ON THE ISOTOPIC COMPOSITION OF PRECIPITATION IN TROPICAL STATIONS (*).

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SUMMARY

Some of the trends and characteristics of the isotopic composition of precipitation in tropical stations are discussed. Stations in small Pacific islands show a variation with latitude, with lower δ-values between 15°N and 15°S and higher values at higher. Inland stations are depleted in heavy isotopes with respect to coastal stations but sometimes this continental effect is rather complex, as for instance in Africa. Mean monthly δ-values show a remarkable correlation with the amount of precipitation, but the slope variations do not show a clear dependence on the mean long term δ-value, as should be expected theoretically. In Southern American stations the seasonal variations of the mean monthly δ-values are correlated and they are greater in inland stations due to continentality. The possible effects of recycling of water vapour by evapotranspiration are also discussed.

1. INTRODUCTION

Recently the IAEA has published the statistical treatment of the isotopic data of precipitation of the stations of the IAEA/WMO global network (IAEA, 1981). On the basis of these results, and of other results available in the IAEA files, I shall try in this paper to briefly review some characteristics of the stable isotope compositon of precipitation in tropical stations. The stations, the data of which will be discussed here, are shown in fig. 1. They are also listed in Table 1, together with their geographical co-ordinates, altitude, mean temperature and mean annual precipitation.

2. LONG TERM MEAN ISOTOPIC COMPOSITION OF PRECIPITATION

The long term mean compositon os stable isotopes in precipitation in tropical stations is included in Table 1. The length of the observation period in the last

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column refers to the oxygen-18 analyses, which are in general more frequently available, and it has been computed by dividing the total amount of precipitation for which the $\delta^{18}O$ values are available by the mean yearly precipitation.

For some stations, the observation period is rather short, well below 5 years, which is probably the minimum period to obtain fully reliable mean values. The values reported from these stations might change therefore in future, when more results are available, but I believe that these changes will not affect this discussion very much.

The mean $\delta^{18}O$ values are also shown in fig. 2. The δD and the $\delta^{18}O$ values are also plotted in fig. 3: they line up very well along the so-called world meteoric water line (Craig 1961; Dansgaard 1964).

2.1 Island stations

Most of the stations located on small islands are in the Pacific Ocean. For these stations one can assume that the precipitation derives directly and exclusively from condensation of atmospheric vapour of oceanic origin and that the influence of the land on the isotopic composition of vapour and of precipitation is negligible, at least at low altitude.

The isotopic composition of precipitation of 11 Pacific island stations depends on the latitude: at stations in the latitude belt between $15^{o}N$ and $15^{o}S$ the δ-values are significantly lower than those at stations at higher latitudes, between 15^{o} and 30^{o}, as is shown in fig. 4. (At even higher latitudes the heavy isotope content of precipitation decreases again, because the effect of cooling becomes predominant).

The reason of the above trend of δ-values with latitude seems to be mainly the "amount" effect: the correlation coefficient between amount of precipitation and $\delta^{18}O$ is -0.571, which is significant at the 90% level. This means that the fraction of atmospheric vapour condensed to produce rains is greater in sub-equatorial islands than in subtropical islands. There are however important exceptions to this behavior: for instance, at Hilo (Hawaii), where the precipitation is high (3470 mm/year) and the $\delta^{18}O$ is in the less negative range (-2.29‰). The amount of precipitation at Hilo is probably determined by the high mountains of the island, the altitude of which exceeds the 4000 m at the two volcanoes Mauna Kea and Mauna Loa.

It is also worthwhile to notice that other low latitude Pacific stations located on large islands, that is Manila, Djajapura and Madang, as well as Darwin in Northern Australia, also follow rather well the isotopic trend observed in small islands.

The same trend of $\delta^{18}O$ with latitude is not found in the Atlantic Ocean, where unfortunately the number of island stations in insufficient. However, the stations on the eastern coast of South America, for which the influence of the continent is probably minimal due to the prevailing wind direction, also do not show any latitude isotopic trend.

The occurrence of the isotopic variation of precipitation with latitude over the Pacific is most probably linked with the position of the intertropical convergence zone, the seasonal displacement of which is rather limited. On the contrary, over the Atlantic the position of intertropical convergence zone is more distorted by the continents and the occurrence of cold marine currents, and its seasonal displacement is rather large.

The $\delta^{18}O$- δD correlation computed for the 18 island tropical stations of Table is:

$$\delta D = (7.40 \pm 0.38)\ \delta^{18}O + (7.6 \pm 1.1)$$

with a orrelation coefficient of 0.976. The deuterium excess is 9.3 ± 0.8. The slope of above correlation is definitely greater than that reported for island stations by Yurtserver & Gat (1981):

$$\delta D = (6.17 \pm 0.51)\ \delta^{18}O + (4.0 \pm 1.5)$$

and than that reported by Dansgaard (1964). For the latter author, the slope is about 3.5 while the intercept ranges from +6.5 to -9.0%.

2.2 Coastal stations

The $\delta^{18}O$ values of precipitation in coastal tropical stations range from -1.5 (Bombay) to -7.8% (Madang). Rather negative values, similar to that of Madang, are unexpectedly frequent, as for instance those observed at Singapore, San Salvador, Hong Kong, Bangkok, Manila. A combination in various proportions of several effects,such as the amount and the continental effects (the atmospheric moisture derives in part from inland), is probably responsible for the low δ values. Also the contribution of recy - cled moisture by evapotranspiration might be important. The correlation of $\delta^{18}O$ with the amount of precipitation is not significant (r = -0.020).

The $\delta^{18}O$-δ D relationship for coastal stations is practically identical to that for island stations:

$$\delta D = (7.60 \pm 0.25)\ \delta^{18}O + (7.4 \pm 1.2)$$

with r = 0.987 and d (deuterium excess) = 9.2 ± 0.6%0.

2.3 Inland stations

Tropical inland stations frequently - but not always - show heavy isotope contents of precipitation which are significantly lower than those of coastal stations,as should be expected as a consequence of the so-called continental effect.

In the Amazonian Basin, the most negative δ values are observed at Porto Velho, which is the most inland station. Intermediate δ values occur at other inland stations (Uaupés, Manaus, Cuiabá, Brasília) which are less distant from the coast.

There is no correlation, in the Amazonian Basin, between isotopic composition and amount of precipitation. This however is not surprising in inland stations,where such a relationship is quite complex: in fact, low δ values can also be associated with low precipitation, if the rain derives for instance from an atmospheric vapour already depleted in heavy isotopes due to previous condensation processes. In addition, any correlation between isotopic composition and amount of precipitation can be completely masked by intense evapotranspiration processes, as are likely to occur in Amazonia. If plant transpiration is the prevailing process, then the isotopic composition if water vapour returned to the atmosphere is equal to that of precipitation. The isotopic com- position of rain deriving to a significant exten from recycled moisture, is no longer related to the amount in a simple way.

Also rather complex is the continental effect on the isotopic composition of precipitation in Africa. The amount of precipitation decreases steadily from West to East, i.e. from Bamako, to Kano, N'Djamena, Geneina and Khartoum, in the latitude belt between 12 and 16^{o}N. Here, however, the strongest precipitation gradient is in the South-North direction, i.e. from the coast to the Sahel and to the Sahara desert, and this is mainly responsible for the aridity of the most northern of the above stations, Khartoum.

The ^{18}O content of precipitation is practically the same at Bamako, Kano and N'Djamena (but in this last station the D content is 5-8‰ higher), and then it increases by about 2‰ at Geneina and Khartoum. This trend is also confirmed by the isotopic composition of groundwater samples of recent age (high tritium and/or carbon-14 content), which behave exactly as precipitation (fig. 5, from Dray **et al.**, 1981). This is a consequence of the fact that in the Northern tropical belt of Africa the atmospheric moisture derives from the Atlantic Ocean in the West, the Gulf of Guiana in the South West and the Indian Ocean in the South East: the influence of the last source is responsible for the less negative δ-values observed in precipitation in Eastern stations, including Addis Ababa, in spite of its elevation (2360 m a.s.l.).

In the past, when the climatic conditions were different and the precipitation more abundant, the West-East continental effect was reversed with respect to the present one, as shown by the isotopic composition of "old" (low ^{14}C content) groundwater samples (fig. 5). In relative terms, therefore, the contribution of Indian Ocean moisture was perhaps less important in the past than nowadays.

The continental effect is also responsible for the local minima of the heavy isotope content of precipitation observed at Luan Prabang, and at Alice Springs.

In stations at high elevation the altitude effect is summed up with the continental effect producing the negative δ-values observed in many stations in Southern Africa and in South America (especially Izobamba and Bogotâ). There are however also stations which do not show any appreciable influence of elevation, as for instance Addis Ababa, Entebbe and perhaps Shillong.

3. MEAN MONTHLY ISOTOPIC COMPOSITION OF PRECIPITATION

The discussion of this section is based on the mean weighted monthly values of the isotopic composition of precipitation. In this way most of the fluctuations of the individual monthly values are smoothed out. These fluctuations in fact may reflect only occasional phenomena and in part mask the main processes governing the isotopic composition of precipitation.

Only stations having a record of data sufficiently long (5 years) have been considered. Also, months with less than three measurements or with low mean precipitation (less than 10 mm) are eliminated, because the mean data are considered scarcely reliable.

3.1 Correlations between mean monthly δ-values and amount of precipitation

In Table 2 the correlation between mean monthly $\delta^{18}O$ and precipitation amount at selected tropical stations is shown. Apart from a few exceptions (Salvador, Midway, Brisbane), this correlation is generally very good, with a significance level above 90% in two stations, above 95% in four, above 98% in five, above 99% in ten and above 99.9% in fifteen. The correlation coefficient is in all cases much greater than that obtained by correlating monthly individual values of isotopic composition and of amount of precipitation, as reported by IAEA (1981). The correlation between mean monthly values is also shown in fig. 6 and in fig. 7 for selected stations in Amazonia and in the Pacific respectively.

Assuming for the precipitation process a simple model of Rayleigh distillation type the slope a of the correlation between the mean monthly values of isotopic composition and the amount of precipitation should be negative (and this occurs, as can be seen from Table 2), and should increase in absolute value at stations where the long term δ values are more negative. This second condition does not seem to be fulfilled, as the correlation coefficient between $\bar{\delta}^{18}O$ and the slope a is only 0.042 (with each pair of values weighted by the determination coefficient r^2 between monthly data of $\delta^{18}O$ and of amount).

Also the intercept b should become more negative together with $\bar{\delta}^{18}O$: b in fact represents the mean isotopic composition of the very first liquid fraction which can be obtained by condensation of the atmospheric vapour reaching the site. In principle, the isotopic composition of the latter should differ from b by the equilibrium fractionation factor liquid-vapour. The correlation coefficient between $\bar{\delta}^{18}O$ and b is 0.462, with a significance level of 95%, which should be considered rather satisfactory. An apparent correlation between a and $\bar{\delta}^{18}O$ can be obtained by subdividing the stations in three groups according to their long term mean isotopic composition. In this way one obtains:

i) For the 13 stations with $\bar{\delta}^{18}O > -3\%$: $\bar{a} = -0.0124$, $\sigma_1 = 0.0066$, $\sigma_n = 0.0026$; $\bar{b}$ (intercept) $= -0.11$, $\sigma_1 = 0.82$, $\sigma_n = 0.32$. *The values of Barbados have not been used in* computation because they differ by more than 2σ from the mean values of the group.

ii) For 8 stations with $\bar{\delta}^{18}O$ ranging from -3 to -5‰: $\bar{a} = -0.0149$, $\sigma_1 = 0.0036$, $\sigma_n = 0.0017$; $\bar{b} = -0.75$, $\sigma_1 = 0.88$, $\sigma_n = 0.42$. For the same reason as for Barbados, the values of Uaupês have not been included in the computations of this group.

iii) For 16 stations with $\bar{\delta}^{18}O < -5‰$: $\bar{a} = -0.0178$, $\sigma_1 = 0.0076$, $\sigma_n = 0.0024$; $\bar{b} = -1.53$, $\sigma_1 = 1.67$, $\sigma_n = 0.53$.

These results show that there is a hint also for $|a|$ to increase as $\bar{\delta}^{18}O$ decreases as in principle it should. However, the differences between mean values of groups are rather small in comparison with their variance, and therefore the level of significance is always below 90%. In addition, according to theory, assuming that condensation of the atmospheric vapour is produced by adiabatic cooling, the slope of the second group and that of the third group should be respectively about 1.3 and 1.8 times greater in absolute value than the slope of the first group, while the values of $\bar{a}$ reported above indicate rather ratios equal to 1.2 and 1.4.

Among the various processes which might lower the absolute value of the slope a of the relationship between the mean monthly values of δ and of the amount of precipitation recycling of vapour through evapotranspiration is probably one of the most important. This process in fact tends to smooth down the isotopic variations of precipitation by recycling into the atmospheric water vapour with a rather constant isotopic composition equal or related to that of groundwater and of surface water bodies, which in turn should be similar to the mean isotopic composition of precipitation. The attenuation of the isotopic variations of precipitations due to recycling of water vapour in the Amazonian basin was shown by Dall'Olio **et al.** (1979) and by Salati **et al.** (1979) on the basis of a multibox model assuming a westward flux of vapour.

Another reason to observe absolute a-values lower than those predicted theoretically, is that the model based on a Rayleigh type condensation process is incorrect, because it implies that the vapour phase is only present in the system, and the liquid formed is continuously removed. In reality, the two phases coexist in the clouds, and rains remove only a part of the liquid water present.

In principle, the slope a should also be different for island and coastal stations with respect to inland stations. Such a difference, however, does not become apparent from the data of Table 2 .

3.2 Correlation of South American stations with Belem

The mean monthly δ values of precipitation of most South American stations show parellel variations. Table 3 includes the values of the slope a and of the intercept b for the reduced major axis linear correlation between various stations and Belem. The correlations are generally good, with the exception of those of Cayenne, which are not significant, and those of Brasilia, which are rather weak (at least for oxygen-18). This confirms that the precipitation has the same seasonal trends and obeys meteorological mechanisms which are to a considerable extent similar in all tropical stations south of the equator.

From Table 3 it can be seen also that all the coastal stations show a value of the slope $a < 1$, that is the seasonal variations of δ are smaller than at Belem. On the contrary, the seasonal variations are larger in inland stations, where the values of a are always greater than 1. This indicates the peculiar situation of Belem, which has a behaviour intermediate between those of coastal and of inland stations, corresponding also to its geographical position at about 100 km from the ocean.

The values of a for the inland Amazonian stations are somewhat surprising, because the recycling of water vapour by evapotranspiration should rather reduce the seasonal variations of the precipitation isotopic composition. This is in competition, however, with the effect continentality, which tends to increase the seasonal δ-variations.

RESUMO

São discutidas algumas tendências e características da composição isotópica das precipitações nas estações tropicais. Em ilhas pequenas do Pacífico, as estações apresentam variação de acordo com a latitude, com valores-δ menores entre 15°N e 15°S e valores maiores a latitudes mais elevadas. Os isótopos pesados, nas estações interioranas, apresentam-se empobrecidos com relação às estações costeiras, porém algumas vezes esse efeito continental é bastante complexo, como por exemplo na África. A média mensal de valores-δ indica uma sensível correlação com a quantidade de precipitação, porém as variações em declive não indicam uma dependência clara da média a longo prazo do valor-δ como era de se esperar teoricamente. Nas estações da América do Sul, de acordo com as estações do ano, há uma correlação entre as variações das médias mensais dos valores-δ os quais são maiores nas estações mais para o interior devido a continentalidade. São também discutidos os possíveis efeitos da reciclagem do vapor dágua proveniente da evapotranspiração.

Table 1 - Long term mean isotopic composition of precipitation at tropical stations of the IAEA-WMO network.

Code	Station & Country	latitude	longitude	altitude m a.s.l.	T°C	precip. mm	$\delta^{18}O$‰	δD‰	t years
	America & Western Atlantic:								
VC	Veracruz, Mexico	19.20N	96.13W	16	25.1	1672	- 3.89	-22.2	10.1
JP	San Juan de Puertorico, USA	18.43N	66.00W	4	25.6	1631	- 2.03	- 4.3	3.9
SS	San Salvador, El Salvador	13.70N	89.12W	615	22.8	1175	- 7.09	-47.9	11.2
BB	Barbados, Barbados	13.07N	59.48W	50	26.3	1273	- 0.66	0.0	8.6
BQ	Barranquilla, Colombia	10.88N	74.78W	14	27.3*	720*	- 4.94	-33.8	4.5
MR	Maracay, Venezuela	10.25N	67.65W	442	24.6	914	- 3.76	-26.6	4.7
HP	Howard AFB, Panama	8.92N	79.06W	13	26.9*	1675*	- 5.69	-36.9	7.6
CY	Cayenne, Franch Guyana	4.83N	52.37W	8	25.5	3744	- 2.07	- 9.9	8.0
BG	Bogotà, Colombia	4.70N	74.13W	2547	13.0*	807*	- 9.20	-61.8	4.5
UP	Uaupès, Brazil	0.13S	67.08W	87	25.2	2917	- 4.14	-21.4	7.6
IZ	Izobamba, Ecuador	0.37S	78.55W	3058	11.0*	1455	-10.45	-71.4	2.9
BE	Belém, Brazil	1.43S	48.48W	24	25.9	2762	- 2.41	-13.6	10.7
MA	Manaus, Brazil	3.12S	60.02W	60	26.7	2102	- 5.68	-31.6	10.8
FZ	Fortaleza, Brazil	3.72S	38.55W	27	26.4*	1722*	- 2.92	-15.0	9.3
NT	Natal, Brazil	5.80S	35.20W	8	26.2	1547	- 2.16	- 7.9	10.2
PV	Porto Velho, Brazil	8.77S	63.92W	105	25.4	2245	- 6.35	-39.7	6.9
SV	Salvador, Brazil	13.00S	38.52W	45	25.0	1863	- 1.74	- 3.5	12.6
CU	Cuiabà, Brazil	15.60S	56.10W	165	25.6	1373	- 5.26	-33.7	12.4
BR	Brasilia, Brazil	15.85S	47.93W	1061	20.5*	1541*	- 4.75	-27.9	10.0
RJ	Rio de Janeiro, Brazil	22.90S	43.17W	26	23.2	1086	- 4.52	-25.8	14.9

N.B. The values of mean temperature and of mean annual precipitation have been taken from the Climatological Normals published by WMO (1971). The asterisks denote mean values computed from the IAEA/WMO records during the period of isotopic monitoring. The lenght t of this period is indicated in the last column, and it is obtained by dividing the total amount of precipitation for which the oxygen isotope analysis is available by the mean annual precipitation.

Table 1 contd.

Code	Station & Country	latitude	longitude	altitude m a.s.l.	T^oC	precip. mm	$\delta^{18}O‰$	$\delta D‰$	t years
	Asia & Indian Ocean:								
BK	Bangkok, Thailand	13.73N	100.50E	2	28.0	1492	- 6.91	-45.6	8.2
SG	Singapore, Singapore	1.35N	103.90E	32	27.1	2282	- 7.35	-47.0	7.7
MH	Mahe, Seychelles Is., UK	4.62S	55.45E	1	26.9	2203	- 3.56	-14.9	2.3
DK	Djakarta, Indonesia	6.18S	106.83E	8	26.9	1755	- 5.64	-35.7	8.2
DG	Diego Garcia Is., Mauritius	7.32S	72.40E	1	27.1	2462	- 3.61	-21.7	11.0
	Australia & Pacific:								
MW	Midway Is., USA	28.22N	177.37E	13	22.2*	1204*	- 2.24	-10.1	14.5
HL	Hilo, Hawaii Is., USA	19.72N	155.07W	9	22.8	3470	- 2.29	- 6.3	6.7
WK	Wake Is., USA	19.28N	166.65E	3	26.7	936	- 2.18	- 9.6	12.1
JO	Johnston Is., USA	16.73N	169.52W	2	26.3	663	- 2.54	-13.5	7.8
MN	Manila, Philippines	14.52N	121.00E	14	27.3	1791	- 6.70	-41.9	4.9
GU	Guam Is., USA	13.55N	144.83E	110	26.2	2249	- 5.10	-30.6	11.5
YP	Yap, W. Caroline Is., USA	9.49N	138.09E	0	27.4	3086	- 5.67	-34.3	7.6
TR	Truk, E. Caroline Is., USA	7.47N	151.85E	2	27.1	3493	- 5.31	-31.9	8.3
DP	Djajapura, Indonesia	2.53S	140.72E	3	27.2	2439*	- 6.34	-39.9	11.5
CN	Canton Is., USA	2.77S	171.72W	2	28.6	748	- 3.65	-20.4	4.3
MD	Madang, Papua New Guinea	5.22S	145.80E	4	26.9*	3397*	- 7.78	-50.4	9.0
DW	Darwin, Australia	12.43S	130.87E	26	27.6	1562	- 5.06	-30.0	12.1
AP	Apia, Samoa	13.80S	171.78W	2	26.3*	2928	- 4.61	-23.8	9.9
RT	Rarotonga, Cook Is., NZ	21.20S	159.80W	6	23.8*	2018*	- 1.50	- 8.3	13.6
AS	Alice Springs, Australia	23.80S	133.88E	546	20.7	250	- 7.65	-44.6	14.5
IP	Isla de Pascua, Chile	27.17S	109.43W	41	20.6*	988*	- 1.42	- 4.7	2.2
BS	Brisbane, Australia	27.43S	153.08E	0	20.4	1092	- 4.91	-23.9	11.6

Table 1 contd.

Code	Station & Country	latitude	longitude	altitude m a.s.l.	T°C	precip. mm	$\delta^{18}O$‰	δD‰	t years
	Africa & Eastern Atlantic:								
KH	Khartoum, Sudan	15.60N	32.55E	382	28.7	164	- 2.03	- 9.2	7.4
GE	Geneina, Sudan	13.48N	22.45E	805	24.2	549	- 1.92	- 8.5	7.0
BM	Bamako, Mali	12.63N	8.03W	329	28.1	1099	- 4.06	-27.5	13.4
DJ	N'Djamena, Chad	12.13N	15.03E	294	27.9	646	- 3.70	-19.9	9.9
KA	Kano, Nigeria	12.05N	8.53E	476	26.1	872	- 3.75	-25.3	6.8
AA	Addis Ababa, Ethiopia	9.00N	38.73E	2360	16.8	1089	- 1.47	1.4	8.4
ST	Sao Tomé Is., Sao Tomé	0.38N	6.72E	8	25.5	872	- 3.32	-15.5	14.4
EN	Entebbe, Uganda	0.05N	32.45E	1155	21.5	1574	- 2.91	-11.6	11.0
KS	Kinshasa, Zaire	4.37S	15.25E	438	24.2*	1371	- 4.67	-24.1	6.3
DS	Dar es Salaam, Tanzania	6.88S	39.20E	55	25.7	1043	- 2.87	-13.6	12.9
AC	Ascension Is., UK	7.92S	14.42W	15	25.4*	238*	- 0.64	3.5	5.2
ML	Malange, Angola	9.55S	16.37E	1194	20.9	1194	- 4.49	-25.4	5.6
ND	N'Dola, Zambia	13.00S	28.65E	1331	20.2*	1280*	- 6.90	-45.6	6.4
SP	Serpa Pinto, Angola	14.67S	17.70E	1348	19.5	868	- 6.26	-39.0	6.3
SH	St. Helena Is., UK	15.97S	5.70W	604	16.8*	892*	- 1.16	4.1	7.4
SA	Salisbury, Zimbabwe	17.83S	31.02E	1471	18.2	863	- 6.17	-34.1	15.8
TA	Tananarive, Madagascar	18.90S	47.53E	1300	16.8	1270	- 7.55	-44.5	7.9
WN	Windhoek, Namibia	22.57S	17.10E	1728	19.0	370	- 4.53	-24.0	13.9
	Asia & Indian Ocean:								
SL	Shillong, India	25.57N	91.88E	1598	16.8*	2152*	- 3.67	-28.8	3.2
KR	Karachi, Pakistan	24.90N	63.13E	23	25.8	204	- 4.24	-23.2	13.0
HK	Hong Kong, UK	22.32N	114.17E	32	22.6	2265	- 6.99	-46.9	8.1
LP	Luang Prabang, Laos	19.88N	102.13E	305	25.3	1137	- 7.49	-50.9	3.4
BO	Bombay, India	18.90N	72.82E	10	27.3	2078	- 1.52	- 3.6	10.6
RG	Rangoon, Burma	16.77N	96.17E	20	27.3	2618	- 4.34	-28.9	2.4

Table 2 - Least square regression of the mean monthly $\delta^{18}O$ values on the amount of precipitation (in mm).

Station	$a \pm \sigma_a$ slope	$b \pm \sigma_b$ intercept	n	correlation coefficient	significance level %
America & Western Atlantic					
Veracruz	-0.0101±0.0020	-0.98±0.29	11	-0.845	99
San Salvador	-0.0072±0.0026	-4.99±0.52	8	-0.757	95
Barbados	-0.0423±0.0090	+3.62±0.95	12	-0.830	99.9
Howard AFB	-0.0303±0.0060	+0.38±0.91	11	-0.862	99.9
Cayenne	-0.0042±0.0014	-0.30±0.43	12	-0.696	98
Uaupès	-0.0365±0.0080	+5.04±1.94	12	-0.822	99.9
Belêm	-0.0136±0.0022	+1.58±0.51	12	-0.893	99.9
Manaus	-0.0186±0.0029	-0.96±0.54	12	-0.901	99.9
Fortaleza	-0.0070±0.0011	-0.82±0.16	12	-0.902	99.9
Natal	-0.0101±0.0021	-0.29±0.23	12	-0.846	99.9
Porto Velho	-0.0155±0.0070	-2.23±1.32	12	-0.579	95
Salvador	-0.0012±0.0018	-1.28±0.33	12	-0.204	n.s.
Cuiabâ	-0.0294±0.0091	-0.18±1.07	11	-0.731	98
Brasilia	-0.0178±0.0052	-1.11±0.87	9	-0.794	98
Rio de Janeiro	-0.0181±0.0039	-1.85±0.40	10	-0.827	99.9
Africa & Eastern Atlantic					
Sao Tomé Is.	-0.0191±0.0062	-1.09±0.58	10	-0.737	98
Entebbe	-0.0124±0.0039	-0.67±0.52	12	-0.712	99
Dar es Salaam	-0.0110±0.0029	-0.83±0.27	12	-0.774	99
Malange	-0.0123±0.0071	-2.40±0.90	9	-0.549	90
St. Helena Is.	-0.0135±0.0046	-0.29±0.34	12	-0.675	98
Tananarive	-0.0174±0.0048	-3.01±0.61	11	-0.771	99
Asia & Indian Ocean					
Hong Kong	-0.0136±0.0029	-1.92±0.54	12	-0.828	99.9
Bangkok	-0.0271±0.0051	-1.07±0.64	11	-0.871	99.9
Singapore	-0.0192±0.0072	-3.46±1.29	12	-0.648	95
Djakarta	-0.0070±0.0018	-3.92±0.28	12	-0.791	99
Diego Garcia	-0.0134±0.0017	-0.25±0.37	12	-0.930	99.9
Australia & Pacific					
Midway Is.	-0.0017±0.0052	-1.94±0.53	12	-0.105	n.s.
Hilo, Hawaii Is.	-0.0045±0.0018	-0.91±0.48	12	-0.641	95
Wake Is.	-0.0212±0.0033	+0.14±0.25	12	-0.901	99.9
Johnston Is.	-0.0250±0.0070	-0.03±0.47	12	-0.749	99
Guam Is.	-0.0196±0.0024	+0.65±0.52	12	-0.936	99.9
Yap Is.	-0.0178±0.0046	-0.85±1.07	12	-0.778	99
Truk Is.	-0.0140±0.0037	-0.68±1.10	12	-0.771	99
Djajapura	-0.0064±0.0040	-4.69±0.81	12	-0.459	90
Madang	-0.0207±0.0031	-1.05±0.86	12	-0.908	99.9
Darwin	-0.0094±0.0019	-1.34±0.38	9	-0.884	99
Apia	-0.0139±0.0025	-0.22±0.62	12	-0.874	99.9
Rarotonga	-0.0105±0.0027	+0.58±0.65	12	-0.782	99
Brisbane	+0.0009±0.0056	-3.65±0.59	12	0.051	n.s.

N.B. a is the slope $d\delta/dP$ of the correlation, and b is the δ-intercept at $P = 0$. n is the number of months in the year for which the regression has been computed. The level of significance is based on the t-test.

Table 3 - Correlation between the mean monthly $\delta^{18}O$ values of precipitation in South American stations with the corresponding values at Belem.

Station	Oxygen-18			Deuterium			^{18}O + D
	a ± σ	b ± σ	r	a ± σ	b ± σ	r	a ± σ
Coastal stations:							
Cayenne	0.58 ± 0.16	-0.68 ± 0.26	0.335	-0.48 ± 0.14	-11.3 ± 1.1	-0.190	
Fortaleza	0.59 ± 0.11	-0.89 ± 0.18	0.774	0.64 ± 0.09	- 0.7 ± 0.7	0.892	0.62 ± 0.07
Natal	0.53 ± 0.08	-0.59 ± 0.12	0.885	0.63 ± 0.08	2.4 ± 0.6	0.902	0.58 ± 0.06
Salvador	0.33 ± 0.07	-0.98 ± 0.11	0.705	0.44 ± 0.10	1.4 ± 0.8	0.688	0.37 ± 0.06
Rio de Janeiro	0.67 ± 0.13	-2.64 ± 0.20	0.778	0.85 ± 0.15	-11.1 ± 1.2	0.790	0.74 ± 0.10
Inland stations:							
Uaupès	1.15 ± 0.24	-2.00 ± 0.38	0.697	1.22 ± 0.26	-11.0 ± 2.0	0.676	1.18 ± 0.18
Manaus	1.26 ± 0.10	-2.47 ± 0.16	0.964	1.32 ± 0.11	-12.6 ± 0.9	0.959	1.29 ± 0.08
Porto Velho	1.73 ± 0.22	-2.46 ± 0.35	0.898	1.77 ± 0.26	-17.7 ± 2.0	0.870	1.75 ± 0.17
Cuiabà	1.74 ± 0.34	-0.60 ± 0.53	0.750	1.80 ± 0.31	- 4.7 ± 2.4	0.811	1.77 ± 0.23
Brasilia	1.28 ± 0.34	-1.27 ± 0.54	0.416	1.45 ± 0.32	- 5.9 ± 2.5	0.651	1.37 ± 0.24

N.B. The correlation is the so-called "reduced major axis correlation". a is the slope dδ (station)/dδ (Belem) and b is the intercept at δ (Belem) = 0.

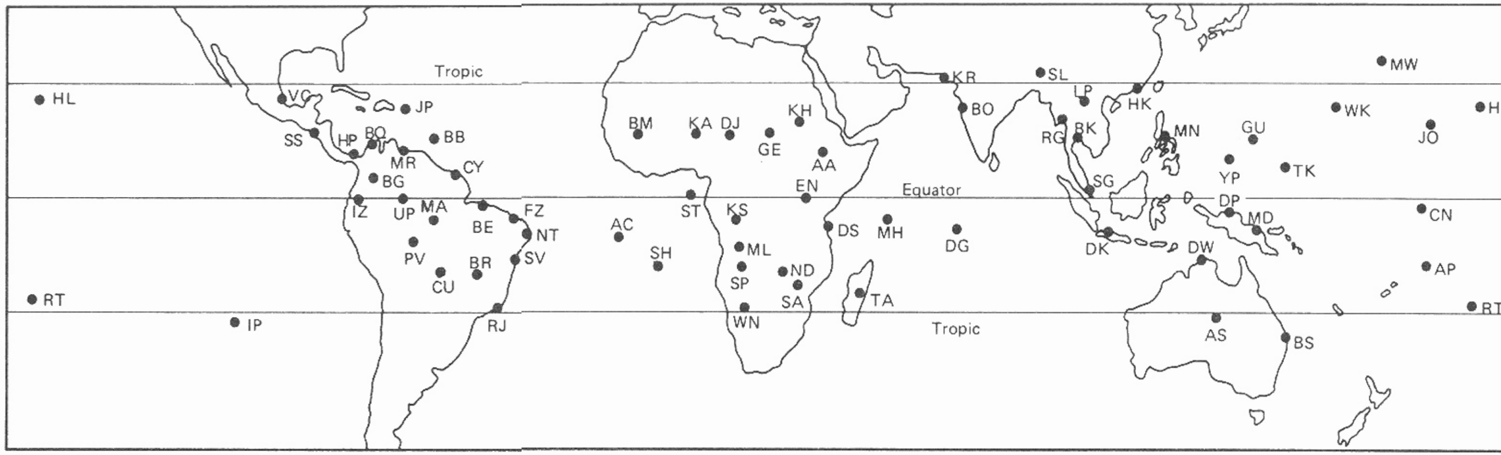

FIG. 1. Location of stations for which the isotopic composition of precipitation is discussed in this paper. The code of stations is reported in Table 1.

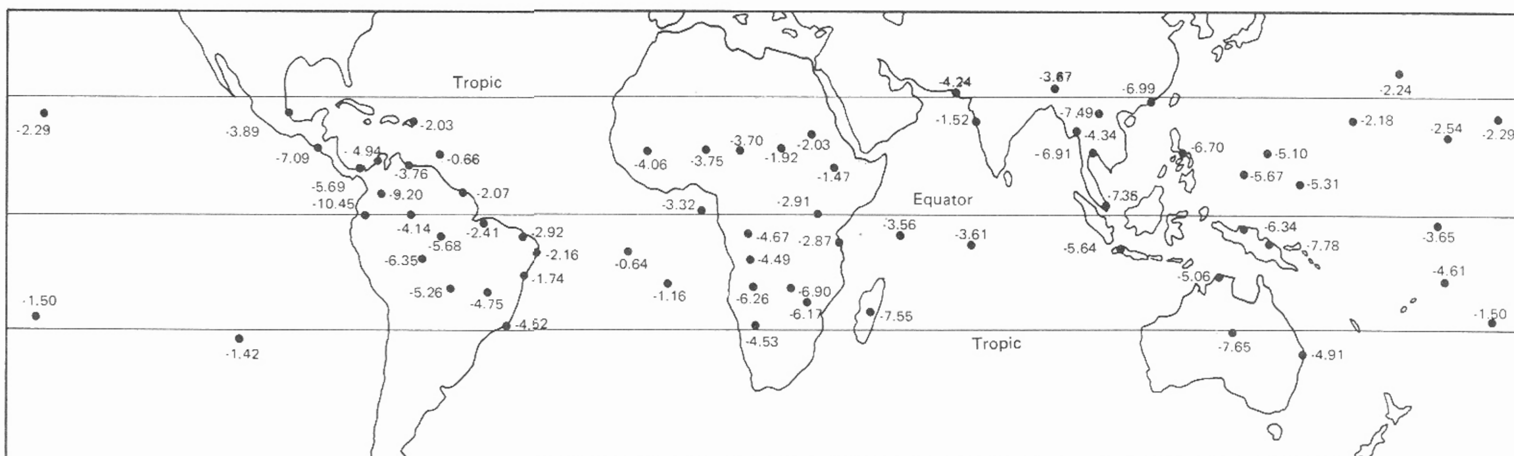

FIG. 2. Long term mean $\delta^{18}O$ values of precipitation in tropical stations belonging to the IAEA/WMO network.

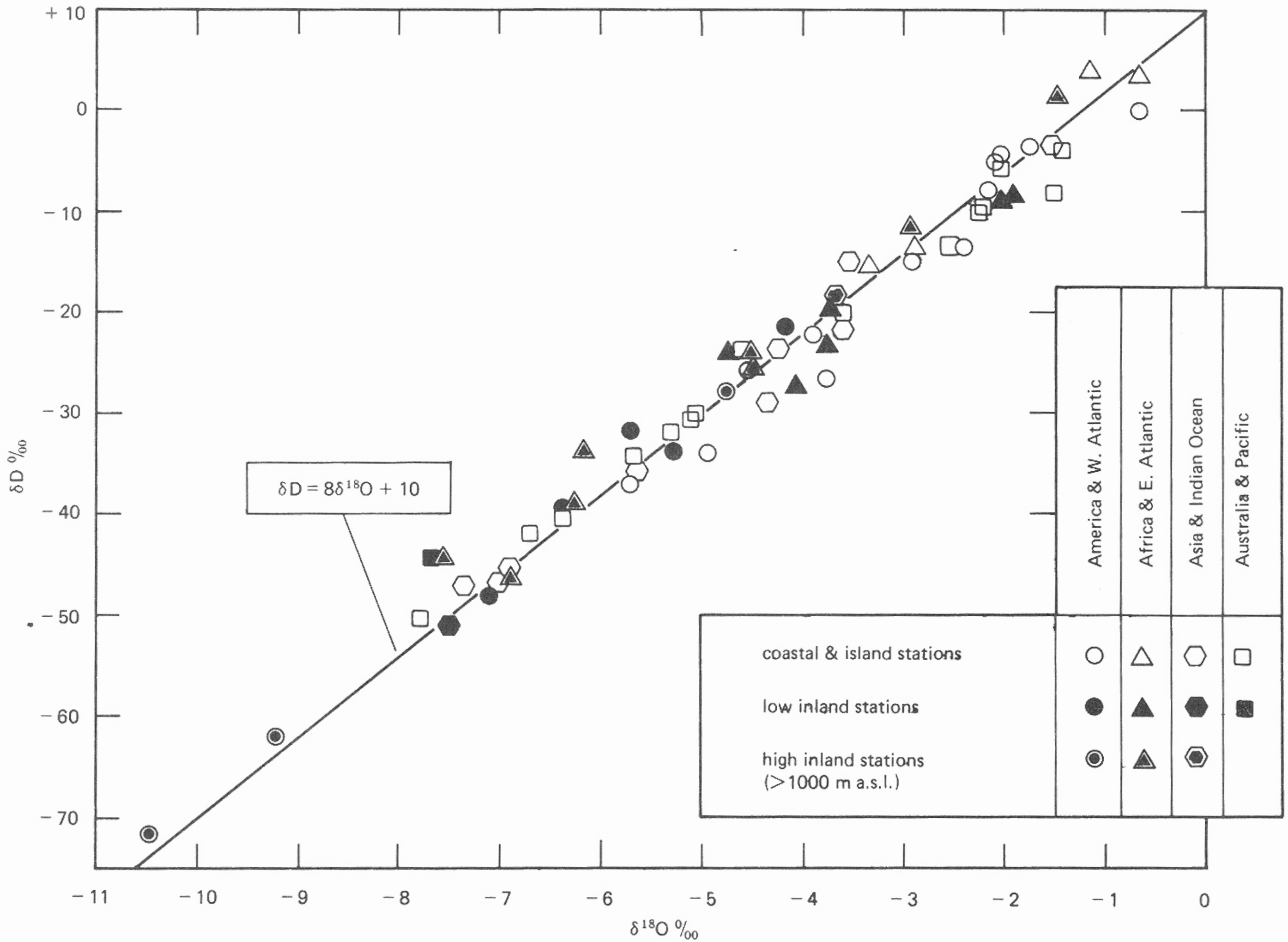

FIG. 3. Plot of the mean oxygen and hydrogen stable isotope composition of precipitation at tropical stations. The so-called world meteoric water line is also shown.

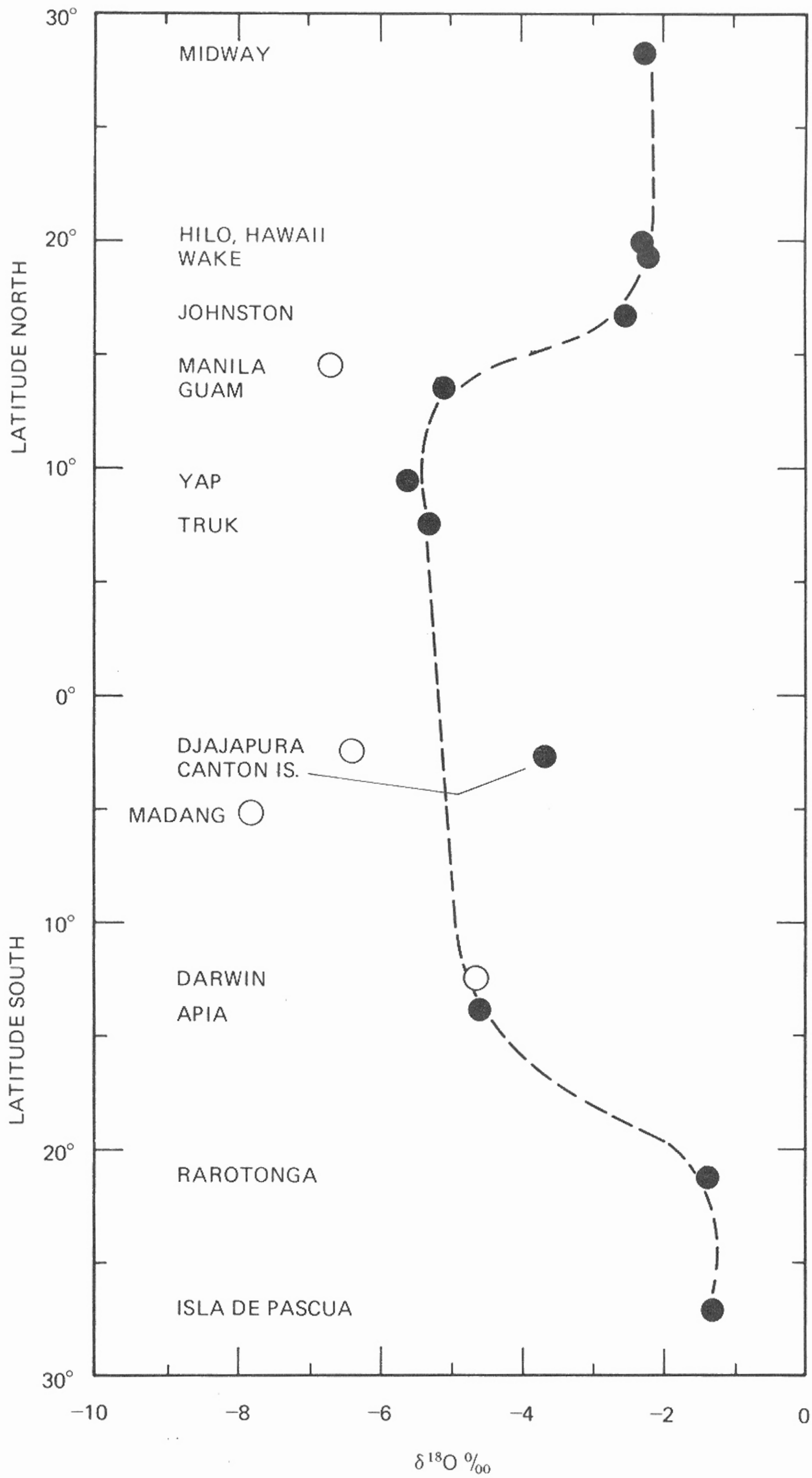

FIG. 4. Variation of the mean $\delta^{18}O$ value with latitude at island stations in the Pacific.

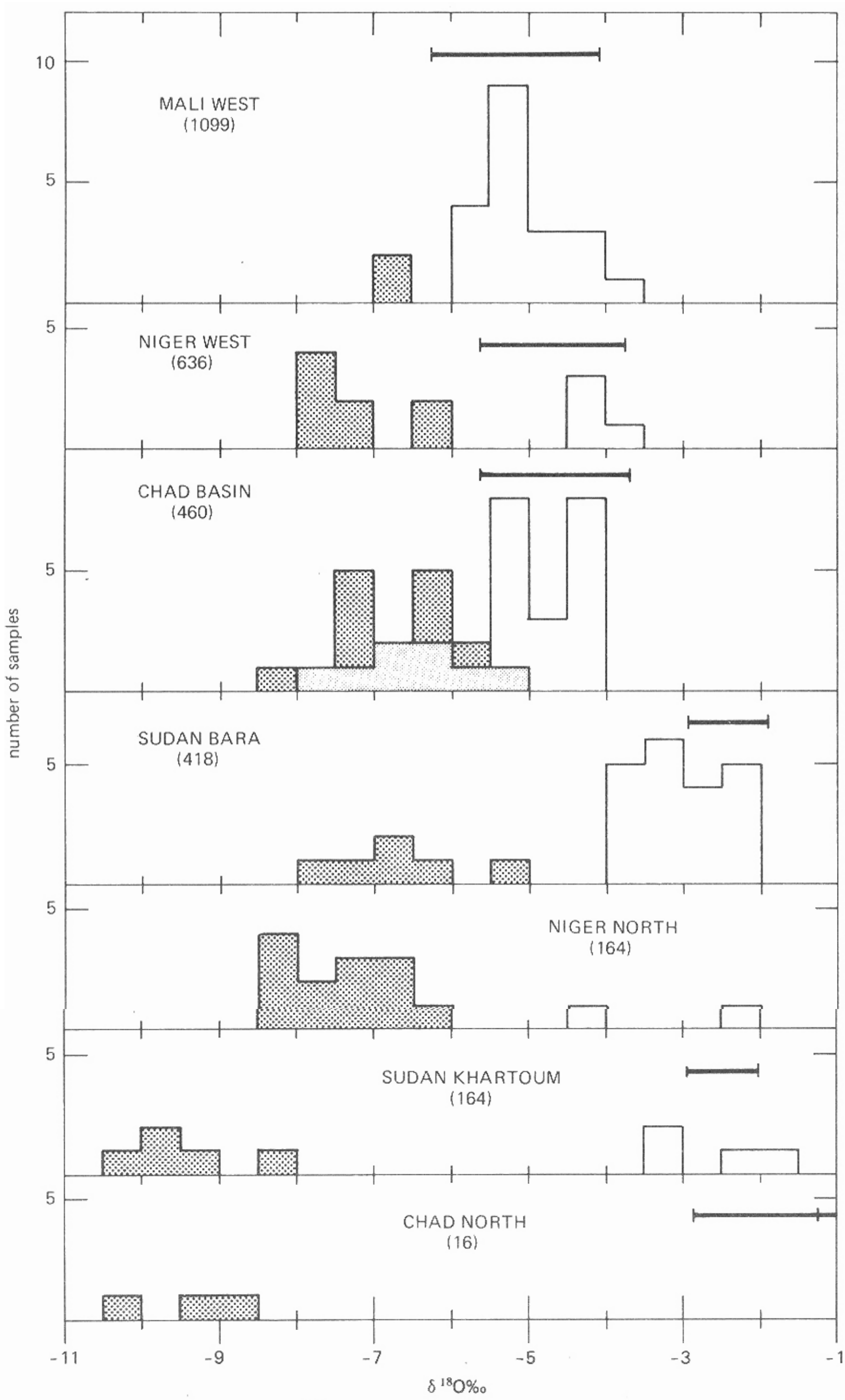

FIG. 5. Histogram showing the ^{18}O distribution in groundwater in the Northern tropical belt of Africa. The figures in brackets are the mean annual precipitation in mm. The bars show the range of isotopic composition of precipitation at each site given by the mean annual value and the mean value of the most rainy month (August). White areas represent modern groundwater (high tritium and/or high ^{14}C), dark grey represent old groundwater (low ^{14}C) and light grey area in the Chad Basin represents the overlap of modern and old groundwater samples. (From Dray et al., 1981).

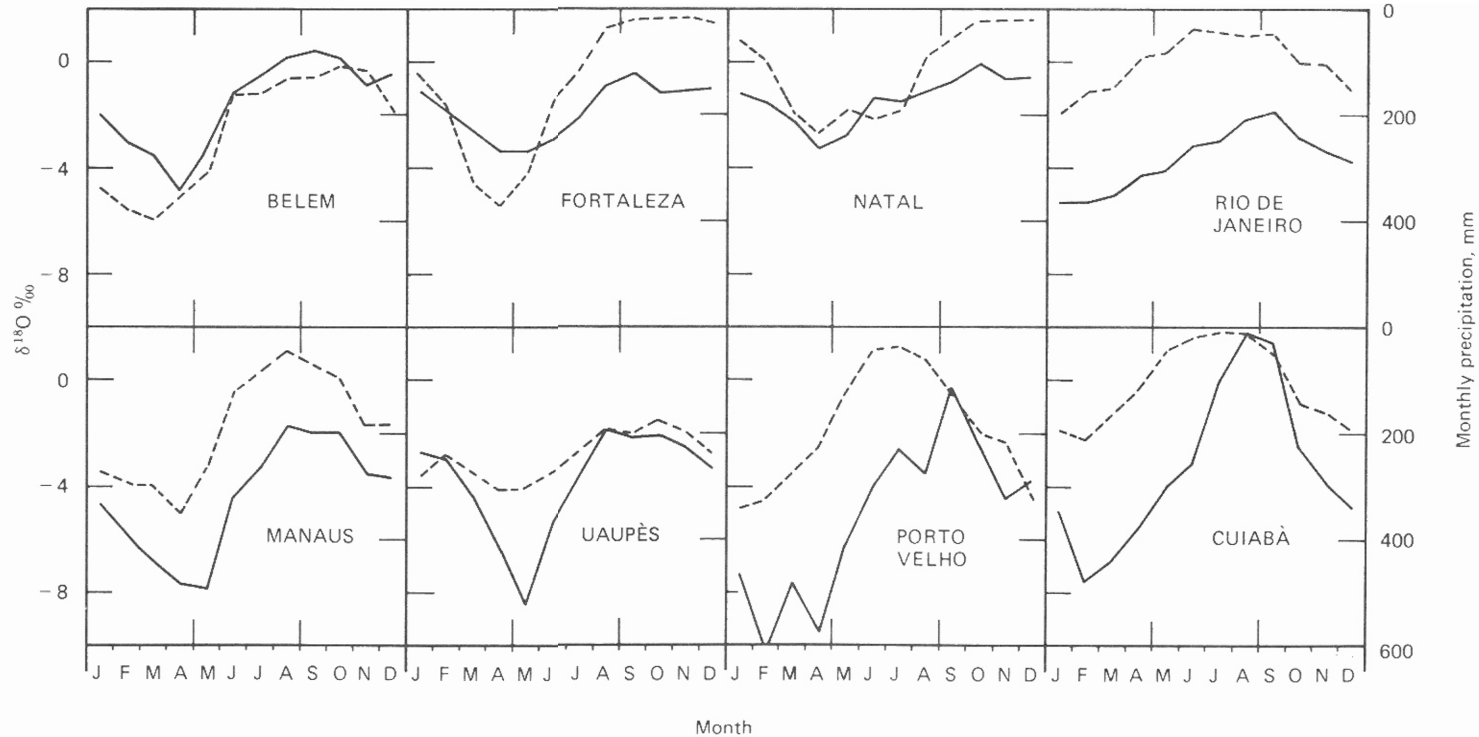

FIG. 6. Mean monthly values of $\delta^{18}O$ (solid line) and of amount of precipitation(dashed line) at selected stations in Amazonia.

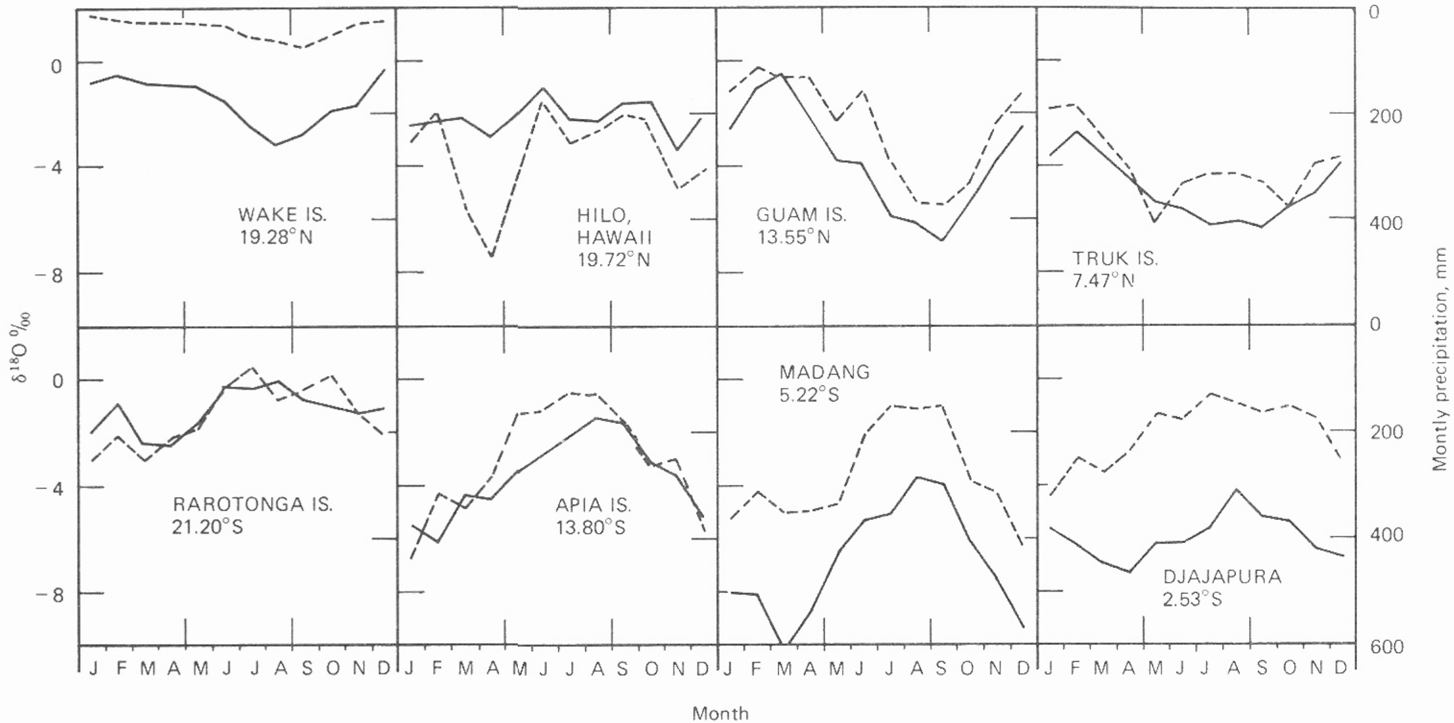

FIG. 7. Mean monthly values of $\delta^{18}O$ (solid line) and of amount of precipitation (dashed line) at selected stations in the Pacific.

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