray and Tree Deformation

The wind regime in the Hawaiian region is characterized by the steady NE tradewinds (Tables 2-3) with 73% of all daily mean winds blowing from between the NNE and ENE directions. The steadiness is greater in summer when the subtropical high intensifies. The daily mean NNE-ENE winds account for 96% in July and 95% in August. But even in winter Hawaiian Islands are exposed to the NE winds considerable amount of time, with NNE-ENE winds blowing 38% of time in January and 54% in February.

The Holoholo wind also blew from NE along a steep air pressure gradient of the strong high pressure cell which stayed to the north of Hawaii (Fig. 12). This wind provided a chance to determine the intensity and frequency of winds which are responsible for the island-wide salt spray damage on plants and at least partly responsible for the deformation of trees in Hawaii.

Tables 2 and 3 show that the frequency of winds below the intensity of the Holoholo wind (10 m/sec for the daily mean and 14 m/sec for the

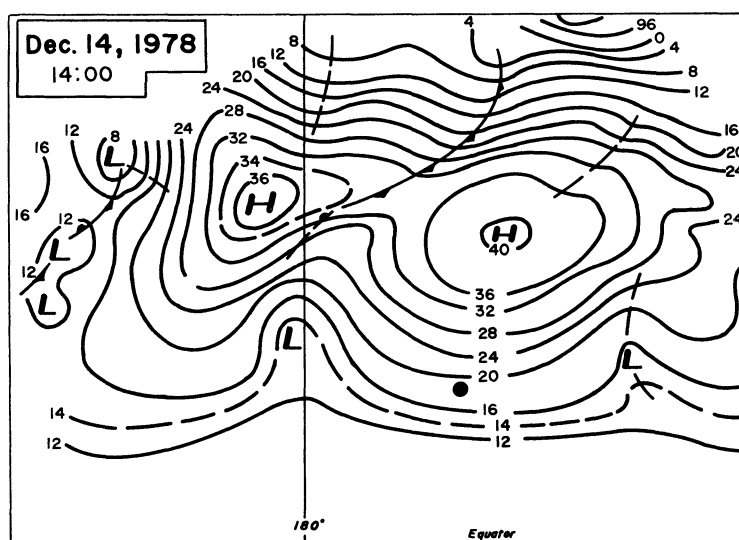


Fig. 12: Surface weather map at the time of the Holoholo wind (Dec. 14, 1978).

Note: Location of Hawaiian Islands indicated by a dot.

fastest 1 min. winds) is far greater than that above it, with more than 99% of all daily mean winds and 98% of all fastest 1 min. winds occurring below the Holoholo wind intensity. Winds greater than the intensity of the Holoholo wind occur, however, with a marked concentration in winter (88% and 80% for daily mean and fastest 1 min. winds, respectively), although the total frequency is small.

If the deformation of tree canopies all over the island is caused by the salt spray associated *only* with strong winds at the Holoholo wind intensity or greater, it follows that Fig. 1 represents a wind pattern under infrequent but strong daily mean wind conditions in winter, which occurs at the rate of 0.4% with 88% winter (Nov.-Apr.) concentration.

However, since the prevailing wind direction at any wind speed intensity is consistent with the most frequent direction of the normal tradewinds in Hawaii (Tables 2 and 3), Fig. 1 also happens to represent mean tradewind conditions.

Winds at the intensity of the Holoholo wind are rare but cause damage on plants on the entire island at the same time. However, it is natural to consider that strong winds, although below the Holoholo wind intensity, would also give a considerable impact on plants in the long run. These winds blow not only in winter but actually more often in summer. However, the causal relationship between the normal tradewind and tree deformation still remains to be determined.

5.2. Salt Spray Damage

Observations of vegetation immediately after the wind showed typical salt spray necrosis on leaf tips and margins on the windward sides of plant canopies in moderately exposed areas, but the necrosis had a tendency to spread to the entire leaf and the whole canopy at more exposed locations.

In the most affected areas (e.g., Kualoa Beach Park and Kailua Beach Park), many street and beach park trees and even some natural coastal plants including *Hibiscus tiliaceus*, *Eugenia cumini*, *Thespesia populnea*, *Prosopis pallida*, *Samanea saman* and *Cassia* spp. were severely damaged.

However, some species which are better adapted to the littoral environment, such as *Casuarina equisetifolia* and particularly outpost species such as *Scaevola taccada*, *Ipomoea pescaprae*, *Tournefortia argentea* and *Rhizophora mangle* were not affected in the slightest. Some non-littoral species were found to take advantage of a shelter provided by the resistant coastal plants, indicating that even an imperfect shelter would help save

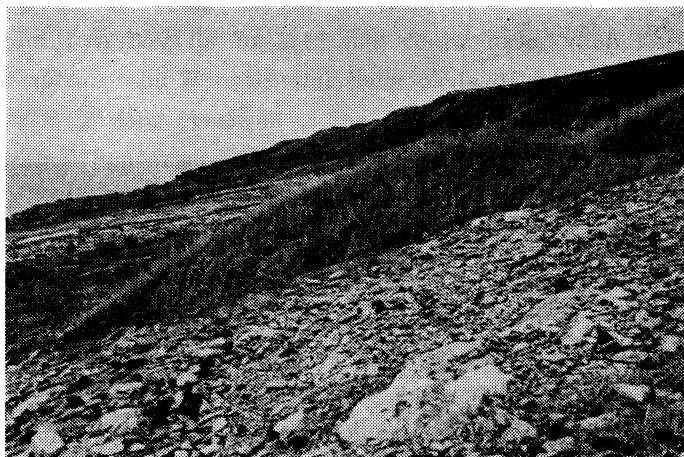


Photo 1: *Prosopis pallida* which has developed a prostrate life form in the littoral environment, Makapuu Point, Oahu.

the life of non-littoral species from fatal necrosis.

Some plants such as *Prosopis pallida* were found to have developed a prostrate life form owing to long frequent exposure to the salty wind near the coast (Photo 1). Our observation showed that the Holoholo wind completely killed all new shoots of this particular tree.

In Kaaawa of windward Oahu, *Samanea saman*, which normally takes an umbrella form in a protected area, looked more unbalanced immediately after the Holoholo wind because of the salt spray damage on the windward side of a canopy (Photo 2)

The follow-up observations of damaged coastal plants in April 1979, four months after the Holoholo wind, showed that gradual recovery from the damage was steadily in progress after the event (Photo 3), implying that the cyclic directional stress of salt spray constitutes an integral part of the physical environment of the littoral ecosystem in Hawaii.

In the leeward coastal areas the necrosis on the NE-facing windward side, and not the leeward ocean side, of plant canopies indicated that the air-borne salt spray accompanying the strong NE tradewinds can contribute to the development of tree deformation all over the island. For the air-borne salt to reach Makakilo and Campbell Industrial Park the wind had to pass the longest trajectory (more than 40 km) over the island (Fig. 1). This is comparable to the situation observed in New England where a hurricane carried sufficient quantities of salt water to damage trees a similar distance inland (Moss 1940).

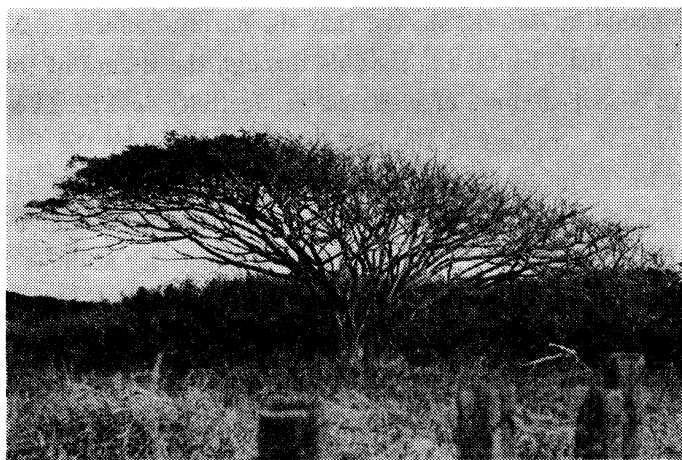


Photo 2: The windward side of the canopy of *Samanea saman* damaged by the salt spray of the Holoholo wind, causing the tree to look more deformed after the wind, Kaaawa, windward Oahu.

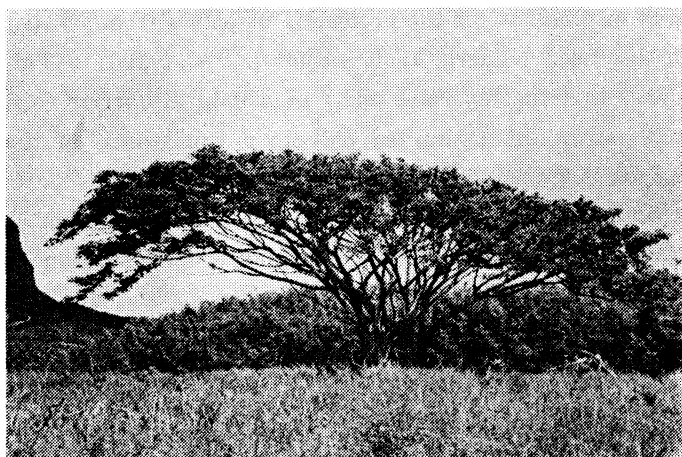


Photo 3: *Samanea saman* in Photo 2 recovering from the salt damage four months after the Holoholo wind, Kaaawa, windward Oahu.

5.3. Exposure and Salt Deposition

Winds at the Holoholo wind or greater intensity are infrequent [0.4% (1.5 days/year) for the daily mean and 2.4% (8.8 days/year) for the fastest 1 min. winds] in the Hawaiian environment. However, the winds strong enough to carry salt particles and cloud eyeglasses of a person a mile or two inland are more frequent. It seems that these salt particles accumulate on exposed leaves and are gradually taken in by leaves through osmosis.

Sideris (1955), in studying the effect of NaCl on leaf tip necrosis of

pineapple plants in Hawaii, showed that the harmful effects of NaCl are due to Cl and that Cl intake is possible through the tissues of the intact leaves. An S-shaped curve of electrical conductivity in Fig. 11 suggests that soluble salt, trapped in the leaf body, came out by the immersion of sample leaves in deionized water and possible breakage of cell walls.

Various findings at Punaluu of windward Oahu, i.e., high electrical conductivity at windy sites, persistently low conductivity at upper leeward site 7, difference in conductivity between the windward and the leeward sides of a canopy, very low conductivity of leaves taken from an extremely protected area and used as a control, and little change in conductivity of a control sample after immersion in water—all suggest that electrical conductivity is a good measure of exposure (i.e., a measure of the air-borne salt or chloride deposition).

Where either strong or steady wind is an important environmental factor in hilly littoral environment, the effectiveness and limitation of barriers and windbreaks for the protection of plants from salt deposition have been discussed (Sideris 1955, Lomas and Gat 1967). This study further shows that the favorable effect of a natural barrier (e.g., a hill and a small mountain) is limited only to a small area on the upper leeward slope, as represented by site 7 at Punaluu. This part of the slope has been reported to be markedly different from other parts of slopes in a valley in terms of the protection from winds due to wind separation (Noguchi 1975) and also in terms of the distribution of temperature, rainfall and evaporation (Noguchi 1982). The upper leeward slope is the only exception in Punaluu Valley where no deformation was found in the form of tree crowns.

6. Conclusion

The effect of air-borne salt spray on plants was studied in relation to the causal relationship between the wind and morphological and physiognomic developments of plants and vegetation in the littoral environment.

Analysis of daily wind data of the Honolulu International Airport for the period of 20 years (1959–1978) showed that the average NE trade-wind is stronger in summer, although infrequent but strong winds, mostly from NE direction and at the intensity equal to or greater than the Holoholo wind intensity (0.4% of time for the daily mean and 2.4% for the fastest 1 min. winds) occur more often in winter (88% and 80% winter concentrations for the daily mean and the fastest 1 min. winds,

respectively) than in summer and cause severe salt spray damage.

A study of salt spray damage on arboreal species by the strong Holoholo wind revealed that salt spray caused necrosis on leaf tips and margins on the windward (NE-facing) side of tree canopies all over the island of Oahu, with the severest damage observed on the most exposed locations on the windward side and promotories. These facts suggest that the tree deformation in Hawaii might be at least caused by the strong salt spray carrying NE winds at the Holoholo wind or greater intensities which occur at the frequency of 1.5 days/year (0.4% for daily mean) and 8.8 days/year (2.4% for fastest 1 min.) with winter concentration, and also that the wind pattern presented by Noguchi (1979) might be representative of such wind conditions, although it may not deviate much from the normal tradewind pattern because of the high frequency of NE winds at all wind speed levels in Hawaii.

Salt spray, carried by strong winds, cause severe damage on coastal plants in Hawaii. The stress of salt spray, however, seems to have become an integral part of the physical environment of coastal ecosystem, with the effect of stress taking the form of tree deformation and not the loss of plant life.

Measurement of electrical conductivity of leaves immersed in deionized water showed that there is a high correlation between the exposure and salt spray deposits and that the upper leeward slope of a mountain in a wind-swept region presents a remarkable difference from other parts of slopes in terms of the protection from the salt spray damage.

References:

- Ambler, H.R. and Bain, A.A.J. (1955) Corrosion of Metals in the Tropics. *J. Appl. Chem. (G.B.)*, 5, 437-467.
- Boodle, L.A. (1920) Scorching of Foliage by Sea Winds. *J. Minist. Agric.*, 27, 379-386.
- Boyce, S.G. (1954) The Salt Spray Community. *Ecol. Monog.*, 24, 29-67.
- Edlin, H.L. (1957) Saltburn Following a Summer Gale in Southeast England. *Quart. J. For.*, 51, 46-50.
- Edwards, R.S. and Claxton, S.M. (1964) The Distribution of Air-borne Salt of Marine Origin in the Aberystwyth Area. *J. Appl. Ecol.*, 1, 253-263.
- Fujiwara, K. and Umejima, S. (1962) On the Distribution of Wind-borne Salt on the Coastal Terrace. *Res. Bull. Exp. Forests., Hokkaido Univ.*, 21, 453-464.
- Goldsmith, F.B. (1973) The Vegetation of Exposed Sea Cliffs at South Stack, Anglesey. II. Experimental Studies. *J. Ecol.*, 61, 819-829.
- Hama, K. and Takagi, N. (1970) Measurement of Sea-Salt Particles on the

- Coast under Moderate Winds. Pap. Met. Geophys., 21, 449-458.
- Karschon, R. (1958) Leaf Absorption of Wind-Borne Salt and Leaf Scorch in *Eucalyptus camaldulensis* Dehn. Ilanot, For. Res. Sta., Israel, No. 4, 25 p.
- Lomas, J. and Gat, Z. (1967) The Effect of Windborne Salt on Citrus Production Near the Sea in Israel. Agri. Met., 4, 415-425.
- Malloch, A.J.C. (1972) Salt-Spray Deposition on the Maritime Cliffs of the Lizard Peninsula. J. Ecol., 60, 103-112.
- Moss, A.E. (1940) Effect on Trees of Wind-driven Salt Water. J. For., 38, 421-425.
- Noguchi, Y. (1975) Effect of Micro-Topography on the Wind Distribution at the Kirigamine Highland. Tenki, 22, 39-48.
- Noguchi, Y. (1979) Deformation of Trees in Hawaii and Its Relation to Wind. J. Ecol., 67, 611-628.
- Noguchi, Y. (1982) Water Balance and Exposure: Their Implication to Vegetation Asymmetry under the Tradewind Regime. PhD Dissertation, Geography Department, University of Hawaii, 361 p.
- Oosting, H.J. (1945) Tolerance to Salt Spray of Plants of Coastal Dunes. Ecology, 26, 85-89.
- Oosting, H.J. and Billings, W.D. (1942) Factors Effecting Vegetational Zonation on Coastal Dunes. Ecology, 23, 131-142.
- Osborn, T.G.B. (1922) A Sketch of the Ecology of the Franklin Islands. Trans. Roy. Soc. S. Austr., 46, 194-206.
- Parsons, R.F. and Gill, A.M. (1968) The Effects of Salt Spray on Coastal Vegetation at Wilson's Promontory, Victoria, Australia. Roy. Soc. Victoria Proc., 81, 1-10.
- Randall, R.E. (1970) Salt Measurement on the Coast of Barbados, West Indies. Oikos, 21, 65-70.
- Reitz, G. (1978) Windschur oder Salzschor? Erdkunde, 32, 1-10.
- Rossknecht, G.F. Elliott, W.P. and Ramsey, F.L. (1973) The Size Distribution and Inland Penetration of Sea-Salt Particles. J. Appl. Met., 12, 825-830.
- Rutter, N. and Edwards, R.S. (1968) Deposition of Air-borne Marine Salt at Different Sites over the College Farm, Aberystwyth (Wales), in Relation to Wind and Weather. Agri. Met., 5, 235-254.
- Sauer, J.D. (1962) Effects of Recent Tropical Cyclones on the Coastal Vegetation of Mauritius. J. Ecol., 50, 275-290.
- Semonin, R.G. (1972) Comparative Chloride Concentrations between Mauna Loa Observatory and Hilo, Hawaii. J. Appl. Met., 11, 688-690.
- Sideris, C.P. (1942) An Atmospheric Halatometer. Plant Physiol., 17, 497-499.
- Sideris, C.P. (1955) Effects of Sea Water Sprays on Pineapple Plants. Phytopathol., 45, 590-594.
- Sideris, C.P. and Young, H.Y. (1954) Effects of Chlorides on the Metabolism

- of Pineapple Plants. *Am. J. Bot.*, 41, 847-854.
- Sloet van Oldruitenborgh, C.J.M. and Heeres, E. (1969) On the Contribution of Air-borne Salt to the Gradient Character of the Voorne Dune Area. *Acta Bot. Neerlandica*, 18, 315-324.
- Smith, G.G. (1957) A Guide to Sand Dune Plants of South-Western Australia. *West. Austra. Nat.*, 6, 1-18.
- Tagami, Y. (1976) Formation of Wind-shaped Trees in Rishirito-island, Hokkaido. *Chigaku Zasshi*, 85, 28-42.
- Wells, B.W. and Shunk, I.V. (1938) Salt Spray: An Important Factor in Coastal Ecology. *Torrey Bot. Club, Bull.*, 65, 485-492.

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