Relations between the *Z* Criterion for the Subtropical High, Hadley Cell Parameters and the Rainfall in Northern Ghana[1]

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ABSTRACT

We use radiosonde data from Tamale in northern Ghana to evaluate the *Z* criterion latitude φ_z. We find it correlates well with other Hadley cell parameters since its variations are apparently controlled by the meridional movement of the subtropical westerly jet. Since the Hadley cell parameters correlate well with Tamale rainfall, we conjecture that it should be possible to predict northern Ghana rainfall on the basis of the southward extension of the subtropical jet once more data have been collected by the Tamale radiosonde. This conjecture is supported by data from other stations in West Africa.

1. Introduction

Since the recent drought in the Sahel zone of West Africa, there has been much interest in predicting climatic change in that region based on changes in globally measured parameters. The monsoon rains of sub-Saharan West Africa are controlled mainly by the north-south movement of the intertropical discontinuity (ITD) which, in turn, is related to the motion of the subtropical high pressure system (STH). Flohn (1964, 1965) has developed the so-called *Z* criterion for locating the STH based on earlier work by Smagorinsky (1963). The criterion is

$$\tan \varphi_z = \mathrm{RiRo}, \tag{1}$$

where Ri and Ro are the Richardson number and Rossby number, respectively, and φ_z is a latitude, interpreted by Flohn to be the latitude of STH. In Flohn's work, Ri and Ro were obtained from the vertical lapse rate and the meridional temperature gradient. Thus, Eq. (1) was interpreted as holding over a long-term average, the geostrophic relations being used to eliminate wind velocities and velocity gradients from Ri and Ro and allowing the use of potential temperature gradients instead.

The radiosonde station at Tamale in northern Ghana has been in operation for approximately two years. It is of interest to see whether the *Z* criterion (1) can be verified on a short-term basis by using the wind and temperature data from this station and whether the *Z* criterion can then be used to predict the rainfall patterns in the region. We find that although φ_z is not exactly equal to the latitude of the STH, the monthly changes of these two parameters are well correlated, as are the monthly changes in φ_z and the location of the ITD. We also find correlations between these parameters and the monthly rainfall in Tamale. Careful investigation of our input in (1) indicates that φ_z is governed mainly by the north-south motion of the subtropical jet. The southward penetration of the subtropical jet during the dry season is different for the two years for which radiosonde data are available and it is conjectured that this penetration is a means by which one can predict the relative amount of rainfall during the subsequent rainy season. This conjecture is supported by data from the two other West African radiosonde stations at Niamey, Niger and Bamako, Mali.

In Section 2 we discuss in detail the calculation of the *Z* criterion from the radiosonde data and the methods for locating the ITD and STH. We give regression equations and correlation coefficients for these parameters as well as relations between these parameters and the monthly mean rainfall at Tamale. In Section 3 we discuss the effect of solar declination on these parameters and obtain correlation coefficients with these effects removed. Our results are summarized in Section 4. In

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the Appendix we examine the correlations between the subtropical jet penetration and rainfall at Niamey and Bamako.

2. The *Z* criterion, Hadley cell parameters and rainfall at Tamale

The general circulation of the tropics is controlled by the Hadley cell convection system in which equatorial warm air rises, moves toward the poles, sinks at mid-latitudes and returns to the equator. The two extremes of the Hadley cell are marked by the equatorial trough of low pressure and the subtropical high pressure system. The air flows due to the northern and southern subtropical highs tend to converge near the equatorial trough. In West Africa this produces a marked discontinuity in surface dew point between the dry northern air (dew point $\ll$15.5°C) and the moist southern air (dew point $>$15.5°C) so that the location of the intertropical discontinuity at which the dew point is 15.5°C gives a measure of the equatorward extent of the Hadley circulation cell. The poleward extent of the African Hadley cell is given by the location of the subtropical high pressure system that is commonly located in the Atlantic ocean. The subtropical high marks the latitude of transition between the tropical Hadley circulation and the mid-latitude Rossby circulation regime.

Smagorinsky (1963) used a linear, two-level model, baroclinic instability calculation (Phillips, 1954) to derive the *Z* criterion given in Eq. (1) which related the Richardson number Ri and the Rossby number Ro with a latitude φ. Smagorinsky (1963) interpreted φ to be the observing latitude and claimed that after geostrophic adjustment, Ri and Ro would have values satisfying (1). Subsequently, Flohn (1964, 1965), Henning (1967) and Bryson (1974) interpreted φ to be the latitude at which wavenumber 1 of a global zonal flow becomes dynamically unstable and which therefore approximates the latitude of transition between the Rossby and Hadley regimes of circulation.

Assuming that this interpretation is correct, we should be able to find a relationship between the *Z* criterion and the parameters of the Hadley cell. We do this by obtaining monthly average values of the Atlantic subtropical high latitude, the latitude of the ITD along the Greenwhich meridian, and the *Z* criterion at Tamale (9.4°N, 0.8°W) in northern Ghana.

The *Z* criterion latitude φ_z is evaluated each day from daily radiosonde data obtained from Tamale at 1100 GMT. Since Phillips' (1954) original derivation was based on a two-level model separated at 500 mb, we find the latitude appropriate to this height. Since we do not expect geostrophic adjustment to occur quickly in the tropics we do not use the geostrophic wind relationships but find Ri and Ro directly from the radiosonde data, where the Rossby number is

$$\mathrm{Ro}=\frac{V}{fa}$$

and the Richardson number is

$$\mathrm{Ri}=\frac{(\theta_{e2}-\theta_{e1})/(h_2-h_1)}{[(U_2-U_1)/(h_2-h_1)]^2}\,\frac{g}{\theta_{e0}},$$

where U is the wind speed, a the earth's radius, f the Coriolis parameter at Tamale, g the acceleration due to gravity, θ_e the partial equivalent potential temperature, and h the height. Subscripts on h, θ and U refer to 500 mb (0), 400 mb (2) and 700 mb (1). The partial equivalent potential temperature is given in terms of the actual potential temperature θ (Holton, 1972) by

$$\theta_e=\theta\exp\left\{\frac{(18eLr)}{29c_pT}\exp\left[L\left(\frac{1}{T_0}-\frac{1}{T}\right)\Big/R\right]\right\},$$

where p is the pressure, c_p the specific heat of air at constant pressure, T the temperature, e the saturation vapor pressure at $T_0(=273\ \mathrm{K})$, L the latent heat of vaporization, r the relative humidity, and R the gas constant per mole of water vapor ($=0.461\ \mathrm{J\ kg^{-1}\ K^{-1}}$). The resulting daily *Z* criterion latitudes

$$\varphi_z=\tan^{-1}(\mathrm{Ri\ Ro})$$

are averaged over a month and the resulting values plotted in Fig. 1.

The location of the ITD (defined as the locus of stations with a dew point of 15.5°C) is marked on the daily surface weather charts prepared by the Ghana Meteorological Services Department. As the *Z* criterion is to be evaluated at Tamale, near the Greenwich meridian, the daily latitude of the ITD along the Greenwich meridian is read from these charts and averaged over a month. The resulting monthly averages are depicted in Fig. 1 and display the well-known dependence of the ITD location on solar delination: the latitude of the ITD is a maximum during the June solstice and a minimum during the December solstice.

We obtain the latitude of the subtropical high by using the maps of monthly average 700 mb height contours that are published in *Monthly Weather Review*. These display a well-defined ridge of high pressure over the Atlantic so that the monthly 700 mb STH location is readily obtained. The values are shown in Fig. 1.

It is evident from the graphs of Fig. 1 that the latitudes of the ITD, STH and *Z* criterion are all well correlated. Using linear regressions on all combinations of variables, we find the lines of best fit (the bisector of the two regression lines of x on y and y on x) to be given by

$$\left.\begin{aligned} \varphi_z &= 6.45+2.71\,\varphi_{\mathrm{ITD}} & (r=0.82)\\ \varphi_z &= -8.02+2.13\,\varphi_{\mathrm{STH}} & (r=0.65)\\ \varphi_{\mathrm{STH}} &= 7.45+1.22\,\varphi_{\mathrm{ITD}} & (r=0.79)\end{aligned}\right\}.$$

In each case the correlation coefficient r is well above the 1% significance level.

The relationship between the subtropical high and the intertropical discontinuity provides indirect confirmation of Bryson's (1973, 1974) claim that a movement in the STH of 1° produces a 3° shift in the ITD position. It appears that Bryson used surface data to locate the STH, and the surface STH varies only about 6° in latitude throughout the year (Pittock, 1973), whereas it varies about 15° at 700 mb (Fig. 1). Since the ITD moves through 12° annually, it does indeed appear that a movement of 1° in the surface STH produces a corresponding shift in ITD location of between 2° and 3°.

To compare the relationship of these Hadley cell parameters to the tropical rainfall, we correlate them with the monthly rainfall in Tamale, also shown in Fig. 1. If Y denotes the monthly Tamale rainfall in centimeters, then the regression equations are

$$\left.\begin{aligned} Y &= -16.89+1.88\,\varphi_{\mathrm{ITD}} & (r=0.82)\\ Y &= -15.27+1.09\,\varphi_{\mathrm{STH}} & (r=0.70)\\ Y &= -4.50+0.36\,\varphi_z & (r=0.50)\end{aligned}\right\}.$$

The relationship between ITD and rainfall is in good agreement with Ilesanmi's (1971) results for the rainfall over Nigeria. Ilesanmi's regression equation would be

$$Y=-8.95+1.51\,\varphi_{\mathrm{ITD}} \quad (r=0.82)$$

when applied to Tamale. The difference between these two equations reflects the fact that the ITD over Nigeria is oriented west-northwest to east-southeast, whereas it is generally east-west over Ghana. However, our correlation coefficient agrees exactly with Ilesanmi's indicating that the same relationship between ITD and rainfall holds in Ghana and Nigeria although the amount of rainfall change due to a one degree latitude change in ITD position is greater in Ghana.

The predictive efficiency is given by

$$E=100[1-(1-r^2)^{\frac{1}{2}}].$$

This gives the rainfall predictive ability of the ITD location as 43%, of the STH location as 29% and the Z criterion as 13%.

3. Solar declination effects

One reason for the high correlations between the STH, ITD and φ_z latitudes is that they are all dominated by the seasonal variation. We attempted to determine whether they were interrelated in a direct physical sense by estimating the latitudinal effects due to the solar declination and subtracting these from the original readings.

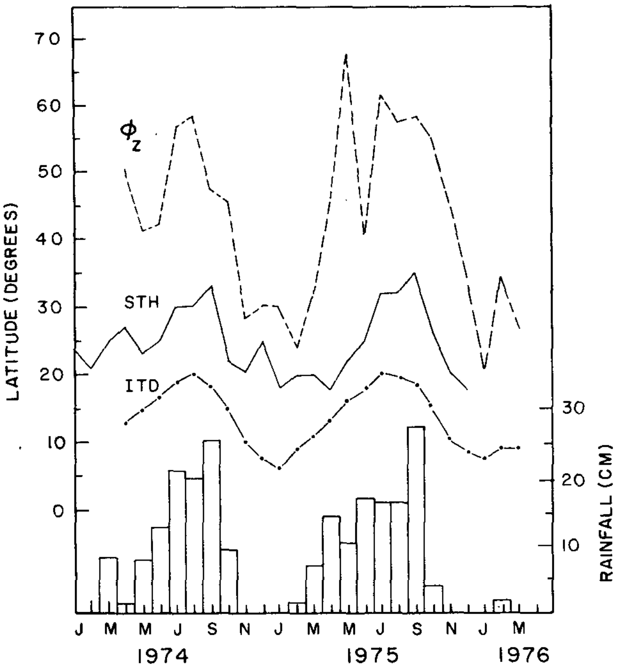

FIG. 1. The latitude of the Z criterion (φ_z) and the locations of the Intertropical Discontinuity (ITD) along the Greenwich meridian, and the subtropical high (STH) over the Atlantic at 700 mb, from January 1974 to March 1976. The histogram is the monthly rainfall at Tamale in northern Ghana.

There are difficulties in estimating the effects due solely to seasonal variations. As an example, one might expect that an average of STH latitude over 30 years would provide a smooth sinusoidal curve characterizing the seasonal variation of STH. In fact Pittock (1973) has shown that this is not the case, the curve being both bumpy and non-sinusoidal. However, for simplicity, we assume sinusoidal behavior and adopt the following procedure: each of the ITD, STH and φ_z latitudes were correlated with δ, the solar declination, and phase-shifted in one-month jumps until a maximum correlation was obtained. The resulting regression equation was taken as the seasonal variation. The results are

$$\left.\begin{aligned} \hat{\varphi}_{\mathrm{ITD}} &= 13.5°+0.26(\delta-1) & (r=0.976)\\ \hat{\varphi}_{\mathrm{STH}} &= 24.3°+0.24(\delta-2) & (r=0.754)\\ \hat{\varphi}_z &= 42.7°+0.63\delta & (r=0.81)\end{aligned}\right\},$$

where $\delta-n$ denotes the value of the solar declination n months beforehand, and where the circumflex is used to denote the "expected" seasonal variation. We then find

$$\left.\begin{aligned} \Delta\varphi_{\mathrm{ITD}} &= \varphi_{\mathrm{ITD}}-\hat{\varphi}_{\mathrm{ITD}}\\ \Delta\varphi_{\mathrm{STH}} &= \varphi_{\mathrm{STH}}-\hat{\varphi}_{\mathrm{STH}}\\ \Delta\varphi_z &= \varphi_z-\hat{\varphi}_z\end{aligned}\right\}$$

and correlate these quantities among themselves. The results are shown in Table 1. These results parallel

TABLE 1. Cross correlations of $\Delta\varphi_{\mathrm{ITD}}$, $\Delta\varphi_{\mathrm{STH}}$ and $\Delta\varphi_z$ (defined in Section 3) for the two years of data at Tamale shown in Fig. 1. The correlations 0.37 and 0.40 have a significance level of between 5% and 10%.

$\Delta\varphi_{\mathrm{ITD}}$	1		
$\Delta\varphi_{\mathrm{STH}}$	0.37	1	
$\Delta\varphi_z$	0.40	0.09	1
	$\Delta\varphi_{\mathrm{ITD}}$	$\Delta\varphi_{\mathrm{STH}}$	$\Delta\varphi_z$

those of Section 2. It appears that the above single-station method of calculating φ_z produces a parameter that is not physically related to the location of the STH but is related to the other Hadley cell parameter.

It should be emphasized that the correlations of Table 1 are highly dependent on the regression equations used to denote the "expected" seasonal variation. These equations were obtained on the assumption that the latitudes of the ITD and STH are linearly related to the solar declination. This is certainly not the case with either the STH (Pittock, 1973) or the ITD. The ITD behaves nonlinearly with respect to δ (Fig. 1) in that it increases in latitude far more slowly than it decreases. Presumably, this is a consequence of the northward asymmetry of the African ITD, for its northward advance must be accompanied by a severe compression of the complete Northern Hemispherical circulation, whereas on its return journey, the areal extent of the southern Hadley cell is only marginally altered.

4. Discussion and summary

The Z criterion latitude, as evaluated at Tamale, seems to be a good indicator of the Hadley parameters when monthly averages are used, and the Hadley parameters provide a reasonable estimate of the rainfall at Tamale. However, when evaluated from a single equatorial station φ_z does not seem to reflect variations in STH, as suggested by Flohn (1964, 1965), but rather varies as the ITD. We investigated the cause of the φ_z variations in order to find the linking mechanism. The link between these parameters appears to be the subtropical jet stream. Closer examination of the radiosonde data shows that the variations in φ_z are caused primarily by the seasonal changes in the wind shear which in turn are caused by the southward movement of the subtropical jet.

The monthly average wind speed was found to be fairly constant at all levels. The variation in wind shear was due mainly to changes in wind direction as can be seen in Fig. 2, where the convention for the direction numbers is such that 0° is northerly (southward), 90° easterly, 180° southerly and 270° westerly. During June, July and August the prevailing winds are easterlies at all heights so that the wind shear term $(\partial U/\partial z)^2$ in the denominator of tan φ_z is small and hence φ_z corresponds to a large angle. Around the December solstice, the southward extension of the subtropical jet causes the 400 mb winds at Tamale to veer westerly, increasing the shear $(\partial U/\partial z)^2$ and reducing the value of φ_z. Since it requires a global network of upper air stations to accurately locate the subtropical jet, the Z criterion seems to be a useful substitute when data from only one radiosonde are available. The resulting correlation between $\Delta\varphi_z$ and $\Delta\varphi_{\mathrm{ITD}}$ then arises because within the equatorial regions the winds of the subtropical jet are affected more by changes in the wind field due to ITD variations than by movements of the STH.

From Fig. 2 it can be seen that the Tamale radiosonde wind is a measure of the strength of soutward penetration of the subtropical jet. The penetration around January 1975 was strong with a peak appearing at 500 mb and even at 700 mb. In contrast, the penetration around January 1976 was weaker, with only a small peak beginning at 500 mb and none at all at 700 mb. We conjecture that the strength of penetration of the subtropical jet is correlated with the rainfall of the subsequent rainy season. If this conjecture is correct, then the Tamale radiosonde data could be used in the future to aid in the prediction of the amount of rainfall in northern Ghana a few months in advance of the rainy season. This conjecture is supported by the data and analysis of the Appendix (see Tables A1 and A2).

Rainfall and average monthly wind direction data are used from the radiosonde stations at Niamey, Niger, and Bamako, Mali, for the 10-year period 1965–75.

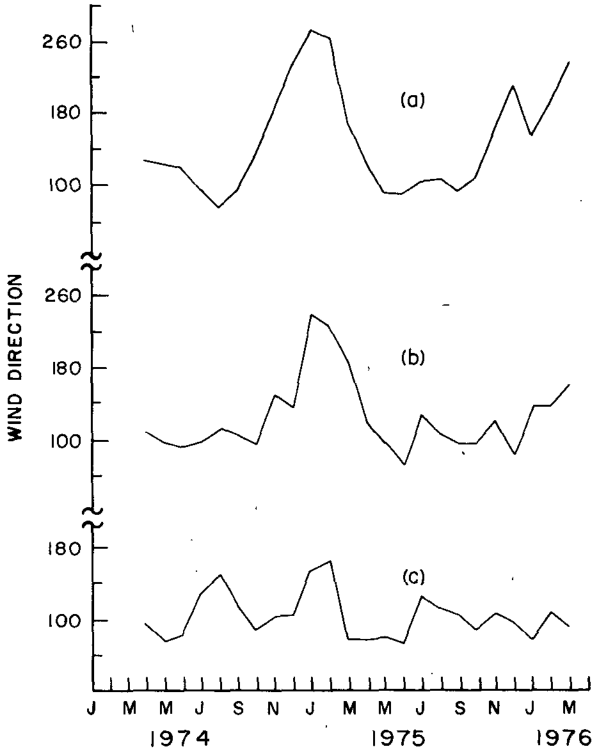

FIG. 2. Monthly average wind direction over Tamale in northern Ghana at (a) 400 mb, (b) 500 mb and (c) 700 mb. The peaks correspond to penetration of the subtropical jet into the prevailing easterlies.

By defining the subtropical jet penetration parameter in a suitable way for a period of months prior to the rainy season, reasonable correlation coefficients are obtained between this parameter and the subsequent amount of rainfall. This is true at both stations for the wind data taken at 300 mb. Because of the importance of rainfall prediction, particularly in the agriculturally fragile sub-Saharan regions of West Africa, and because of the limited number of radiosonde stations in that region, we intend to do a more detailed study of the correlations between subtropical jet penetration and subsequent rainfall in a future publication.

We note that the results of the Appendix tend to contradict those of Schupelius (1976). He states that precipitation at a given station in West Africa is not correlated with wind measurements made at that station, although no data are presented in the reference to support this conclusion. Schupelius' general approach is that rainfall is not correlated with any of the measurements made at an individual station and that only area-averaged data can be used. We believe that the results of our Appendix contradict this point of view and that measurements made at an individual station can be used as an aid in rainfall prediction.

Returning to the data taken in Northern Ghana, we note that the data of Fig. 1 indicate that the difference in rainfall pattern at Tamale in 1975 as compared with 1974 was not due to a greater northward penetration of the ITD, but instead that it was due to the ITD staying near its maximum northward extent for a longer period than in 1974. Nevertheless, both the Z criterion and STH values show larger maxima during 1975 than during 1974. It will be of interest to see whether the relationships and correlations established between the Hadley cell parameters and the Tamale rainfall persist in the future data taken at the Tamale radiosonde station.

In summary we have used the data from the recently established radiosonde station at Tamale, northern Ghana, to obtain monthly average values for the latitude φ_z in the Z criterion. Our results support Flohn (1964, 1965) in his general assertion that strong correlations exist between φ_z and the locations of the ITD and STH. When we remove the seasonal variations it appears that φ_z responds to variations in the ITD latitude alone. When we compare our results for φ_z (Fig. 1) with the annual variation of the location of the subtropical jet (Klein, 1958), it might seem more reasonable to consider it to be the latitude of the core of the subtropical jet rather than the latitude of the STH. However, this interpretation would be incorrect since 1) φ_z evaluated on a global basis seems to agree with the location of the STH (Pittock, 1973), and 2) the location of the core of the subtropical jet depends strongly on the STH and not very strongly on the ITD, whereas our results for φ_z indicate the reverse. Accordingly, it appears that φ_z when evaluated from a single equatorial station provides a convenient measure of ITD location and of equatorial penetration of the subtropical jet.

The variation of the Z criterion φ_z at Tamale is governed mainly by the southward penetration of the subtropical jet during the dry season. We also find correlation between the various Hadley cell parameters and the Tamale monthly rainfall. Our results are in agreement with a study made by Ilesanmi of rainfall patterns in Nigeria relative to the motion of the ITD. The variation of the Z criterion latitude φ_z at Tamale is governed mainly by the southward penetration of the subtropical jet during the dry season. We conjecture that the strength of this penetration is correlated with the amount of rainfall in the subsequent rainy season and this is supported in the Appendix by correlations in the data from other stations in West Africa.

APPENDIX

Subtropical Jet Penetration and Rainfall at Stations in West Africa

In order to test the hypothesis that the southward penetration of the subtropical jet is related to the amount of rainfall in the subsequent rainy season, we have used the data in *Monthly Climatic Data for the World* supplied by the Environmental Data Service of the National Oceanic and Atmospheric Administration. We have chosen two stations in West Africa which are similar in location to Tamale and which have been operating as radiosonde stations for reasonably long periods of time. These are Niamey, Niger (13.6°N, 2.2°E), for which we consider data from January 1965 through December 1975, and Bamako, Mali (12.8°N, 7.9°W), at which the radiosonde began operation in January 1966 and therefore for which we consider data from January 1966 through December 1975.

The data of interest to us are the total yearly rainfall and the monthly average wind direction at 700, 500 and 300 mb. We define a subtropical jet penetration parameter σ_i, $i=3$, 5, 7, corresponding to the levels 300, 500, 700 mb, respectively, which gives a measure of the southward jet penetration. For a given month, we average the values of the wind direction given in *Monthly Climatic Data for the World* over the years 1965–75 for Niamey and 1966–75 for Bamako at 300, 500 and 700 mb. The results are shown in Fig. 3. The characteristic shapes of the curves are the same as those in Fig. 2 for the data at Tamale. The discussion in Section 2 of the curves in Fig. 2 relating their shape to the southward penetration of the subtropical jet applies to Fig. 3 as well. We note that deep penetration of the subtropical jet implies large values for the wind direction. Strong penetration occurs at 300 mb between October and May at both stations. The corresponding penetration at Tamale, shown in Fig. 2a, seems to be of somewhat shorter duration, as is to be expected due to its more southward location, but definite statements

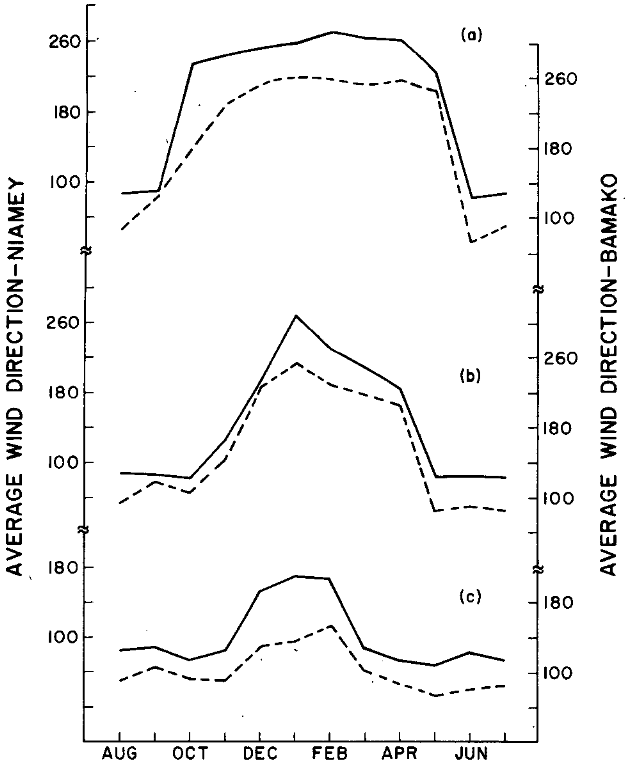

FIG. 3. Monthly average wind direction, each month averaged over the years 1965–75 for Niamey (solid lines) and 1966 through 1975 for Bamako (dashed lines). The wind data are at (a) 300 mb, (b) 500 mb and (c) 700 mb.

about this station will have to await a more extensive accumulation of data.

TABLE A1. Subtropical jet penetration parameters σ_i and total yearly rainfall for Niamey. The correlation coefficients r are between σ_i and the yearly rainfall using data only for those years where the number of unreported months is two or less. The significance level for the correlation for σ_3 is between 5% and 10%. Data from *Monthly Climatic Data for the World.*

Year	Total rainfall (mm)	σ_7	Missing months at 700 mb	σ_5	Missing months at 500 mb	σ_3	Missing months at 300 mb
1966	512	−215		+ 24	1	+ 43	1
1967	874	−195		− 3		− 58	
1968	555	−166		+ 29	1	−126	1
1969	609	−176		− 78		+136	
1970	446	−217		−111	2	−369	3
1971	466	− 22		−121		+101	
1972	343	+136		+127		+136	
1973	395	+294	2	− 12	2	+132	2
1974	529	+241		+ 95		+ 99	7
1975	690	+431	1	+ 22	1	−151	1
r		−0.17		−0.07		−0.64	

TABLE A2. As in Table A1 except for Bamako. The significance level for the correlation for σ_3 is approximately 20%.

Year	Total rainfall (mm)	σ_7	Missing months at 700 mb	σ_5	Missing months at 500 mb	σ_3	Missing months at 300 mb
1967	1492	+102	1	+ 66	1	−339	1
1968	956	+112	1	− 82	1	− 52	1
1969	967	+ 46		− 69	1	+101	
1970	849	− 91	2	− 72	2	− 88	2
1971	1043	−111	1	− 45	2	+ 36	1
1972	626	−103	5	+ 31	5	+ 25	5
1973	881	− 43	6	− 35	6	−142	6
1974	1261	+276		+262		+ 71	
1975	905	−107	2	+108	3	+ 49	5
r		0.60		0.68		−0.56	

The deviations from the averages shown in Fig. 3 are obtained for each station, for each month, at all three levels. The deviations are then summed for the months from September through June. These sums are the penetration factors σ_i shown in Tables A1 and A2 for Niamey and Bamako, respectively, along with the number of months of data that were not reported in *Monthly Climatic Data for the World* for the 10-month interval. The year assigned to σ_i is the later year in the September–June interval. The interval was chosen since it corresponds to the deep penetration period for the subtropical jet at 300 mb. We have changed the interval by a few months on either end and have found that our correlation coefficients are not changed significantly. However, we intend to study this aspect of the problem in greater detail in the future.

We also give in Tables A1 and A2 the rainfall for the entire year, taken from *Monthly Climatic Data for the World*. Positive values of σ_i correspond to greater than average southward penetration of the subtropical jet and this, in turn, should correspond to decreased rainfall. Thus, we expect negative correlation coefficients. The correlation coefficients shown in Tables A1 and A2 are between rainfall and σ_i and have been calculated only for years in which no more than two months of data are missing in the September–June interval (the deviations used in calculating σ_i for the missing months are taken to be zero). The correlation coefficients are negative for all levels at Niamey, with a strong negative value for the data at 300 mb. The data from Bamako are relatively poor compared with Niamey, with many more months not reported. The correlation coefficients are positive at 700 and 500 mb, but a negative correlation coefficient is obtained for the 300 mb data from Bamako.

We conclude that, at least for the data at 300 mb, the southward penetration of the subtropical jet is correlated as expected with the total rainfall of the subsequent rainy season at stations in the sub-Saharan region of West Africa. Once sufficient data are available at Tamale, averages analogous to the ones shown in Fig. 3 can be obtained and the parameter σ_i calculated on a year by year basis. These parameters could then be used as an aid in predicting the amount of rainfall in northern Ghana.

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