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BERICHTE UND MITTEILUNGEN

CLIMATIC UNIFORMITY AND DIVERSITY IN THE GALAPAGOS ISLANDS AND THE EFFECTS ON AGRICULTURE

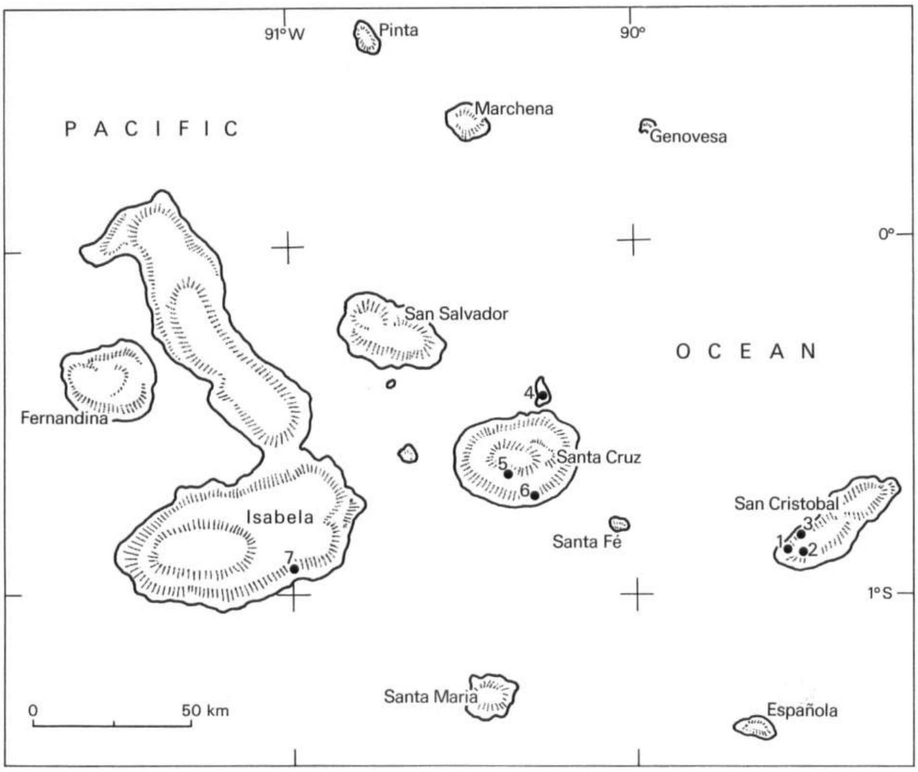
With 9 figures and 3 tables

Simon Nieuwolt

Zusammenfassung: Die klimatischen Eigenheiten der Galápagos-Inseln und ihre Einflüsse auf die Landwirtschaft

Im Gegensatz zu anderen äquatorial-maritimen Klimaten ist das der Galápagos Inseln durch deutliche jahreszeitliche Unterschiede in Temperatur und Niederschlag gekennzeichnet. Diese werden verursacht durch Lageveränderungen der innertropischen Konvergenzzone. Stärke und Beständigkeit der Passate werden dadurch beeinflußt. Auch Temperaturwechsel der Ozeanoberfläche und das El Niño-Phänomen haben deutliche Wirkungen auf das Klima. Die landwirtschaftlichen Nutzungsmöglichkeiten auf den Inseln werden vor allem durch die Regenfälle bestimmt. Im Tiefland ist Anbau ohne Bewässerung unmöglich; im Hochland wird die Pflanzzeit vor allem durch die Unregelmäßigkeit der Niederschläge begrenzt.

The Galápagos Islands (officially: Archipielago de Colon) are situated about 1000 km west of the South American continent in the equatorial Pacific Ocean (Fig. 1). Because some unique animal species have



1 Puerto Baquerizo (6 m above sea level)
2 El Progreso (250 m)
3 La Soledad (400 m)
4 Seymour (6 m)
5 Bellavista (194 m)
6 Charles Darwin (6 m)
7 Puerto Villamil (6 m)

Fig. 1: The main islands of the Galápagos group and the location of the meteorological stations used in this study

developed in this remote situation, the islands have attracted the interest of many scientists, primarily biologists and ecologists. The literature about their climate is nevertheless rather limited (ALPERT 1946, 1981; GRANT a. BOAG 1980). Several authors have treated the islands together with the coastal climates of Ecuador and Peru (JOHNSON 1976; SCHÜTTE 1967, 1968). The recent publication of official statistics by the Ecuadorian meteorological service over the period 1959–1981 now allows a quantitative climatological analysis for several stations on the islands (*Instituto Nacional* 1962–1983).

The data include a description of the location of the meteorological stations, but unfortunately the islands are covered very unevenly (Fig. 1). Some rainfall statistics are interrupted by gaps in the records and figures for relative humidity, wind speed and cloudiness are impaired by several unexplained inconsistencies, probably due to changes in the method of computation or instruments. For this article, all doubtful data were discarded.

The equatorial-marine situation of the islands suggests seasonal, annual and regional climatic uniformity (NIEUWOLT 1977, pp. 15–17, 110–114, 176–178). However, the climate of the Galápagos Islands shows a number of unexpected variations in all three respects.

Most of this diversity is related to the general circulation of the atmosphere over the eastern Pacific Ocean, which is dominated by the southeasterly trade winds. These originate from a permanent cell of high pressure centered around 3° S and 90° W. From there the trades run approximately parallel to the coast of Peru. During most of the year the southeasterlies cross over the equator and meet their counterparts of the northern hemisphere at around 5° North, in the Inter Tropical Convergence Zone, a broad area of rising air masses. But the whole circulation system moves seasonally with the apparent position of the sun, and from January to March the I.T.C.Z. is frequently very close to the equator and therefore over the Galápagos Islands (HASTENRATH 1985, p. 129; HASTENRATH a. LAMB 1977). The southeasterlies bring cool and relatively stable air masses to the islands during most of the year, when they prevail in 70–80 percent of all observations. In the period from

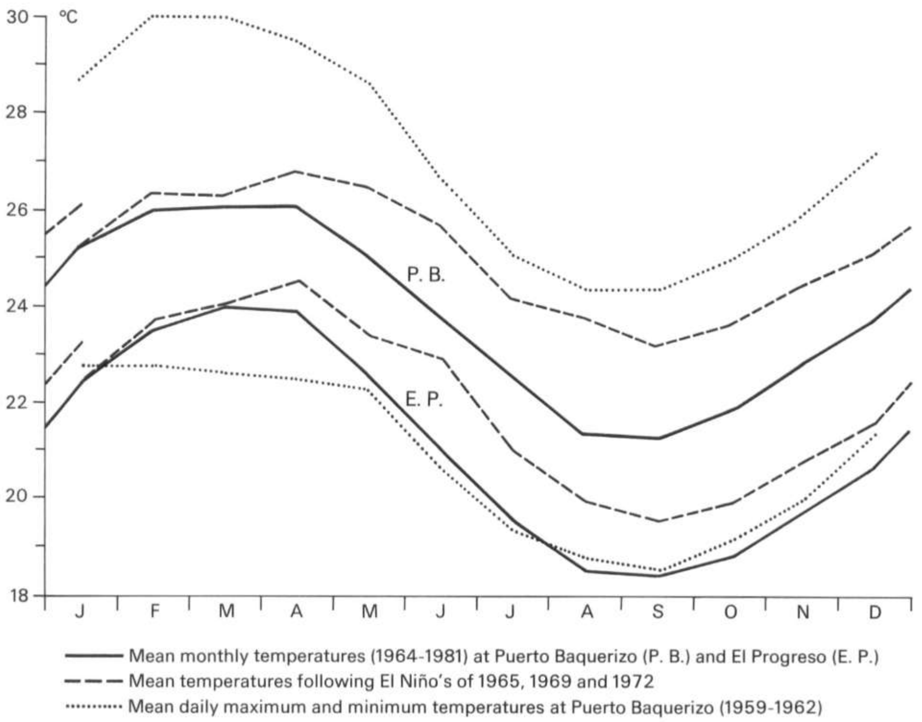


Fig. 2: Mean temperatures at Puerto Baquerizo and El Progreso

January to April, however, their dominance is often interrupted: their frequency may be less than 40 percent and calms may reach up to 40 percent of all observations. In this season the air masses around the islands are warm and humid and often conditionally unstable.

A second source of annual and seasonal climatic variations are the sea surface temperatures around the islands. The South Equatorial Current is a continuation of the cool Peru Current, which moves northwards along the west coast of South America. Off-shore winds in Ecuador cause upwelling and a further cooling of surface waters, which have temperatures around 23 °C during most of the year. However, in February and March they may go up to about 26° (*U.S. Navy Atlas* 1979). In years with a strong El Niño the sea around the Galápagos Islands may be several degrees warmer, particularly from March to May (Hastenrath 1985, p. 259–261; Oliver 1987; Rasmusson 1985). This warming is usually accompanied by exceptionally low frequencies of the trade winds; calms prevail and it seems that the warmer sea surface attracts and intensifies the Inter Tropical Convergence Zone.

Finally, local landforms cause climatic differences between stations on the islands. As the winds are predominantly from one main direction, strong differences in wind speed, rainfall and humidity are caused by exposure, steepness of slope and elevation. Though only a few stations can be compared, these regional variations are clearly illustrated.

Temperatures

A strong regional uniformity characterizes the temperature conditions on the Galápagos Islands: all lowland stations have mean monthly temperatures which differ less than 1.5 °C from those at Puerto Baquerizo. The only differences are caused by elevation, as shown by data for El Progreso, 250 m above sea level (Fig. 2).

Differences from year to year are also small: at all stations the standard deviations of monthly mean temperature over the period 1964–1981 were smaller than 1.5°, and for the period from January to April even less than 1 °C. On the other hand, the effects of El Niño are striking: three years with a strong El Niño brought temperatures more than 2° over the long-term mean, and this influence lasted until January of the following year (Fig. 2).

A comparison with other equatorial stations shows that annual mean temperatures in the Galápagos Islands are clearly lower but that the annual ranges are higher than in similar climates (Table 1). These features give the impression that the trade winds and

Table 1: Climatic data for the Galápagos Islands and some other equatorial stations

STATION (elevation)	TEMPERATURE (° C) Annual mean	Annual range	PRECIPITATION (mm) Annual mean	Months w. mean below 50 mm	Max. in 24 hrs. mean (years)
Puerto Baquerizo (6 m) (Nr. 1 on Fig. 1)	23.8	4.8	325	8	130 (15)
Charles Darwin (6 m) (Nr. 6 on Fig. 1)	23.8	5.3	397	8	95 (10)
Puerto Villamil (6 m) (Nr. 7 on Fig. 1)	23.9	5.2	327	9	136 (9)
El Progreso (250 m) (Nr. 2 on Fig. 1)	21.1	5.6	1458	0	235 (15)
Seymour (6 m) (Nr. 4 on Fig. 1)	23.5	4.2	62	12	49 (6)
Portoviejo, Ecuador (44 m) (1°4′ S., 80°26′ W.)	31	2	362	8	80 (10)
Quito, Ecuador (2818 m) (0°13′ S., 78°30′ W.)	22	2	1109	2	54 (10)
Belém, Brazil (24 m) (1°28′ S., 48°27′ W.)	25.7	1.3	2732	0	126 (?)
Libreville, Gabon (12 m) (0°27′ N., 9°25′ E.)	30	3	2592	3	248 (16)
Nairobi, Kenya (1675 m) (1°18′ S., 36°45′ E.)	19.6	4.0	1066	4	112 (9)
Mombasa, Kenya (16 m) (4°2′ S., 39°37′ E.)	26.7	4.1	1198	2	150 (17)
Singapore (8 m) (1°21′ N., 103°54′ E.)	26.7	2.0	3453	0	279 (24)
Tarawa, Gilbert Isl. (4 m) (1°25′ N., 172°56′ W.)	27.8	0.5	1996	0	191 (?)
Ocean Island (65 m) (0°52′ S., 169°35′ E.)	28.0	0.7	1848	0	

Sources: World Survey of Climatology, Vol. 9, 10, 12, 15

the Peru Current have transported temperatures from a latitude of about 10° South to the equator. The diurnal range of temperature reaches an annual mean of 6° C at Puerto Baquerizo, the only station for which it has been recorded. It therefore exceeds the annual range, a characteristic of equatorial climates (Fig. 2).

Temperatures in the Galápagos Islands therefore exhibit regional and inter-annual uniformity as well as seasonal and diurnal differentiation.

Precipitation

In most of the tropics, convection is the main cause of rainfall as air masses are predominantly warm and humid and surface temperatures high. A large proportion of tropical rainfall therefore comes in the form of convectional rainstorms, short periods of very intensive rain, accompanied by thunder and lightning, which occur mainly during the afternoon (Nieuwolt 1977, pp. 122–126; Riehl 1979, pp. 108–114).

In the Galápagos Islands, however, convection is of little importance from about May to December, when surface temperatures are relatively low (Fig. 2). Moreover, the air masses brought by the southeasterly winds are usually rather stable because they contain the typical trade wind inversion layer. They are also cooled from below by the cold ocean surface around the islands, and this creates low clouds or fogs, locally called *garúa,* but no rain. The only process causing precipitation during this period is orographic lifting, when the air masses are forced to rise rapidly by the strong wind, but this brings only rain to the highlands.

From December to March convection takes place on the islands. Both land and sea surface temperatures are higher and the reduced strength of the trade

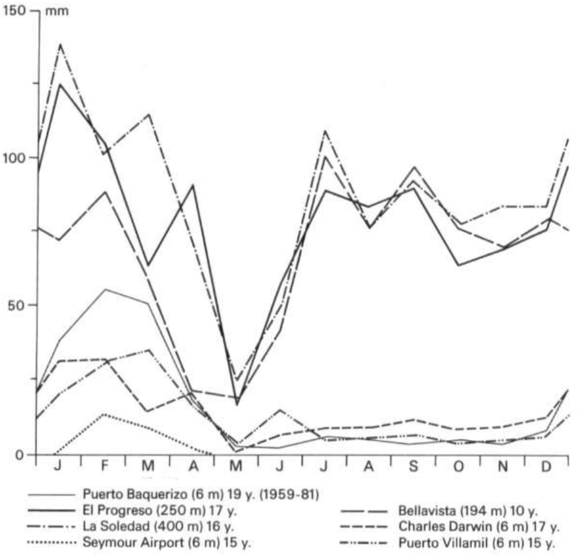


Fig. 3: Median monthly rainfall at seven stations

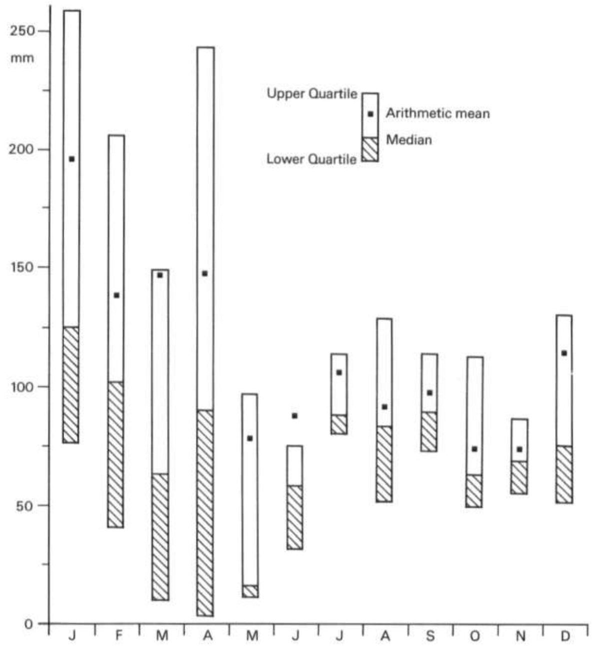


Fig. 4: Variation of monthly rainfall at El Progreso, 1964–1981

winds gives the air masses sufficient time to absorb water vapour from the warmer ocean surface. The slow general circulation also favours local convection and converging sea breezes and valley wind often help. These processes are intensified during years with a strong El Niño. Still, thunderstorms are relatively rare: the few data available indicate that they occur only in the months of February to April and not more than during 2 or 3 days at any station.

Obviously these conditions create strong seasonal, regional and inter-annual variations: as in most of the tropics, rainfall is the most variable element of climate in the Galápagos Islands.

The *seasonal distribution* shows a rainy season from December to March at all stations (Fig. 3). It is followed by a dry season of 5–7 months at the lowland stations (Nr. 1, 4, 6 and 7), but in the highlands only May is really dry. Though the curves are a bit irregular, due to the relatively short records used, the diagram illustrates the strong regional differences, particularly between lowland and highland stations. Seymour Airport (Nr. 4) is continuously dry, as it is effectively shielded from the southeasterly winds by the neighbouring island of Santa Cruz (Fig. 1).

In Fig. 3 medians of rainfall are indicated because the more commonly used arithmetic means may be inflated by a few exceptionally high individual monthly totals, especially when short series of data are used. An illustration of this effect is given for El Progreso (Fig. 4). The arithmetic mean exceeds the median throughout the year, but in March and June it reaches and exceeds the Upper Quartile, the amount that was reached by only 25% of the months on record. This high *inter-annual variability* of monthly rainfall prevails at all stations, but is particularly strong at the lowland stations. The coefficient of variation (standard deviation in percent of the mean), V, exceeds 80 from January to June at all stations with only one exception (February at Bellavista, when V = 64), and exceeds 50 during the rest of the year at most stations. At Seymour, the driest station, V exceeds 140 throughout the year.

El Niño years usually bring high rainfall to the islands, but the effects seem to last only from about February to June (Table 2). On the other hand, January 1973 brought very heavy rainfall at all stations, though it was not an El Niño year. This can be explained by sea surface temperatures, which remained abnormally high for more than a year after the 1972 El Niño (Rasmusson 1985, p. 169).

The long dry season of the lowlands in the Galápagos Islands is rather unusual for equatorial regions: it is only duplicated at the nearby West coast of Ecuador (Portoviejo). It is also reflected by the very low annual total rainfall in comparison to other stations (Table 1).

Total annual rainfall shows a high variability (Fig. 5). The records for Puerto Baquerizo are the longest series available, and to fill some gaps, records for Charles Darwin were used. To ensure comparability, all annual totals are expressed in percent of the annual mean. For 1973 and 1979 no complete records were available at either station.

Fig. 5 demonstrates the effect of El Niño years: 1965, 1969, 1972 und 1975 all had totals well above

Table 2: Monthly rainfall during 3 El Niño years (1965, 1969, 1972) and in January 1973, in percent of the mean over 1964–1981

Station	Jan.	Feb.	March	April	May	June	July	Aug.	Jan. 1973
Ch. Darwin	55	54	137	322	404	369	70	73	632
La Soledad	47	122	259	246	359	186	92	86	285
El Progreso	49	118	259	328	384	266	115	65	377
P. Villamil	46	108	168	405	344	244	75	111	827
Seymour	3	168	246	350	83	–	–	–	759
Bellavista	53	130	170	299	294	191	104	66	–

–: no record

the mean. The second year after a strong El Niño can also have much rainfall, as shown by 1959 and 1976. Highland stations have more regular annual totals: the coefficient of variation is 69.7 at Puerto Baquerizo, but only 51.1 at El Progreso (250 m above sea level) over 15 years.

An important characteristic of tropical rainfall is its *high intensity* (Nieuwolt 1977, pp. 121–126; 1988). It is well indicated by the maximum received during 24 hours, though the period of observation should be considered. In the Galápagos Islands these maxima were all recorded during February or March. In magnitude they are similar to those observed at other equatorial stations (Table 1). This shows that although convection is limited to one season only, it is of the same intensity as in other equatorial climates.

Precipitation in the lowlands of the Galápagos Islands shows the long dry season typically found at latitudes of about 15–20 degrees, but in the highlands the short dry period, the strong inter-annual variations and the high intensity are more of an equatorial type of rainfall regime.

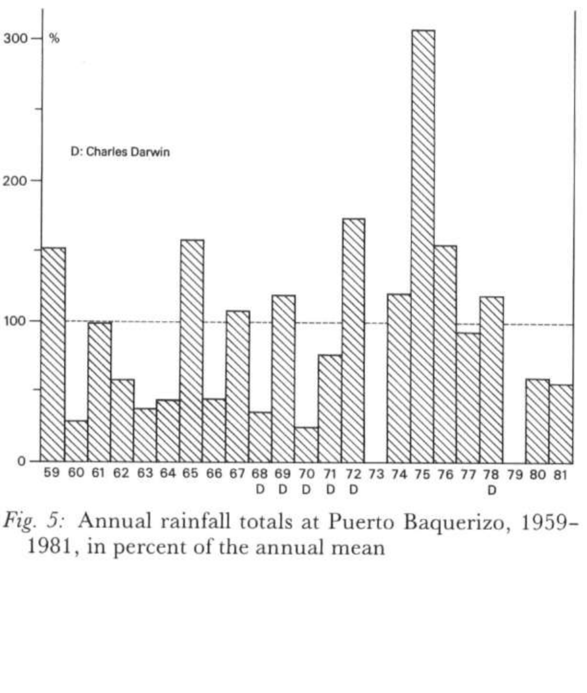


Fig. 5: Annual rainfall totals at Puerto Baquerizo, 1959–1981, in percent of the annual mean

Other elements of climate

The other elements of climate are less documented than temperature and rainfall, not only because they were observed at fewer stations, but also because some records had to be disregarded for unexplained discrepancies.

Daytime relative humidity, recorded at 1300 hrs local time, could be determined for 4 stations (Fig. 6, top). It is much higher at the highland stations (El Progreso, Bellavista) than in the lowlands, particularly from June to December, when cooling of the lower air layers by the ocean surface produces frequent fogs

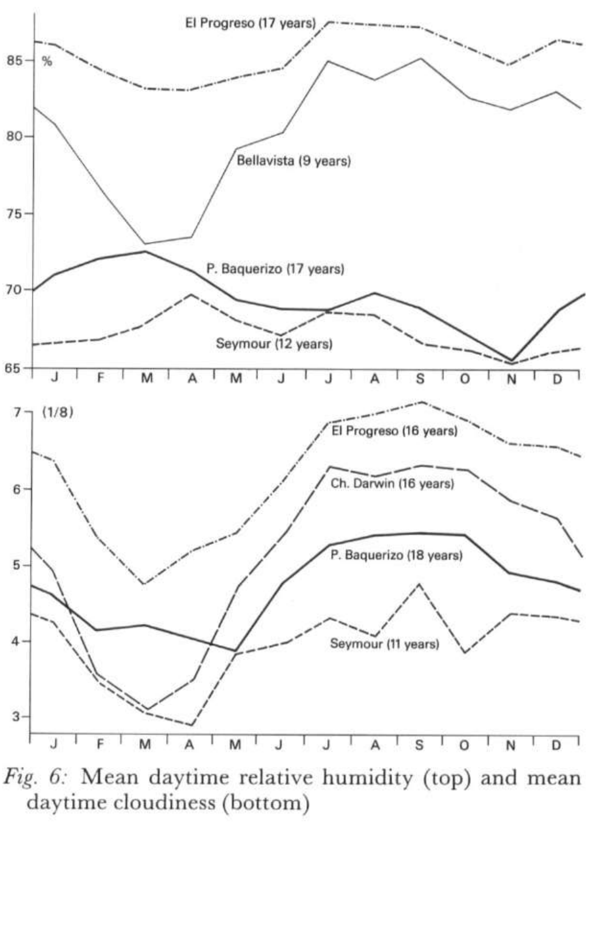


Fig. 6: Mean daytime relative humidity (top) and mean daytime cloudiness (bottom)

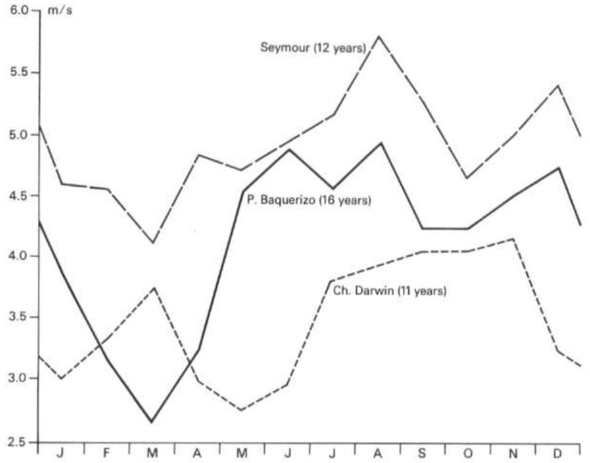


Fig. 7: Mean daytime wind speed

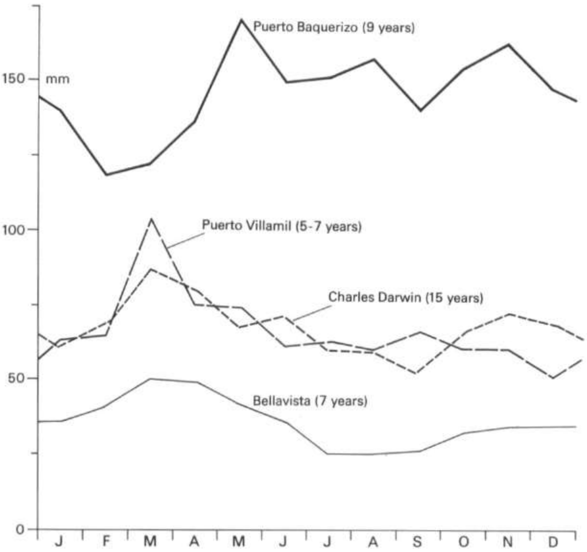


Fig. 8: Mean monthly pan evaporation

or low clouds. The lowland stations show a slight seasonal maximum during the rainy season from January to April. The relative humidity at night is comparatively uniform, as at most tropical stations, because it often reaches 100% due to cooling of air near the ground, resulting in the formation of dew.

Daytime cloudiness exhibits strong seasonal variations at all four stations for which it could be determined (Fig. 6, bottom). It is heaviest during the dry season of July to December, when fogs and low clouds are frequent occurrences, and lighter during the rainy season. Regional differences are caused by local factors: the low cloudiness at Seymour is related to its sheltered position regarding the southeasterlies; the difference with the other stations are smallest from February to May when the trade winds are often interrupted. Data for sunshine hours are only available for Puerto Baquerizo, they confirmed the above pattern of cloudiness.

Wind speeds at 13.00 hrs local time show strong local and seasonal differences. The high wind speeds at Seymour are related to the development of sea breezes at that station; at Puerto Baquerizo the interruption of the trade winds is clearly reflected, while at Charles Darwin frequent sea breezes from February to April keep wind speeds relatively high (Fig. 7).

Agriculture in relation to climate

For many of the approximately 6000 inhabitants of the Galápagos Islands agriculture is the major source of income, particularly in the highlands where tourism and fishing are of less importance than near the coasts.

The main crops produced are perennials: coffee, sugarcane, fruit trees like bananas, papayas, citrus, mangoes; and annuals, mainly vegetables (onions, cabbage, lettuce), maize, tobacco and peanuts (Koford 1966). In addition, some pastures in the highlands are used for the raising of cattle, though most cattle runs more or less wild and is frequently hunted. Most agriculture is for subsistence, though the tourist hotels are a local market, and coffee, potatoes and cattle are exported to the mainland.

The standard of living of most farmers on the islands is very low and improvements in agriculture are badly needed. Yet the intensification of present production systems and the introduction of new crops are severely restricted by climatic conditions. As in most tropical climates, the limiting factor is the supply of moisture, temperatures being favourable to most crops throughout the year. As irrigation is used only for some fruit and vegetable gardens, rainfall is the decisive element of climate in relation to agriculture.

The water needs of crops vary according to plant species and the stage in the development cycle, but the minimum required can generally be estimated as about 40 percent of the potential evaporation, measured by evaporation pans or calculated by various formulae (Doorenbos a. Pruitt 1977). Evaporation data are available for 4 stations in the islands and they show large regional differences (Fig. 8). The low values for Bellavista are due to its elevation (194 m); the high values at Puerto Baquerizo to its high wind speeds (Fig. 7).

A direct comparison between rainfall and plant water requirements is facilitated by the Agricultural Rainfall Index, which expresses rainfall in percent of the mean evaporation or potential evapotranspiration (Nieuwolt 1982). For the Galápagos Islands, median rainfall figures are used, as they provide

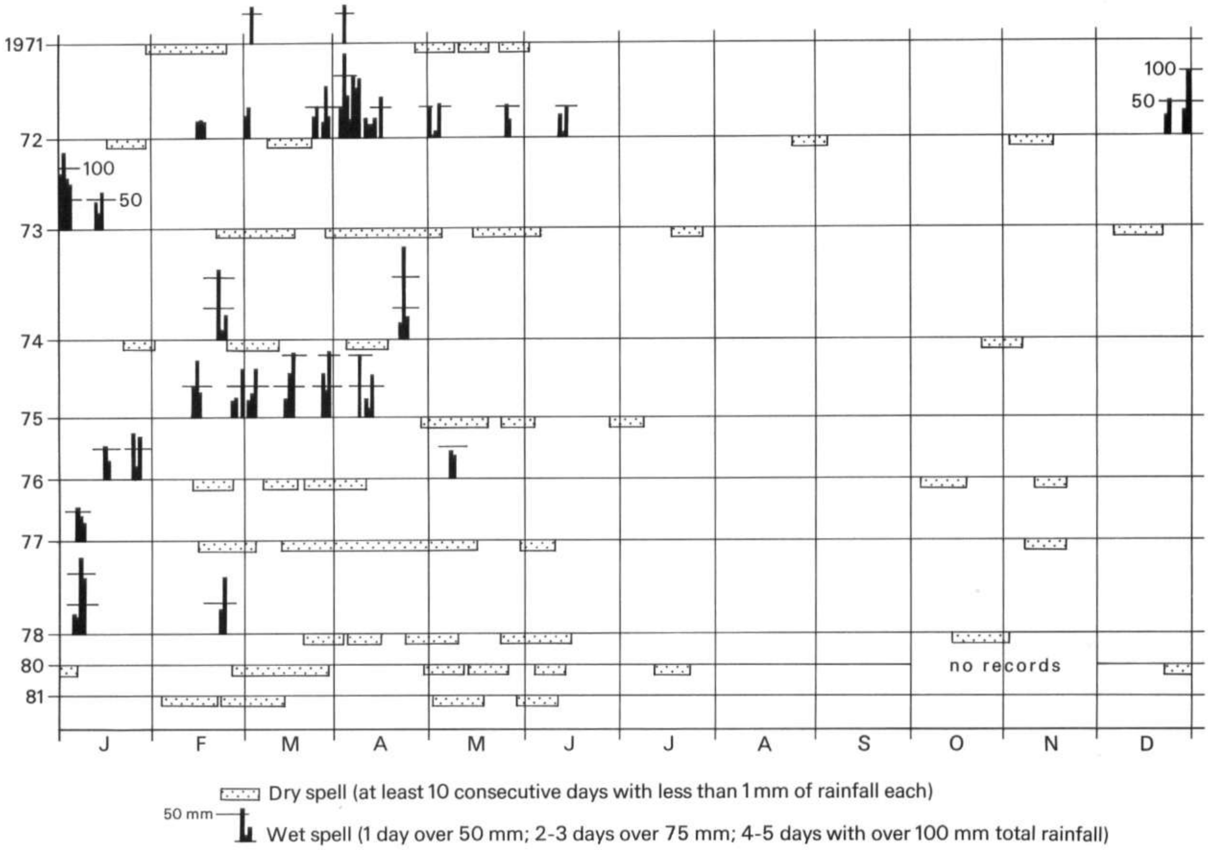


Fig. 9: Wet and dry spells at El Progreso, 1971–1981

a good estimate of the amounts of rainfall that may be expected (Table 3). For El Progreso, where no evaporation data are available, the potential evapotranspiration was estimated from temperature data (Hargreaves 1985).

These figures show that agricultural production without irrigation is practically impossible in the lowlands, where only one or two months regularly receive sufficient rainfall. In the highlands, however, there is a reliable supply of adequate moisture during most of the year, even if the data for Bellavista seem to draw a too favourable picture, due to its rather low evaporation figures; the data for other highland stations suggest values comparable to those at El Progreso.

In the tropics, monthly data may conceal serious risks for agriculture because the rainfall is often very irregular: even during months with a favourable total, periods of drought and water surpluses may reduce yields or damage crops. Only daily rainfall figures can provide an indication of these dangers, but they should cover a period of at least ten years (Nieuwolt 1989). In the Galápagos Islands such a series of records is available only for El Progreso, which is in an agricultural area.

The occurrence of dry and wet spells at this station illustrates the risks to crops (Fig. 9). The limits of both events were set when serious damage to tropical crops is likely and young plants might be destroyed (Nieuwolt 1989). At El Progreso, during ten years

Table 3: The Agricultural Rainfall Index, based on median rainfall

Station	Elev. (m)	J	F	M	A	M	J	J	A	S	O	N	D
P. Baquerizo	6	27	46	42	14	1	1	4	3	2	3	2	5
Ch. Darwin	6	50	46	16	26	1	9	15	15	21	13	13	18
P. Villamil	6	31	47	33	23	4	24	9	10	10	7	8	11
Bellavista	194	202	214	115	43	42	116	398	302	367	234	210	227
El Progreso	250	125	105	64	90	17	58	89	84	90	64	69	76

Table 4: Dry and wet spell indices at El Progreso (1971–78, 1980–81)

	J	F	M	A	M	J	J	A	S	O	N	D
D_{10}(%)	9.4	33.9	44.8	37.3	48.7	21.0	9.4	2.3	1.3	14.0	16.3	8.1
W(mm)	113	69	92	119	27	10	0	0	0	0	0	22

these risks occurred at least once in every month of the year, but mostly during the main rainy season from December to May, when both dry and wet spells may happen in the same month.

These agricultural dangers can be quantified for all years on record by two indices. D_{10} gives the percentage of all days that belonged to a dry spell of at least 10 days – it shows the probability of these droughts. W measures the surplus rainfall received per year of record. Both indices fully represent spells that overlapped from one month into the next (Table 4). The indices illustrate that at El Progreso, where total rainfall is sufficient, dry spells are a major risk from February to June, wet spells from December to May. As young crops are particularly sensitive to these dangers, new plantings should take place only from July to September. Perennials and pastures, less sensitive to droughts and water surpluses, should be preferred over annual crops.

Daily rainfall data for other highland stations suggest very similar effects of rainfall irregularity, but the series of observation are too short and too often interrupted to support as detailed an analysis as made here for El Progreso.

The limitations to agriculture set by precipitation should be considered when the introduction of new crops and the intensification of production are proposed to improve living conditions for the farmers on the Galápagos Islands (Koford 1966).

Acknowledgement

The author wishes to express his thanks to the librarians of the Royal Netherlands Meteorological Institute, De Bilt, who supplied him with the meteorological data and most of the literature used in this study.

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