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Agroclimatological Rainfall Analysis for Semi-Arid Africa.

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2. Detailed description of the definition of onset date.

1. Summary.

The major scope of this report are 4 countries in Sahelian west Africa: Senegal, Mali, Burkina Faso and Niger. Besides these countries, limited analysis has been done for Chad and Botswana.

In Sahelian west Africa, common reductions in annual rainfall since 1970 are 20% and the highest reductions are found in Senegal.

The date of onset of the growing season is defined as the date on which the (additional) soil moisture content exceeds 40 mm. This onset date appears to be a valuable **predictor** for further characteristics of this season, especially the rainfall amount in the season and the season duration. With an earlier onset date, a longer season duration and more seasonal rainfall can be expected. For every day that onset is later, duration will be one day shorter, on average. Decrease in rainfall amount with one day later onset is in general 3 to 4 mm. The farmer can **adjust his management decisions** to this knowledge.

For all locations analyzed, rainfall amount and rainfall intensity are less when averaged over years after 1970, compared to years before 1970, at only a few locations end date of the rainy season is later and at about one third of the locations onset date is earlier and duration longer.

In Botswana, the date of onset seems to be as useful as a predictor as in the Sahel. Here, the rainfall is less concentrated in the rainy season than it is in the Sahel. A larger percentage of the rain falls outside the rainy season. In addition, the season duration is significantly longer, compared to Sahelian locations with about the same mean annual rainfall. Thus, the season rainfall intensity (= amount/duration) in Botswana is rather low. This suggests that long dry spells have a higher probability of occurrence and that the growing season, although longer, will be less reliable!

In the southern Sahel, date of onset is more **variable** from year to year than in the northern Sahel. Senegal is a clear exception. In south Senegal the onset tends to be

rather fixed. The variability in the end date of the rainy season is much less than the variability in the onset date. Like onsets, end dates are less variable in the south of Senegal, resulting in stable durations and rainfall amounts in this region.

The **spatial variability** of annual rainfall is high: even nearby locations show little correlation. Onset dates of locations in the southern Sahel are poor predictors for onset dates of locations more to the north. **Pre-season rainfall** as a predictor in addition to date of onset, does not significantly improve the predictions, compared to onset date as the only predictor.

Persaud (1986) based the definition for the growing season duration for Niger on decadal rainfall and potential evapotranspiration (PET). In this study a similar analysis has been done. Durations based on this method and durations based on the method described earlier, are about the same. A third definition for the season duration is based on probabilities of dry spells. Probabilities of having one or more dry spells of at least consecutive 10 days in the following 30 days have been calculated for each day. The duration is arbitrarily defined as the longest period of consecutive days that this probability is under 30%.

More **recent** data are needed, especially because climate is not fixed in time, but changing!

2. Introduction

The food production situation in the Sahel and other semi arid tropic (SAT) areas of West Africa is not so promising. The productivity of traditional agriculture is declining, and the threat of serious food shortages is rising in the rainfed SAT.

The SAT are characterized by seasonally wet climates. The rainy season is generally short. The dry season lasts for several continuous months during the year. In semi-arid agriculture, water is one of the most limiting resources. In most situations, dryland farming is the primary management system; therefore, rainfall amount,

intensity, frequency, and variability are important factors in developing a cropping system. The climate, soil, nutrients, and biological resources are linked with social and economic constraints to collectively circumscribe the alternative strategies for dryland agriculture.

In the Sahel sorghum, millet, and groundnut are commonly grown food crops. The crops yields are low. Crop failures due to recurrence of droughts is common. The past two decades have witnessed a drastic reduction in the amount and length of the rainy season. This region presents a serious challenge to the agricultural sciences for innovating technologies to stabilize and increase food production.

The spatial and temporal variations in rainfall in the semi-arid tropics are due to seasonal migration of the equatorial trough or the intertropical convergence zone (ITCZ) which occurs in response to the seasonal variation in the latitude of maximum insolation. Thus the annual rainfall over the semi-arid tropics can be thought of as the integrated effect of the annual visit of the ITCZ to the region.

The monsoon arrives in the higher rainfall areas of the southern Sahel in late April, May or June, then moves northward reaching the drier latitudes verging on the Sahara Desert in July or August. The pattern is unimodal (single peak in rainfall) with recession or withdrawal of the monsoon generally in late September or early October, but sometimes - especially in recent years in the northern part - in August. Virtually all annual rainfall is received within this season.

In an agricultural sense, then, the length of the crop growing season in the SAT is primarily limited by the duration of the rainy period. The reliability of the rainfall at the beginning of the season is generally low, because early rains usually are caused by isolated storms. Consequently the SAT exhibits a high degree of risk to the establishment of crops, because the soil moisture reserves at this time are practically nonexistent. The soil temperatures are also fairly high, generally the surface 5 cm soil has a maximum temperature of 40 - 50 °C. The variability of rainfall at the end of the

season is also high, affecting crop yield and their quality.

Evaporative rates and temperatures in the region are high during the monsoon growing season. Hargreaves and Samani (1986) indicate that evaporation rates (Class A pan equivalent) during the onset period of the rainy season at Niamey, Niger are about 9 mm/day in June, declining in July to about 8 and in August to about 7 due to cloudiness and rains. Temperatures through the season average about 29 °C (84 °F).

In semi-arid agriculture, an agroclimatologist is primarily concerned with rainfall variability and less with average rainfall amount. If the cropping season were always uniform in rainfall, the farmer would choose a single management plan. He would plant certain crops on specific soil/topography areas of his farm. His planting date, seeding rate, fertility, herbicide, and insecticide would be planned for the optimal yield for that anticipated single rainfall pattern. Obviously, life is not that simple, and the high variability of rainfall creates major problems for the farmer. He must begin the season with a perception of what the rainfall pattern will be. As the season progresses, he makes alternative management decisions based on what the rainfall pattern has been. Thus, it is important that the farmer knows with a significant degree of confidence the expected rainfall pattern in order to make decisions within or even before the growing season.

Most of the rainfall analysis, presented in this report, has been done for 4 countries in Sahelian west Africa: Senegal, Mali, Burkina Faso and Niger. Figure 1 shows the location of these countries. Many of the following figures are also maps of west Africa, each showing a different aspect of the rainfall regime. These maps however, don't have true proportions: they are put in such a format, as to utilize the A4 size paper optimally for the region concerned (the region between 16 and 11 °North and between 17 °West and 13 °East). Besides these 4 countries, limited analysis has been done for Chad (section 5.1) and Botswana (section 4.2).

A data set has been supplied by Dr. Sivakumar (ICRISAT, Niamey, Niger) and has been used for most of the analysis, presented in this report. From this data set, about 70 locations have been selected for analysis. Selection criteria were length of record and availability of recent records. The selected locations are shown in Figure 2, in Table 1 with the years of complete rainfall records, and in Table 2 with their coordinates. Other daily climatological data used for this report were obtained from AGRHYMET and the Royal Meteorological Institute of Belgium.

Appendix 1 is a paper called 'Agroclimatological perspectives in semi-arid tropical agriculture', which shows more about the context in which this report has been made and which discusses some of the same and other aspects of (basically) rainfall in the semi-arid tropics.

3. Annual rainfall.

Table 3 and Figures 3a, b and c show the annual rainfall before 1971, after 1970 and the reduction since 1971. 1970/1971 as a breakpoint in the rainfall records is an arbitrary choice, but somewhere around these years the rainfall started dropping markedly in the Sahel (Todorov, 1984). Figures 3a and b show that the annual rainfall increases to the south and also slightly to the west. Tables 4a and b give the results of the regression of annual rainfall versus latitude. When the analysis is done separately for locations west of 8 °West and east of 6 °West, the correlation between annual rainfall and latitude improves (see the r^2's), indicating a longitude effect.

The relative rainfall reduction since 1971 is indicated best by Figure 3c. Common reductions are 20% and the highest reductions are found in Senegal. Note however that the rainfall records after 1970 for the locations in Senegal are short (Table 1). Table 4b shows that absolute reduction is more in the south than in the north.

4. Onset of the rainy season as a predictor for further season characteristics.

In order to develop 'response farming' strategies, Stewart studied relationships between onset of the rainy season versus duration of the rainy season and onset versus rainfall amount during the rainy season, for two locations in Niger: Niamey and Bouza (Stewart, 1987). Response farming strategies are cropping strategies that the farmer can use in response to the (predicted) weather of the actual season. The date of onset acts as a rainfall (duration, amount, intensity) predictor for the actual rainy season. Current rainfall is used to determine the management strategies, which thus are responsive to the weather pattern.

4.1. Definitions.

The date of onset is defined as the date on which the soil moisture content exceeds 40 mm. This threshold was determined by Stewart (1986). To every location a critical date has been assigned, before which onset is not allowed. This is to reduce the risk of a false onset, i.e. an onset after which a long dry spell follows. The critical dates are subjectively determined, simply by looking at the daily rainfall records of the location. They are listed in Table 5 and show a close relationship to latitude and to annual rainfall: the more south and the higher annual rainfall, the earlier the critical date. However, there are a few exceptions, like in south west Senegal. An onset, earlier than the critical date, is allowed when the soil moisture content exceeds 40 mm + 2*(critical date - actual date) mm. For example, if the critical date is May 30 and the actual date May 20, then the minimum soil moisture content required to get a valid onset is 40 + 2*10 = 60 mm. In appendix 2 the onset definition is described in detail.

The end of a rainy season is the day when the accumulation of daily rainfall exceeds 10 mm, when counting backwards in time. Counting starts at October 31 and then October 30, 29, 28, etc. For Botswana counting starts at April 30. Duration = end date minus onset date. Season rainfall amount is defined as rain, fallen between

onset date (not included) and enddate (included) plus soil moisture content at onset date.

4.2. Relation between onset - duration, onset - amount and means of several rainfall characteristics.

Figure 4 shows the correlation between onset date and season duration at Niamey, Niger. It is obvious from this figure, that with an early onset, a longer duration can be expected. The correlation between onset and amount (Figure 5) is less pronounced, but still of practical use for making farm decisions. Table 6 shows the earliest, median and latest onset date of the record for each analyzed location.

In west Mali it takes about 90 days for the monsoon to travel from 11 °N to 17 °N (Table 7a and b), in Burkina Faso + east Mali 105 days, in Niger 80 days and in Senegal it takes about 40 days from 14 °N to 17 °N. Median onset date of any given location can be predicted on the basis of the latitude of this location, for example for location 'A' in Niger with a latitude of 13 °N, the median onset is June 29 (Table 7b).

Table 8 shows means for onset date, end date, duration, rainfall amount and -intensity, as well as the linear regression coefficients for the correlations onset - duration and onset - amount. Figures 6a and b show mean onset dates before and after 1970 respectively. At about one third of the locations the onset date is earlier in recent years (Figure 6c). Compared to onset, the end date is rather constant with latitude (Figures 7a and b). End dates are somewhat earlier in the north than in the south (about 20 days difference between 11 and 17 °N in recent years; Table 9a and b). Earliest ending dates are in Niger, latest in Senegal and Burkina Faso (Figure 7a and b).

At only a few locations the end date is later in recent years (Figure 7c), at about one third of the locations duration is longer (Figures 8a, b and c) and at all locations rainfall intensity is less (Figures 9a, b and c), except for Dagana (Table 8), which is due to years with for example a duration of one day and an amount of 60 mm, giving

an intensity of 60mm/day for that particular year! Also rainfall amounts are less in recent years for all locations analyzed. The later ending dates are all found in the south (Figure 7c). Earlier onsets and longer durations in recent years show no significant correlation with latitude (Figure 6c and 8c).

Onset - duration correlations have a slight tendency of being greater in the south (Figure 10a), while the opposite is true for onset - amount correlations (Figure 11a). However, in recent years, one can hardly see any correlation with latitude (r^2's of .00 and .03; Table 9a, Figures 10b and 11b).

Table 10 shows that the correlation between onset and duration is much better than the correlation between onset and amount (average r^2's of .72 and .23 resp.). In recent years the relation onset - amount has improved (average r^2 of 0.35 versus 0.22 in early years). This might be due to the fact that the whole record experienced climatic changes, whereas the recent record is more uniform. In Niger the improvement is the highest; the average r^2 for recent years is .51, compared to .26 for all years.

In general b1 for the linear regression equation 'duration = b0 + b1*onset' is about -1 (Table 8). This means that for every day that onset is later, duration will be one day shorter. At about three fourths of the locations b1 is more negative in recent years compared to early years. This means that for these locations one day of later onset will decrease the duration more in recent in years, compared to early years. In the north the decrease in duration with one day later onset is less than in the south (Figure 12). Decrease in rainfall amount with one day later onset is in general 3 to 4 mm. In the north it is more (Figure 13). For about 50% of the locations, one day of later onset will decrease the rainfall amount more in recent years (Table 8).

Many aspects of rainfall become worse when going to the east (and to the north, obviously): annual rainfall, season duration, intensity, etc.

Botswana

The annual rainfall in Botswana is 650 mm in the north to 250 mm in the southwest (Figure 14). In general 90% of the rainfall is received in the period October to April. The rainfall is unimodal with a peak during January.

The locations of Francistown, Mahalapye and Gaborone have been selected, to evaluate the relationship between onset of the growing season versus the duration of it and onset versus growing season rainfall amount, using the same definitions as have been used for the Sahel analysis. The three locations have about the same mean annual rainfall (Figure 14).

The results of the analysis are shown in Table 11. In the regression equations, the day of year should be used to calculate expected duration and amount. If the onset is so late that it falls in the beginning of the next year, then the day of year + 365 should be used. For example, one year in Francistown the onset is on January 15. The expected duration equals a1 - b1*(15+365) = 536 - 1.24*380 = 65 days.

The correlations seem to be as useful as in the Sahel, because both for onset versus duration and onset versus amount the r^2's are of about the same magnitude. Even Gaborone is not as hopeless as it looks . When two extremely abnormal years (1957 and 1959) of the thirty years are left out of the regression analysis, the r^2 for the onset - duration correlation increases from .15 to .76 and for the onset - amount correlation from .09 to .25!

In Botswana, the rainfall is less concentrated in the rainy season than it is in the Sahel. A larger percentage of the rain falls outside the rainy season. In addition, the season duration is significantly longer, compared to Sahelian locations with about the same mean annual rainfall, like Bouza and Dori. Thus, the season rainfall intensity (= amount/duration) in Botswana is rather low. This suggests that long dry spells have a higher probability of occurrence and that the growing season,

although longer, will be less reliable!

4.3. Year to year variability of rainfall characteristics.

Table 12 shows standard deviations of several aspects of the rainy season. There is a general tendency of onset being more variable in the south than in the north (Table 13a and b and Figure 15). Senegal is a clear exception. In south Senegal the onsets tend to be rather fixed from year to year. Locations with more than 1000 mm of annual rain (for this analysis only locations with less than 1000 mm/year have been used), farther south in Senegal, which are not shown in Table 13b nor in Figure 15, confirm this.

The variability in the end date of the rainy season is much less than the variability in the onset date (Table 13b). Unlike onset, the variability in end date does not vary with latitude. The duration variability does vary with latitude in the same way as onset does: more variability in the south. In relative terms however, the duration variability is larger in the north. For seasonal rainfall amount the variability is slightly larger in the south. Relatively this variability is much larger in the north (Figure 16). Variability in end date shows weak correlation with variability in onset (r^2 = 0.04; Table 14a and b), except for Senegal. Here there is a positive correlation between onset- and end variability: a smaller variability in onset corresponds with a smaller one in end. Onsets are less variable in the south of Senegal and so are ends, resulting in stable durations and rainfall amounts.

4.4. Rainfall intensity during the rainy season.

An important characteristic of the rainy season is the rainfall intensity, defined as the season rainfall amount divided by the season duration (mm/day). The high correlation between onset and duration and the low correlation between onset and amount suggests low intensities for early starting seasons and high ones for late starting seasons. An extreme example makes this point clear: if the r^2 of the

correlation between onset and duration equals some positive value and the r^2 of the correlation between onset and amount equals 0.00, then one would be sure of lower intensities in seasons with earlier onset. In this case rainfall amount would not depend on onset date, so an early onset, giving a longer duration, would result in a lower intensity (=amount/duration).

For the analysis of intensities, eleven locations were used (Table 15a) with a slightly different data set than shown in Tables 1a through d. For all the eleven locations, except Dori, Burkina Faso, was found that seasons with later onsets have higher intensities. This might mean that, although with an early onset the season duration is longer, this season is less reliable because of the lower intensity, which in turn might be due to longer dry spells at the beginning of the rainy season. This potential danger is at least partly covered by the definition of onset: for very early onsets (earlier than the critical date) the soil moisture requirements are higher, so that the expected dry spells can be encountered properly (see section 4.1).

When the intensity analysis is based on the years 1971 and onward, representing the recent dry period, the results become more promising. Six of the eleven locations have been analyzed on this basis, having 9 or more years of rainfall records for 1971 and onward: Niamey, Bouza and Gaya in Niger and Dori, Kaya and Boromo in Burkina Faso. The other five have not been analyzed, because of lack of recent records: 6 or less years of records for 1971 and onward.

For recent years, five of the six locations still show a higher intensity for seasons with late onsets, Niamey being the exception with a considerable higher intensity for early onset seasons (Table 15b). For Gaya, Bouza and Boromo, the analysis shows a considerable lessening of the difference in intensity between late and early onset seasons. Dori and Kaya show a slight opposite effect.

5. Other predictors.

5.1. Onset of rainy season at one location being predicted from the onset at another location.

On average in the Sahel the rainy season starts earlier as you proceed south. If in every year the onset at location A would be x days later than the onset at location B, then the onset at A could be simply predicted, once the onset at B is there. The correlation between the onsets of two locations has been evaluated, to determine the potential of this kind of predictor: an r^2 of 1.00 would mean a perfect predictive potential; every year the number of days between onset at A and B would be the same. An r^2 of 0.00 means no predictive potential. Column 3 of Table 16 shows these r^2's in descending order. For this analysis a data set has been used with the years 1967 - 1978, thus with a maximum number of 12 years. Column 4 shows the missing years and column 5 the number of years. For some locations with good correlations the same analysis has been done for longer records than 12 years. This is shown in the lower part of the table. The results are quite disappointing: the r^2 for the correlation Fada - Dori drops from .43 to .01, Gaya - Tahoua from .40 to .03, Diourbel - St. Louis from .40 to .01 and Gaoua - Dori from .38 to .00.

The r^2's that are relatively high, usually belong to locations very close to each other, and, therefore of no prediction value. Why the correlation is good between certain locations and bad between others, remains obscure. For example Gaya - Tahoua (Niger) has a r^2 of .40 and Gaya - Niamey (Niger) only .09, the latter locations being much closer to each other!

Also r^2's have been calculated for the correlation between the mean of onsets of several locations and the onset of one location (Table 17). The idea is that if the mean of onsets is early, that then the Intertropical Convergence Zone (ITCZ) is early in that area, while if only at one location onset is early, this might be due to an accidental shower and not to an early ITCZ. So, a few locations in the south are compared to one

in the north. For a prediction, one has to wait until the last onset in the south is there, since only then the onset of the one location in the north can be predicted.

The correlations indeed are better than the one to one correlations, with Boromo, Ouagadougou, Fada - Dori as the best one with an r^2 of .73, dropping to 0.38 for a record of 30 years. Onset at Dori = 17 + 1.16*mean onset. On average this prediction can be made 25 days before the onset at Dori. This is the mean difference between the latest onset in the south and the onset at Dori. Still better correlations might be found if some locations in the south predict not one but a few in the north. Then not the onset for one location is predicted but the average onset in this particular year for a region. For example in Senegal the combination Ziguinchor, Kolda, Tambacounda, Kedougou could predict the average onset of the region Saint-Louis, Linguere, Podor, Matam. An example of still better correlations with this latter method is Pala, Moundou, Sarh - Timan, Mongo in Chad (r^2 = .70); Pala, Moundou, Sarh - Timan 'only' gives an r^2 of .56 and Pala, Moundou, Sarh - Mongo only .28. However the question is how to use this knowledge in a prediction. Assume the equation '$onset_{Mongo,Timan} = 1.1*onset_{Pala,Moundou,Sarh} + 50$', r^2 = .70 exists. How then is the onset predicted at Timan, at Mongo or at a location in between? For this reason this type of prediction may not be very useful.

Also relations between yearly rainfall amount of two locations have been analyzed in terms of correlation. An r^2 of .00 means that if location A has a good year, location B might equally have a good year or a bad year. Between nearby locations one would expect therefore a high r^2. But numerous times this is not so: Maradi - Zinder (Niger; r^2 = .09), Bobo - Boromo (Burkina Faso; r^2 = .12), Koutiala - San (Mali; r^2 =.04), etc. (Table 16).

We would anticipate that yearly amounts would have the greatest potential for correlation between locations. So, if there is no correlation in yearly amounts, then also there probably will be no correlation in onsets or other characteristics. However, it

[illegible] there are some location pairs, having poor yearly amount correlations and much better onset correlations: Gaoua - Dori and Fada - Dori (Burkina Faso) (Table 16).

5.2. Pre-season rain as a predictor.

In India the rainfall before the actual rainy season was used as a predictor of rainy season characteristics (Stewart, 1986). The same has been evaluated in this study for 11 locations in the Sahel.

Table 18 shows that using early rainfall as a predictor in addition to date of onset, does not significantly improve the predictions, compared to onset date as the only predictor. For the prediction of rainfall amount only Nioro, Bouza and Boromo and for duration only Bouza have improved significantly. A reason that early rain as a predictor in India works better than in the Sahel might be the fact that the Sahel simply has less rainfall before the rainy season starts.

6. Other definitions for season duration.

6.1. Season duration based on rainfall and potential evapotranspiration.

Persaud (1986) based the definition for the growing season duration for Niger on decadal rainfall and potential evapotranspiration (PET). In this study a similar analysis has been done for Senegal, Mali, Burkina Faso and Niger. The time period here is not decade but a month. Three monthly rainfall probabilities (25, 50 and 75%) are compared with two monthly PET levels (.50*PET and .35*PET). Start- and end date are defined as the crossing points of the rainfall and PET curves (Figure 17).

Table 19 shows values for onset, end and duration for the 6 PET - rainfall probability combinations and Figures 18,19 and 20 show the values for the combination .50*PET, 50% rainfall probability. Figures 20a and b show that for more recent years durations are shorter, because of lower rainfall. In reality they will be even more

shorter, because most probably PET will have increased as rainfall decreased in recent years. Durations based on this method (.50*PET, 50% rainfall probability) and durations based on the method described in section 4.1, are about the same for recent years (Figures 20b and 8b).

6.2. Season duration based on dry spell probabilities.

Probabilities of having one or more dry spells of at least 10 consecutive days in the following 30 days have been calculated for each day. To smooth the thus obtained data series, the result for each day has been replaced by the average of 9 days: 4 days before, 4 days after and the day itself. Typical curves, obtained using this method, can be seen in Figure 21 and 22. For 70 locations in the countries of Senegal, Mali, Burkina Faso and Niger durations of the growing season, both for early (to 1970 included) and recent (from 1971) years are given in Table 20. The duration is arbitrarily defined as the longest period that the above described probability is under 30%.

The duration map based on dry spell probabilities (Figure 23) and the duration map based on the method described in section 4.1 (Figure 8a), show the same pattern. In the first one the dip between 10 and 5 °W may be more pronounced. Duration differences between early and recent years are larger for the durations based on dry spell probabilities and for this definition there are more locations where duration becomes longer in recent years (36% of the locations versus 25% for the definition in section 4.1; Table 20 and Figure 24). Sometimes one definition gives a longer duration, while the other one gives a shorter duration for the same location!

7. Evaluation of different sources for potential evapotranspiration (PET).

In this study the main source for monthly PET data, used in the analysis, is Manuel de climatologie..(Virmani, 1980). However, others also have published data on PET. One of these publications is World Water for Agriculture (Hargreaves, 1986). The monthly PET data of Hargreaves and Virmani show considerable differences

(Table 21). One cause can be different methods of calculation (which do not become clear in the publications). Another cause can be difference in used data base. For example, PET based on years after 1970 probably will be higher.

Generally Hargreaves' PET's are higher, especially at northern (dry) locations (Podor, N'Guigmi, Kidal) and at the end of the rainy season (August, September, October). The onset definition of section 4.1 depends on PET. However the onset date appears to be very insensitive to PET: for Niamey there is no difference in mean onset date between onsets calculated with Hargreaves' PET and onsets calculated with Virmani's PET. If for every month a PET of 100 mm is used in the calculation, the mean onset at Niamey is only 4 days earlier, compared to the onset using either Virmani's or Hargreaves' PET, and with 50 mm only 7 days earlier. This insensitiveness shows that onset definition could as well be based on rainfall only!

The calculation of season duration on the basis of PET and rainfall (section 6.1) however, is affected more by PET. With Virmani's PET the season duration for Niamey with rainfall probability 50% and 0.5*PET is 87 days and with Hargreaves' PET 80 days. For Podor and N'Guigmi, the difference will be even greater.

8. Conclusions.

A dramatic climatic shift has taken place in the Sahel since about 1970. The annual rainfall is about 20% less than before. The onset date of the growing season appears to be a valuable predictor for further characteristics of this season, especially the rainfall amount in the season and the season duration. In Botswana growing season durations are longer, but these seasons are less reliable, compared to Sahelian locations with the same annual rainfall.

Year to year variability of onset is rather large with an average standard deviation of about 20 days. In the south of Senegal it is more stable with standard deviations of about 13 days. Also season ends tend to be more stable in southern Senegal. Pre-

season rainfall does not seem to be a valuable predictor for rainy season characteristics. Onsets of locations in the south are poor predictors for onsets of locations more to the north.

More recent data are needed, especially because climate is not fixed in time, but changing!

9. References

FAO. 1984. *Agroclimatological data for Africa. Volume 2: Countries south of the equator.*

Hargreaves, G.H. and Zohrab A. Samani. 1986. *World water for agriculture - precipitation management.* International Irrigation Center, Department of Agricultural and irrigation Engineering Center, Utah State University. 617 p.

Jaafer, M.N., E.T. Kanemasu, and W.L. Powers. 1978. *Estimating soil factors for nine Kansas soils used in an evapotranspiration model.* Trans. Kans. Acad. Sci., 81: 57-63.

Persaud, N., I. Alfari, M. Gandah and M. Ouattara. 1986. *Probability of receiving specified decadal rainfall totals for selected stations in Niger, West Africa.* Tropsoils, INRAN, Niamey, Niger.

Sivakumar, M.V.K. 1987. *Predicting rainy season potential from beginning of rains in the Sahelian and Sudanian climatic zones of West Africa.* Proceedings, INRAN-ICRISAT-TROPSOILS-USAID-USDA Workshop on Soil and Water Management systems for Rainfed Agriculture in the Sudan-Sahelian zone, Niamey, Niger. January 11-16, 1987. 17p.

Steiner, J.L., E.T. Kanemasu, W.L. Powers, and D.L. Pope. 1979. *Monitoring soil moisture in irrigated corn and sorghum with a programmable calculator.* Contribution

No. 79-398-J, Agron. Dept., Evapotranspiration Laboratory, Kansas Agric. Exp. Stn., Kansas State University.

Stewart, J. Ian. 1986. *Development of management strategies for minimizing the impact of seasonal variation in rainfall.* Presented at the International Consultants' Meeting on Research on Drought Problems in the Arid and Semi-Arid Tropics (ICRISAT). Nov 17-20.

Stewart, J. Ian. 1987. *Potential for response farming in sub-Saharan Africa.* Proceedings, INRAN-ICRISAT-TROPSOILS-USAID-USDA Workshop on soil and Water Management Systems for Rainfed agriculture in the Sudano-Sahelian Zone, Niamey, Niger. January 11-16 1987. 26p.

Todorov, A.V. 1984. *Sahel: The changing rainfall regime and the 'normals' used for its assessment.* Journal of climate and applied meteorology. Vol. 24, no. 2.

Virmani, S.M., S.J. Reddy and M.N.S. Bose. 1980. *Manuel de climatologie pluviale de l'Afrique occidentale: Donnees pour des stations selectionnees.* Bulletin d'information No. 7, ICRISAT, Patancheru, A.P. 502 324, India.

Figure 1: Location in West Africa of the 4 principal countries, analyzed in this report.

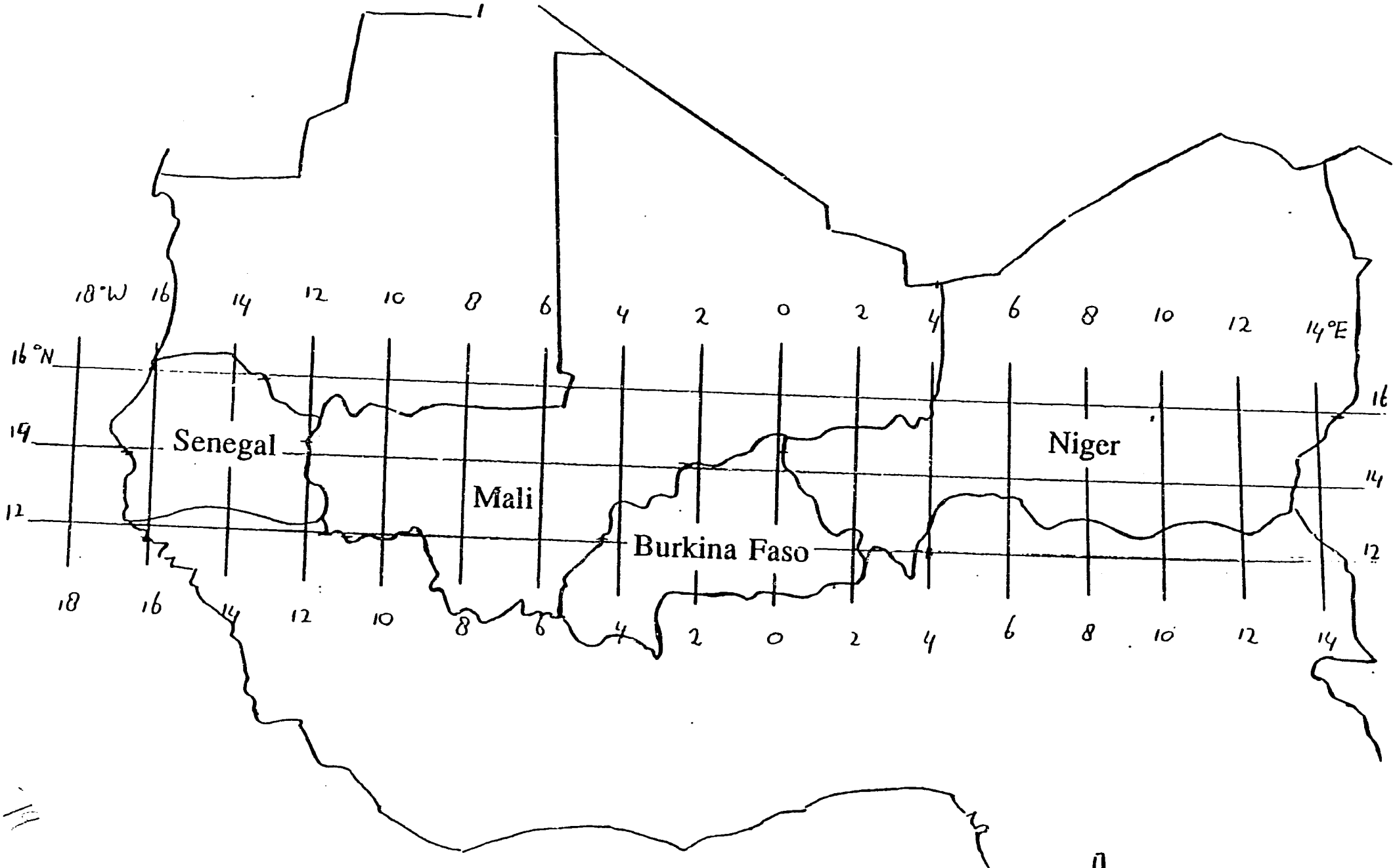

Figure 2: Location in West Africa of rainfall stations, analyzed in this report.

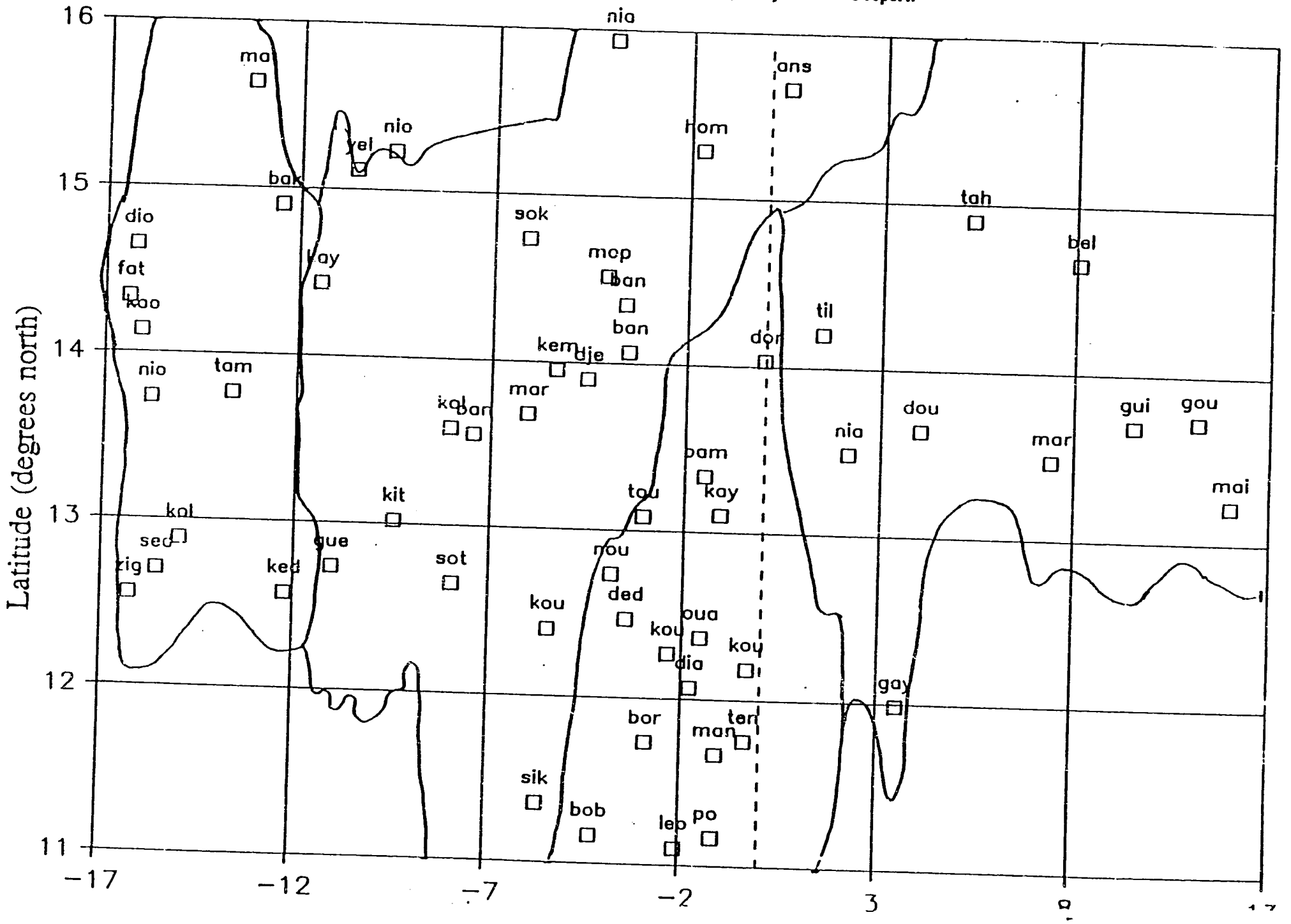

Figure 3a: Annual rainfall (mm) before 1971.

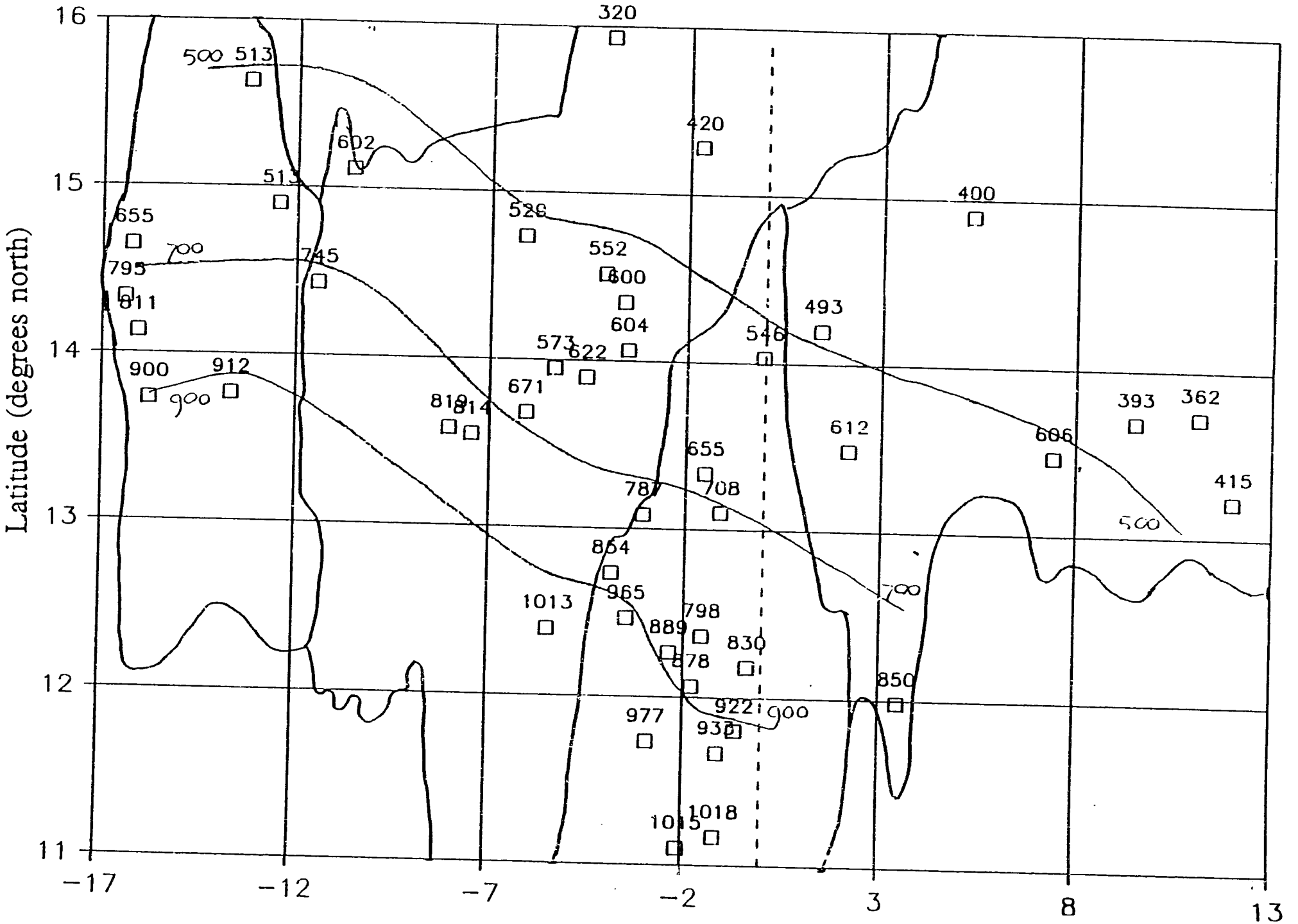

Figure 3b: Annual rainfall (mm) after 1970.

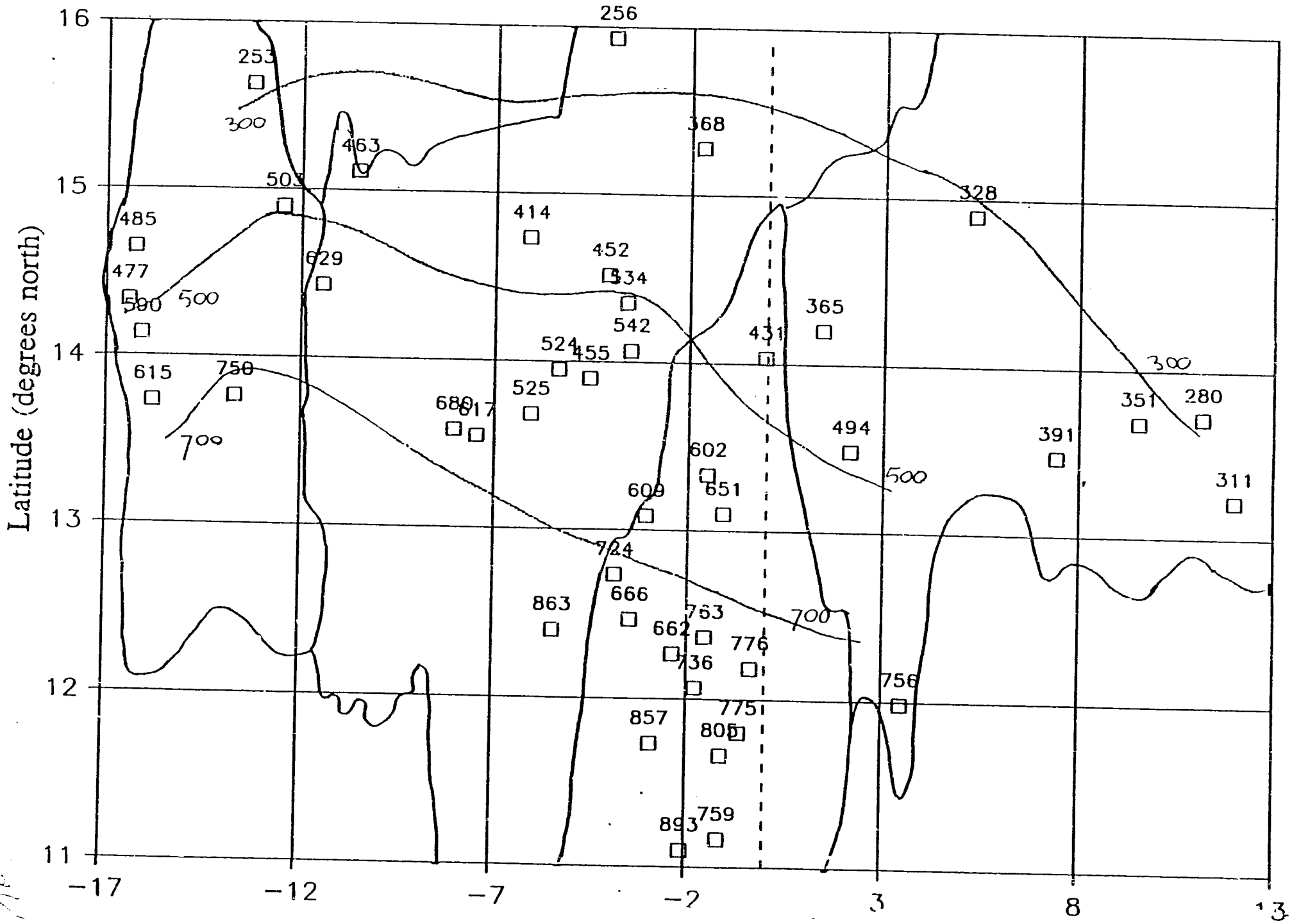

Figure 3c: Reduction (%) in annual rainfall since 1970.

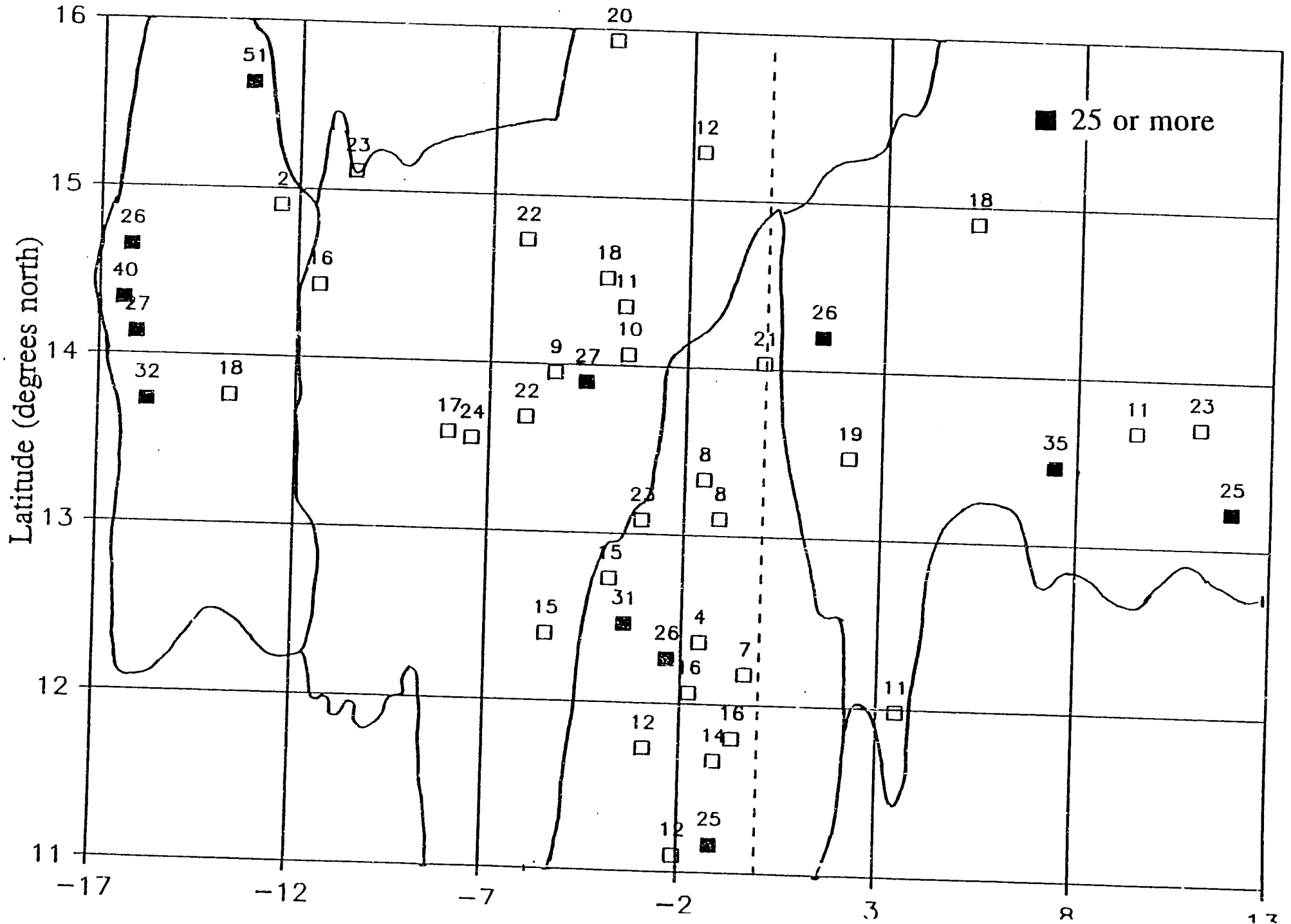

Figure 4: Correlation between onset date and growing season duration at Niamey, Niger.

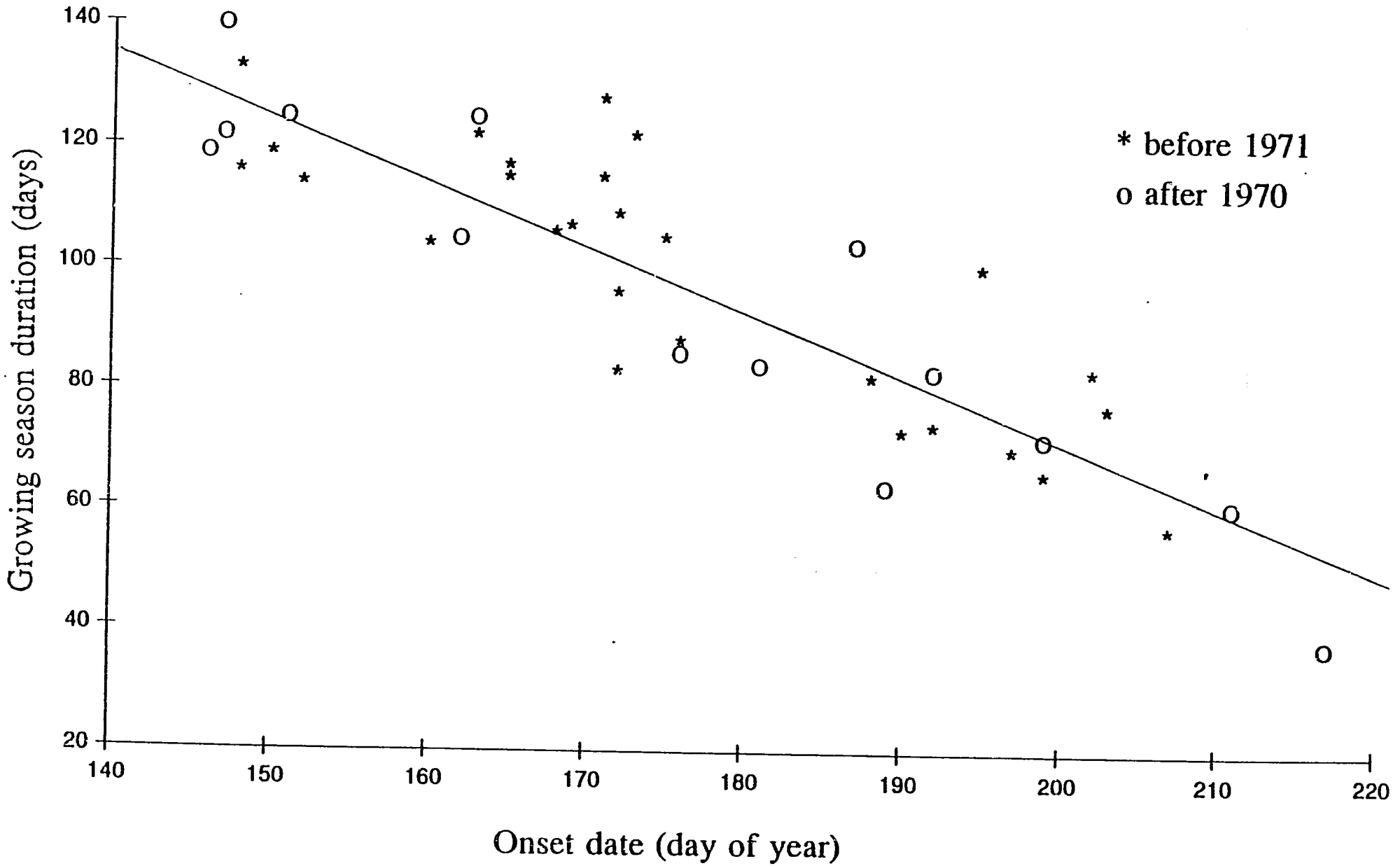

Figure 5: Correlation between onset date and growing season rainfall at Niamey, Niger.

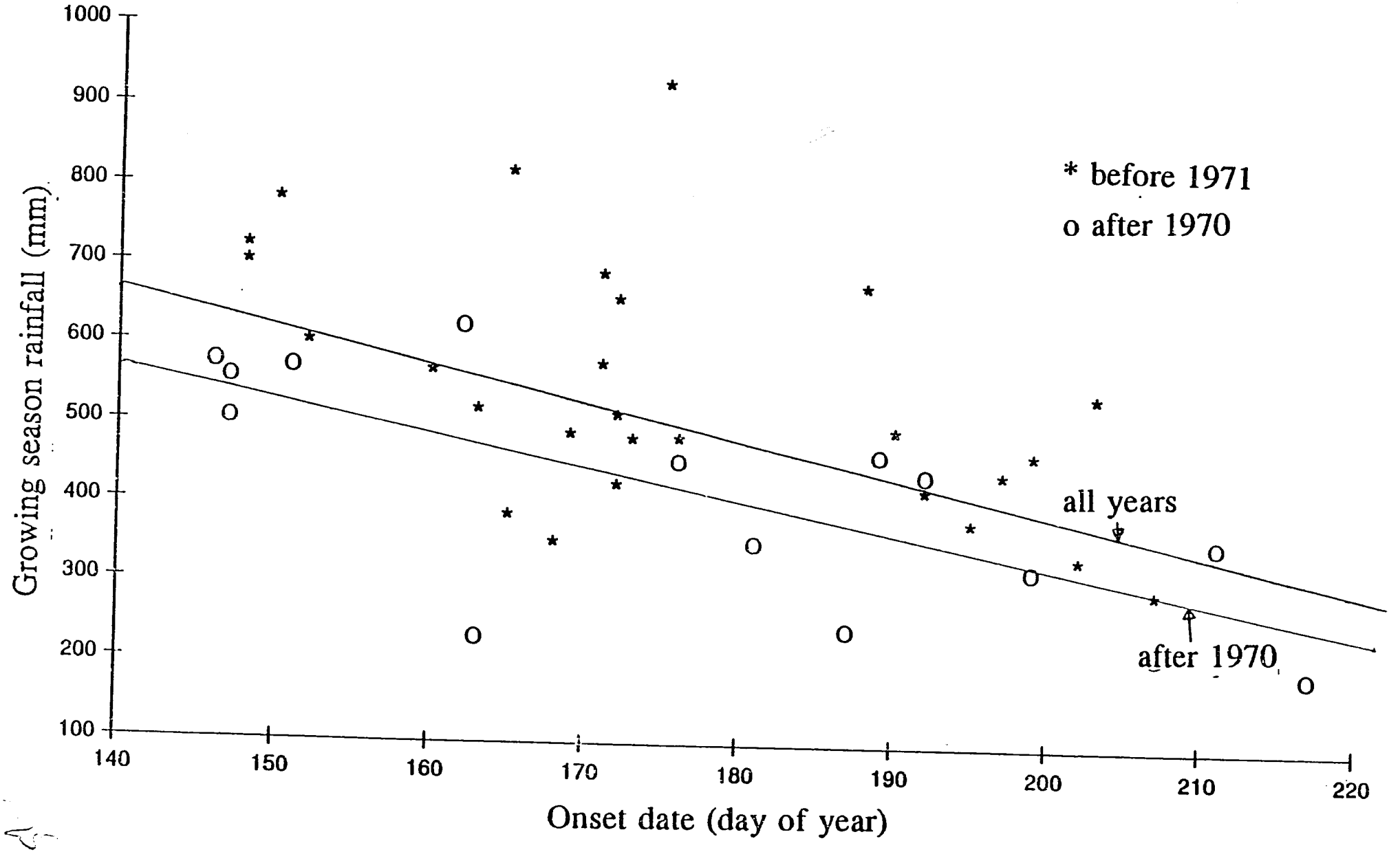

Figure 6a: Mean onset date (day of year) before 1971.

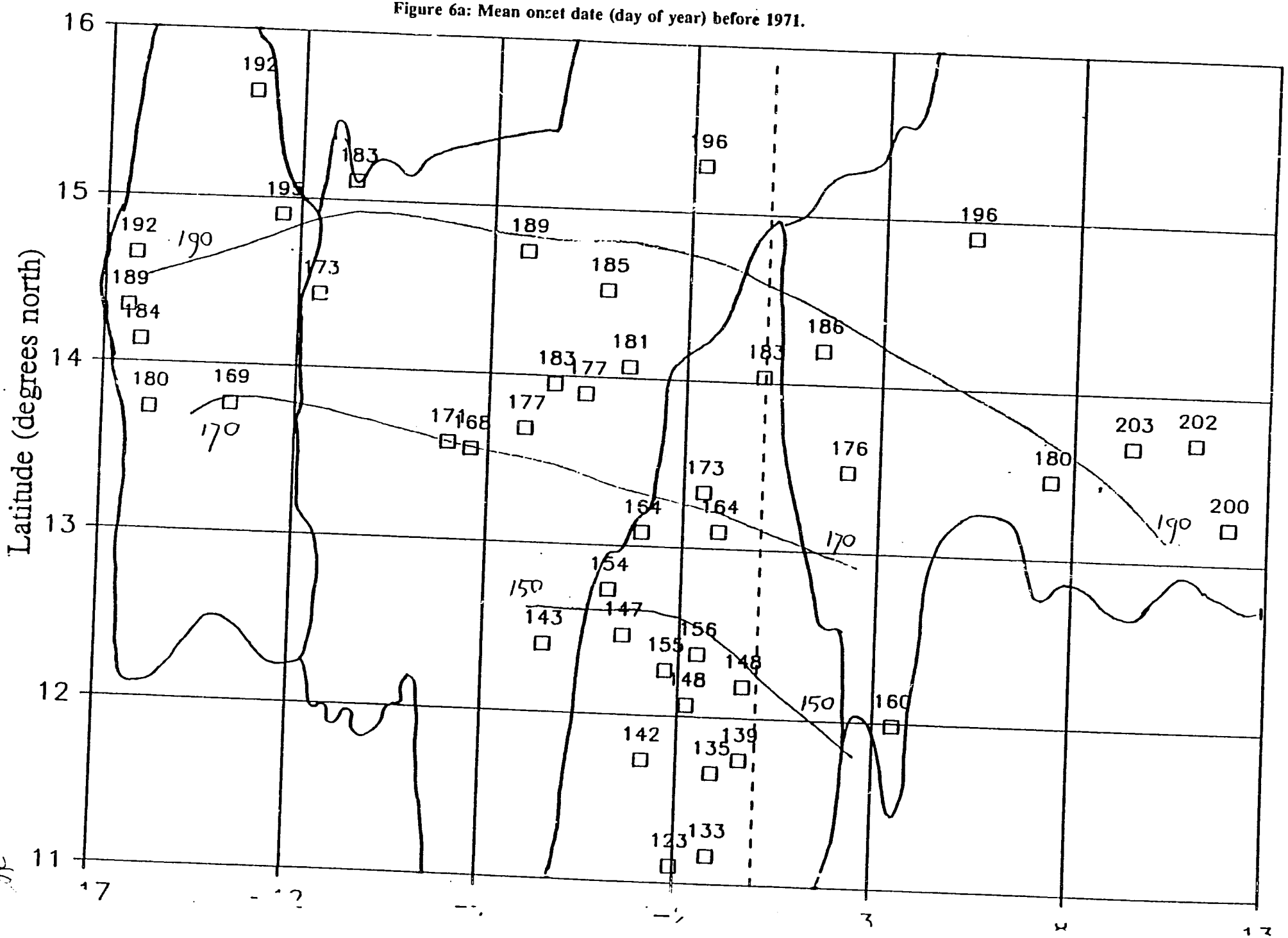

Figure 6b: Mean onset date (day of year) after 1970.

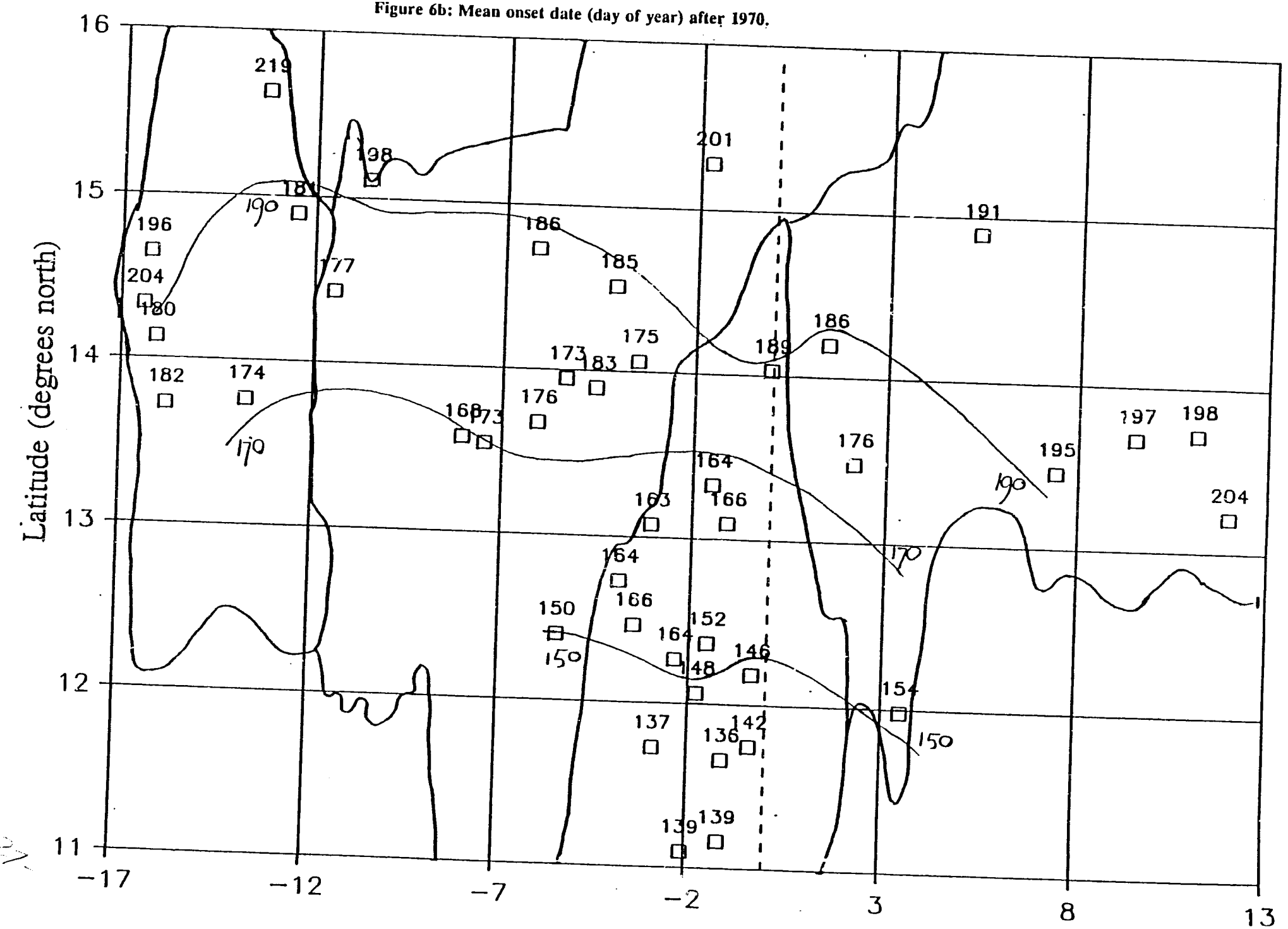

Figure 6c: Mean onset date of years before 1971 minus that of years after 1970 (days).

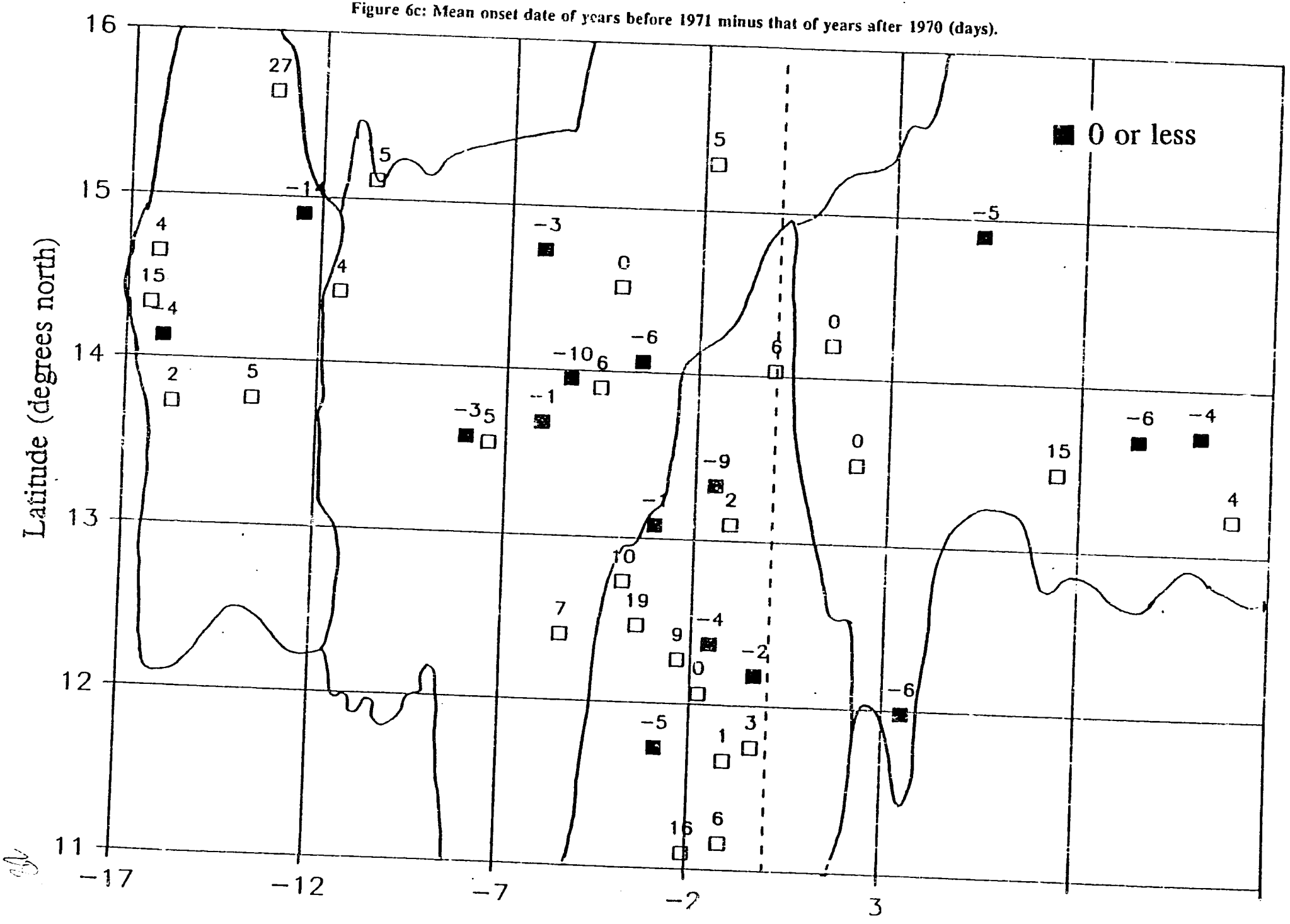

Figure 7a: Mean end date (day of year) before 1971.

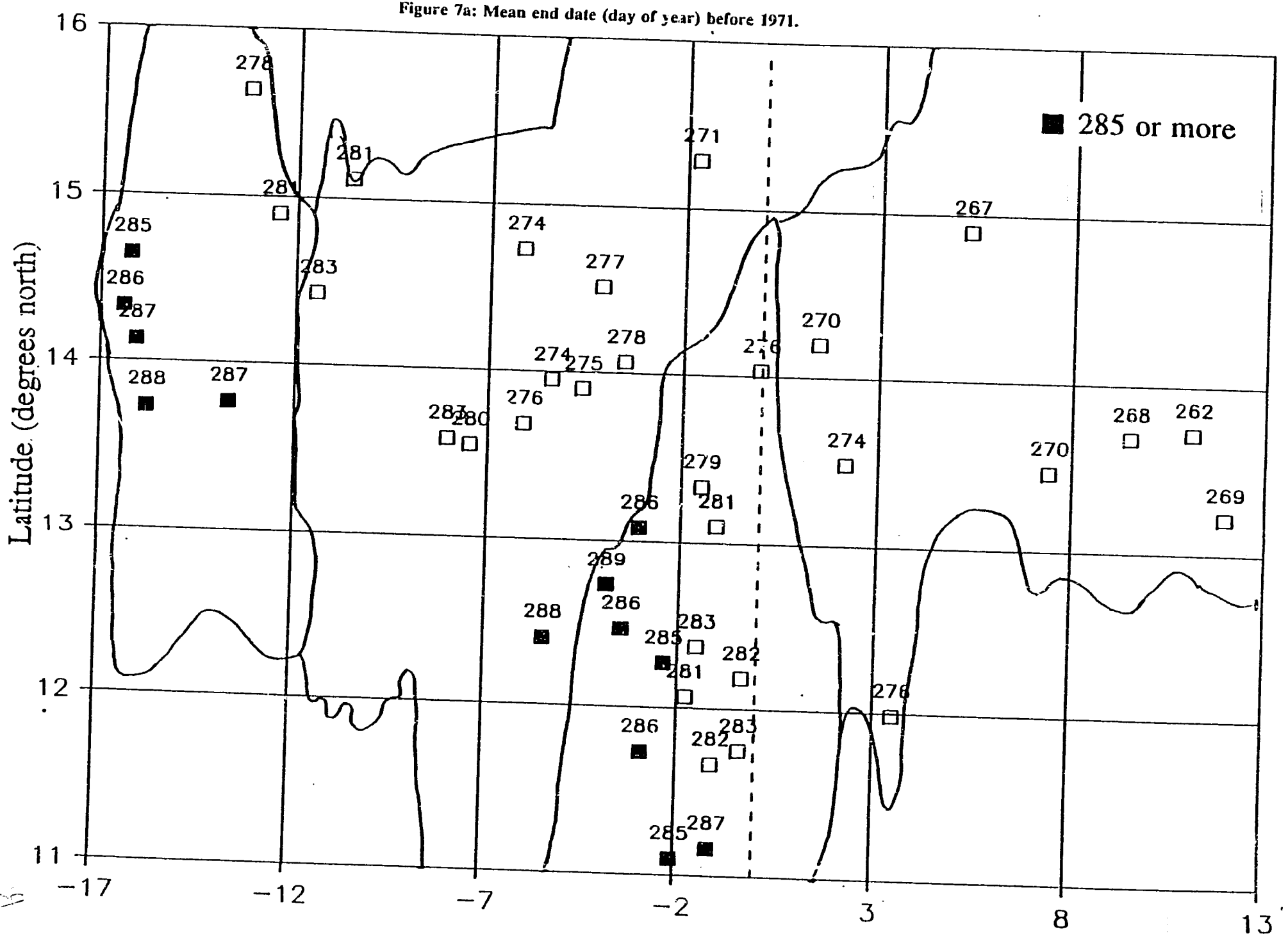

Figure 7b: Mean end date (day of year) after 1970.

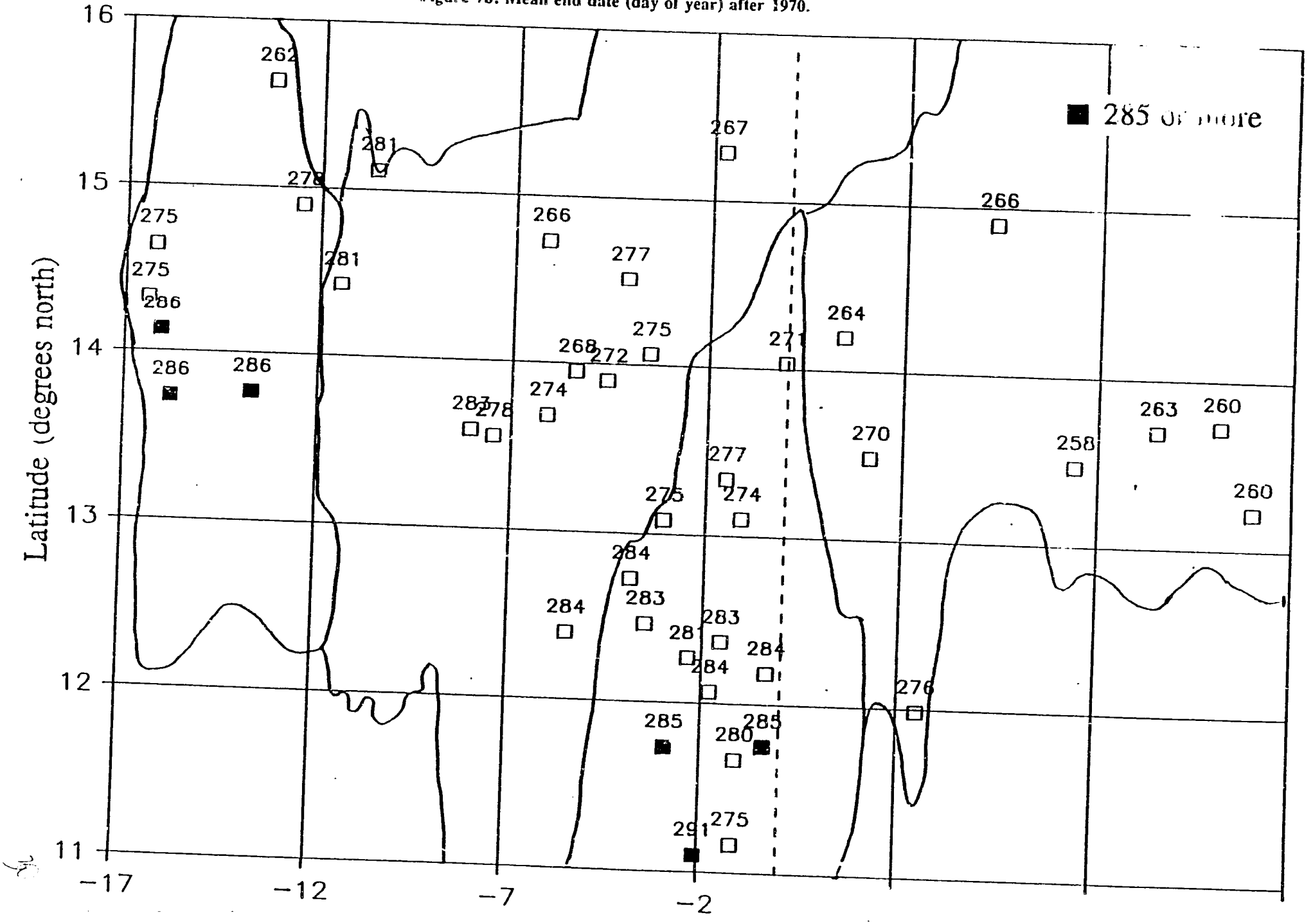

Figure 7c: Mean end date of years before 1971 minus that of years after 1970 (days).

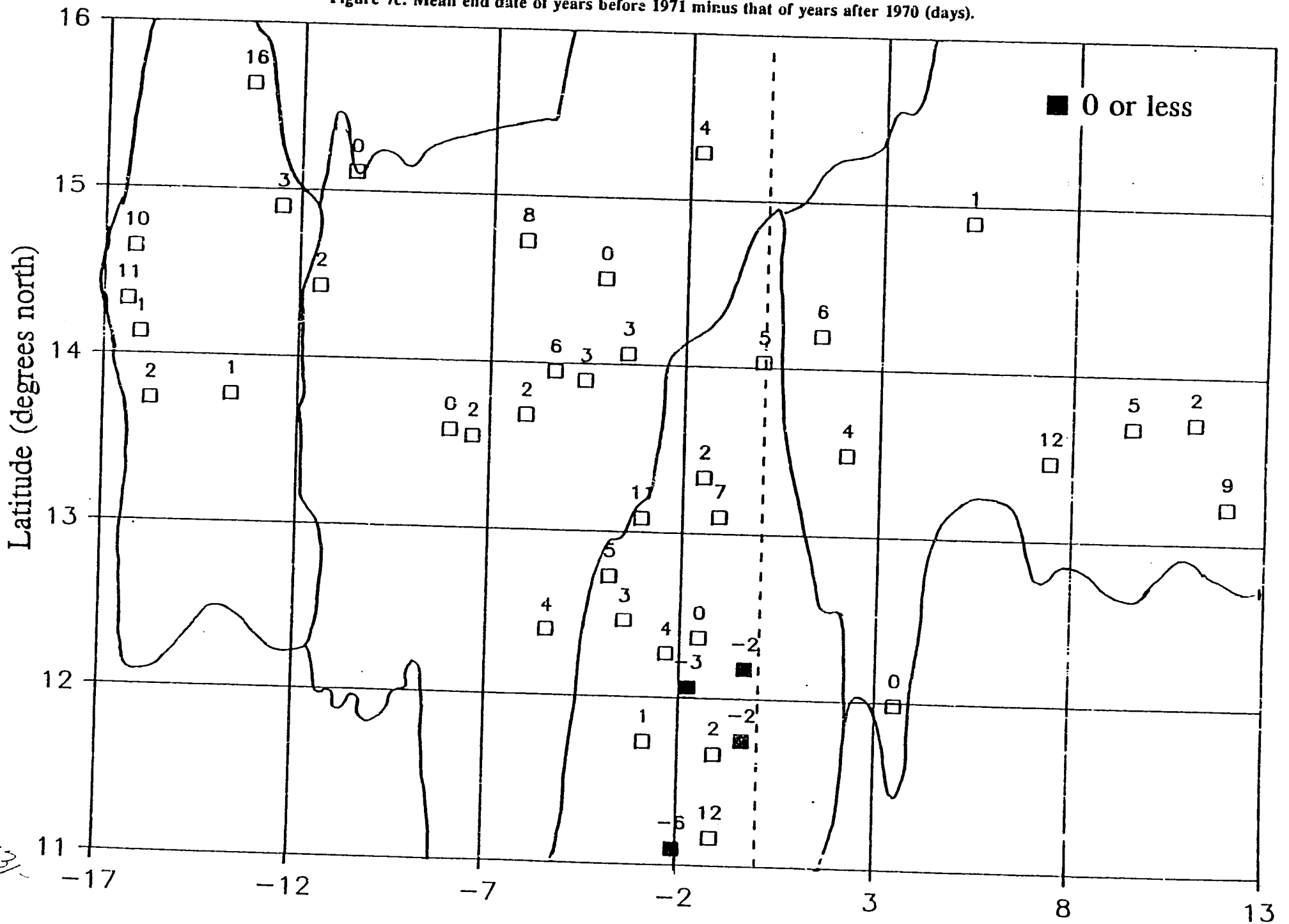

Figure 8a: Mean rainy season duration (days) before 1971.

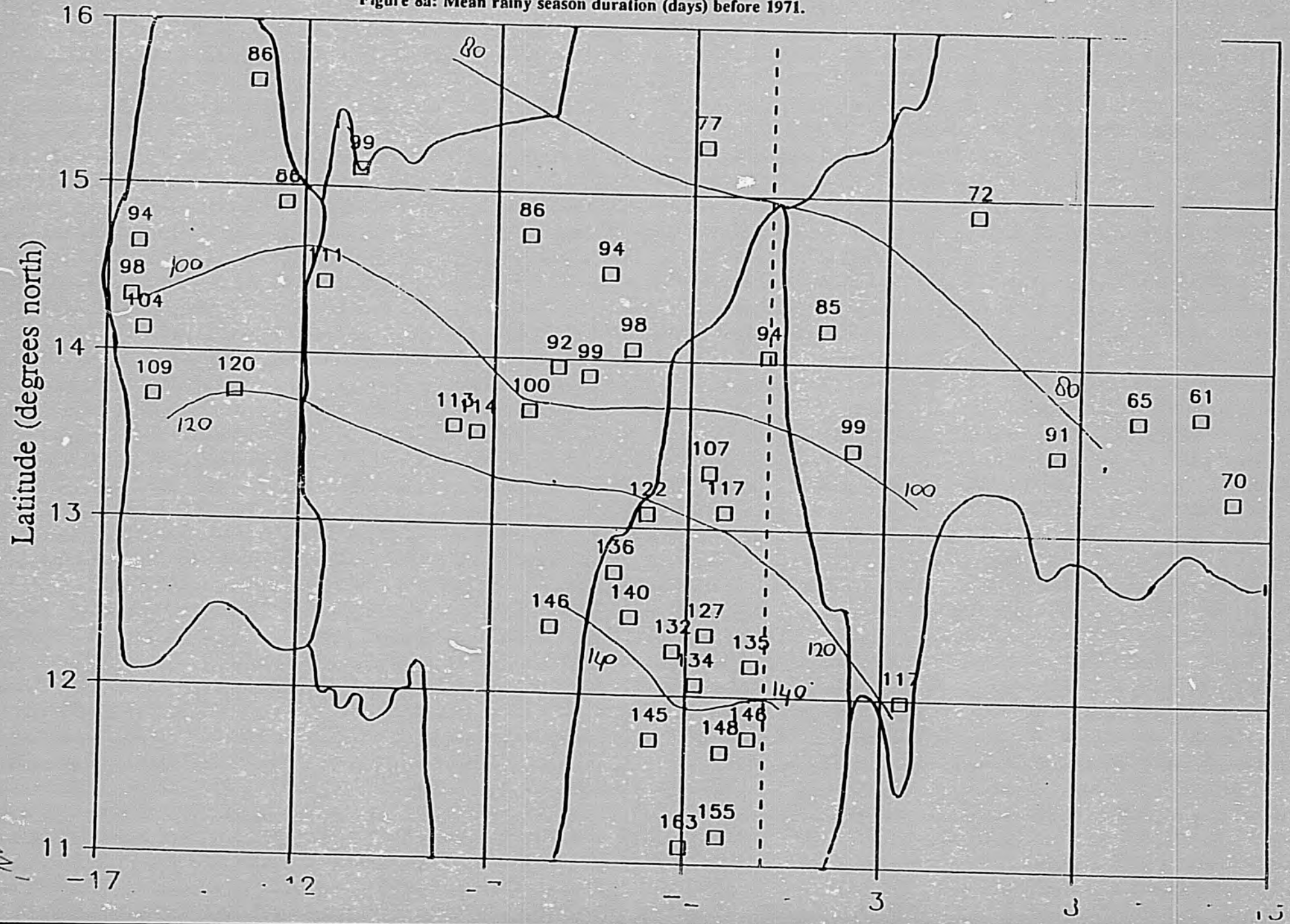

Figure 8b: Mean rainy season duration (days) after 1970.

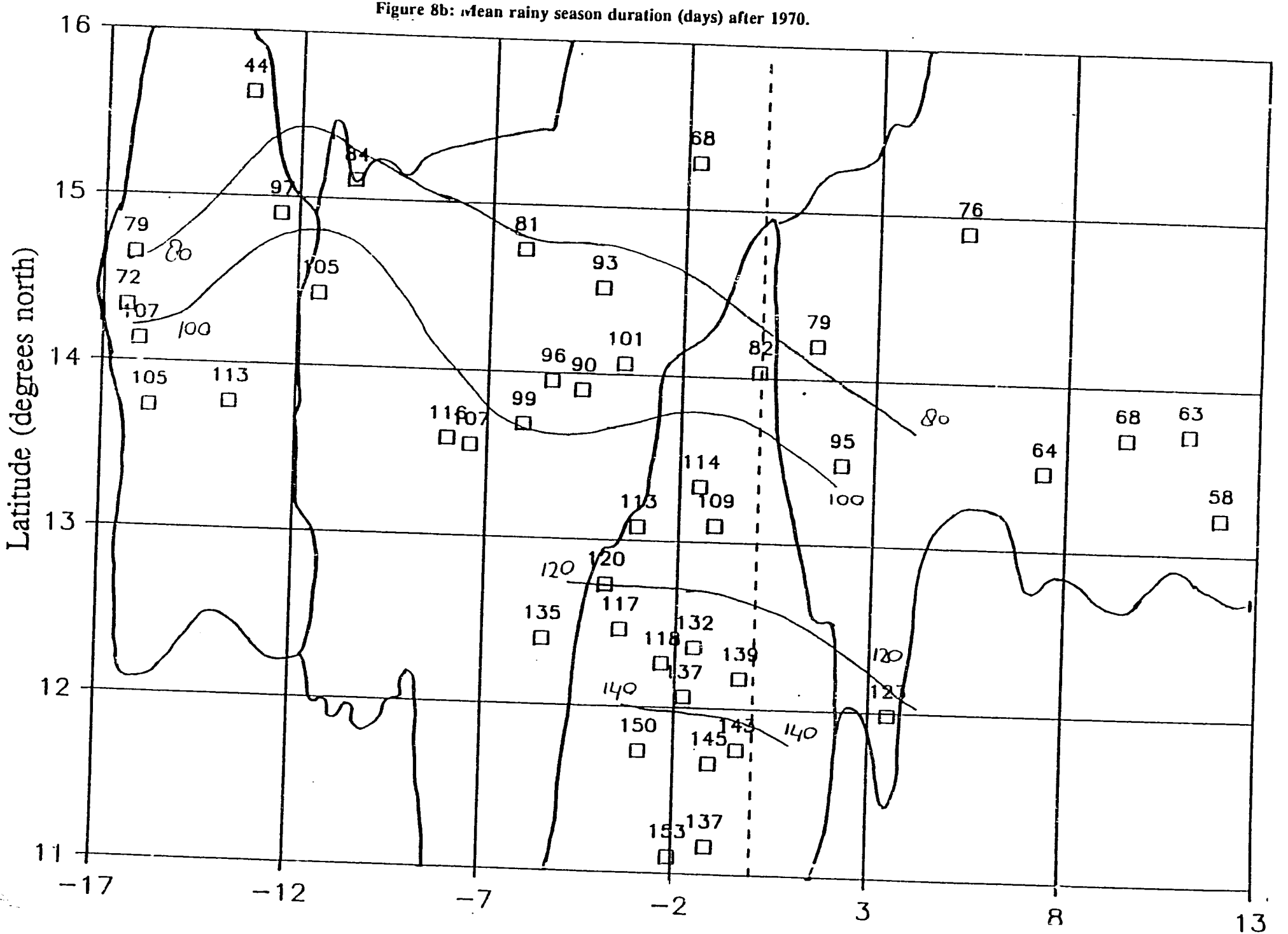

Figure 8c: Mean rainy season duration of years before 1971 minus that of years after 1970 (days).

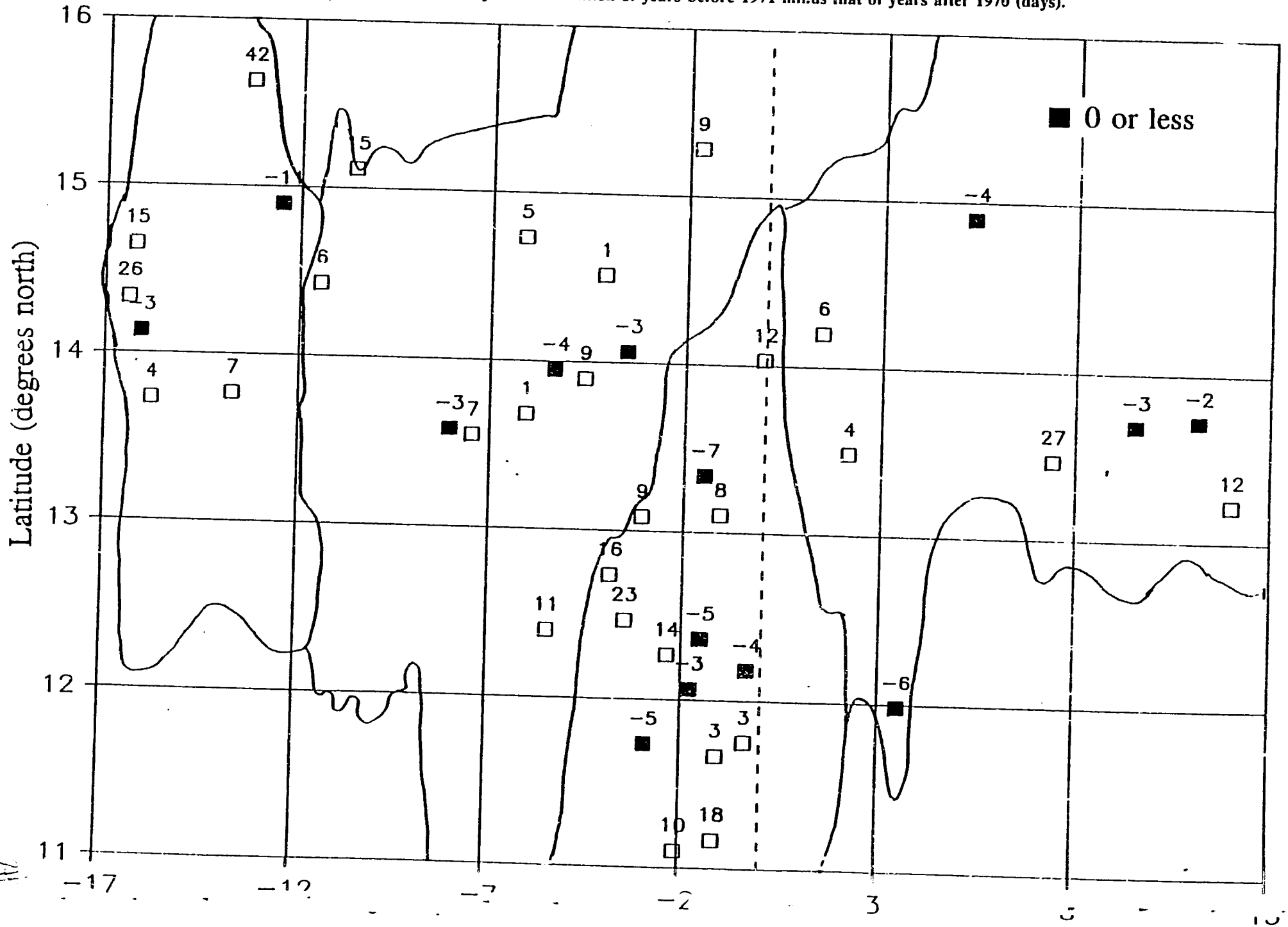

Figure 9a: Mean rainfall intensity (mm/day) during the rainy season before 1971.

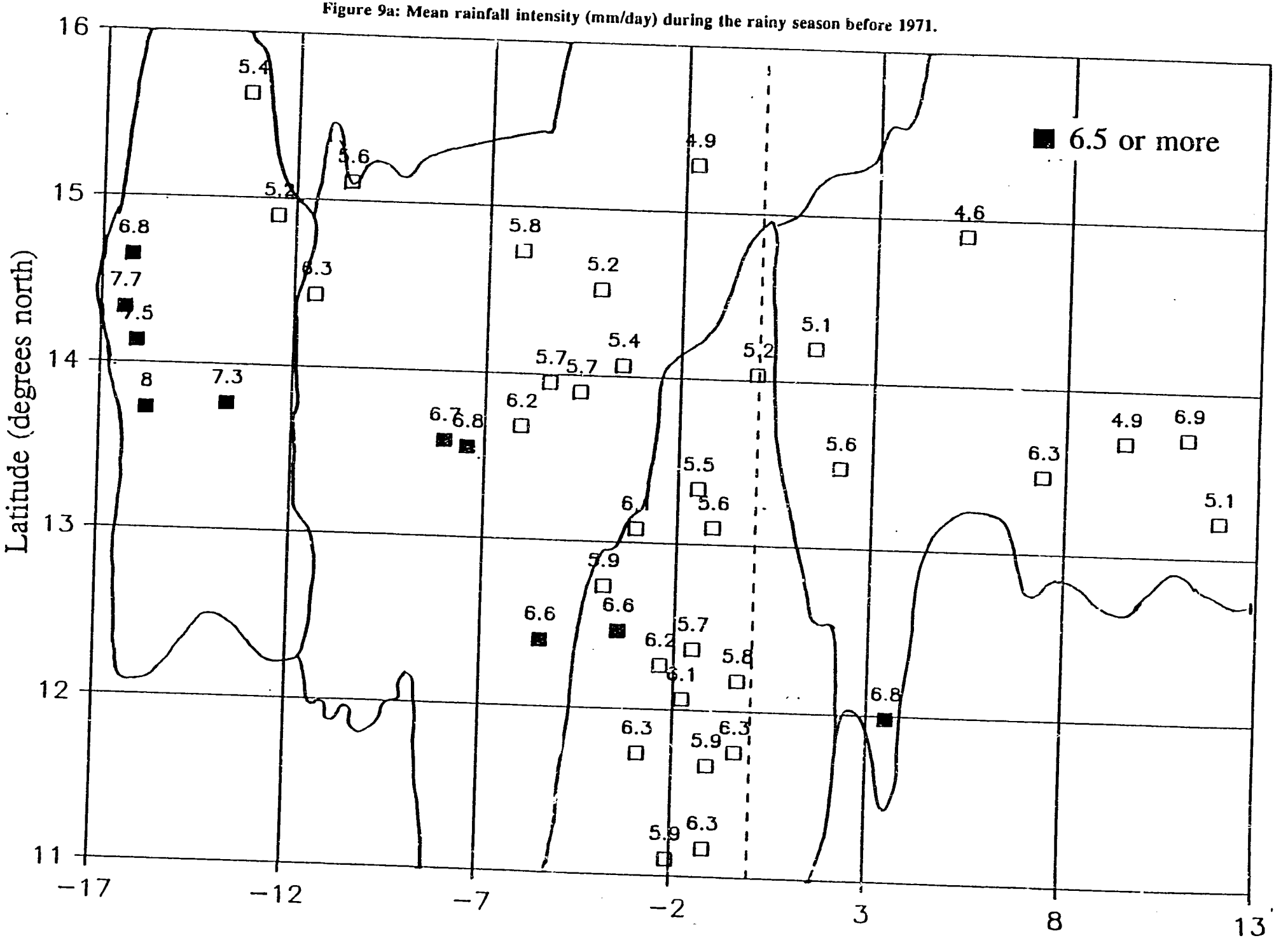

Figure 9b: Mean rainfall intensity (mm/day) during the rainy season after 1970.

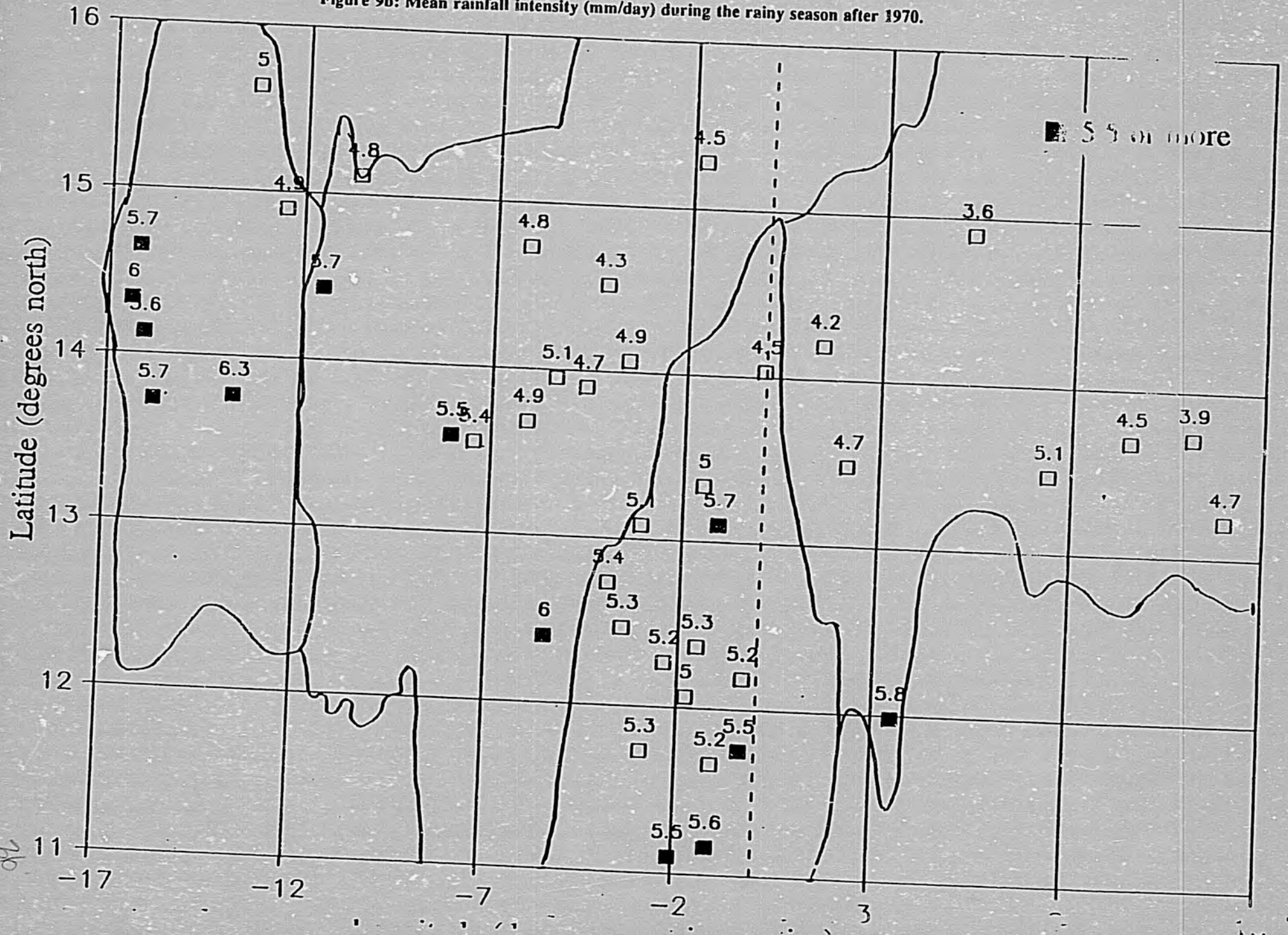

Figure 9c: Mean rainfall intensity of years before 1971 minus that of years after 1970 (mm/day).

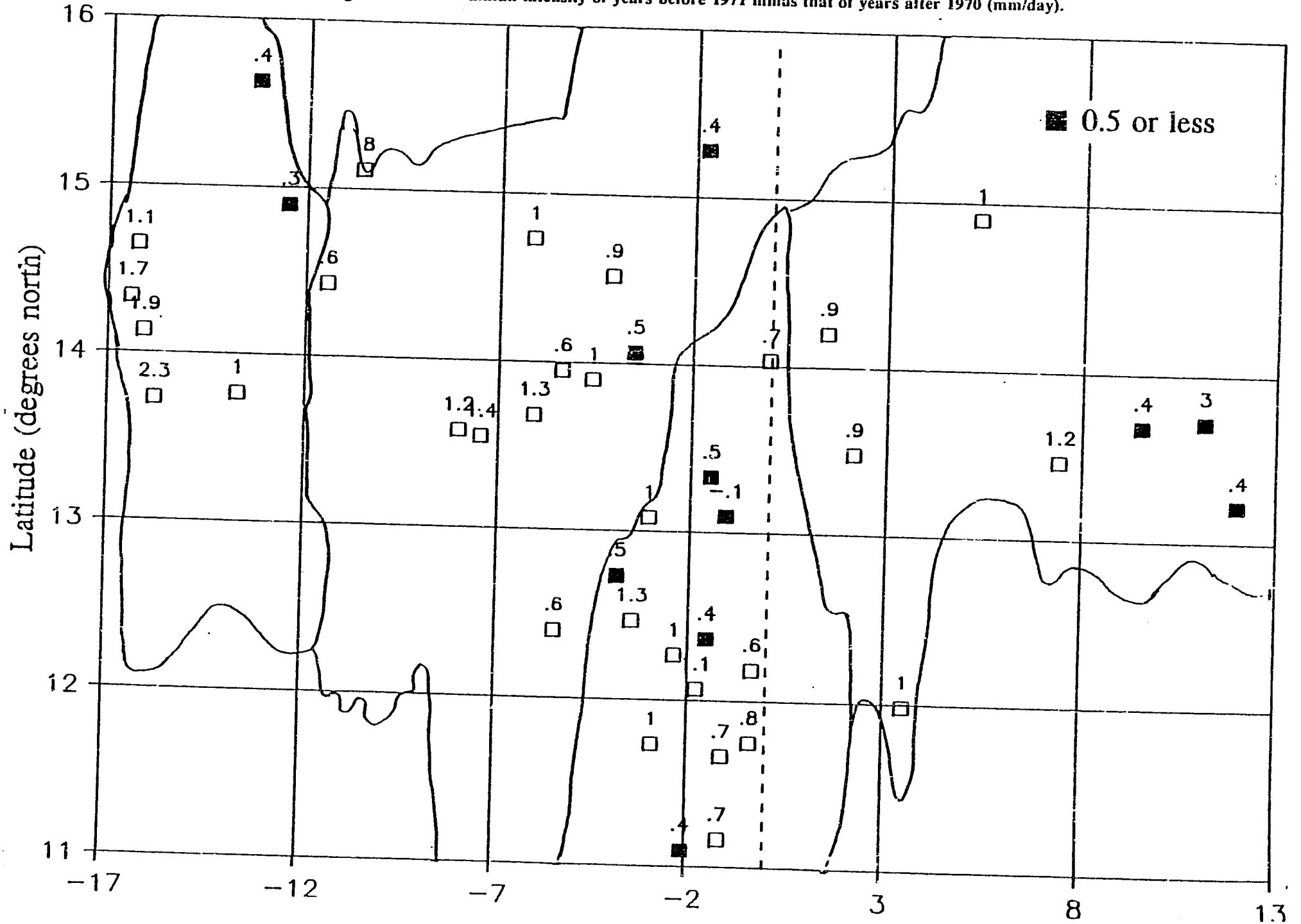

Figure 10a: R squares of correlation between onset date and season duration, before 1971.

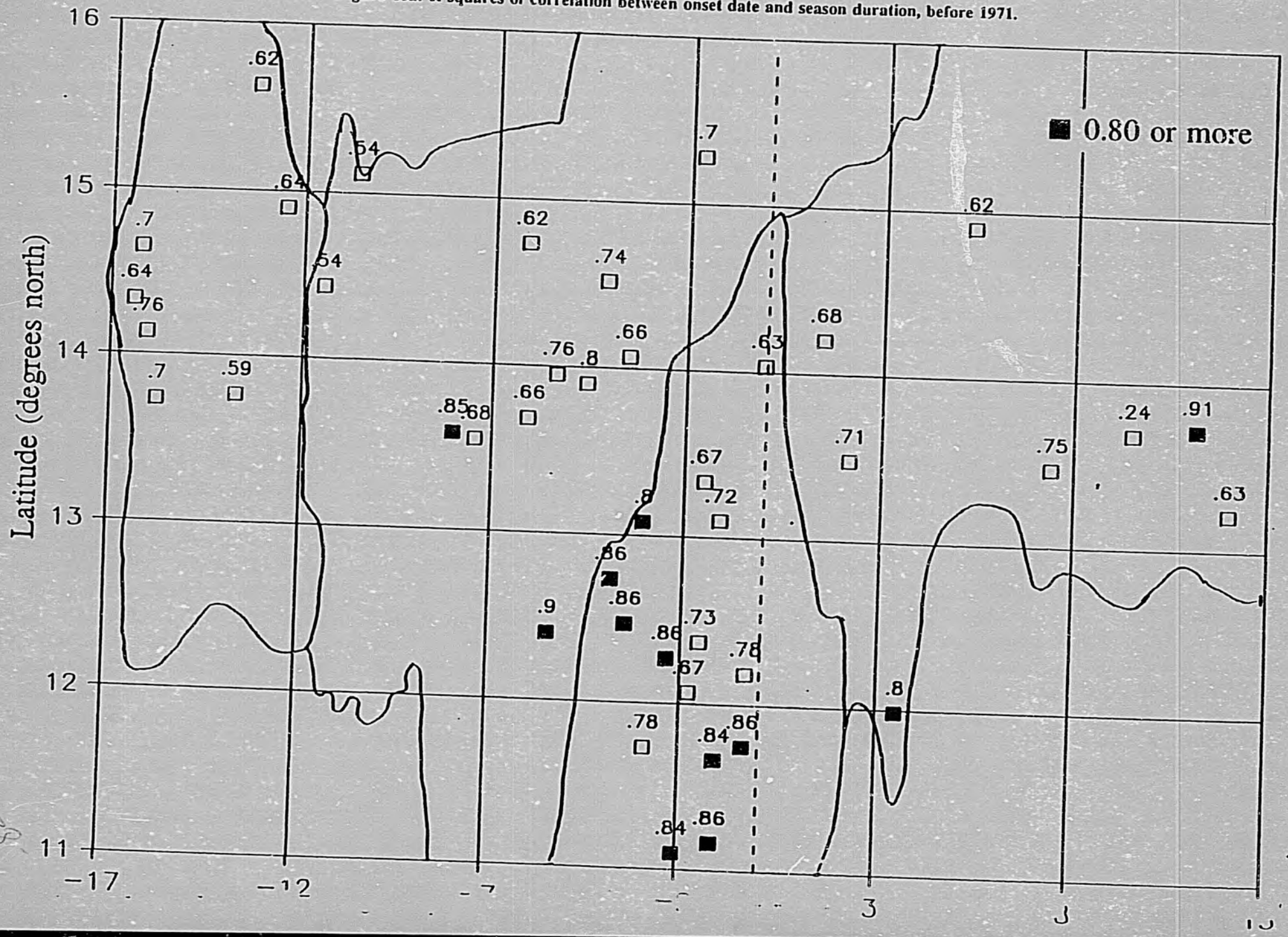

Figure 10b: R squares of correlation between onset date and season duration, after 1970.

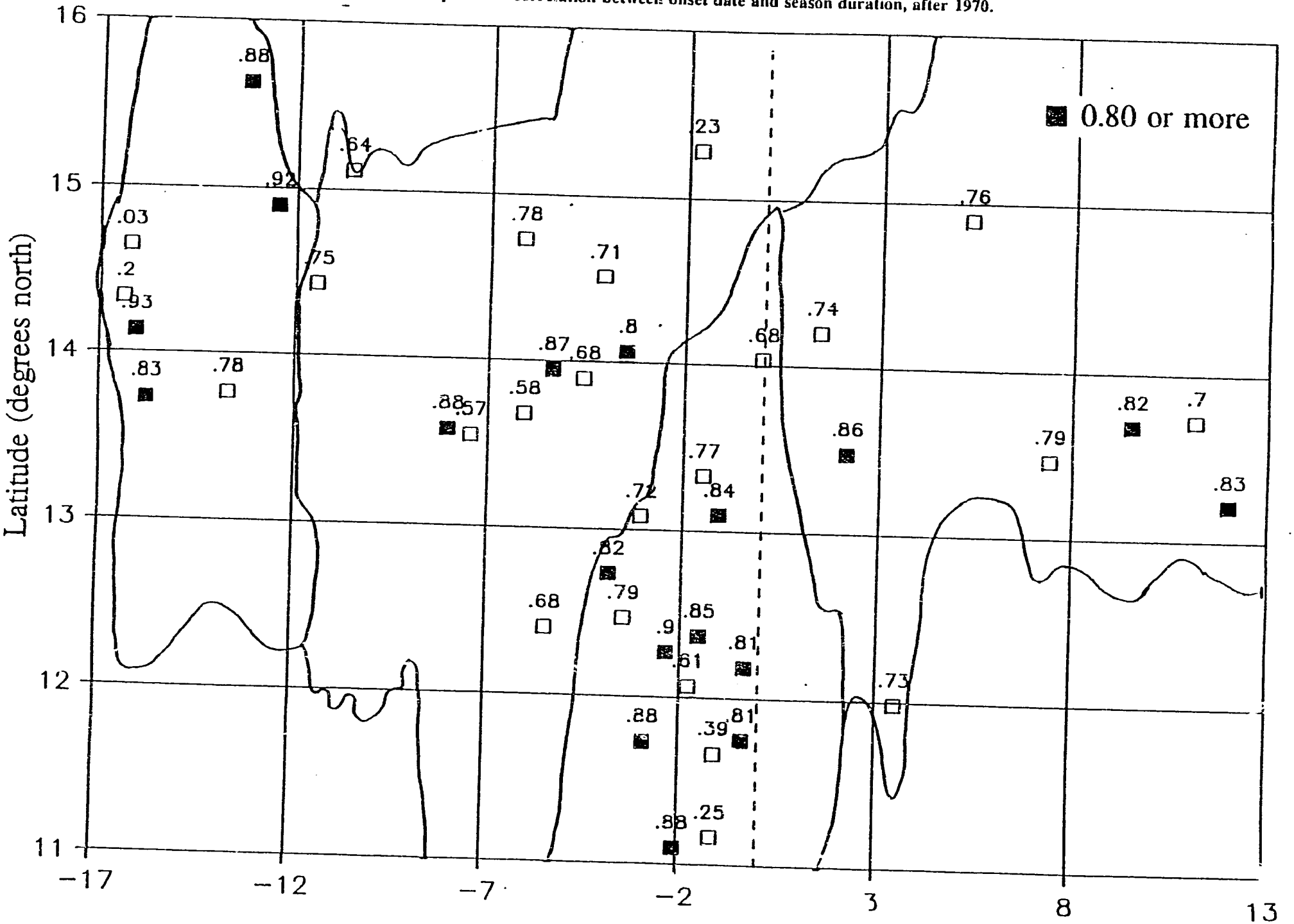

Figure 11a: R squares of correlation between onset date and season rainfall amount, before 1971.

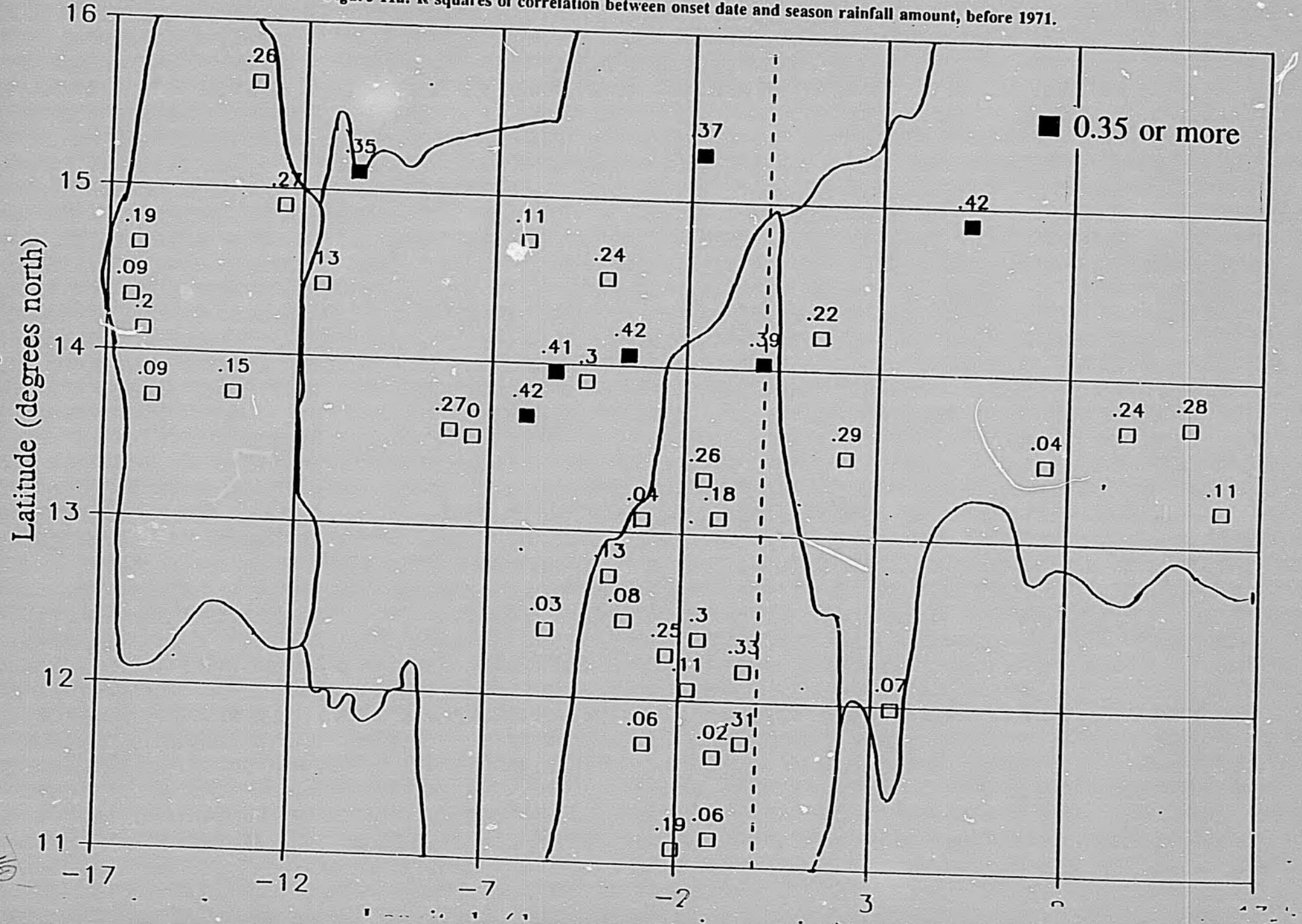

Figure 11b: R squares of correlation between onset date and season rainfall amount, after 1970.

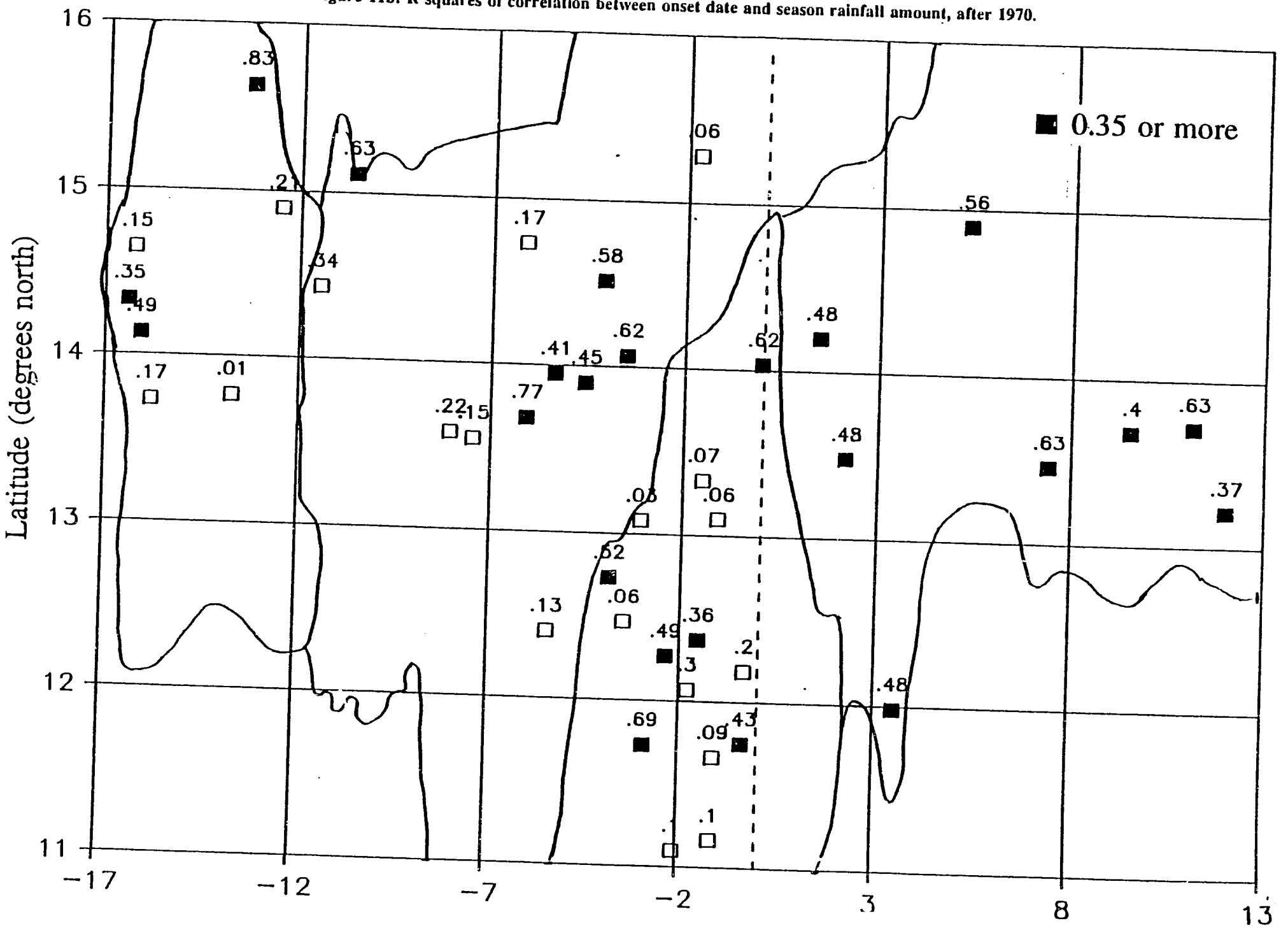

Figure 12: Decrease (days) of season duration when onset is one day later.

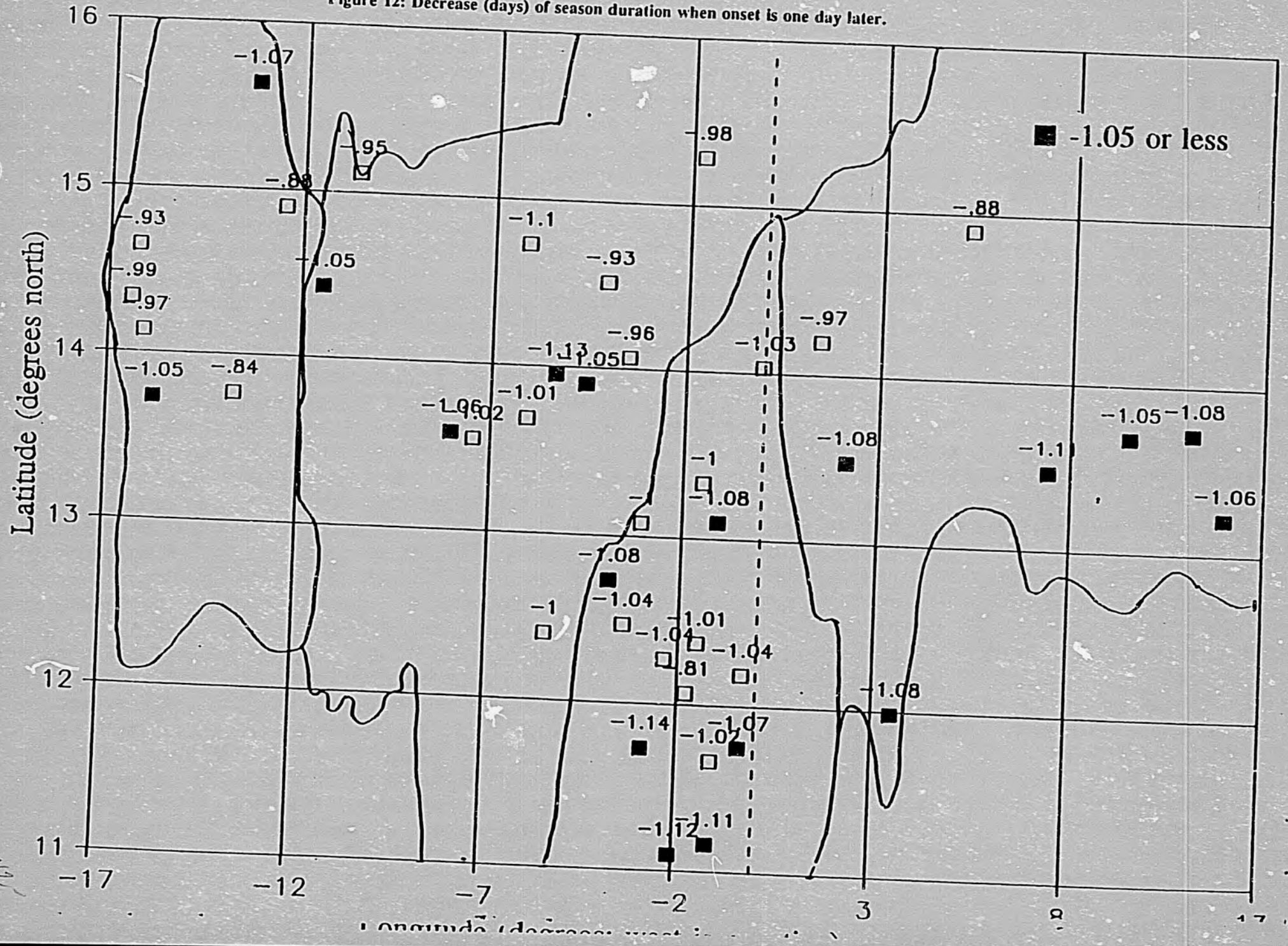

Figure 13: Decrease (mm) of season rainfall amount when onset is one day later.

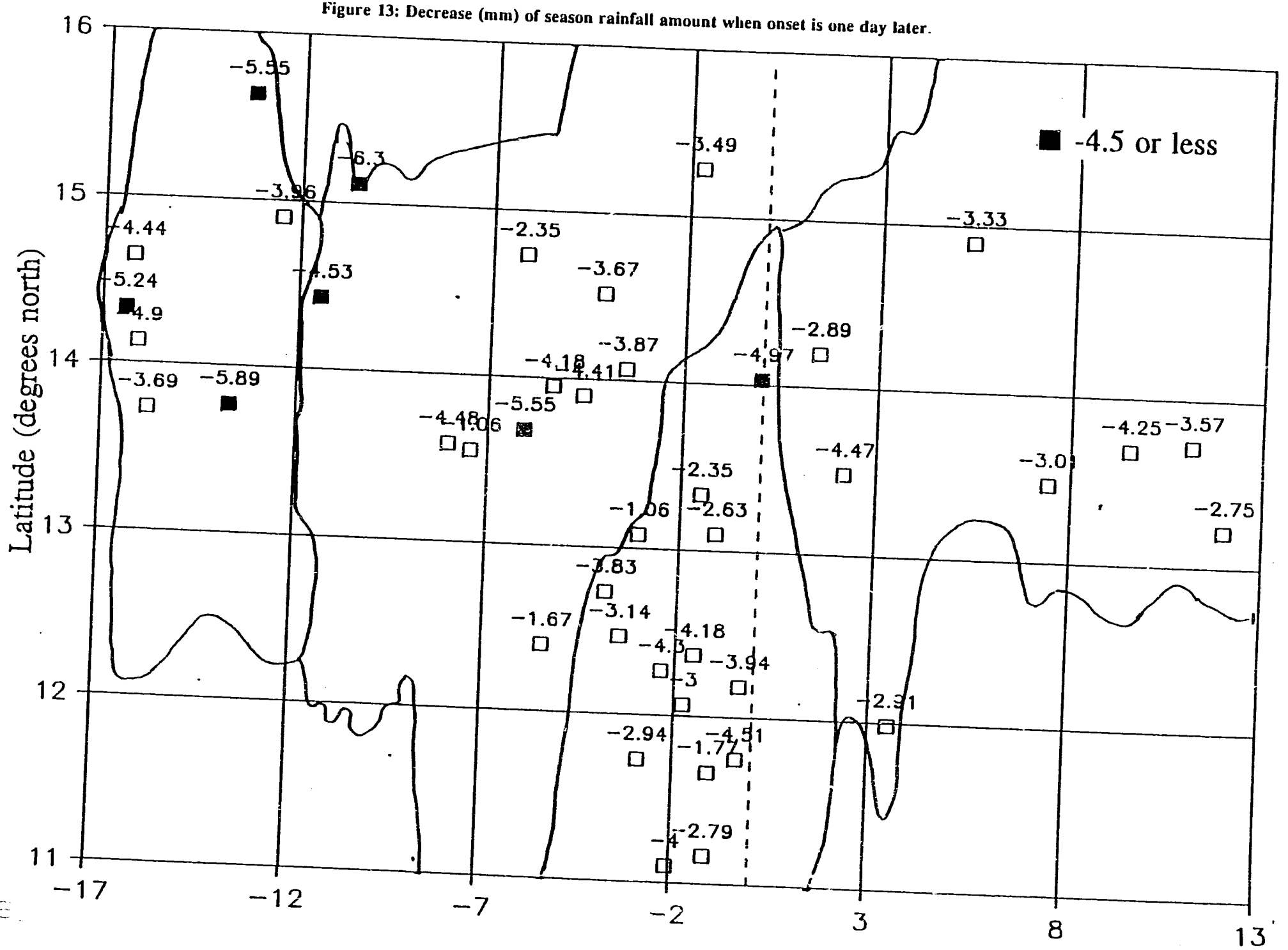

Figure 14: Annual rainfall (mm) and location of three rainfall stations in Botswana, analyzed in this report.

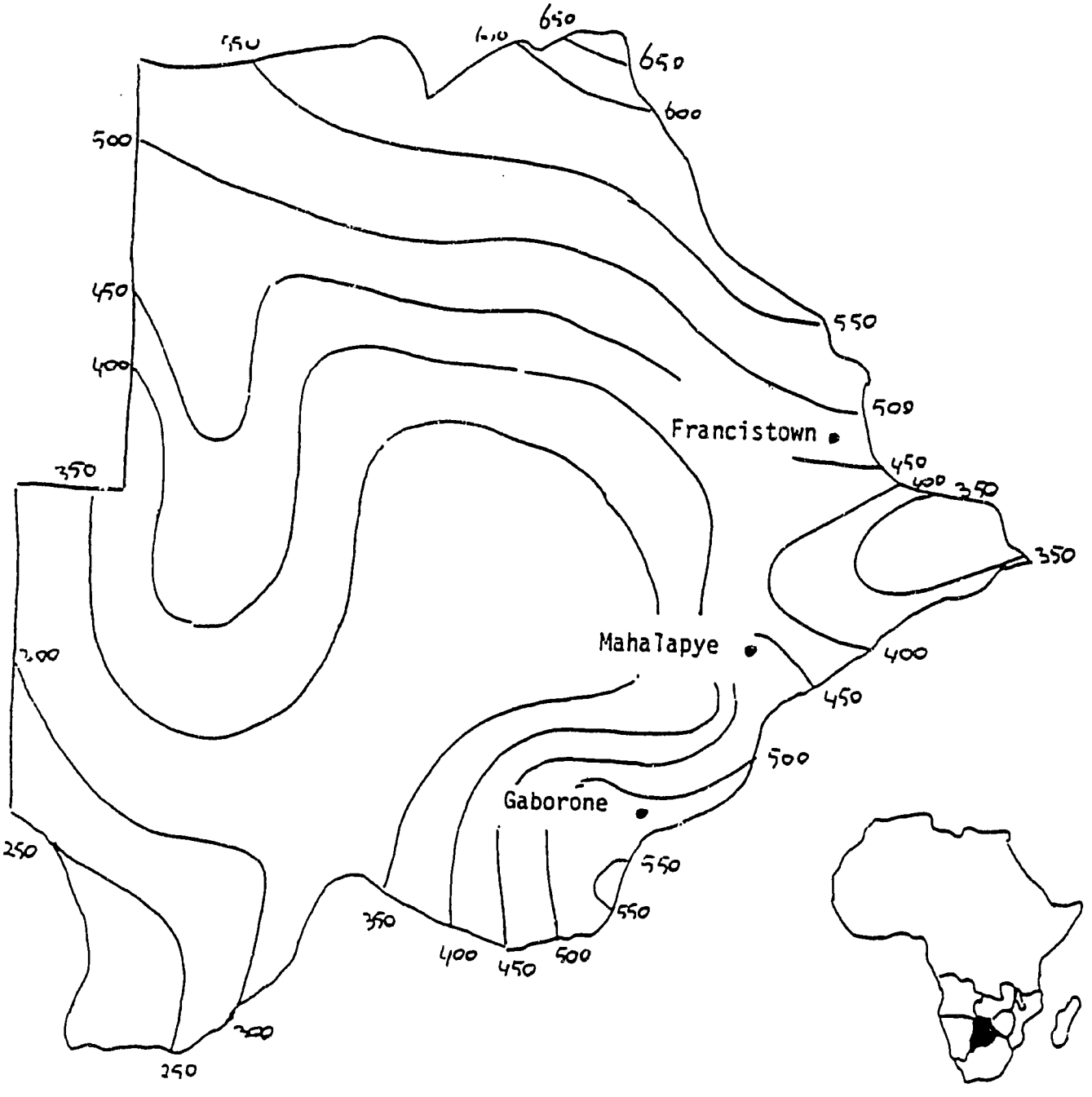

Figure 15: Standard deviation (days) of onset date.

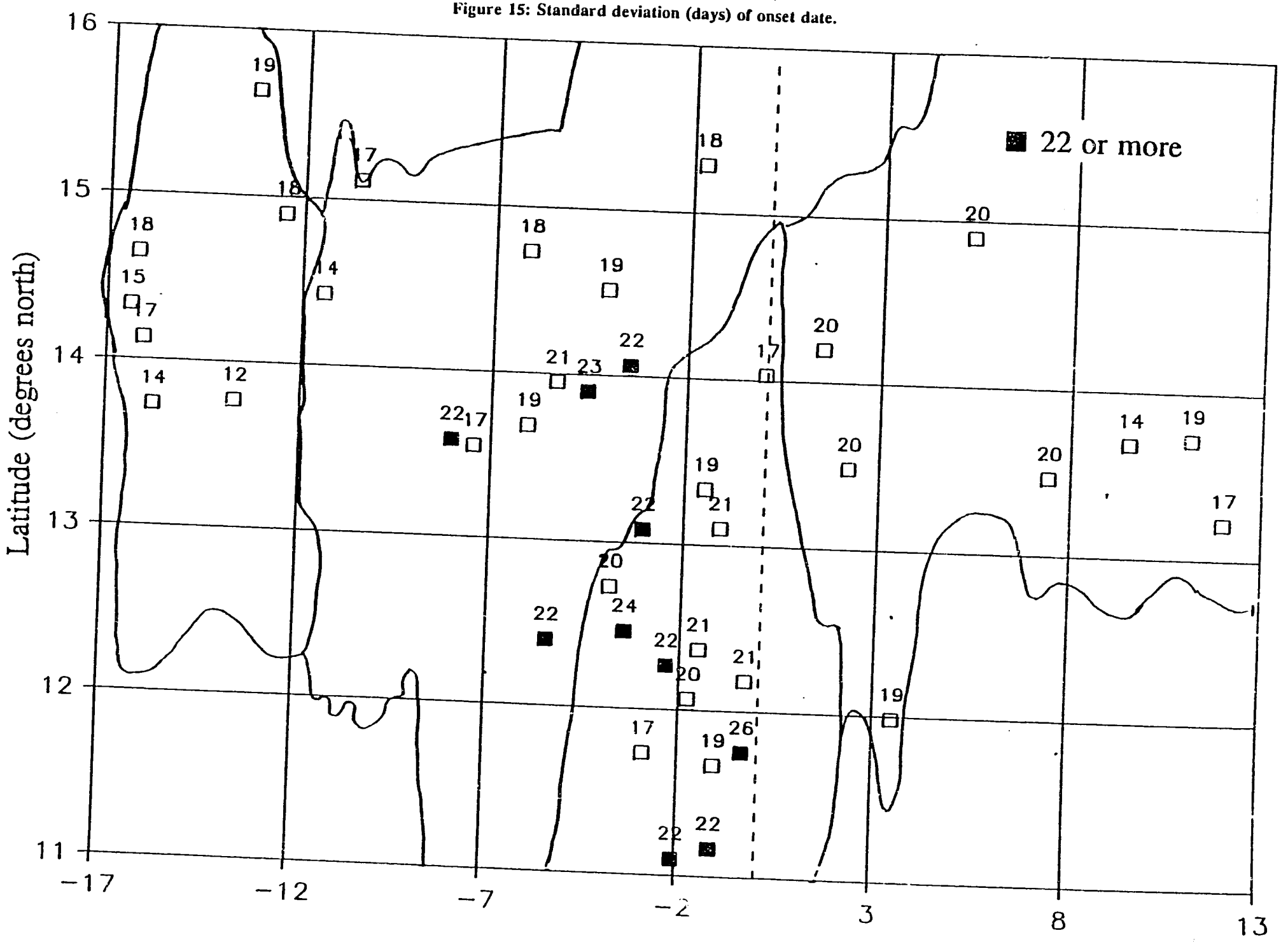

Figure 16: Coefficient of variation (%) of season rainfall amount.

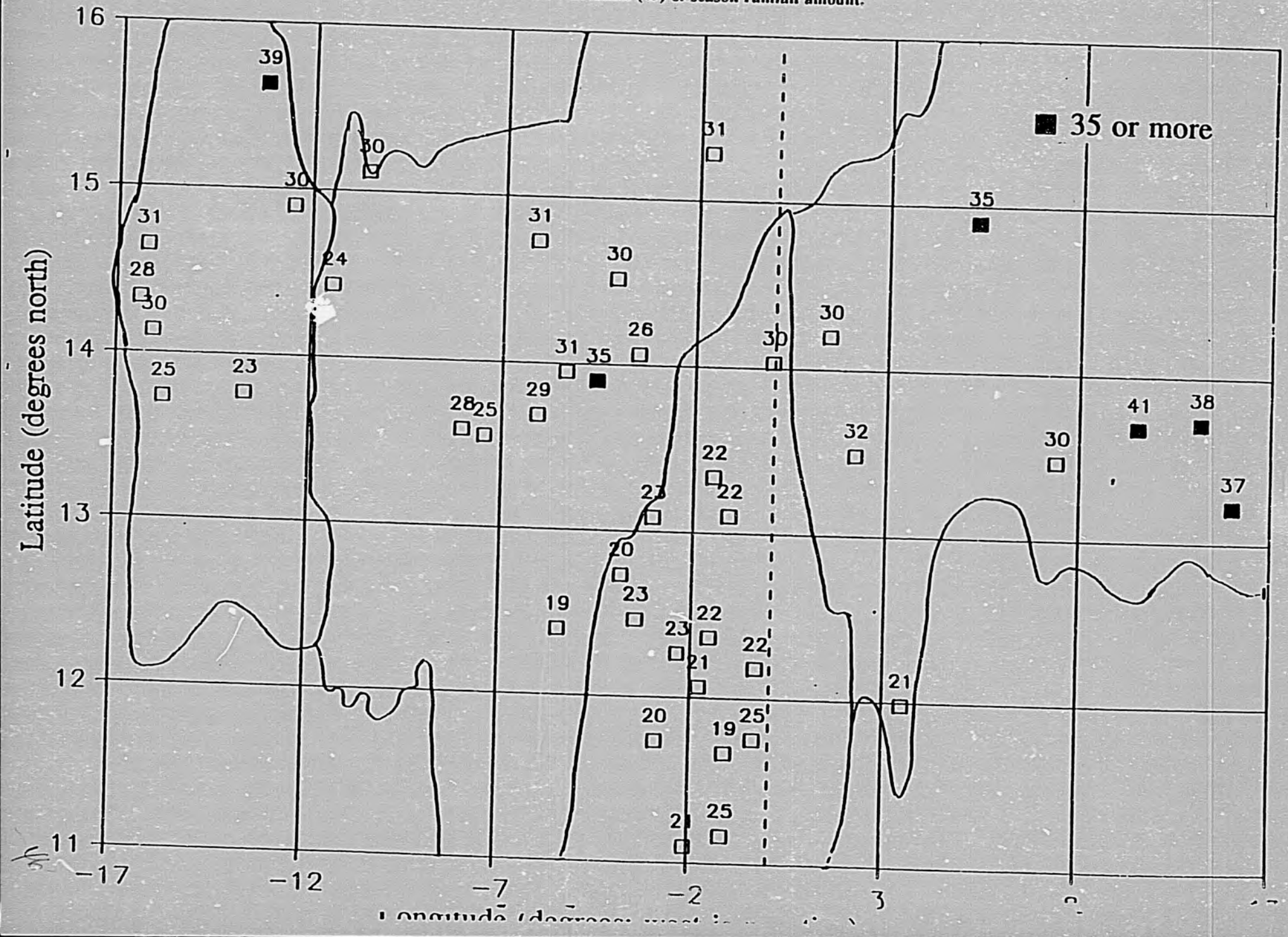

Figure 17: Season duration at Niamey, Niger, based on monthly rainfall (50% probability) and potential evapotranspiration (times 0.5).

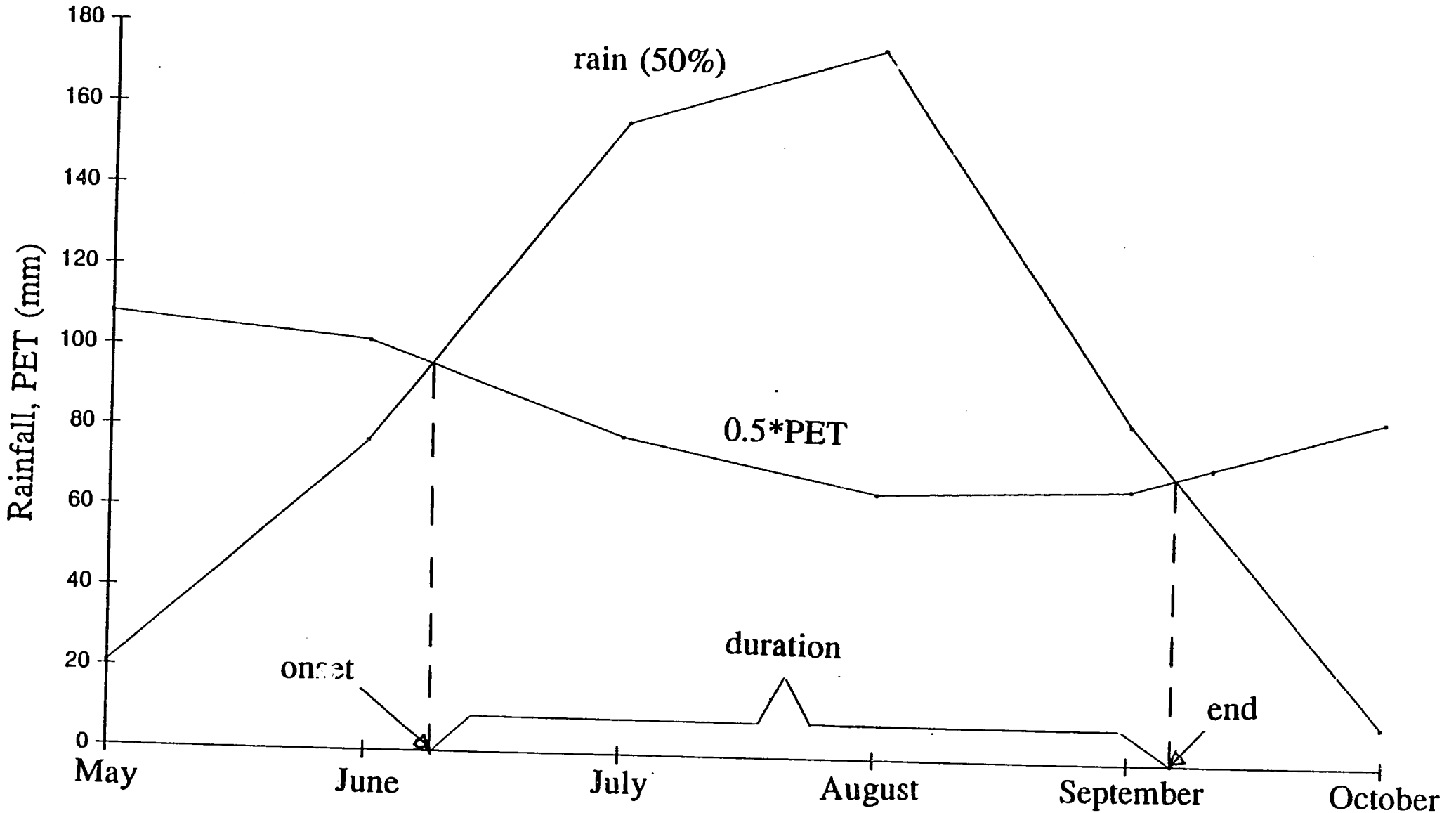

Figure 18a: Mean onset date (day of year), based on 0.5*PET and 50% rainfall probability; years before 1971.

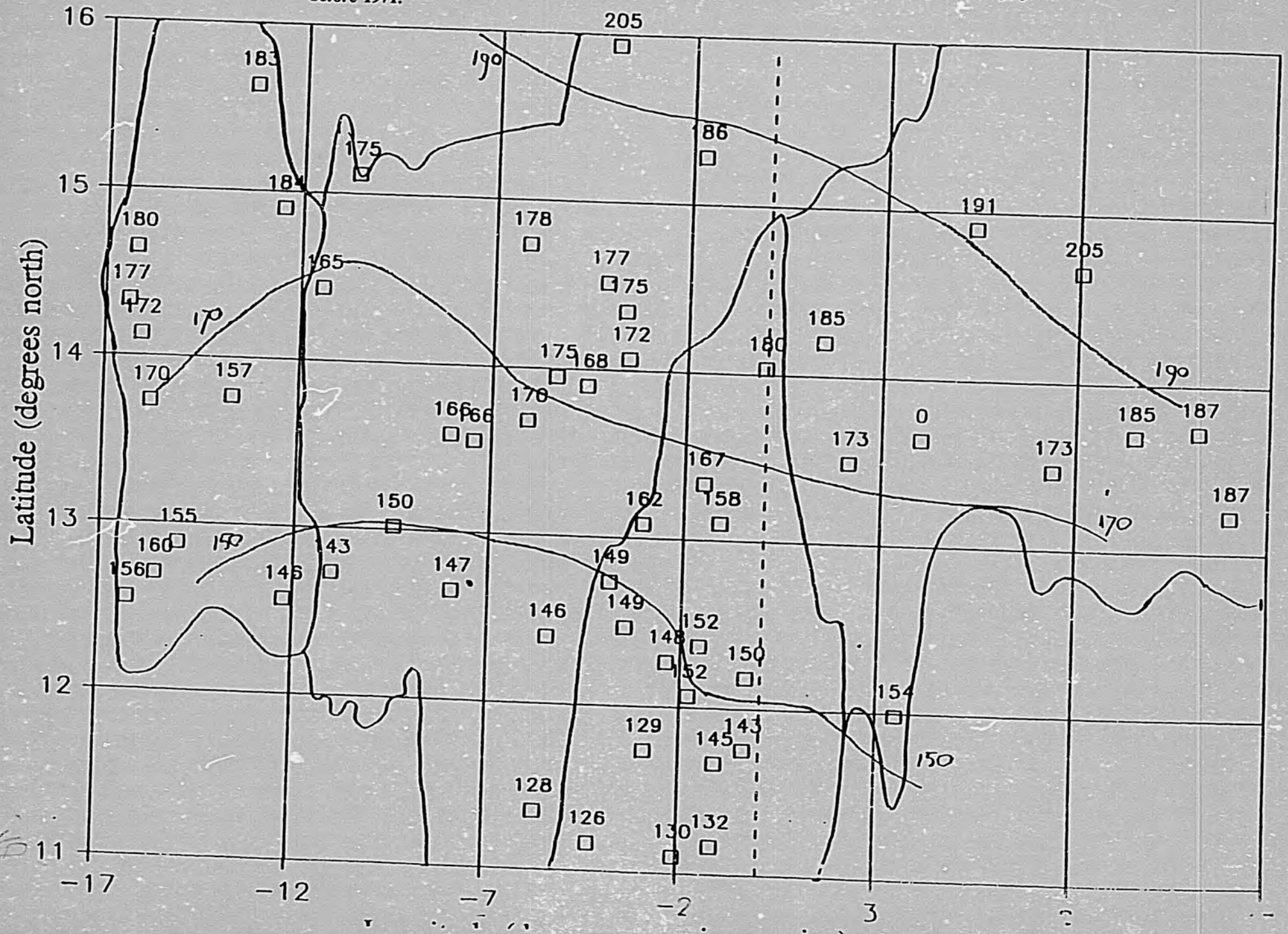

Figure 18b: Mean onset date (day of year), based on 0.5*PET and 50% rainfall probability; years after 1970.

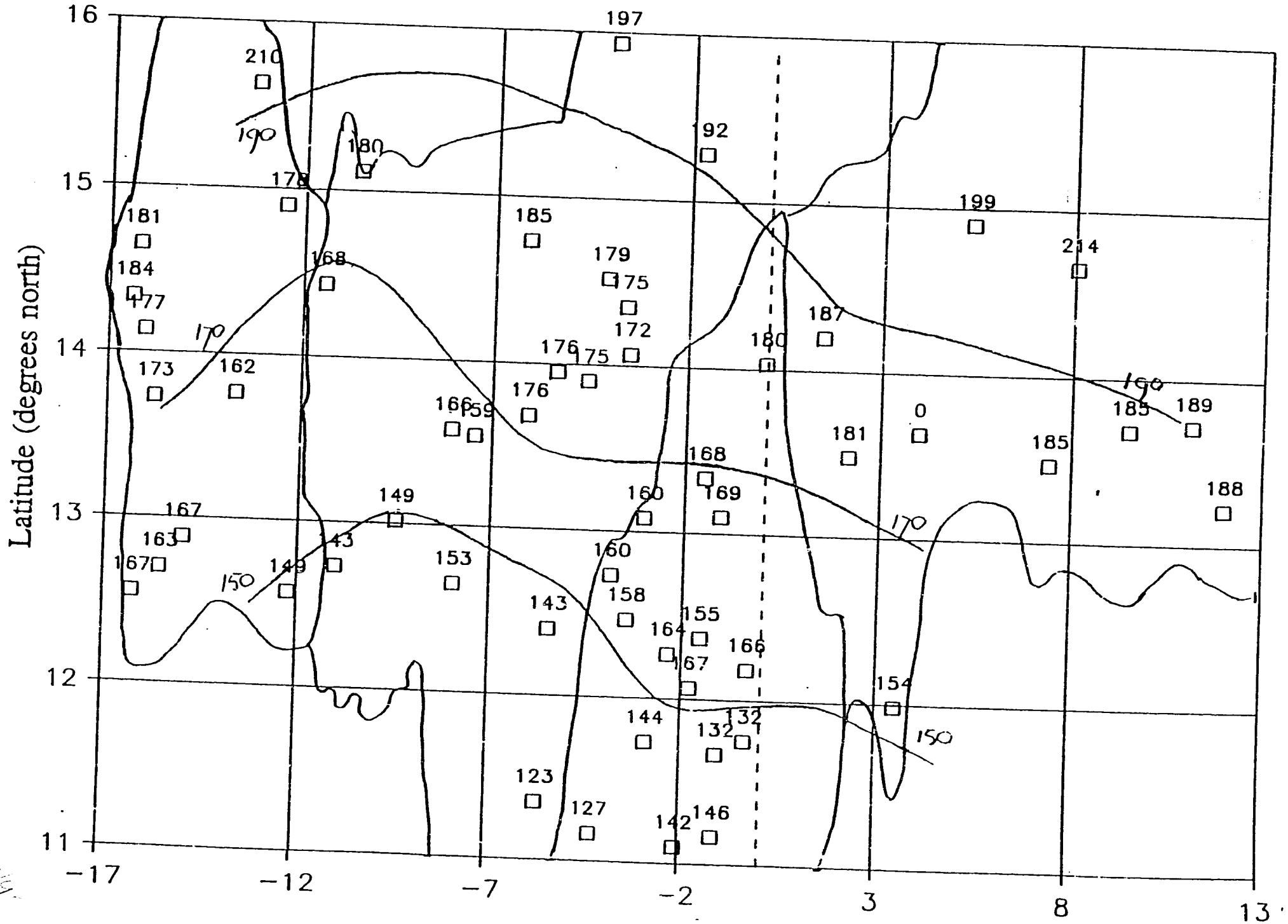

Figure 19a: Mean end date (day of year), based on 0.5*PET and 50% rainfall probability; years before 1971.

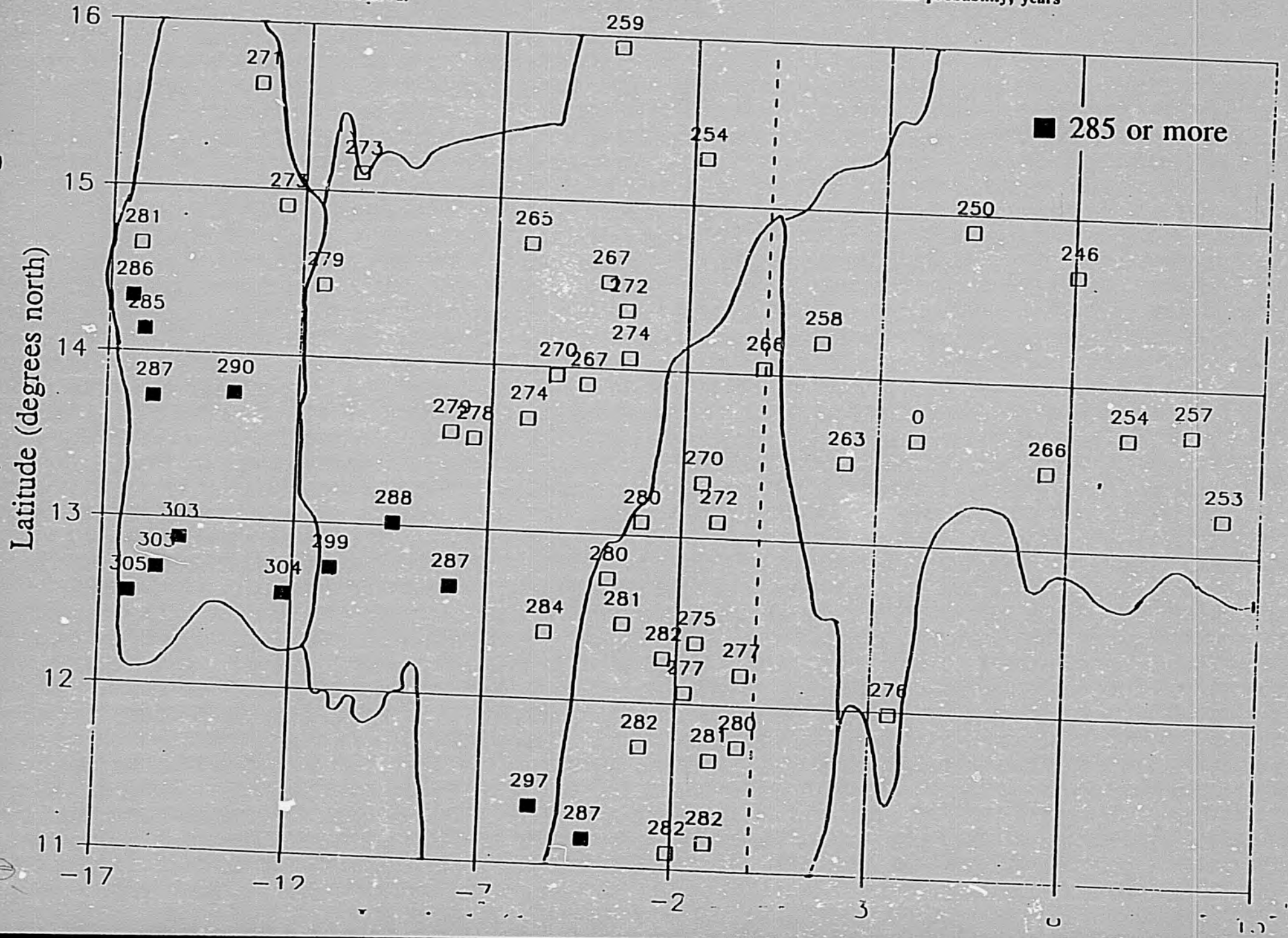

Figure 19b: Mean end date (day of year), based on 0.5*PET and 50% rainfall probability; years after 1970.

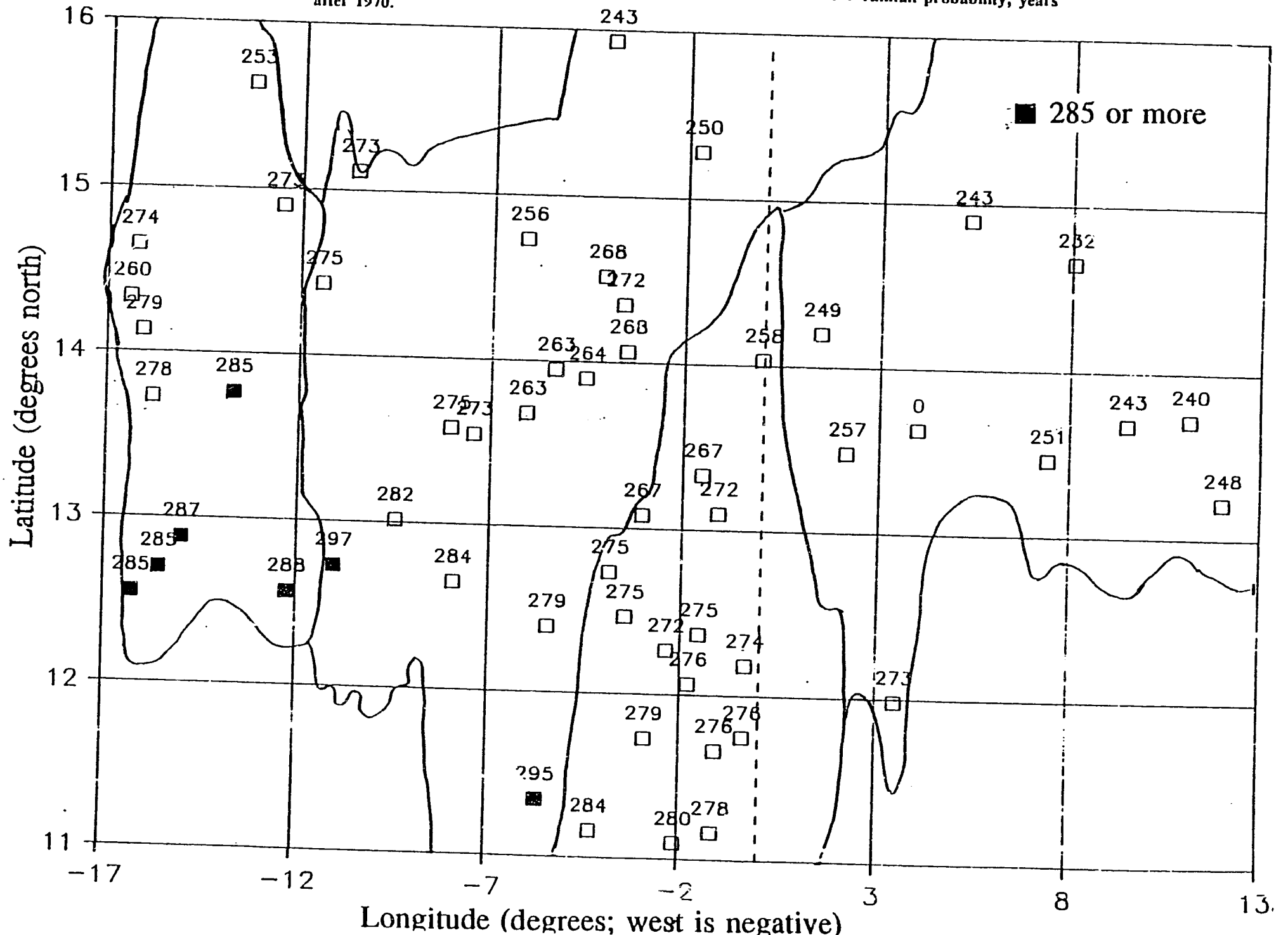

Figure 20a: Mean season duration (days), based on 0.5*PET and 50% rainfall probability; years before 1971.

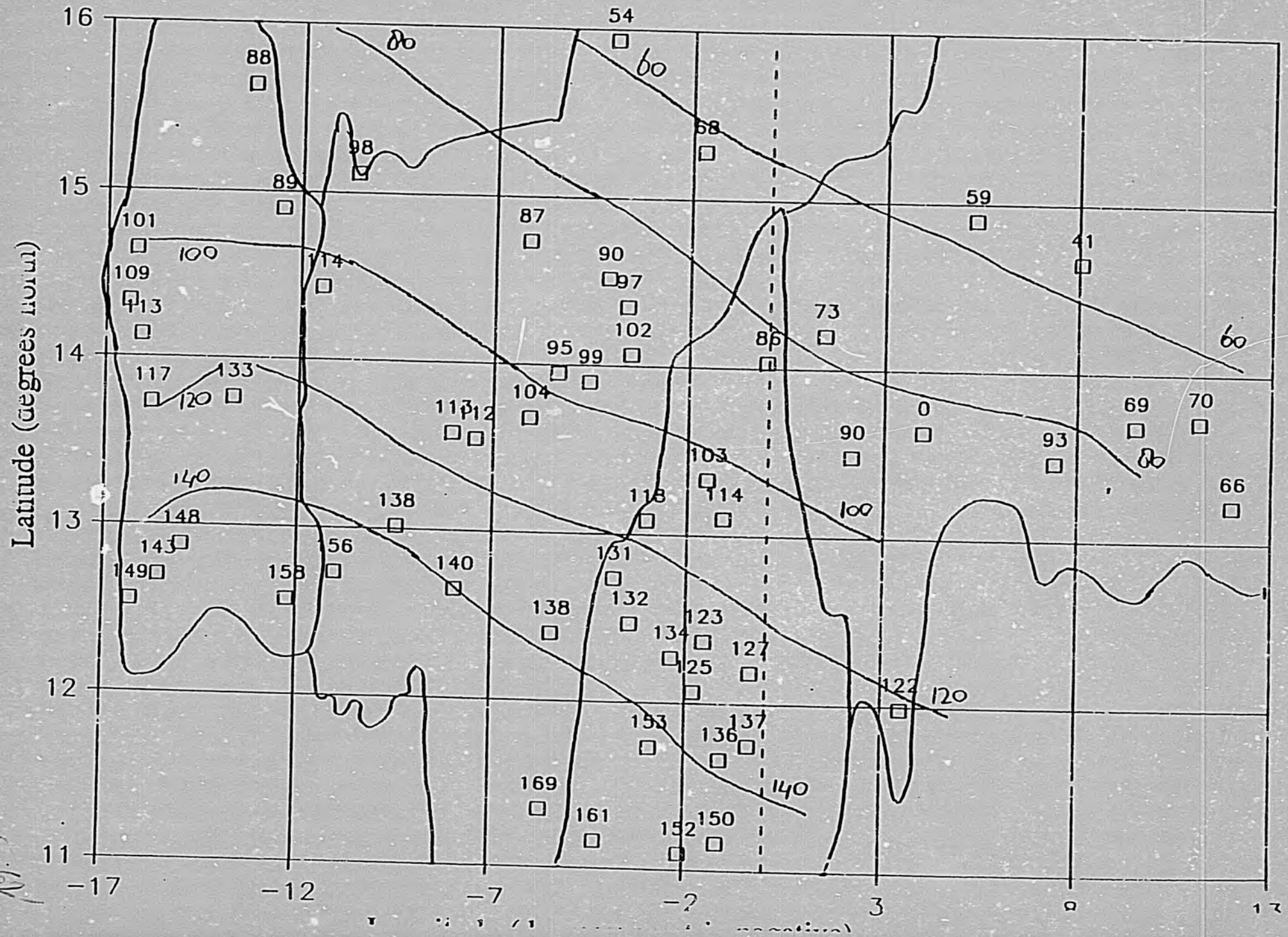

Figure 20b: Mean season duration (days), based on 0.5*PET and 50% rainfall probability; years after 1970.

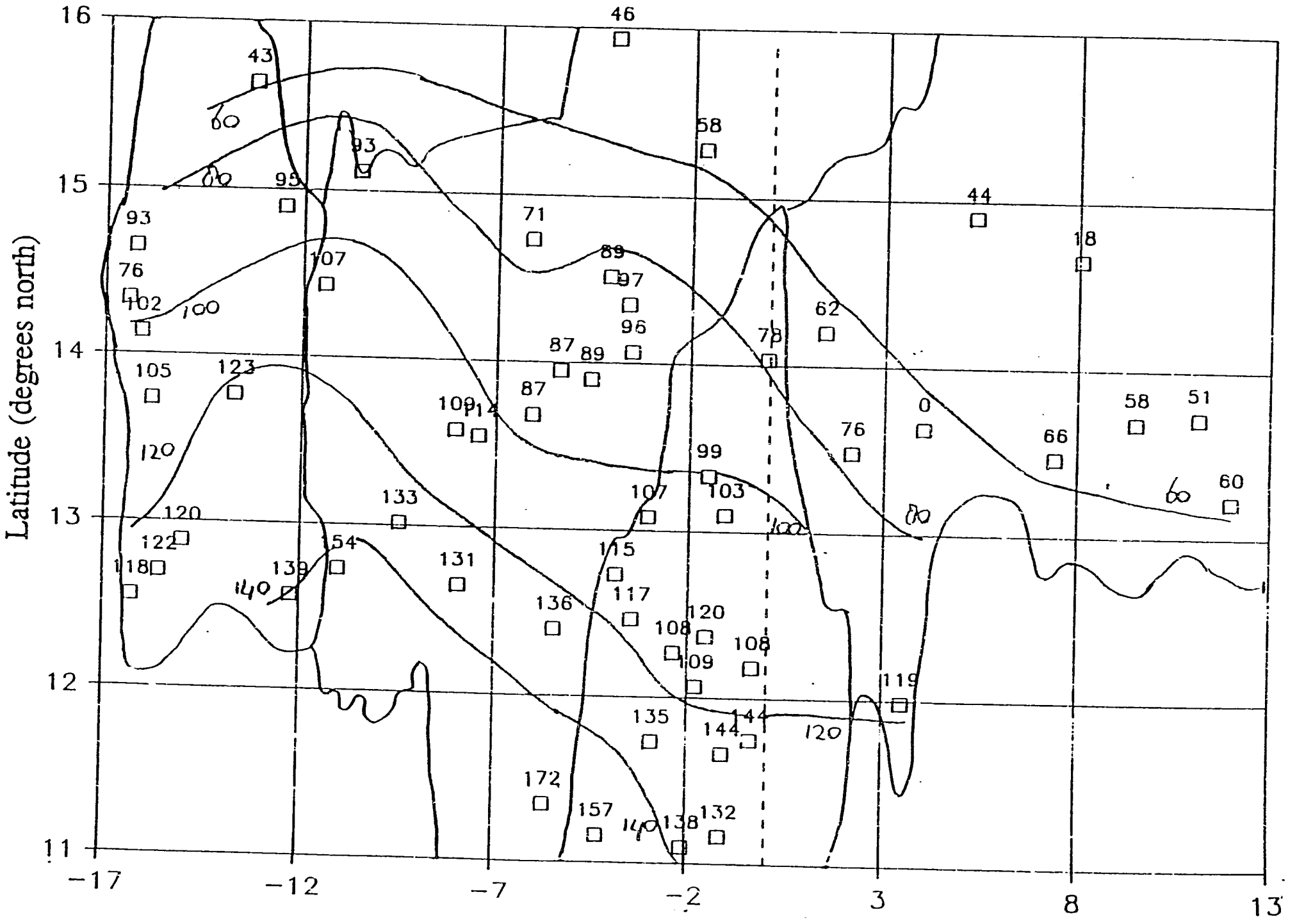

Figure 21: Probability of having one or more dry spells of at least 10 days in the following 30 days; Niamey, Niger.

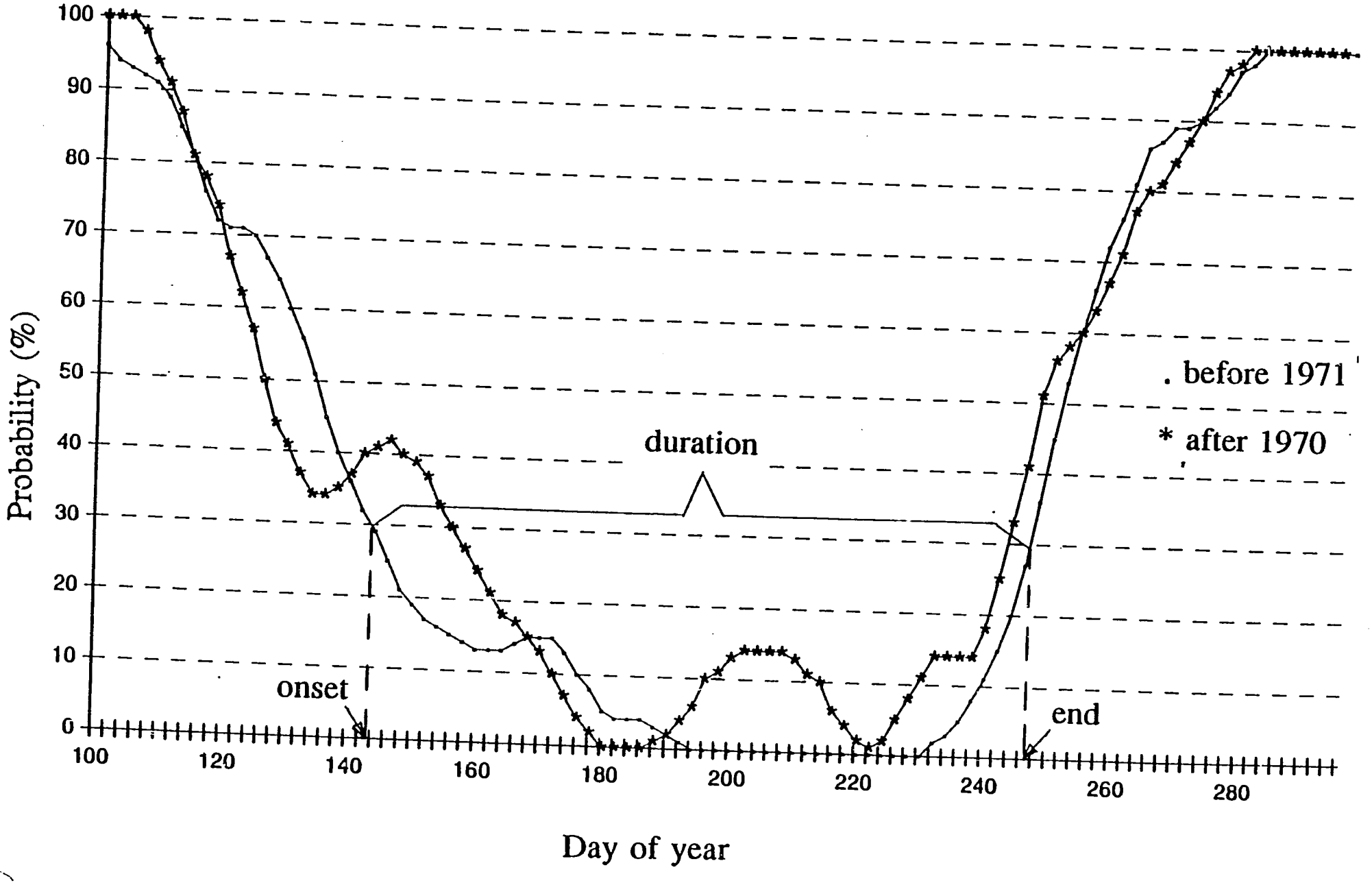

Figure 22: Probability of having one or more dry spells of at least 10 days in the following 30 days; Podor, Senegal.

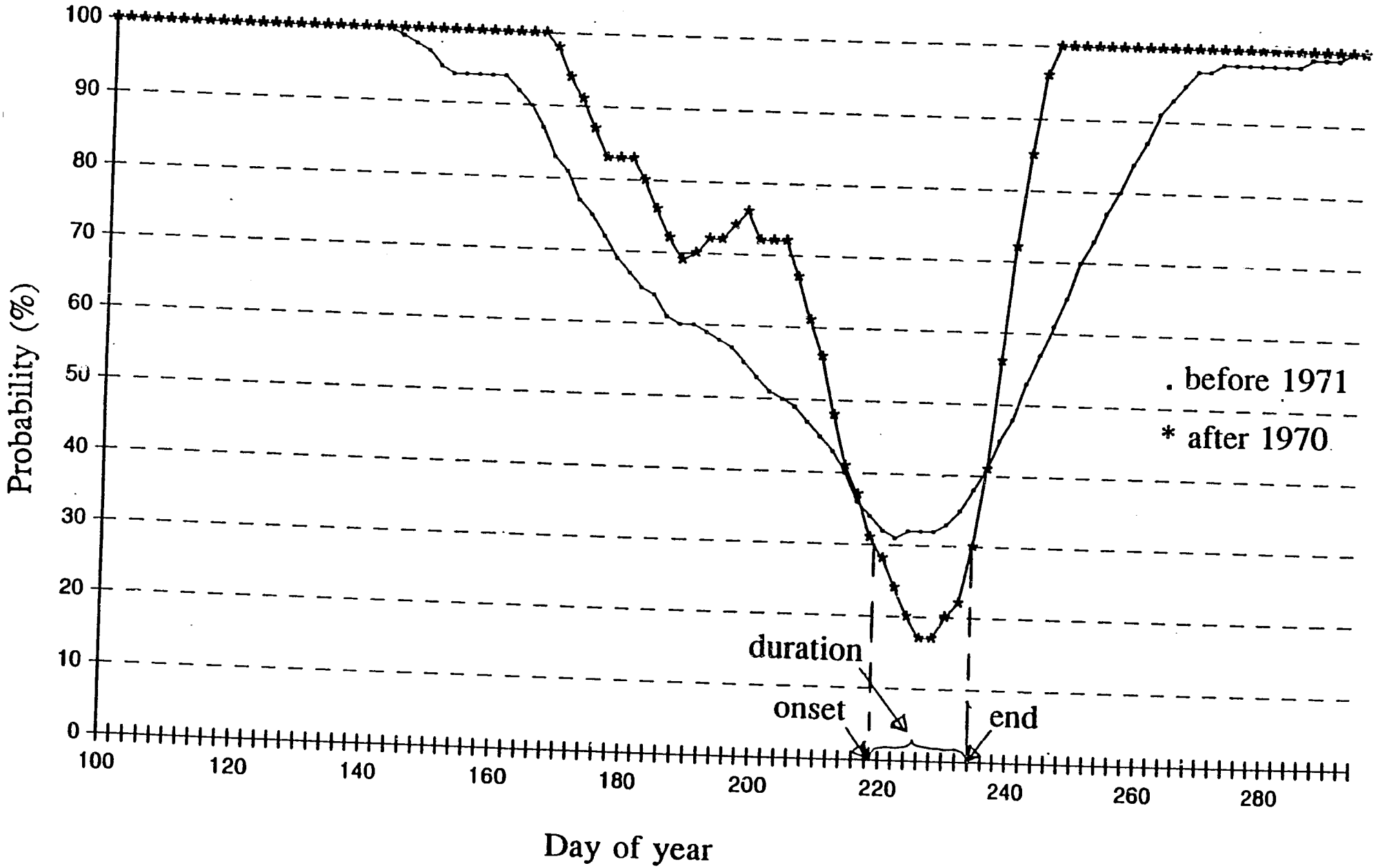

Figure 23: Season duration (days), based on dry spell probabilities; years before 1971.

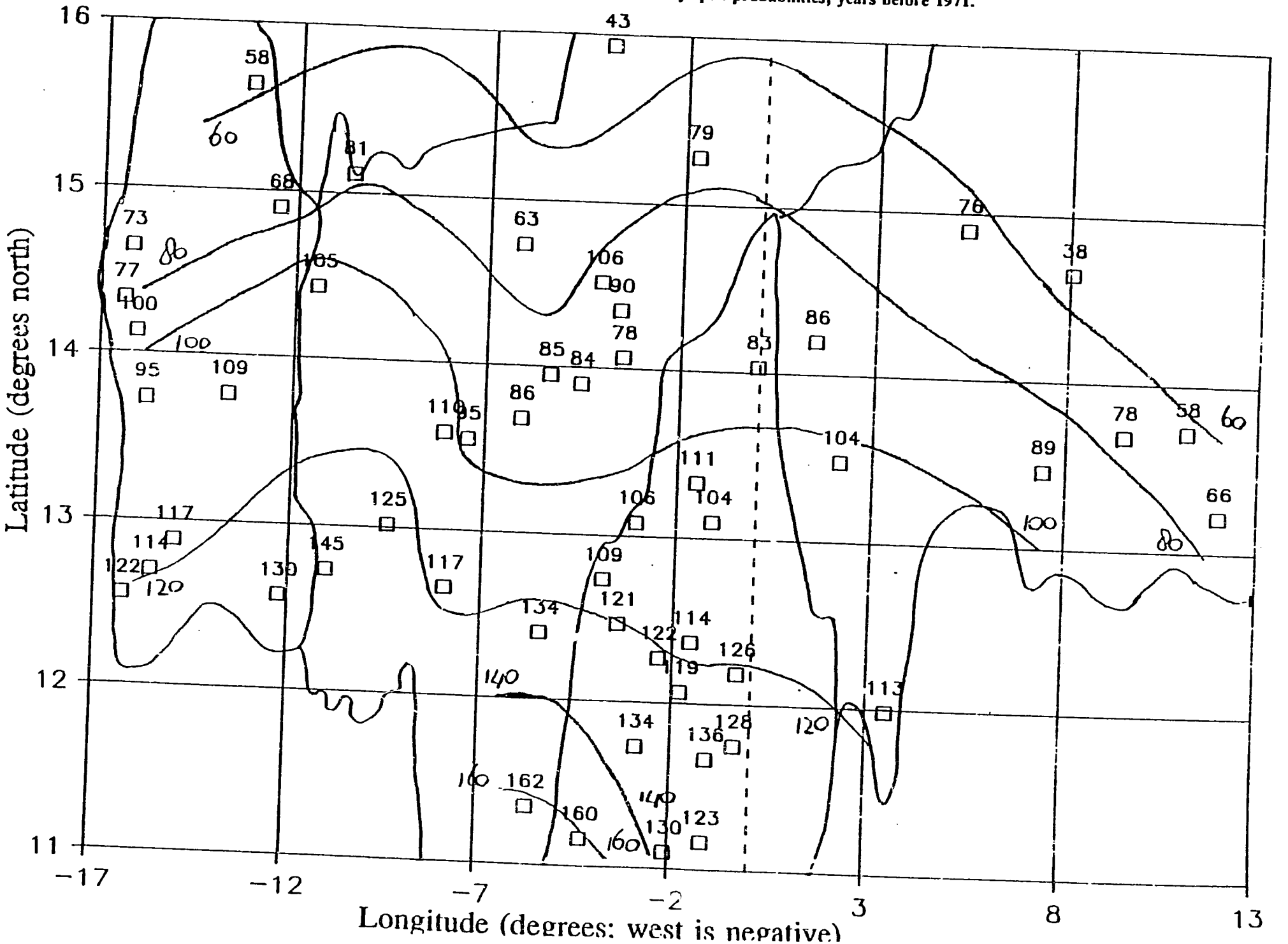

Figure 24: Season duration of years before 1971 minus that of years after 1970 (days) based on dry spell probabilities.

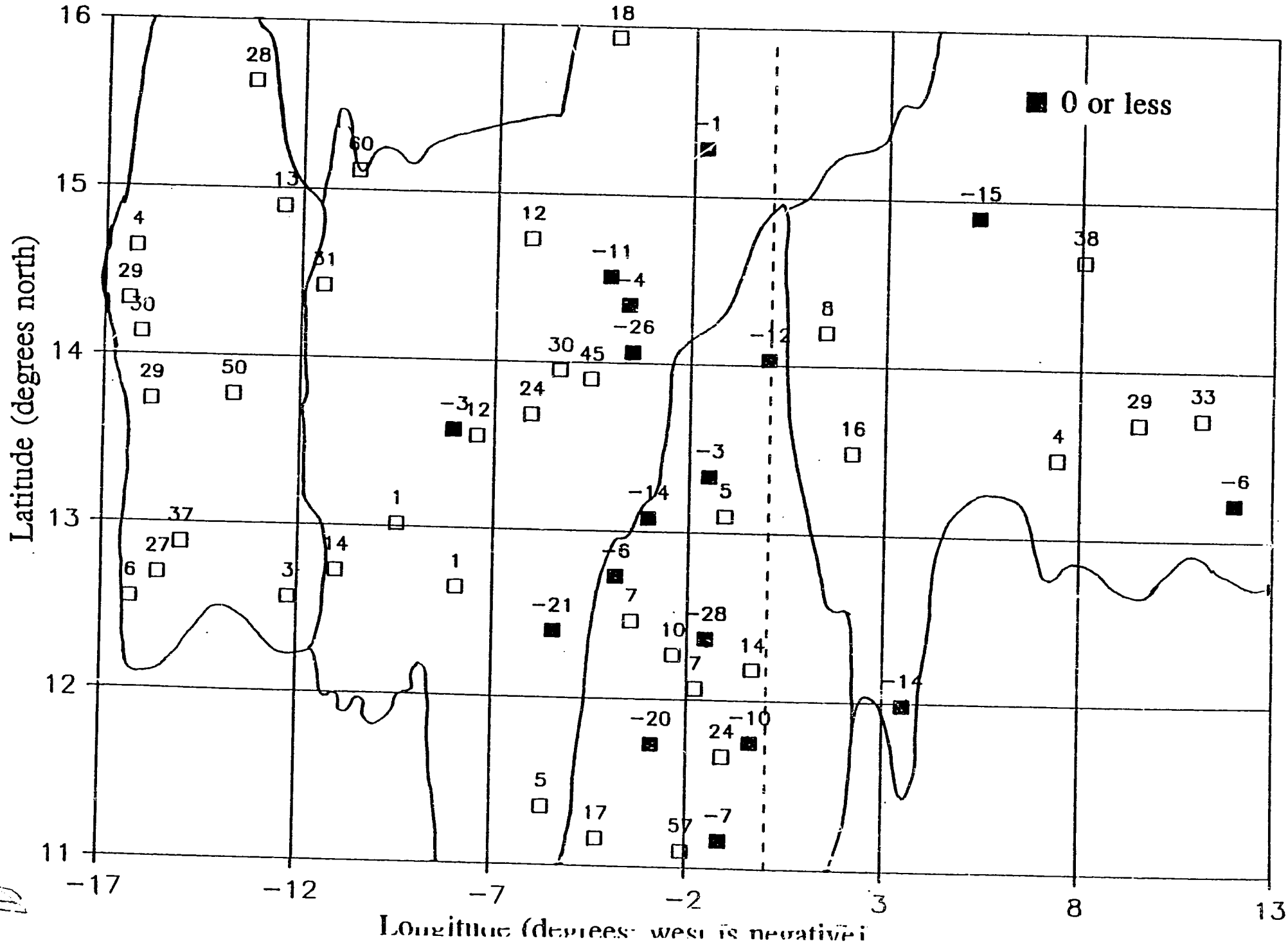

Table 1: Years with complete rainfall data.

location	n	years with complete rainfall data
ANSONGO	44	1925 1928-1937 1939-1947 1949-1964 1966-1970 1974-1976
BAKEL	50	1922-1928 1930-1932 1934-1959 1961-1974
BAM (TOURCOING)	37	1946-1959 1961-1983
BANAMBA	44	1935-1938 1941-1980
BANDIAGARA	52	1922-1927 1931-1937 1940-1967 1970-1980
BANFORA	58	1922-1927 1930-1963 1965-1967 1969-1977 1979-1984
BANKASS	28	1953-1980
BELBEDJI	23	1960-1978 1980-1983
BOBO-DIOULASSO	66	1909-1913 1920 1922-1928 1930-1934 1936 1938-1984
BOROMO	54	1923-1930 1933-1937 1939-1949 1951-1976 1978 1980-1982
BOUREM	45	1926-1927 1931-1938 1942-1959 1964-1980
DAGANA	53	1920-1927 1930-1974
DEDOUGOU	61	1922-1923 1925-1977 1979-1984
DIAPAGA	53	1930-1931 1933-1983
DIEBOUGOU	55	1924-1953 1956-1977 1980-1982
DIOURBEL	55	1919 1922-1930 1932-1975 1977
DJENNE	53	1924-1934 1936-1937 1939-1941 1943-1959 1961-1980
DOGONDOUTCHI	54	1923 1925-1931 1933-1966 1969-1975 1980-1984
DORI	55	1925-1927 1929-1946 1950-1978 1980-1984
FADA N GOURMA	57	1922-1925 1928 1930-1931 1933-1976 1978 1980-1984
FATICK	52	1922-1957 1959-1974
GAO	13	1966-1978
GAOUA	61	1908 1910-1913 1923-1928 1930-1949 1951-1957 1959-1975 1978 1980-1984
GARANGO	37	1947-1983
GAYA	49	1932-1933 1935-1943 1945-1946 1949-1984
GOUDOUMARIA	27	1954-1956 1958-1963 1965 1968-1984
GOURMA-RHAROUS	47	1927-1929 1931-1946 1948-1958 1960 1962-1966 1970-1980
GUENE-GORE	23	1957-1960 1962-1980
GUIDIMOUNI	26	1955-1960 1962-1963 1965-1976 1979-1984
HOMBORI	45	1923-1925 1937 1940-1980
KABARA	55	1923-1955 1957-1959 1961-1969 1971-1980
KALANA	25	1952-1953 1955-1966 1969-1972 1974-1980
KAOLACK	53	1921-1973
KAYA	61	1921-1961 1963-1972 1974-1978 1980-1984
KAYES	53	1896 1898 1907 1927 1929-1930 1932 1934-1941 1943-1980
KE-MACINA	48	1931-1958 1960-1962 1964-1980
KEDOUGOU	51	1922-1951 1953-1957 1962-1977
KIDAL	53	1924-1927 1929-1931 1933-1945 1948-1980
KITA	50	1931-1980

n: number of years with complete rainfall data.

location	n	years with complete rainfall data
KOGONI	30	1951-1980
KOLDA	51	1922-1926 1928-1930 1932 1934-1947 1949-1975 1977
KOLOKANI	48	1923 1925-1926 1933 1935-1937 1939-1961 1963-1980
KOUDOUGOU	57	1922-1927 1929-1931 1933-1977 1980-1982
KOUPELA	58	1923 1925-1938 1940-1982
KOUTIALA	56	1922-1937 1939-1945 1948-1980
LEO	57	1921 1923 1925-1926 1928-1939 1941-1964 1966-1977 1979-1982 1984
MAINE SOROA	45	1939-1943 1945-1984
MANGA	32	1950-1951 1953-1982
MARADI	47	1933-1938 1940-1974 1979-1984
MARKALA	34	1940-1952 1954-1956 1958 1961 1963 1965-1966 1968-1980
MATAM	49	1922-1926 1928 1933-1934 1936-1975 1977
MOPTI	52	1922-1923 1925-1929 1936-1980
N GUIGMI	59	1922-1926 1928-1932 1934-1938 1940-1945 1947-1984
NIAFUNKE	47	1922-1924 1926-1931 1933-1935 1937 1939-1960 1963-1964 1966-1968 1972 1974-1979
NIAMEY AERO	41	1944-1984
NIANGOLOKO	31	1952-1977 1979-1983
NIORO DU RIP	37	1932-1950 1953-1958 1962-1965 1967-1974
NIORO DU SAHEL	58	1922-1933 1935-1980
NOUNA	42	1940-1965 1967-1974 1976-1983
OUAGADOUGOU AERO	31	1953-1976 1978-1984
OUAGADOUGOU MISSIO	76	1902-1948 1952-1954 1956 1958-1972 1974-1976 1978-1984
PO	39	1944-1977 1979-1983
PODOR	51	1923-1925 1928 1930-1975 1977
SAINT LOUIS VILLE	75	1856-1859 1865 1868 1872-1882 1891-1893 1896 1898-1913 1916-1919 1922-1929 1931 1933-1938 1940-1958
SEDHIOU	53	1905-1907 1909-1912 1923-1925 1929-1930 1932-1936 1939-1974
SIKASSO	55	1920 1922-1928 1931 1933-1948 1950-1979
SOKOLO	36	1937 1941-1961 1965-1966 1969-1980
SOTUBA	29	1952-1980
TAHOUA	60	1922-1931 1934-1942 1944-1984
TAMBACOUNDA	51	1922-1925 1927 1931-1975 1977
TENKODOGO	58	1922 1926 1928-1983
TILLABERY	61	1923-1931 1933-1984
TOUGAN	47	1934-1941 1943-1965 1967-1977 1979-1983
YELIMANE	43	1922-1924 1936-1962 1968-1980
ZIGUINCHOR	54	1921-1925 1928 1930-1977

Table 2: Coordinates of locations, analyzed in this report.

	latitude (North)		longitude			latitude (North)		longitude	
location	degrees	minutes	degrees	minutes	location	degrees	minutes	degrees	minutes
ansongo	15	40	-0	30*	ke-machina	13	57	5	22
bakel	14	54	12	28	kidal	18	26	-1	21
bam	13	20	1	30	kita	13	01	9	27
banamba	13	33	7	27	kogoni	14	44	6	2
bandiagara	14	21	3	37	kolda	12	53	14	58
banfora	10	37	4	46	kolokani	13	35	8	2
bankass	14	4	3	31	koudougou	12	16	2	22
belbedji	14	39	-8	4	koupela	12	11	0	21
bobo	11	10	4	18	koutiala	12	24	5	28
boromo	11	44	2	55	leo	11	6	2	6
bourem	16	57	0	21	st. louis	16	1	16	30
dagana	16	31	15	30	maine soroa	13	13	-12	1
dedougou	12	28	3	28	manga	11	40	1	6
diapaga	12	4	1	47	maradi	13	28	-7	25
diebougou	10	58	3	15	markala	13	41	6	5
diourbel	14	39	16	14	matam	15	38	13	15
djenne	13	54	4	34	mopti	14	31	4	6
dori	14	2	0	2	niafunke	15	56	3	59
dogondoutchi	13	38	-4	0	niamey	13	29	-2	10
fada	12	4	0	21	niangoloko	10	16	4	55
fatick	14	20	16	24	nioro du rip	13	44	15	47
gao	16	16	0	3	nioro du sahel	15	14	9	36
gaoua	10	20	3	11	nouna	12	44	3	52
garango	11	48	0	38	ouagadougou	12	22	1	32
gaya	11	59	-3	30	po	11	10	1	9
goudoumaria	13	43	-11	10	podor	16	38	14	56
gourma	16	53	1	56	sedhiou	12	42	1	53
guene-gore	12	44	11	1	sikasso	11	21	5	41
guidimouni	13	41	-9	31	sokolo	14	44	6	8
n guigmi	14	15	-13	7	sotuba	12	39	7	56
hombori	15	17	1	42	tahoua	14	54	-5	18
kabara	16	42	2	59	tambacounda	13	46	13	41
kalana	10	47	8	12	tenkodogo	11	45	0	23
kaolack	14	8	16	4	tillabery	14	12	-1	27
kaya	13	6	1	5	tougan	13	5	3	4
kayes	14	26	11	26	yelimane	15	7	10	34
kedougou	12	34	12	13	ziguinchor	12	33	16	16

* The longitude of Ansongo is 0 degrees and 30 minutes East (negative is east).

Table 3: Annual rainfall in West Africa; before and after 1970.

location	n (years)	before 1971 (mm)	n (years)	after 1970 (mm)	absolute reduction (mm)	relative reduction (%)
bakel	46	513	4	503	10	2
bam	24	655	13	602	53	8
banamba	34	814	10	617	197	24
bandiagara	42	600	10	534	66	11
bankass	18	604	10	542	62	10
boromo	44	977	10	857	120	12
dagana	49	315	4	206	109	35
dedougou	48	965	13	666	299	31
diapaga	40	878	13	736	142	16
diourbel	49	655	6	485	170	26
djenne	43	622	10	455	167	27
dori	42	546	13	431	115	21
fada	45	890	12	764	126	14
fatick	48	795	4	477	318	40
garango	24	922	13	775	147	16
gaya	35	850	14	756	94	11
goudoumaria	13	362	14	280	82	23
guidimouni	14	393	12	351	42	11
hombori	35	420	10	368	52	12
kaolack	50	811	3	590	221	27
kaya	49	708	12	651	57	8
kayes	43	745	10	629	116	16
ke-machina	38	573	10	524	49	9
kolokani	38	819	10	680	139	17
koudougou	47	889	10	662	227	26
koupela	46	830	12	776	54	7
koutiala	46	1013	10	863	150	15
leo	45	1015	12	893	122	12
maine soroa	31	415	14	311	104	25
manga	20	933	12	805	128	14
maradi	37	606	10	391	215	35
markala	24	671	10	525	146	22
matam	43	513	6	253	260	51
mopti	42	552	10	452	100	18
niafunke	40	320	7	256	64	20
niamey	27	612	14	494	118	19
nioro du rip	33	900	4	615	285	32
nouna	30	854	12	724	130	15
ouagaa	18	882	13	760	122	14
ouagam	64	798	12	763	35	4
po	27	1018	12	759	259	25
sokolo	26	529	10	414	115	22
tahoua	46	400	14	328	72	18
tambacounda	45	912	6	750	162	18
tenkodogo	45	963	13	821	142	15
tillabery	47	493	14	365	128	26
tougan	35	787	12	609	178	23
yelimane	33	602	10	463	139	23

Table 4a: Regression coefficients for the correlation between annual rainfall and latitude.

region	period	a	b	r^2
west Africa	..1970	2450.514*	-129.3242	0.65
	1971..	2219.020	-122.0552	0.71
Senegal + west Mali	..1970	3640.438	-201.8956	0.92
	1971..	3085.858	-175.9542	0.87
east Mali + Burkina Faso + Niger	..1970	2862.828	-164.2711	0.81
	1971..	2447.267	-141.5223	0.77

* annual rainfall = 2450.514 - 129.3242*latitude (mm)

west Africa: 48 locations
Senegal + west Mali: 11 locations west of 8 °West
east Mali + Burkina Faso + Niger: 34 locations east of 6 °West

Table 4b: Latitude and corresponding annual rainfall, based on the regression equations of Table 4a.

region	latitude (°N)	..1970 (mm)	1971.. (mm)	difference (mm)	reduction (%)
west Africa	11	1028	876	152	15
	12	899	754	144	16
	13	769	632	137	18
	14	640	510	130	20
	15	511	388	122	24
	16	381	266	115	30
	17	252	144	108	43
Senegal + west Mali	11	1420	1150	269	19
	12	1218	974	243	20
	13	1016	798	217	21
	14	814	622	191	24
	15	612	447	165	27
	16	410	271	140	34
	17	208	95	114	55
east Mali + Burkina Faso + Niger	11	1056	891	165	16
	12	892	749	143	16
	13	727	607	120	16
	14	563	466	97	17
	15	399	324	74	19
	16	234	183	52	22
	17	70	41	29	41

Table 5: Critical dates, used in the definition of onset of the rainy season.

location	critical date (day of year)	location	critical date (day of year)	location	critical date (day of year)
abeche	165	gaborone	288	markala	140
agadez	195	gao	170	matam	175
ansongo	170	gaoua	90	menaka	170
ati	160	garango	110	mongo	150
bakel	150	gaya	135	mopti	145
bam	140	goudoumaria	160	moundou	90
bamako	120	gourma	175	nara	155
bamakoa	120	guene-gore	105	niamey	150
banamba	135	guidimouni	155	niangoloko	90
bandiagara	145	n guigmi	150	nioro du rip	160
banfora	95	hombori	155	nioro du sahel	155
banfora	95	kabara	170	nouna	120
bankass	145	kalana	90	ouagaa	130
belbedji	160	kaolack	155	ouagam	130
bilma	200	kaya	135	ouahigoua	150
birni	150	kayes	145	pala	110
bobo	95	kedougou	130	po	100
bokoro	150	ke-machina	140	podor	195
bol	160	kenieba	120	san	125
boromo	120	kidal	190	sarh	105
bourem	175	kita	125	sedhiou	150
bousso	125	kogoni	145	segou	135
bouza	160	kolda	140	sikasso	95
dagana	195	kolokani	135	sokolo	145
dakar	160	koudougou	120	sotuba	130
dedougou	120	koupela	120	tahoua	150
diapaga	120	koutiala	110	tambacounda	150
diebougou	100	leo	100	tenkodogo	110
diourbel	160	linguere	170	tessalit	200
djenne	140	st. louis	170	tillabery	150
dori	160	mahalapye	303	tombouctou	170
dosso	145	maine soroa	150	tougan	130
dogondoutchi	150	manga	105	yelimane	155
fada	120	mao	165	ziguinchor	150
fatick	155	maradi	150	zinder	150
francistown	303				

Table 6: Earliest, median and latest onsets (calendar date;mm-dd) of the record.

location	earliest	median	latest
bakel	06-05	07-13	08-18
bam	04-26	06-21	07-24
banamba	05-12	06-20	07-22
bankass	05-15	06-29	08-14
boromo	04-24	05-20	06-26
dagana	07-06	08-09	09-09
dedougou	04-19	05-30	07-23
diapaga	04-14	05-26	08-03
diourbel	05-27	07-12	09-07
djenne	05-10	06-30	08-03
dori	06-03	07-05	08-13
fada	04-23	05-30	08-05
fatick	06-04	07-13	08-07
garango	03-29	05-15	07-22
gaya	04-30	06-05	07-23
goudoumaria	06-15	07-14	09-05
guidimouni	06-15	07-18	08-20
hombori	05-25	07-15	08-21
kaolack	05-27	06-30	08-10
kaya	04-30	06-11	07-24
kayes	05-21	06-23	08-02
ke-machina	05-12	07-04	08-11
kolokani	05-11	06-20	08-08
koudougou	04-24	06-03	07-27
koupela	04-05	05-25	07-16
koutiala	04-19	05-27	07-06
leo	03-26	05-05	07-03
maine soroa	06-12	07-19	08-27
manga	04-13	05-15	07-04
maradi	05-16	07-07	08-06
markala	04-20	07-01	07-21
matam	06-14	07-12	08-23
mopti	05-27	07-09	08-08
niamey	05-26	06-21	08-05
nioro du rip	06-08	07-01	07-26
nouna	04-28	06-07	07-18
ouagaa	04-26	05-28	07-13
ouagam	04-26	06-03	07-22
po	04-08	05-18	07-03
sokolo	05-28	07-11	08-10
tahoua	06-01	07-15	08-29
tambacounda	05-22	06-17	07-10
tenkodogo	03-16	05-17	07-16
tillabery	05-26	07-08	08-14
tougan	04-30	06-16	07-23
yelimane	06-03	07-07	08-16

Table 7a: Regression coefficients for the correlation between onset date and latitude.

region	onset	a	b	r^2
west Africa	earliest*	-98.041	17.0796	0.73
	median	-51.845	16.6419	0.84
	latest	58.824	11.5499	0.62
Senegal	earliest	-25.887	12.4519	0.72
	median	-17.122	14.1338	0.79
	latest	-26.266	17.1352	0.63
west Mali	earliest	-111.337	17.4987	0.79
	median	-32.476	15.0562	0.76
	latest	19.303	13.8780	0.73
east Mali + Burkina Faso	earliest	-89.796	16.1218	0.75
	median	-69.229	17.8251	0.95
	latest	55.693	11.7862	0.69
Niger	earliest	-7.447	11.6584	0.34
	median	3.089	13.5985	0.50
	latest	54.044	12.9242	0.49

* earliest onset = -98.041 + 17.0796*latitude (day of year)

west Africa: 46 locations
Senegal: 8 locations west of 12 °West.
west Mali: 10 locations between 12 and 4 °West.
east Mali + Burkina Faso: 21 locations between 4 °West and 2 °East.
Niger: 7 locations east of 2 °East.

Table 7b: Latitude and the corresponding onset date (calendar date:mm-dd), based on the regression equations of Table 7a.

region	latitude(°N)	earliest	median	latest
west Africa	11	03-31	05-11	07-05
	12	04-17	05-28	07-16
	13	05-04	06-13	07-28
	14	05-21	06-30	08-09
	15	06-07	07-17	08-20
	16	06-24	08-02	09-01
	17	07-11	08-19	[illegible]
Senegal	14	05-28	06-30	[illegible]
	15	06-10	07-14	08-19
	16	06-22	07-28	09-05
	17	07-05	08-11	09-22
west Mali	11	03-22	05-13	06-21
	12	04-09	05-28	07-05
	13	04-26	06-12	07-19
	14	05-14	06-27	08-02
	15	05-31	07-12	08-15
	16	06-18	07-27	08-29
	17	07-05	08-11	09-12
east Mali + Burkina Faso	11	03-29	05-07	07-04
	12	04-14	05-25	07-16
	13	04-30	06-11	07-28
	14	05-16	06-29	08-09
	15	06-01	07-17	08-20
	16	06-17	08-04	09-01
	17	07-03	08-22	09-13
Niger	11	05-01	06-02	07-15
	12	05-12	06-15	07-28
	13	05-24	06-29	08-10
	14	06-05	07-12	08-23
	15	06-16	07-26	09-05
	16	06-28	08-09	09-18
	17	07-10	08-22	10-01

Table 8: Means and regression coefficients for several characteristics of the rainy season.

bakel	years	onset	end	duration (days)	b0	b1	r^2	amount (mm)	b0	b1	r^2	intensity (mm/day)
all years	50	194	280	87	258*	-0.88	0.65	448	1216**	-3.96	0.26	5.2
.... 1970	46	195	281	86	254	-0.86	0.64	446	1228	-4.01	0.27	5.2
1971	4	181	278	97	462	-2.01	0.92	469	1741	-7.02	0.21	4.9
bam												
all years	37	169	278	110	280	-1.00	0.71	563	961	-2.35	0.14	5.3
.... 1970	24	173	279	107	262	-0.90	0.67	577	1174	-3.46	0.26	5.5
1971	13	164	277	114	308	-1.18	0.77	538	788	-1.53	0.07	5.0
banamba												
all years	44	169	280	112	284	-1.02	0.63	702	882	-1.06	0.01	6.5
.... 1970	34	168	280	114	272	-0.95	0.68	747	750	-0.02	0.00	6.8
1971	10	173	278	107	342	-1.36	0.57	550	1064	-2.98	0.15	5.4
bankass												
all years	28	179	277	99	272	-0.96	0.74	509	1201	-3.87	0.44	5.2
.... 1970	18	181	278	98	271	-0.95	0.66	529	1377	-4.69	0.42	5.4
1971	10	175	275	101	273	-0.98	0.80	473	1130	-3.75	0.62	4.9
boromo												
all years	54	141	286	146	307	-1.14	0.80	880	1293	-2.94	0.08	6.1
.... 1970	44	142	286	145	307	-1.15	0.78	901	1297	-2.79	0.06	6.3
1971	10	137	285	150	307	-1.15	0.88	787	1443	-4.80	0.69	5.3
dagana												
all years	52	219	275	57	278	-1.01	0.57	260	1050	-3.60	0.28	5.1
.... 1970	49	218	276	58	265	-0.95	0.54	264	1051	-3.60	0.27	4.9
1971	3	232	260	29	461	-1.86	0.99	183	-167	1.51	0.09	8.5
dedougou												
all years	61	151	285	135	292	-1.04	0.86	838	1313	-3.14	0.16	6.3
.... 1970	48	147	286	140	288	-1.01	0.86	903	1150	-1.69	0.08	6.6
1971	13	166	283	117	295	-1.07	0.79	601	861	-1.57	0.06	5.3
diapaga												
all years	53	148	282	135	254	-0.81	0.63	777	1220	-3.00	0.14	5.8
.... 1970	40	148	281	134	273	-0.94	0.67	809	1243	-2.94	0.11	6.1
1971	13	148	284	137	229	-0.62	0.61	678	1122	-3.00	0.30	5.0
diourbel												
all years	54	192	283	92	271	-0.93	0.66	603	1457	-4.44	0.19	6.7
.... 1970	48	192	285	94	275	-0.95	0.70	622	1430	-4.21	0.19	6.8
1971	6	196	275	79	59	0.10	0.03	452	1410	-4.88	0.15	5.7
djenne												
all years	53	178	275	97	285	-1.05	0.77	523	1309	-4.41	0.31	5.5
.... 1970	43	177	275	99	280	-1.02	0.80	552	1322	-4.35	0.30	5.7
1971	10	183	272	90	303	-1.16	0.68	398	1041	-3.51	0.45	4.7
dori												
all years	55	185	275	91	281	-1.03	0.65	448	1365	-4.97	0.42	5.0
.... 1970	42	183	276	94	273	-0.98	0.63	474	1373	-4.91	0.39	5.2
1971	13	189	271	82	290	-1.10	0.68	361	1108	-3.95	0.62	4.5

onset: date of onset of the rainy season (day of year)
end: date of end of the rainy season (day of year)
* duration = 258 - 0.88*onset (days)
** amount = 1216 - 3.96*onset (mm)

fada	years	onset	end	duration (days)	b0	b1	r^2	amount (mm)	b0	b1	r^2	intensity (mm/day)
all years	57	150	281	132	289	-1.04	0.76	792	1386	-3.96	0.26	6.1
.... 1970	45	153	281	129	289	-1.04	0.76	814	1672	-5.60	0.45	6.4
1971	12	139	282	144	290	-1.05	0.67	707	989	-2.02	0.19	5.0
fatick												
all years	52	190	285	96	283	-0.99	0.62	725	1722	-5.24	0.14	7.6
... 1970	48	189	286	98	273	-0.93	0.64	749	1457	-3.74	0.09	7.7
1971	4	204	275	72	272	-0.99	0.20	428	3429	-14.75	0.35	6.0
garango												
all years	37	142	281	140	315	-1.23	0.85	814	1361	-3.85	0.51	6.1
.... 1970	24	139	283	145	294	-1.07	0.86	861	1342	-3.47	0.52	6.1
1971	13	148	278	131	357	-1.52	0.89	727	1275	-3.70	0.53	6.1
gaya												
all years	49	158	276	119	290	-1.08	0.78	752	1213	-2.91	0.13	6.5
.... 1970	35	160	276	117	291	-1.09	0.80	776	1113	-2.10	0.07	6.8
1971	14	154	276	123	290	-1.08	0.73	693	1548	-5.55	0.48	5.8
goudoumaria												
all years	25	200	261	62	279	-1.08	0.82	279	992	-3.57	0.38	5.5
.... 1970	13	202	262	61	312	-1.24	0.91	298	812	-2.55	0.28	6.9
1971	12	198	260	63	237	-0.88	0.70	258	1322	-5.38	0.63	3.9
guidimouni												
all years	26	200	266	66	277	-1.05	0.63	301	1153	-4.25	0.24	4.7
.... 1970	14	203	268	65	195	-0.64	0.24	315	1620	-6.41	0.24	4.9
1971	12	197	263	68	312	-1.24	0.82	284	1128	-4.29	0.40	4.5
hombori												
all years	45	197	271	75	268	-0.98	0.64	344	1033	-3.49	0.34	4.8
.... 1970	35	196	271	77	275	-1.01	0.70	359	1062	-3.59	0.37	4.9
1971	10	201	267	68	191	-0.62	0.23	294	585	-1.45	0.06	4.5
kaolack												
all years	53	184	287	104	282	-0.97	0.77	754	1653	-4.90	0.14	7.3
.... 1970	50	184	287	104	279	-0.96	0.76	765	1817	-5.72	0.20	7.5
1971	3	180	286	107	324	-1.21	0.93	569	-660	6.83	0.49	5.6
kaya												
all years	61	165	279	116	294	-1.08	0.74	628	1062	-2.63	0.16	5.6
.... 1970	49	164	281	117	287	-1.03	0.72	640	1119	-2.92	0.18	5.6
1971	12	166	274	109	319	-1.27	0.84	582	801	-1.32	0.06	5.7
kayes												
all years	53	174	282	110	293	-1.05	0.61	673	1461	-4.53	0.16	6.2
.... 1970	43	173	283	111	280	-0.98	0.54	695	1462	-4.43	0.13	6.3
1971	10	177	281	105	316	-1.20	0.75	578	1269	-3.92	0.34	5.7
ke-machina												
all years	48	181	272	93	297	-1.13	0.77	498	1252	-4.18	0.35	5.6
.... 1970	38	183	274	92	282	-1.04	0.76	509	1412	-4.94	0.41	5.7
1971	10	173	268	96	354	-1.49	0.87	454	1009	-3.20	0.41	5.1
kolokani												
all years	48	171	283	113	295	-1.06	0.85	716	1481	-4.48	0.23	6.4
.... 1970	38	171	283	113	289	-1.03	0.85	742	1546	-4.69	0.27	6.7
1971	10	168	283	116	332	-1.29	0.88	616	1377	-4.53	0.22	5.5

koudougou	years	onset	end	duration (days)	b0	b1	r^2	amount (mm)	b0	b1	r^2	intensity (mm/day)
all years	57	156	285	129	292	-1.04	0.86	775	1446	-4.30	0.29	6.1
.... 1970	47	155	285	132	283	-0.98	0.86	814	1412	-3.87	0.25	6.2
1971	10	164	281	118	315	-1.20	0.90	592	1139	-3.33	0.49	5.2
koupela												
all years	58	147	282	136	289	-1.04	0.78	758	1338	-3.94	0.26	5.6
.... 1970	46	148	282	135	282	-0.99	0.78	768	1318	-3.72	0.33	5.8
1971	12	146	284	139	325	-1.28	0.81	719	1499	-5.36	0.20	5.2
koutiala												
all years	56	145	288	144	288	-1.00	0.87	919	1161	-1.67	0.04	6.5
.... 1970	46	143	288	146	285	-0.97	0.90	947	1119	-1.20	0.03	6.6
1971	10	150	284	135	308	-1.15	0.68	788	1227	-2.93	0.13	6.0
leo												
all years	57	127	286	161	302	-1.12	0.84	923	1430	-4.00	0.21	5.8
.... 1970	45	123	285	163	307	-1.17	0.84	949	1441	-3.99	0.19	5.9
1971	12	139	291	153	312	-1.15	0.88	826	1175	-2.51	0.10	5.5
maine soroa												
all years	45	201	267	66	280	-1.06	0.66	313	866	-2.75	0.16	5.0
.... 1970	31	200	269	70	258	-0.94	0.63	343	772	-2.15	0.11	5.1
1971	14	204	260	58	337	-1.37	0.83	247	995	-3.67	0.37	4.7
manga												
all years	32	135	281	147	285	-1.02	0.59	819	1059	-1.77	0.05	5.7
.... 1970	20	135	282	148	322	-1.29	0.84	861	971	-0.82	0.02	5.9
1971	12	136	280	145	253	-0.79	0.39	749	1082	-2.45	0.09	5.2
maradi												
all years	47	183	267	85	288	-1.11	0.77	496	1048	-3.01	0.18	6.1
.... 1970	37	180	270	91	276	-1.03	0.75	544	746	-1.12	0.04	6.3
1971	10	195	258	64	279	-1.10	0.79	320	1410	-5.60	0.63	5.1
markala												
all years	34	176	275	100	278	-1.01	0.63	570	1550	-5.55	0.41	5.8
.... 1970	24	177	276	100	271	-0.97	0.66	612	1568	-5.41	0.42	6.2
1971	10	176	274	99	298	-1.14	0.58	471	1557	-6.18	0.77	4.9
matam												
all years	48	195	276	82	291	-1.07	0.70	441	1524	-5.55	0.38	5.4
.... 1970	43	192	278	86	270	-0.96	0.62	466	1355	-4.62	0.26	5.4
1971	5	219	262	44	227	-0.84	0.88	228	1728	-6.86	0.83	5.0
mopti												
all years	52	185	277	93	265	-0.93	0.71	460	1137	-3.67	0.26	5.0
.... 1970	42	185	277	94	251	-0.85	0.74	479	1124	-3.49	0.24	5.2
1971	10	185	277	93	335	-1.30	0.71	380	1193	-4.39	0.58	4.3
niamey												
all years	41	176	273	98	287	-1.08	0.78	505	1290	-4.47	0.30	5.3
.... 1970	27	176	274	99	276	-1.01	0.71	547	1394	-4.82	0.29	5.6
1971	14	176	270	95	297	-1.15	0.86	423	1128	-4.00	0.48	4.7
nioro du rip												
all years	37	181	288	108	298	-1.05	0.71	832	1498	-3.69	0.06	7.8
.... 1970	33	180	288	109	295	-1.03	0.70	862	1623	-4.22	0.09	8.0
1971	4	182	286	105	328	-1.23	0.83	582	74	2.80	0.17	5.7

nouna	years	onset	end	duration (days)	b0	b1	r^2	amount (mm)	b0	b1	r^2	intensity (mm/day)
all years	42	157	287	132	300	-1.08	0.85	748	1347	-3.83	0.25	5.7
.... 1970	30	154	289	136	289	-0.99	0.86	791	1169	-2.46	0.13	5.9
1971	12	164	284	120	328	-1.26	0.82	641	1588	-5.76	0.52	5.4
ouagaa												
all years	31	149	283	135	282	-0.99	0.78	761	1538	-5.20	0.30	5.7
.... 1970	18	149	283	135	255	-0.80	0.57	814	1916	-7.40	0.38	6.0
1971	13	150	282	134	293	-1.06	0.87	689	1325	-4.25	0.33	5.2
ouagam												
all years	76	156	283	128	285	-1.01	0.75	720	1370	-4.18	0.30	5.7
.... 1970	64	156	283	127	283	-1.00	0.73	725	1380	-4.19	0.30	5.7
1971	12	152	283	132	290	-1.04	0.85	690	1364	-4.42	0.36	5.3
po												
all years	39	135	283	149	299	-1.11	0.48	871	1248	-2.79	0.08	6.0
.... 1970	27	133	287	155	292	-1.03	0.86	950	1178	-1.71	0.06	6.3
1971	12	139	275	137	307	-1.22	0.25	693	1191	-3.58	0.10	5.6
sokolo												
all years	36	188	272	84	292	-1.10	0.66	442	884	-2.35	0.09	5.5
.... 1970	26	189	274	86	280	-1.03	0.62	473	950	-2.52	0.11	5.8
1971	10	186	266	81	319	-1.28	0.78	363	870	-2.73	0.17	4.8
tahoua												
all years	60	195	267	73	245	-0.88	0.66	307	956	-3.33	0.40	4.4
.... 1970	46	196	267	72	248	-0.90	0.62	320	1029	-3.62	0.42	4.6
1971	14	191	266	76	240	-0.86	0.76	266	869	-3.16	0.56	3.6
tambacounda												
all years	51	169	287	119	261	-0.84	0.61	853	1850	-5.89	0.14	7.2
.... 1970	45	169	287	120	257	-0.82	0.59	872	1847	-5.78	0.15	7.3
1971	6	174	286	113	293	-1.03	0.78	710	926	-1.25	0.01	6.3
tenkodogo												
all years	58	139	284	145	294	-1.07	0.85	869	1498	-4.51	0.29	6.1
.... 1970	45	139	283	146	294	-1.07	0.86	901	1582	-4.92	0.31	6.3
1971	13	142	285	143	297	-1.08	0.81	761	1083	-2.27	0.43	5.5
tillabery												
all years	60	186	269	84	264	-0.97	0.69	401	939	-2.89	0.22	4.9
.... 1970	47	186	270	85	255	-0.92	0.68	424	948	-2.81	0.22	5.1
1971	13	186	264	79	287	-1.12	0.74	316	905	-3.17	0.48	4.2
tougan												
all years	47	164	283	120	284	-1.00	0.75	674	849	-1.06	0.02	5.8
.... 1970	35	164	286	122	287	-1.01	0.80	719	935	-1.32	0.04	6.1
1971	12	163	275	113	279	-1.02	0.72	544	661	-0.72	0.03	5.1
yelimane												
all years	43	187	281	95	273	-0.95	0.60	513	1689	-6.30	0.48	5.4
.... 1970	33	183	281	99	267	-0.92	0.54	547	1518	-5.30	0.35	5.6
1971	10	198	281	84	287	-1.03	0.64	400	1787	-7.02	0.63	4.8

Table 9a: Regression coefficients for the correlation between latitude and several characteristics of the rainy season.

region	correlation of latitude versus	period	b0	b1	r^2
west Africa	end	all years*	308	-2.206	0.17
		.. 1970	308	-2.095	0.16
		1971 ..	326	-3.753	0.30
	r^2 dur	all years	1.149	-0.032	0.18
		.. 1970	1.468	-0.056	0.31
		1971 ..	0.806	-0.006	0.00
	r^2 amt	all years	-0.165	0.030	0.09
		.. 1970	-0.087	0.023	0.05
		1971 ..	-0.040	0.029	0.03
Senegal	end	all years	358	-5.124	0.94
		.. 1970	351	-4.606	0.94
		1971 ..	426	-10.177	0.89
	r^2 dur	all years	1.066	-0.028	0.17
		.. 1970	1.293	-0.044	0.37
		1971 ..	-0.725	0.097	0.06
	r^2 amt	all years	-1.102	0.088	0.70
		.. 1970	-0.699	0.061	0.60
		1971 ..	-0.551	0.057	0.04
west Mali	end	all years	316	-2.634	0.17
		.. 1970	312	-2.322	0.16
		1971 ..	306	-2.122	0.08
	r^2 dur	all years	1.901	-0.085	0.47
		.. 1970	2.366	-0.118	0.60
		1971 ..	0.180	0.039	0.07
	r^2 amt	all years	-0.965	0.085	0.20
		.. 1970	-0.641	0.062	0.11
		1971 ..	-0.807	0.084	0.09
east Mali + Burkina Faso	end	all years	326	-3.569	0.65
		.. 1970	326	-3.472	0.59
		1971 ..	339	-4.761	0.61
	r^2 dur	all years	0.954	-0.017	0.03
		.. 1970	1.387	-0.050	0.34
		1971 ..	1.164	-0.035	0.04
	r^2 amt	all years	-0.256	0.039	0.10
		.. 1970	-0.286	0.042	0.09
		1971 ..	0.096	0.016	0.01
Niger	end	all years	315	-3.440	0.36
		.. 1970	316	-3.446	0.41
		1971 ..	311	-3.450	0.21
	r^2 dur	all years	1.200	-0.035	0.16
		.. 1970	1.532	-0.064	0.07
		1971 ..	0.718	0.005	0.01
	r^2 amt	all years	-1.102	0.101	0.65
		.. 1970	-1.495	0.126	0.61
		1971 ..	0.025	0.036	0.09

r^2 dur: r^2 of duration versus onset r^2 amt: r^2 of amount versus onset

* end = 308 - 2.206*latitude (day of year)

Table 9b: Latitude and corresponding values based on Table 9a.

		end date (mm-dd)			r^2 duration			r^2 amount		
region	latitude (°N)	all	..1970	1971..	all	..1970	1971..	all	..1970	1971..
west Africa	11	10-11	10-12	10-12	0.80	0.85	0.74	0.16	0.17	0.28
	12	10-09	10-10	10-08	0.76	0.79	0.73	0.19	0.19	0.31
	13	10-07	10-07	10-04	0.73	0.74	0.73	0.22	0.21	0.34
	14	10-04	10-05	10-01	0.70	0.68	0.72	0.25	0.24	0.37
	15	10-02	10-03	09-27	0.67	0.63	0.72	0.28	0.26	0.39
	16	09-30	10-01	09-23	0.64	0.57	0.71	0.31	0.28	0.42
	17	09-28	09-29	09-19	0.60	0.51	0.70	0.34	0.31	0.45
Senegal	14	10-13	10-14	10-10	0.68	0.68	0.63	0.14	0.15	0.25
	15	10-08	10-09	09-30	0.65	0.64	0.72	0.22	0.21	0.30
	16	10-03	10-05	09-20	0.63	0.59	0.82	0.31	0.27	0.36
	17	09-28	09-30	09-10	0.60	0.55	0.92	0.40	0.33	0.42
west Mali	11	10-14	10-13	10-10	0.97	1.07	0.61	-0.03	0.04	0.11
	12	10-11	10-11	10-08	0.88	0.95	0.65	0.06	0.10	0.20
	13	10-08	10-09	10-06	0.80	0.83	0.69	0.15	0.16	0.28
	14	10-06	10-06	10-04	0.71	0.71	0.73	0.23	0.23	0.36
	15	10-03	10-04	10-02	0.63	0.59	0.77	0.32	0.29	0.45
	16	10-01	10-02	09-29	0.54	0.47	0.81	0.40	0.35	0.53
east Mali + Burkina Faso	11	10-14	10-14	10-14	0.77	0.84	0.78	0.17	0.17	0.28
	12	10-10	10-11	10-09	0.75	0.79	0.75	0.21	0.22	0.29
	13	10-07	10-07	10-04	0.74	0.74	0.71	0.25	0.26	0.31
	14	10-03	10-04	09-29	0.72	0.69	0.68	0.29	0.30	0.32
	15	09-29	09-30	09-25	0.70	0.64	0.64	0.33	0.34	0.34
	16	09-26	09-27	09-20	0.69	0.59	0.61	0.37	0.38	0.36
	17	09-22	09-24	09-15	0.67	0.54	0.57	0.40	0.42	0.37
Niger	11	10-04	10-05	09-30	0.82	0.83	0.77	0.00	-0.11	0.42
	12	09-30	10-02	09-27	0.78	0.76	0.78	0.11	0.02	0.45
	13	09-27	09-28	09-23	0.75	0.70	0.78	0.21	0.14	0.49
	14	09-23	09-25	09-20	0.71	0.63	0.79	0.31	0.27	0.53
	15	09-20	09-21	09-17	0.68	0.57	0.79	0.41	0.40	0.56
	16	09-17	09-18	09-13	0.64	0.50	0.80	0.51	0.52	0.60
	17	09-13	09-14	09-10	0.61	0.44	0.80	0.61	0.65	0.63

r^2 duration: r^2 of duration versus onset
r^2 amount: r^2 of amount versus onset

Table 10: Means of r squares for the correlation between onset - duration and onset - amount.

region	onset versus	all years	..1970	1971..
west Africa	duration	0.72	0.72	0.73
	amount	0.23	0.22	0.35
Senegal	duration	0.66	0.65	0.70
	amount	0.20	0.19	0.29
west Mali	duration	0.70	0.70	0.73
	amount	0.24	0.23	0.37
east Mali + Burkina Faso	duration	0.74	0.76	0.72
	amount	0.23	0.24	0.30
Niger	duration	0.73	0.67	0.78
	amount	0.26	0.21	0.51

Table 11: Means and regression coefficients for several characteristics of the rainy season for three locations in Botswana.

location	years	onset	duration (days)	b0	b1	r^2	amount (mm)	b0	b1	r^2
Gaborone	30	321	130	346*	-0.67	0.15	407	973**	-1.76	0.09
Francistown	49	338	118	536	-1.24	0.82	386	1485	-3.25	0.25
Mahalapye	53	333	127	432	-0.91	0.78	388	1147	-2.28	0.31

onset: date of onset of the rainy season (day of year)

* duration = 346 - 0.67*onset (days)

** amount = 973 - 1.76*onset (mm)

Table 12: Standard deviations (sd) of several aspects of the rainy season.

location	onset (days)	end (days)	duration (days)	duration (relative,%)	amount (mm)	amount (relative,%)	intensity (mm per day)
bakel	18	12	19	22	137	30	1.27
bam	19	12	23	21	122	22	1.41
banamba	17	13	22	19	173	25	1.81
bankass	22	13	25	25	130	26	0.97
boromo	17	10	22	15	180	20	1.23
dagana	16	14	22	39	112	43	2.49
dedougou	24	10	27	20	189	23	1.48
diapaga	20	13	21	15	164	21	1.29
diourbel	18	12	21	22	186	31	1.85
djenne	23	13	28	28	182	35	1.58
dori	17	13	22	24	133	30	1.30
fada	21	12	25	19	163	21	1.17
fatick	15	11	19	20	207	28	1.92
garango	27	15	36	25	145	18	1.43
gaya	19	11	24	20	156	21	1.57
goudoumaria	19	10	22	36	107	38	5.03
guidimouni	14	11	19	28	122	41	1.89
hombori	18	13	22	29	107	31	1.48
kaolack	17	9	19	18	223	30	2.09
kaya	21	13	26	22	138	22	1.38
kayes	14	12	19	17	160	24	1.28
ke-machina	21	13	28	30	152	31	1.52
kolokani	22	10	25	22	204	28	1.80
koudougou	22	9	25	19	177	23	1.18
koupela	21	12	25	18	163	22	1.08
koutiala	22	8	23	16	173	19	1.37
leo	22	11	27	17	194	21	1.13
maine soroa	17	13	22	33	117	37	1.80
manga	19	17	26	18	157	19	1.01
maradi	20	13	26	30	146	30	1.80
markala	19	15	24	24	166	29	1.22
matam	19	13	24	29	170	39	1.28
mopti	19	11	21	22	136	30	1.35
niamey	20	11	24	25	162	32	1.48
nioro du rip	14	9	17	16	206	25	1.94
nouna	20	9	23	18	153	20	1.09
ouagaa	20	10	22	16	186	24	1.14
ouagam	21	12	24	19	159	22	1.05
po	22	26	36	24	220	25	1.37
sokolo	18	14	24	29	136	31	1.88
tahoua	20	13	22	30	107	35	1.47
tambacounda	12	8	13	11	193	23	1.52
tenkodogo	26	12	30	21	217	25	1.40
tillabery	20	13	23	28	122	30	1.40
tougan	22	13	26	21	155	23	1.71
yelimane	17	13	20	22	152	30	1.19

sd of duration (relative) = 100*(sd of duration)/duration
sd of amount (relative) = 100*(sd of amount)/amount

Table 13a: Regression coefficients for the correlation between latitude and standard deviations of several aspects of the rainy season.

region	correlation of latitude versus standard deviation of	a	b	r^2
west Africa	onset*	35.802	-1.2255	0.25
	end	14.892	-0.2027	0.01
	duration	45.830	-1.6621	0.25
	duration (relative)	-10.945	2.5055	0.28
	amount	298.765	-10.3504	0.17
	amount (relative)	-22.463	3.7066	0.55
Senegal	onset	-3.243	1.3169	0.29
	end	-19.245	2.0564	0.86
	duration	-20.461	2.7000	0.61
	duration (relative)	-106.003	8.7117	0.96
	amount	663.817	-32.9469	0.70
	amount (relative)	-68.662	6.7848	0.94
west Mali	onset	47.603	-2.0308	0.30
	end	-8.320	1.4672	0.30
	duration	41.347	-1.2832	0.10
	duration (relative)	-9.846	2.3413	0.14
	amount	394.105	-16.4954	0.36
	amount (relative)	-20.295	3.4674	0.35
east Mali + Burkina Faso	onset	32.729	-0.9300	0.16
	end	20.941	-0.6486	0.04
	duration	49.262	-1.8823	0.24
	duration (relative)	-10.513	2.4724	0.45
	amount	451.573	-23.0669	0.67
	amount (relative)	-7.547	2.4411	0.55
Niger	onset	15.440	0.2215	0.01
	end	5.637	0.4504	0.10
	duration	33.995	-0.8361	0.11
	duration (relative)	-17.929	3.4675	0.32
	amount	361.386	-17.0747	0.40
	amount (relative)	-35.372	5.0990	0.44

* Standard deviation of onset = 35.802 - 1.2255*latitude (days)

Table 13b: Latitude and corresponding values, based on the regression equations of Table 13a.

		standard deviation of					
region	latitude (°N)	onset (days)	end (days)	duration (days)	duration (rel.) (%)	amount (mm)	amount (rel.) (%)
west Africa	11	22	13	28	17	185	18
	12	21	12	26	19	175	22
	13	20	12	24	22	164	26
	14	19	12	23	24	154	29
	15	17	12	21	27	144	33
	16	16	12	19	29	133	37
	17	15	11	18	32	123	41
Senegal	14	15	10	17	16	203	26
	15	17	12	20	25	170	33
	16	18	14	23	33	137	40
	17	19	16	25	42	104	47
west Mali	11	25	8	27	16	213	18
	12	23	9	26	18	196	21
	13	21	11	25	21	180	25
	14	19	12	23	23	163	28
	15	17	14	22	25	147	32
	16	15	15	21	28	130	35
	17	13	17	20	30	114	39
east Mali + Burkina Faso	11	22	14	29	17	198	19
	12	22	13	27	19	175	22
	13	21	13	25	22	152	24
	14	20	12	23	24	129	27
	15	19	11	21	27	106	29
	16	18	11	19	29	83	32
	17	17	10	17	32	59	34
Niger	11	18	11	25	20	174	21
	12	18	11	24	24	156	26
	13	18	11	23	27	139	31
	14	19	12	22	31	122	36
	15	19	12	21	34	105	41
	16	19	13	21	38	88	46
	17	19	13	20	41	71	51

Table 14a: Regression coefficients for the correlation between the standard deviation of onset date and the standard deviation of end date.

region	a	b	r^2
west Africa*	8.435	0.1930	0.04
Senegal	1.045	0.6174	0.46
west Mali	17.134	-0.2570	0.13
east Mali + Burkina Faso	9.809	0.1406	0.01
Niger	9.942	0.0962	0.03

* $sd_{enddate} = 8.435 + 0.1930 * sd_{onsetdate}$ (days)

Table 14b: Standard deviation of onset and corresponding standard deviation of end, based on the regression equations of Table 14a.

sd of onset (days)	standard deviation of end date (days)				
	west Africa	Senegal	west Mali	east Mali + Burkina Faso	Niger
10	10	7	15	11	11
15	11	10	13	12	11
20	12	13	12	13	12
25	13	16	11	13	12
30	14	20	9	14	13

Table 15a: Rainfall intensities during the rainy season; seasons with early onset versus seasons with late onset.

country	location	intensity (mm per day)			difference (% of early)
		onsets early*	onsets late	diffe-rence	
Senegal	Nioro du Rip	7.02	8.03	1.01	14
	Podor	4.40	5.28	0.88	20
Mali	Kayes	5.78	6.55	0.77	13
	Ansongo	3.54	4.75	1.30	37
	Kolokani	6.66	6.96	0.30	5
Burkina Faso	Boromo	5.82	6.42	0.60	10
	Dori	5.08	5.08	0.00	0
	Kaya	5.14	6.05	0.91	18
Niger	Niamey	5.07	5.34	0.27	5
	Gaya	5.95	7.12	1.17	20
	Bouza	4.93	5.07	0.14	3

* Onset dates before the median onset date are defined to be early and other ones to be late.

Table 15b: Rainfall intensities during the rainy season, recent years versus all years.

country	location	day of year 1)	intensity (mm)		day of year 2)	intensity (mm)		difference	
			all	1971..		all	1971..	all years	..1971
Niger	Niamey	130	4.7*	5.0	210	5.1	3.0	0.4**	-2.0***
	Gaya	120	5.5	5.5	210	9.2	6.7	3.7	1.2
	Bouza	150	4.3	4.0	220	6.0	4.5	1.7	0.5
Burkina Faso	Dori	150	5.2	4.2	210	5.2	4.7	0.0	0.5
	Kaya	120	4.5	4.2	195	6.3	6.7	1.8	2.5
	Boromo	113	5.2	5.2	180	7.5	6.0	2.3	0.8

1) This is an arbitrary day early in the growing season.
2) This is an arbitrary day late in the growing season.

*) This is the rainfall intensity at onset date 130, based on the regression coefficients for the correlations onset-duration and onset-amount.
**) column 7 minus column 4.
***) column 8 minus column 5.

Table 16: Potential of the onset at one location predicting the onset at a location more to the north.

predictor location	predicted location	r^2 onset	missing years (19..)	n (years)	r^2 annual
Pala	Timan	.64	76-78	9	
Bouza	Tahoua	.54		12	
Fada	Dori	.43	76,77	10	.00
Gaya	Tahoua	.40	67-70	8	.35
Diourbel	St. Louis	.40		12	.47
Gaoua	Dori	.38	77	11	.0
Bamako Aero	Kita	.33	75	11	.63
Ouagadougou	Dori	.29	77	11	.53
Ouagadougou	Kaya	.28	73,77	10	
Pala	Bokoro	.27	67,69,75,77	8	
Sarh	Timan	.27	76-78	9	
Moundou	Bokoro	.22	67,69,75,77	8	
Bamako Aero	Bougouni	.22	75	11	.44
Kaya	Dori	.20	73,77	10	
Pala	Mongo	.18		12	
Niamey	Tillabery	.18		12	.41
Gaoua	Boromo	.18	77	11	.17
Moundou	Mongo	.12		12	
Bobo	Boromo	.12	77	11	.04
Maradi	Zinder	.09		12	.02
Kaolack	Linguere	.09		12	.34
Gaya	Niamey	.09	67-70	8	.53
Kolda	Linguere	.08	74	11	.34
Gaoua	Bobo	.08	77	11	.57
Sarh	Mongo	.07		12	
Koutiala	San	.04		12	.00
Diourbel	Kaolack	.04		12	.63
Moundou	Timan	.04	76-78	9	
Sarh	Bokoro	.03	67,69,75,77	8	
San	Bougouni	.02		12	.00
Maradi	Bouza	.02		12	
Kenieba	Kayes	.02		12	.24
Tambacounda	Matam	.01	72	11	.28
Kayes	Bougouni	.01		12	.42
Timan	Abeche	.01	76-78	9	
Gaoua	Ouagadougou	.00	77	11	.02
Pala	N Djamena		78	11	.05
Gaya	Tahoua	.03		many	.46
Diourbel	St. Louis	.01		33	
Fada	Dori	.01		52	
Gaoua	Dori	.00		53	

r^2 onset: r^2 of linear regression equation $onset_{predicted} = a + b^{*} onset_{predictor}$
r^2 annual: r^2 of linear regression equation annual $rain_{predicted} = a + b^{*}$annual $rain_{predictor}$

Table 17: Potential of the onset at several locations predicting the onset at one or more locations more to the north.

predictor locations	predicted location(s)	r^2 onset	missing years (19..)	n (years)
Boromo,Ouagadougou,Fada	Dori	.73	76,77	10
Pala,Moundou,Sarh	Timan	.56	76-78	9
Pala,Moundou,Sarh	Bokoro	.35	67,69,75,77	8
Ziguinchor,Kolda,Tambacounda	Linguere	.32	74	11
Niamey,Gaya,Birni N Konni	Tahoua	.31	67-70	8
Pala,Moundou,Sarh	Mongo	.28		12
Pala,Moundou,Sarh	Mongo	.28		12
Boromo,Ouagadougou,Fada	Ouahigouya	.28	76,77	10
Bobo,Boromo,Gaoua	San	.22	77	11
Dori,Ouagadougou,Boromo,Ouahigouya	Menaka	.20	76,77	10
Gaya,Niamey,Tillabery	Menaka	.16	67-70,74,76	7
Pala,Moundou,Sarh	Abeche	.13		12
Maradi,Zinder	Tahoua	.11		12
Bougouni,Sikasso,Koutiala	Mopti	.11		12
Bobo,Boromo,Gaoua	Ouahigouya	.09	77	11
Dori,Ouagadougou,Boromo,Ouahigouya	Hombori	.02	77	11
Bobo,Boromo,Gaoua	Mopti	.02	77	11
Pala,Moundou,Sarh	Bousso	.01		12
Pala,Moundou,Sarh	Bol	.01	67-69,72,78	7
Bougouni,Sikasso,Koutiala	Hombori	.01		12
Bougouni,Sikasso,Koutiala	Gao	.01	74	11
Kolda,Tambacounda,Kedougou	Matam	.00	67,72,74	9
Kenieba,Kita,Bamako	Nioro	.00	75	11
Dori,Ouagadougou,Boromo,Ouahigouya	Gao	.00	74,77	10
Bougouni,Sikasso,Koutiala	Menaka	.00	76	11
Boromo,Ouagadougou,Fada	Dori	.38		30
Pala,Moundou,Sarh	Timan,Mongo	.70	76-78	9
Pala,Moundou,Sarh	Abeche,Mongo,Timan	.46	76-78	9
Pala,Moundou,Sarh	Bokoro,Mongo	.45	67,69,75,77	8
Pala,Moundou,Sarh	Abeche,Mongo	.39		12
Niamey,Gaya,Birni N Konni,Tillabery	Gao,Menaka	.12	67-70,74,76	6
Bougouni,Sikasso	San,Segou	.12		12
Dori,Ouagadougou,Boromo,Ouahigouya	Menaka,Hombori,Gao	.09	74,76,77	9
Bougouni,Sikasso,Koutiala	Mopti,Hombori,Gao	.09	74	11
Ziguinchor,Kolda,Tambacounda,Kedougou	Linguere,Matam	.04	67,72,74	9
Ziguinchor,Kolda,Tambacounda,Kedougou	St. Louis,Matam	.00	67,72,74	9

Table 18: Potential of pre-season rain as a rainfall predictor in combination with onset.

	r squares			
	amount		duration	
location	onset+pre	onset	onset+pre	onset
Ansongo	.44	.41	.74	.73
Boromo	.26	.08	.78	.78
Bouza	.26	.20	.78	.66
Dori	.41	.41	.67	.65
Gaya	.17	.16	.81	.81
Kaya	.14	.11	.73	.73
Kayes	.09	.09	.50	.49
Kolokani	.26	.25	.85	.85
Niamey	.42	.38	.78	.77
Nioro du Rip	.27	.07	.71	.71
Podor	.48	.46	.60	.60

onset: amount (duration) = a + b*onset date
onset + pre: amount (duration) = a + b*onset date + c*pre-season rain

Table 19: Onset, end and duration of the rainy season, for two PET fractions and three different rainfall probabilities.

			50*PET			35*PET		
location	period		25%	50%	75%	25%	50%	75%
bakel	..1970	onset	173	184	191	166	174	180
		end	282	273	261	287	279	270
		dur	109	89	70	121	105	90
	1971..	onset	177	178	188	170	171	177
		end	274	273	266	280	278	273
		dur	97	95	78	110	107	96
bam	..1970	onset	158	167	175	147	155	163
		end	279	270	262	285	276	269
		dur	121	103	87	138	121	106
	1971..	onset	149	168	181	139	154	159
		end	272	267	257	279	274	265
		dur	123	99	76	140	120	106
banamba	..1970	onset	155	166	171	145	154	163
		end	285	278	271	291	283	276
		dur	130	112	100	146	129	113
	1971..	onset	155	159	171	147	152	161
		end	279	273	267	285	280	273
		dur	124	114	96	138	128	112
bandiagara	..1970	onset	166	175	182	155	165	173
		end	280	272	259	286	279	268
		dur	114	97	77	131	114	95
	1971..	onset	168	175	195	154	159	176
		end	277	272	265	283	277	272
		dur	109	97	70	129	118	96
banfora	..1970	onset	103	122	143	91	110	124
		end	304	289	281	316	301	285
		dur	201	167	138	225	191	161
	1971..	onset	111	131	156	98	116	142
		end	299	282	277	306	288	283
		dur	188	151	121	208	172	141
bankass	..1970	onset	166	172	181	152	160	171
		end	280	274	259	286	280	268
		dur	114	102	78	134	120	97
	1971..	onset	167	172	189	153	163	170
		end	276	268	259	283	274	267
		dur	109	96	70	130	111	97
belbedji	..1970	onset	189	205	220	178	193	202
		end	252	246	233	259	254	244
		dur	63	41	13	81	61	42
	1971..	onset	183	214	0	174	189	210
		end	242	232	0	250	243	234
		dur	59	18	0	76	54	24

onset: onset of the rainy season (day of year)
end: end of the rainy season (day of year)
dur: duration of the rainy season (days)

			50*PET			35*PET		
location	period		25%	50%	75%	25%	50%	75%
bobo	..1970	onset	114	126	143	104	113	126
		end	302	287	281	309	298	285
		dur	188	161	138	205	185	159
	1971..	onset	116	127	149	99	113	134
		end	288	284	277	298	290	281
		dur	172	157	128	199	177	147
boromo	..1970	onset	123	129	152	112	118	134
		end	289	282	275	300	287	280
		dur	166	153	123	188	169	146
	1971..	onset	128	144	158	102	122	138
		end	286	279	270	295	284	277
		dur	158	135	112	193	162	139
bourem	..1970	onset	0	0	0	203	0	0
		end	0	0	0	239	0	0
		dur	0	0	0	36	0	0
	1971..	onset	0	0	0	0	0	0
		end	0	0	0	0	0	0
		dur	0	0	0	0	0	0
dagana	..1970	onset	197	208	222	184	199	211
		end	273	260	240	282	271	262
		dur	76	52	18	98	72	51
	1971..	onset	210	216	0	200	206	224
		end	260	253	0	269	265	236
		dur	50	37	0	69	59	12
dedougou	..1970	onset	136	149	160	119	139	150
		end	288	281	276	298	286	282
		dur	152	132	116	179	147	132
	1971..	onset	134	158	166	124	136	155
		end	281	275	265	289	282	273
		dur	147	117	99	165	146	118
diapaga	..1970	onset	132	152	167	118	132	148
		end	280	277	273	285	281	277
		dur	148	125	106	167	149	129
	1971..	onset	133	167	172	123	131	149
		end	280	276	266	287	282	273
		dur	147	109	94	164	151	124
diebougou	..1970	onset	109	128	143	98	113	129
		end	297	285	280	306	293	284
		dur	188	157	137	208	180	155
	1971..	onset	115	129	144	98	110	130
		end	286	282	278	295	286	282
		dur	171	153	134	197	176	152
diourbel	..1970	onset	171	180	191	165	173	183
		end	297	281	273	304	286	279
		dur	126	101	82	139	113	96
	1971..	onset	175	181	187	171	177	181
		end	277	274	271	281	278	276
		dur	102	93	84	110	101	95

			50*PET			35*PET		
location	period		25%	50%	75%	25%	50%	75%
djenne	..1970	onset	161	168	181	148	157	171
		end	274	267	262	280	274	270
		dur	113	99	81	132	117	99
	1971..	onset	170	175	194	161	168	181
		end	275	264	252	284	273	260
		dur	105	89	58	123	105	79
dori	..1970	onset	170	180	186	156	170	177
		end	272	266	260	279	273	267
		dur	102	86	74	123	103	90
	1971..	onset	177	180	191	164	168	181
		end	262	258	246	271	265	254
		dur	85	78	55	107	97	73
fada	..1970	onset	134	145	162	120	130	147
		end	282	278	272	286	282	277
		dur	148	133	110	166	152	130
	1971..	onset	141	158	165	127	137	145
		end	282	276	260	287	281	269
		dur	141	118	95	160	144	124
fatick	..1970	onset	168	177	183	161	171	177
		end	297	286	277	304	294	282
		dur	129	109	94	143	123	105
	1971..	onset	181	184	198	174	177	189
		end	268	260	253	276	269	258
		dur	87	76	55	102	92	69
gao	..1970	onset	201	220	0	186	198	213
		end	247	232	0	254	245	235
		dur	46	12	0	68	47	22
	1971..	onset	224	0	0	201	221	0
		end	230	0	0	243	229	0
		dur	6	0	0	42	8	0
gaoua	..1970	onset	100	113	131	81	100	112
		end	309	297	286	317	305	294
		dur	209	184	155	236	205	182
	1971..	onset	106	111	143	79	96	107
		end	296	285	280	303	293	285
		dur	190	174	137	224	197	178
garango	..1970	onset	126	138	165	113	123	145
		end	284	280	275	288	284	279
		dur	158	142	110	175	161	134
	1971..	onset	129	169	176	119	132	169
		end	287	280	271	297	287	276
		dur	158	111	95	178	155	107

			50*PET			35*PET		
location	period		25%	50%	75%	25%	50%	75%
gaya	..1970	onset	136	154	172	122	134	157
		end	281	276	272	285	280	277
		dur	145	122	100	163	146	120
	1971..	onset	129	154	173	119	131	149
		end	277	273	271	282	278	276
		dur	148	119	98	163	147	127
goudoumaria	..1970	onset	184	187	191	178	179	183
		end	262	257	248	270	266	257
		dur	78	70	57	92	87	74
	1971..	onset	182	189	0	176	181	191
		end	253	240	0	258	249	239
		dur	71	51	0	82	68	48
gourma	..1970	onset	222	0	0	193	210	0
		end	230	0	0	244	239	0
		dur	8	0	0	51	29	0
	1971..	onset	0	0	0	213	0	0
		end	0	0	0	232	0	0
		dur	0	0	0	19	0	0
guene-gore	..1970	onset	136	143	147	126	134	140
		end	312	299	286	315	306	293
		dur	176	156	139	189	172	153
	1971..	onset	138	143	151	129	136	143
		end	303	297	289	309	304	298
		dur	165	154	138	180	168	155
guidimouni	..1970	onset	175	185	191	170	176	182
		end	261	254	243	269	263	254
		dur	86	69	52	99	87	72
	1971..	onset	180	185	192	170	176	183
		end	253	243	238	257	251	247
		dur	73	58	46	87	75	64
n guigmi	..1970	onset	194	212	227	185	200	214
		end	250	238	228	255	245	237
		dur	56	26	1	70	45	23
	1971..	onset	204	0	0	194	214	0
		end	244	0	0	250	235	0
		dur	40	0	0	56	21	0
hombori	..1970	onset	177	186	201	170	177	189
		end	263	254	249	272	262	258
		dur	86	68	48	102	85	69
	1971..	onset	176	192	197	170	180	183
		end	259	250	236	269	262	246
		dur	83	58	39	99	82	63

			50*PET			35*PET		
location	period		25%	50%	75%	25%	50%	75%
kabara	..1970	onset	202	221	0	188	200	219
		end	244	231	0	254	244	233
		dur	42	10	0	66	44	14
	1971..	onset	221	0	0	195	209	0
		end	231	0	0	244	237	0
		dur	10	0	0	49	28	0
kalana	..1970	onset	115	127	143	103	113	128
		end	313	303	288	318	312	298
		dur	198	176	145	215	199	170
	1971..	onset	99	133	147	90	118	139
		end	301	293	287	308	302	296
		dur	202	160	140	218	184	157
kaolack	..1970	onset	162	172	184	154	164	176
		end	297	285	280	304	292	284
		dur	135	113	96	150	128	108
	1971..	onset	170	177	197	164	173	188
		end	280	279	272	284	282	278
		dur	110	102	75	120	109	90
kaya	..1970	onset	147	158	171	133	148	161
		end	280	272	266	285	278	273
		dur	133	114	95	152	130	112
	1971..	onset	156	169	175	141	154	162
		end	275	272	260	280	277	268
		dur	119	103	85	139	123	106
kayes	..1970	onset	158	165	173	151	157	164
		end	291	279	271	300	284	277
		dur	133	114	98	149	127	113
	1971..	onset	157	168	179	151	160	170
		end	280	275	261	285	281	270
		dur	123	107	82	134	121	100
kedougou	..1970	onset	139	146	151	132	141	146
		end	312	304	294	315	309	302
		dur	173	158	143	183	168	156
	1971..	onset	141	149	153	133	144	146
		end	297	288	285	305	297	288
		dur	156	139	132	172	153	142
ke-machina	..1970	onset	169	175	184	158	167	177
		end	275	270	259	281	276	267
		dur	106	95	75	123	109	90
	1971..	onset	170	176	192	148	168	180
		end	277	263	254	281	270	263
		dur	107	87	62	133	102	83

			50*PET			35*PET		
location	period		25%	50%	75%	25%	50%	75%
kidal	..1970	onset	0	0	0	215	0	0
		end	0	0	0	239	0	0
		dur	0	0	0	24	0	0
	1971..	onset	0	0	0	223	0	0
		end	0	0	0	232	0	0
		dur	0	0	0	9	0	0
kita	..1970	onset	141	150	159	131	142	151
		end	299	288	282	306	298	286
		dur	158	138	123	175	156	135
	1971..	onset	146	149	154	141	144	147
		end	285	282	275	292	287	280
		dur	139	133	121	151	143	133
kolda	..1970	onset	150	155	162	145	149	155
		end	309	303	294	313	308	302
		dur	159	148	132	168	159	147
	1971..	onset	155	167	170	149	160	166
		end	295	287	284	303	297	288
		dur	140	120	114	154	137	122
kolokani	..1970	onset	149	166	172	140	153	166
		end	285	279	273	292	283	278
		dur	136	113	101	152	130	112
	1971..	onset	156	166	171	147	155	158
		end	280	275	269	285	282	278
		dur	124	109	98	138	127	120
koudougou	..1970	onset	136	148	164	122	137	150
		end	287	282	276	298	286	281
		dur	151	134	112	176	149	131
	1971..	onset	148	164	171	128	147	156
		end	278	272	258	285	279	267
		dur	130	108	87	157	132	111
koupela	..1970	onset	130	150	160	115	133	148
		end	281	277	271	285	282	277
		dur	151	127	111	170	149	129
	1971..	onset	136	166	174	120	132	163
		end	279	274	268	287	282	275
		dur	143	108	94	167	150	112
koutiala	..1970	onset	137	146	156	[illegible]6	137	146
		end	294	284	279	303	289	284
		dur	157	138	123	187	152	138
	1971..	onset	130	143	158	120	127	140
		end	290	279	273	299	283	278
		dur	160	136	115	179	156	138

			50*PET			35*PET		
location	period		25%	50%	75%	25%	50%	75%
leo	..1970	onset	113	130	147	99	110	127
		end	293	282	277	303	286	281
		dur	180	152	130	204	176	154
	1971..	onset	122	142	169	110	125	135
		end	285	280	272	290	285	279
		dur	163	138	103	180	160	144
st. louis	..1970	onset	190	201	216	180	193	208
		end	278	268	257	284	275	267
		dur	88	67	41	104	82	59
	1971..	onset	0	0	0	0	215	215
		end	0	0	0	0	266	266
		dur	0	0	0	0	51	51
maine soroa	..1970	onset	178	187	197	171	178	187
		end	258	253	246	269	258	253
		dur	80	66	49	98	80	66
	1971..	onset	182	188	212	175	180	193
		end	256	248	237	264	255	247
		dur	74	60	25	89	75	54
manga	..1970	onset	140	145	162	121	127	134
		end	286	281	275	295	285	279
		dur	146	136	113	174	158	145
	1971..	onset	122	132	167	112	120	139
		end	285	276	271	294	283	278
		dur	163	144	104	182	163	139
maradi	..1970	onset	167	173	182	153	166	174
		end	273	266	261	279	273	269
		dur	106	93	79	126	107	95
	1971..	onset	179	185	187	170	177	179
		end	261	251	244	269	256	250
		dur	82	66	57	99	79	71
markala	..1970	onset	164	170	178	152	161	171
		end	281	274	269	286	279	275
		dur	117	104	91	134	118	104
	1971..	onset	168	176	183	156	168	174
		end	273	263	257	283	273	265
		dur	105	87	74	127	105	91
matam	..1970	onset	175	183	193	169	175	184
		end	283	271	261	292	278	269
		dur	107	88	68	123	103	85
	1971..	onset	198	210	218	189	203	210
		end	261	253	247	270	263	259
		dur	63	43	29	81	60	49

			50*PET			35*PET		
location	period		25%	50%	75%	25%	50%	75%
mopti	..1970	onset	169	177	187	157	170	176
		end	275	267	257	282	274	265
		dur	106	90	70	125	104	89
	1971..	onset	173	179	189	162	168	176
		end	272	268	259	281	277	268
		dur	99	89	70	119	109	92
niafunke	..1970	onset	188	205	227	179	189	200
		end	267	259	228	274	268	249
		dur	79	54	1	95	79	49
	1971..	onset	193	197	220	181	186	200
		end	256	243	233	266	254	249
		dur	63	46	13	85	68	49
niamey	..1970	onset	161	173	184	149	164	174
		end	273	263	257	279	271	265
		dur	112	90	73	130	107	91
	1971..	onset	171	181	189	150	171	178
		end	263	257	249	272	265	261
		dur	92	76	60	122	94	83
niangoloko	..1970	onset	89	105	125	75	91	109
		end	306	294	285	316	305	291
		dur	217	189	160	241	214	182
	1971..	onset	115	121	144	107	111	129
		end	294	287	282	303	297	287
		dur	179	166	138	196	186	158
nioro du rip	..1970	onset	158	170	176	151	163	170
		end	300	287	282	306	296	287
		dur	142	117	106	155	133	117
	1971..	onset	168	173	186	159	166	177
		end	280	278	276	283	282	281
		dur	112	105	90	124	116	104
nouna	..1970	onset	142	149	159	129	137	146
		end	285	280	267	293	285	276
		dur	143	131	108	164	148	130
	1971..	onset	142	160	163	129	146	151
		end	282	275	260	289	281	269
		dur	140	115	97	160	135	118
ouagaa	..1970	onset	125	138	153	116	126	133
		end	283	277	272	287	282	278
		dur	158	139	119	171	156	145
	1971..	onset	140	156	164	119	135	149
		end	281	273	268	286	279	274
		dur	141	117	104	167	144	125

			50*PET			35*PET		
location	period		25%	50%	75%	25%	50%	75%
ouagam	..1970	onset	137	152	164	123	136	153
		end	281	275	268	286	280	274
		dur	144	123	104	163	144	121
	1971..	onset	140	155	163	122	133	151
		end	280	275	267	285	280	274
		dur	140	120	104	163	147	123
po	..1970	onset	115	132	153	100	118	142
		end	287	282	278	297	286	283
		dur	172	150	125	197	168	141
	1971..	onset	123	146	166	112	126	131
		end	285	278	264	294	283	272
		dur	162	132	98	182	157	141
podor	..1970	onset	196	207	0	182	197	218
		end	275	263	0	284	272	246
		dur	79	56	0	102	75	28
	1971..	onset	217	225	0	203	213	221
		end	238	231	0	251	246	237
		dur	21	6	0	48	33	16
sedhiou	..1970	onset	151	160	164	146	153	156
		end	310	303	291	313	308	300
		dur	159	143	127	167	155	144
	1971..	onset	155	163	173	149	155	169
		end	287	285	281	297	288	285
		dur	132	122	108	148	133	116
sikasso	..1970	onset	114	128	142	104	115	132
		end	307	297	287	313	306	296
		dur	193	169	145	209	191	164
	1971..	onset	115	123	133	105	112	120
		end	307	295	286	314	304	295
		dur	192	172	153	209	192	175
sokolo	..1970	onset	173	178	184	168	172	177
		end	276	265	255	281	273	263
		dur	103	87	71	113	101	86
	1971..	onset	173	185	198	161	174	187
		end	268	256	249	275	264	256
		dur	95	71	51	114	90	69
sotuba	..1970	onset	143	147	155	136	140	146
		end	298	287	278	305	295	283
		dur	155	140	123	169	155	137
	1971..	onset	142	153	158	131	140	148
		end	295	284	277	303	292	282
		dur	153	131	119	172	152	134

			50*PET			35*PET		
location	period		25%	50%	75%	25%	50%	75%
tahoua	..1970	onset	181	191	206	171	179	188
		end	259	250	239	268	258	251
		dur	78	59	33	97	79	63
	1971..	onset	184	199	225	172	183	204
		end	250	243	229	259	253	243
		dur	66	44	4	87	70	39
tambacounda	..1970	onset	150	157	165	145	150	158
		end	303	290	282	308	299	286
		dur	153	133	117	163	149	128
	1971..	onset	156	162	168	150	155	162
		end	294	282	275	302	291	282
		dur	138	123	107	152	136	120
tenkodogo	..1970	onset	122	143	163	110	127	143
		end	285	280	275	291	284	280
		dur	163	137	112	181	157	137
	1971..	onset	129	132	168	117	123	152
		end	286	276	272	295	281	278
		dur	157	144	104	178	158	126
tillabery	..1970	onset	177	185	197	167	174	184
		end	266	258	252	274	265	258
		dur	89	73	55	107	91	74
	1971..	onset	178	187	210	167	176	194
		end	259	249	242	267	259	251
		dur	81	62	32	100	83	57
tougan	..1970	onset	154	162	171	141	149	160
		end	286	280	271	295	286	277
		dur	132	118	100	154	137	117
	1971..	onset	153	160	172	137	149	161
		end	275	267	256	280	274	263
		dur	122	107	84	143	125	102
yelimane	..1970	onset	168	175	181	159	168	174
		end	279	273	267	285	279	273
		dur	111	98	86	126	111	99
	1971..	onset	177	180	186	169	172	179
		end	277	273	266	283	279	273
		dur	100	93	80	114	107	94
ziguinchor	..1970	onset	151	156	166	146	150	159
		end	311	305	291	314	310	300
		dur	160	149	125	168	160	141
	1971..	onset	166	167	172	158	161	169
		end	292	285	282	301	288	285
		dur	126	118	110	143	127	116

Table 20: Rainy season duration (days) based on dry spell probabilities.

location	..1970	1971..	difference	location	..1970	1971..	difference
bakel	68	55	13	ke-machina	85	55	30
bam	111	114	-3	kidal	0	19	-19
banamba	95	83	12	kita	125	124	1
bandiagara	90	94	-4	kolda	117	80	37
banfora	139	126	13	kolokani	110	113	-3
bankass	78	104	-26	koudougou	122	112	10
belbedji	38	0	38	koupela	126	112	14
bobo	160	143	17	kutiala	134	155	-21
boromo	134	154	-20	leo	130	73	57
bourem	0	0	0	maine soroa	66	72	-6
dagana	0	17	-17	manga	136	112	24
dedougou	121	114	7	maradi	89	85	4
diapaga	119	112	7	markala	86	62	24
diebougou	130	124	6	matam	58	30	28
diourbel	73	69	4	mopti	106	117	-11
djenne	84	39	45	niafunke	43	25	18
dori	83	95	-12	niamey	104	88	16
fada	127	137	-10	niangoloko	156	165	-9
fatick	77	48	29	nioro du rip	95	66	29
gao	39	49	-10	nouna	109	115	-6
gaoua	159	150	9	ouagaa	132	143	-11
garango	113	63	50	ouagam	114	142	-28
gaya	113	127	-14	po	123	130	-7
goudoumaria	58	25	33	podor	0	15	-15
gourma	0	0	0	sedhiou	114	87	27
guene-gore	145	131	14	sikasso	162	157	5
guidimouni	78	49	29	sokolo	63	51	12
n guigmi	19	29	-10	sotuba	117	116	1
hombori	79	80	-1	tahoua	76	91	-15
kabara	0	0	0	tambacounda	109	59	50
kalana	134	117	17	tenkodogo	128	138	-10
kaolack	100	70	30	tillabery	86	78	8
kaya	104	99	5	tougan	106	120	-14
kayes	105	74	31	yelimane	81	21	60
kedougou	130	127	3	ziguinchor	122	116	6

Table 21: Comparison of monthly PET data (mm) from two different sources.

location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
agadez	H	138	152	190	219	233	226	226	213	209	198	155	133
	V	138	161	193	204	219	204	202	175	170	169	146	130
	D	0	-9	-3	15	14	22	24	38	39	29	9	3
bobo	H	139	153	175	177	183	155	147	138	144	161	156	149
	V	147	155	187	173	163	131	123	116	118	138	128	133
	D	-8	-2	-12	4	20	24	24	22	26	23	28	16
boromo	H	140	155	178	182	185	152	149	141	145	155	157	142
	V	145	153	189	182	175	139	131	114	118	147	132	133
	D	-5	2	-11	0	10	13	18	27	27	13	25	9
dori	H	148	173	214	214	224	203	181	165	176	199	172	157
	V	150	163	202	209	214	200	163	135	132	166	144	138
	D	-2	10	12	5	10	3	18	30	44	33	28	19
gaya	H	143	157	185	185	187	164	158	149	153	167	144	125
	V	133	148	177	178	194	187	147	119	130	150	133	126
	D	10	9	8	7	-7	-23	11	30	23	17	11	-1
n guigmi	H	131	153	198	205	218	209	191	193	183	187	153	132
	V	115	130	163	177	184	178	164	140	145	150	129	112
	D	16	23	35	28	34	31	27	53	38	37	24	20
kayes	H	139	154	190	199	207	191	171	163	159	170	129	124
	V	139	146	190	200	260	173	144	117	127	137	126	124
	D	0	8	0	-1	-53	18	27	46	32	33	3	0
kedougou	H	143	157	185	197	185	173	154	144	147	159	131	124
	V	130	134	174	179	181	145	117	100	105	128	119	115
	D	13	23	11	18	4	28	37	44	42	31	12	9
kidal	H	138	145	192	207	234	222	224	215	210	191	151	127
	V	132	165	210	224	240	214	182	161	174	181	147	136
	D	6	-20	-18	-17	-6	8	42	54	36	10	4	-9
niamey	H	152	177	218	217	224	200	180	164	174	200	173	160
	V	163	165	207	202	215	204	157	131	135	172	154	141
	D	-11	12	11	15	9	-4	23	33	39	28	19	19
podor	H	132	145	196	216	215	228	207	206	184	174	135	118
	V	124	124	158	166	160	152	151	136	138	141	118	122
	D	8	21	38	50	55	76	56	70	46	33	17	-4
sikasso	H	135	150	176	179	178	158	150	140	144	162	138	131
	V	140	157	177	177	170	146	123	114	113	137	129	137
	D	-5	-7	-1	2	8	12	27	26	31	25	9	-6
ziguinchor	H	121	144	158	172	185	147	142	134	129	144	137	107
	V	133	134	158	174	177	161	131	125	128	140	125	123
	D	-12	10	0	-2	8	-14	11	9	1	4	12	-16

H: source for PET data is World Water for Agriculture (Hargreaves, 1986)
V: source for PET data is Manuel de climatologie... (Virmani, 1980)
D: difference between Hargreaves and Virmani.

Appendix 1

Agroclimatological Perspectives in Semi-Arid Tropical Agriculture. [1)]

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1. Introduction

The semi-arid tropics (SAT) is a region of limited, erratic rainfall and nutrient-poor soils. It is populated by more than 700 million people, most of whom live at subsistance levels and depend for their food on the limited production of small farms. Current yields are low and production is unstable due to aberrant weather. Semi-arid tropics with 13% of world's land and 15% of its people produce only 11% of its food.

Due to rising populations, food deficits in the SAT are increasing. The situation is alarming in some regions. As an example, it is projected that countries of Sub-Saharan Africa will need food imports in excess of 20 million tons per annum by 1990s. India, where over 100 million ha of land are dryland farmed, has also a very large area of land under irrigated agriculture (some 40 - 50 million ha). She has accumulated food reserves of over 20 million tons, she may lose substantial portion of this reserve in the current drought year. Thus there is an urgent need to harness soil and climatic resources in an agroecologically balanced sense for sustained and increased agricultural production in the SAT.

The (SAT) are relatively dry areas of the tropics. These regions are characterized by a uniformly high temperature throughout the year and have seasonally wet climates. The rainy season is generally short. The dry season lasts for several continuous months during the year. Therefore in semi-arid agriculture, water is one of the most limiting resources. In most situations, dryland farming is the primary management system; therefore, rainfall amount, intensity, frequency, and variability are important factors in developing a cropping system. Thus, the climate, soil, nutrients, and biological resources are linked with social and economic constraints to collectively circumscribe the alternative strategies for dryland agriculture.

In semi-arid agriculture, an agroclimatologist is primarily concerned with

rainfall variability and less with average rainfall amount. If the cropping season were always uniform in rainfall, the farmer would choose a single management plan. He would plant certain crops on specific soil/topography areas of his farm. His planting date, seeding rate, fertility, herbicide, and insecticide would be planned for the optimal yield for that anticipated single rainfall pattern. Obviously, life is not that simple, and the high variability of rainfall creates major problems for the farmer. He must begin the season with a perception of what the rainfall pattern will be. As the season progresses, he makes alternative management decisions based on what the rainfall pattern has been. Thus, it is important that the farmer knows with a significant degree of confidence the expected rainfall pattern in order to make decisions within or even before the growing season.

In this paper we will present:

1) the agroecological features of the semi-arid tropics;
2) agroclimatic analyses of some selected areas for identifying agroclimatic constraints for increased agricultural production;
3) an overview of the impacts of climatic variability and changes that have occurred in the recent years in the Sahelian SAT, in relation to dependable harvests in this marginal agroecological zone; and finally
4) summary and conclusions of this study.

2. Agroecological features of the semi-arid tropics

The climate of the SAT has a prevasive influence on agricultural production. It is also clearly a primary constraint to agricultural development. We therefore commence this paper with a general description of the climatic characteristics of the SAT. For classifying SAT climate a number of geographic techniques have been proposed. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has accepted the climatic classification proposed by Troll (1965) as the

working definition for defining its world mandate region. According to Troll the tropical areas can be classified as follows:

Climate Class	Length of Rainy Season	Associated Vegetation
1.	tropical rainy climates with 9.5 to 12 humid months	tropical rainforest
2.	tropical rainy climates with 7 to 9.5 humid months	humid savanna
3.	wet-dry tropical climates with 4.5 to 7 humid months	dry savanna
4a.	tropical dry climates with 2 to 4.5 humid months	thorn savanna
5.	tropical semi-desert climates with less than 2 humid months	semi-desert

A humid month is defined as a month in which mean monthly rainfall exceeds potential evapotranspiration. The classes of interest in terms of semi-arid climates are the wet-dry tropical climates and the tropical dry climates. The ICRISAT climatologists consider that Troll's climate classes 3 and 4a generally represent what is usually termed as semi-arid tropics or SAT. This agroecological zone is typified by dry and thorn savannas. In terms of the length of the rainy season the wet-dry tropical climates (also termed wet SAT) have a longer humid period than the tropical dry climatic region (also termed dry SAT). The wet SAT represents a climatic zone where the growing season may extend from 150 - 210 days; in the dry SAT the growing season ranges between 60 and 150 days or longer. World regions that have climate in accord with this classification scheme are depicted in Figure 1.

2.1. Rainfall and PE in the SAT

The spatial and temporal variations in rainfall in the semi-arid tropics are due to seasonal migration of the equatorial trough or the intertropical convergence zone (ITCZ) which occurs in response to the seasonal variation in the latitude of maximum insolation. Thus the annual rainfall over the semi-arid tropics can be

thought of as the integrated effect of the annual visit of the ITCZ to the region. The annual distribution of rainfall and potential evapotranspiration for some typical dry SAT locations is set out in Table 1. The annual rainfall in the dry SAT varies from about 500 to 1200 mm. The PE values range between 1200 and 2000 mm. The rainfall is unimodal with a peak corresponding to the time at which the ITCZ is over the region. In these latitudes the month receiving maximum amount of rainfall is August or September. In the southern latitudes peak rainfall is observed in any of the months during the period December to May. For example, at Motopos, Zimbabwe peak rainfall is recorded in the month of December, while the month of April registers maximum rainfall at Moragoro, Tanzania. In the equatorial zone, the rainfall is bimodal. Nairobi, lying just 1° south of the equator shows the first rainfall peak during the in the month of November during the 'long rains'. Debre-Zeit located 8 °N of the equator shows the first peak of rainfall in the month of April and the second peak in July.

The atmospheric demand for water in the semi-arid tropics is high. It is particularly high before the rainy season or at the beginning of the rainy season. For example, in the month of May, we have noted the average open-pan evaporation to range around 10 mm/day, while on some days it could be as high as 15 mm both at Hyderabad and Niamey. Mean monthly and annual PE averaged over 169 locations in India is shown in Table 2. These data show that the variability of PE during the prerainy and rainy seasons extending from April to October is somewhat lower compared to other months of the year and that the atmospheric demand for water in the SAT is consistently high.

High rates of evaporation coupled with low and variable rainfall in the semi-arid tropics often leads to periods of water deficit and, have serious implications for stability of crop production in this ecological zone. It is only the rainy period of the year during which the rainfall exceeds PE, when the soil moisture reserves are

recharged. This period extends from 2 to 4.5 months in the dry SAT.

2.2. Rainfall during crop growing season

In an agricultural sense, then, the length of the crop growing season in the SAT is primarily limited by the duration and other characteristics of the rainy period. The reliability of the rainfall at the beginning of the season is generally low. Consequently the SAT exhibits a high degree of risk to the establishment of crops, because the soil moisture reserves at this time are practically non-existent. The soil temperatures are also fairly high, generally the surface 5 cm soil has a maximum temperature of 40 - 50 °C. The variability of rainfall at the end of the season is also high, affecting crop yield and their quality.

In agronomic sense, the year in the SAT climates can be divided into 4 phases:

(1) The pre-rainy season, which may extend from one to two months, and is also sometimes called as the period of 'short rains'.

(2) The rainy season, which is the period during which the monsoons or the ITCZ is active. It is also called the period of 'long rains'.

(3) The post-rainy season which is generally a cool and dry season. The crops during this time thrive on the moisture stored in the soil profile.

(4) A hot dry season which may extend from a month to several months. It generally precedes the rainy season. During this period the temperatures are quite high.

In the following sections agroclimate characteristics and recent advances in agroclimatological research to aid in increasing and stabilizing agricultural production for some selected areas of SAT are discussed. These areas are: the Indian sub-continent, the sub-saharan Sahelian zone, and Botswana.

3. The Indian SAT.

Semi-arid area covers almost 80% of the total land surface of India of which a major proportion lies in the dry SAT (Fig. 1). The Indian dry SAT is characterized by a short and intense rainy season followed by a relatively long dry season. The amount of rainfall received annually ranges between 400 and 1400 mm, the rainy season may have one peak (unimodal) or two peak periods (bimodal) of rainfall. The rainfall distribution of some SAT locations of India is shown in Fig. 2.

The Indian SAT areas lying between 5 and 12 °N latitude are distinctly bimodal, while the rainfall is generally unimodal in areas located above 20 °N latitude. In the Indian SAT some 85 % of the total annual rainfall is received during the rainy months. As was described in the previous section, the dry SAT areas show considerable variability of rainfall from year to year. The annual rainfall variability for the five locations is shown in Fig. 3. The mean annual rainfall based on data from 1941 - 1970 ranged between 382 mm (Jodhpur) and 1001 mm (Indore) and the coefficient of variation ranged between 20 (Hyderabad) and 42 % (Jodhpur). In the Indian SAT droughts occur frequently. The Indian Planning Commission defines a year as drought year when the annual rainfall is 75 % or less of the long term average of the location. Accordingly, the number of years which received rainfall below 75 % of the corresponding average for the location was 8 in Jodhpur, 6 in Anantpur, 2 in Hyderabad, 4 in Dharwad, and 6 in Indore (out of 30 years).

Therefore for planning any agricultural development strategy, the relative distribution of drought years when the crops are likely to fail or yield poorly should be taken into consideration. This is one of the major considerations for the farmers for the adoption of improved technologies because these require investments in new seeds, fertilizers and crop protection against diseases and pests. The small farmers of the SAT can ill afford to lose a cropping season.

The distribution of rainfall during the year in the SAT is quite erratic. Distribution of rainfall during 3 years at the ICRISAT Center is shown in Figure 4 as an example. The figure depicts that the rainfall is quite unevenly distributed and that there are periods of marked high rainfall followed by relatively dry or rainless periods. Therefore for developing alternate crop production strategies, it is important to consider rainfall distribution pattern as well as its reliability. At ICRISAT, it has been found that the rainfall can be characterized, in agronomic terms, most usefully by estimating the probabilities of soil moisture in a stochastic process. Markov chain procedures can be used effectively for defining the dependability of rainfall during the rainy season (Robertson, 1976; Virmani et. al. 1982; Huda and Virmani 1987). The risks that sowing rains received by crops will not be enough to ensure survival, and the dependability of rainfall later at critical stages of crop development, can then be assessed through such analyses.

We examined the mean weekly rainfall distribution and the probability of receiving at least 10 mm and 20 mm rainfall in each week for these five locations (Figure 5). The average number of weeks receiving at least 20 mm was 11 in Jodhpur, 10 in Anantpur, 16 in Hyderabad, 22 in Dharwad, and 16 in Indore. The continuity of rainfall is important for determining length of growing season. The consecutive weeks receiving at least 20 mm rainfall were 11 in Jodhpur, 5 in Anantpur, 15 in Hyderabad, 15 in Dharwad, and 16 in Indore.

The results of the Markov chain procedure to determine the probability of receiving different amounts of rainfall in each week are also depicted in Fig. 5. The number of weeks with at least 70 % probability of receiving > 20 mm was 5 in Indore, 2 in Hyderabad, 1 in Dharwad, and 0 each in Jodhpur and Anantapur. These results indicate the relative risks of growing rainy season crops across the range of agroclimates represented by these locations.

Considering the discussion on the distribution and dependability of rainfall

presented so far for the Indian subcontinent, the following could be considered as main agroclimatic constraints/attributes of the 5 selected locations to increased crop production.

1. Jodhpur [26° 18′ N; 73° 01′ E; elevation 224 m. Soils Orthids and Psamments]. In this western Indian location water is the most limiting factor and improved agriculture production should aim at stabilizing crop production. The average length of the growing season is 88 days. Risks to dependable crop production are high due to recurrence of droughts. One short duration crop of pearl millet yielding in excess of 1500 kg/ha can be harvested 4 years in 10; in other years the grain yield is likely to be low. The agroenvironment in Jodhpur represents a large tract of western India (Fig. 6) where the rainy season is restricted to about 2 months, the PE rates during the rainy cropping season are high and the soils are light textured. Agropastural rather than crop production systems would be more productive and ecologically sound for areas with an agroclimate like Jodhpur.

2. Anantpur [14° 41′ N; 77° 37′ E; elevation 348 m. Soils Ustalfs]. In this southern Indian bimodal rainfall location, the average rainfall is 563 mm which meets 30 % of the annual ET demand. Although the rainy season commences in May and the rains continue up to October, the average monthly rainfall is always less than ET. The soils of Anantpur region are shallow sandy Alfisols, therefore the growing season is restricted to 120 days, out of which the stress free period extends to only 45 days in the months of August and September. In this location, as in Jodhpur, successful crop production is generally limited to 4 out of 10 years. Foxtail millet and groundnut crops are commonly growing. Agroecologically the area seems more suitable for agroforestry systems.

3. Dharwad [15° 27′ N; 75° 00′ E; elevation 740m. Soils Usterts]. This location represents a area of less dependable rainfall in central and southern peninsular India

(Fig. 6). The rainy season here commences in May and ends in October. The rainfall is bimodal. The first peak of rainfall is seen in June and the second in October. The month of September is a transition period. It is dry in most years. The Dharwas area is suited for growing a long duration crop with an indeterminate growth habit (e.g., cotton). Two short duration crops can be grown. Yields are intermediate.

4. Hyderabad [17° 27′ N; 78° 28′ E; elevation 545 m. Soils Usterts and Ustalfs]. This southern Indian location represents a substantial area of dependable rainfall of the semi-arid tropics in peninsular India (Fig. 6). Two types of soils contrasting in their water holding capacity are represented here. The Alfisols are sandy loams with 50 cm to 100 cm depth and can hold about 100 mm available soil moisture in the root zone. The Vertisols are clay loam soils generally more than 100 cm deep and can hold about 200 mm available soil water in the root zone. Therefore, in Alfisols the growing season is about 150 days whereas in the Vertisols it extends to 210 days. In the Alfisols of the Hyderabad region intercropping of a short duration crop e.g. sorghum, or millet with a long duration crop of groundnut, or castor, has proven successful. In the Vertisols maize-pigeonpea intercropping or maize followed by a sequential crop of chickpea has generally performed well. In extremely shallow soils, the agroforestry systems have been found to stabilize agricultural production. The Hyderabad climatic zone represents a medium to high potential for dryland crop production. Good harvest of crops is feasible about 8 years in 10 years in the Vertisols, and 6 or 7 years in every 10 years in the Alfisols.

5. Indore [22° 43′ N; 75° 48′ E; elevation 567 m. Soils Usterts, Orthents]. This central Indian location represents a high potential crop production zone of Vertisols in the peninsular India (Fig. 6). Dryland agriculture is commonly practised

in this region. At Indore the growing season length is about 200 days extending from June to December. Two crops can be grown in succession or an intercrop of a short duration cereal in combination with a medium duration (180 - 210 days) pulse crop has been found as a successful practice. Currently intercropping of soybean with pigeonpea is being adopted progressively. Provision of adequate drainage facility of excess water received in July, August, and September is important for successful land use of Vertisols. Watershed-based land and water management systems are essential for obtaining increased and stabilized crop production in dryland in this area. Fairly high yields of crops can be harvested at least 8 years out of every 10 years in this peninsular Indian region.

4. The Sahelian SAT

This is a broad belt lying south of the great Saharan desert. The Sahelian region comprises parts of the West African countries like Senegal, Gambia, Guinea Bissau, Guinea, Mauritania, Mali, Burkina Faso, Ghana, Niger, Togo, Benin, Nigeria, Cameroon, Chad, etc. In this region sorghum, millet, groundnut and maize are commonly grown food crops. The crops yields are low. Dryland agriculture is commonly practised. Crop failures due to recurrence of droughts is common. The past two decades or so have witnessed a drastic reduction in the amount and length of the rainy season. This region presents a serious challenge to the agricultural sciences for innovating technologies for increasing and stabilizing food production of this marginal agroecological zone.

4.1. Climatology of the Sahel

Three bioclimatic zones based on the length of the rainy period/crop growing season are recognised. These are the southern Sahelian bioclimatic zone with a growing season ranging from 75 - 90 days, the Sudan bioclimatic zone with a growing season extending to 165 days and the northern Guinean bioclimatic zone

having a growing season from 165 to 210 days. The distribution of these bioclimates in West Africa is shown in Figure 7. Data in Figure 8 depicts that the monsoon arrives in higher rainfall areas of southern Sahel (Sudan bioclimatic zone) in late April, May or June, then moves northward reaching the drier latitudes verging on the Sahara Desert in July, August or early September. The pattern is unimodal (single peak in rainfall) with recession or withdrawal of the monsoon generally in late September or early October, but sometimes - especially in recent years in the Sahelian bioclimatic locations - in August. Virtually all annual rainfall is received within this season.

Evaporative rates and temperatures in the region are high during the monsoon growing season. Hargreaves and Samani (1986) indicate that evaporation rates (Class A pan equivalent) during the onset period at Niamey, Niger are about 9 mm/day in June, declining in July to about 8 and in August to about 7 due to cloudiness and rains. Temperatures through the season average about 29 °C (84 °F).

The relatively high temperatures and evaporative rates tend to be compensated for by high rainfall intensities. This section will show, for two quite different rainfall zones of Niger, intensities ranging from 4-7 mm/day, with extremes somewhat higher and lower. With reference to lower intensities, findings on the climatic shift since 1971 will be presented and discussed.

Daily climatological data for this paper were obtained from ICRISAT, AGRHYMET, and the Royal Meteorological Institute of Belgium.

4.2. Onset of the rainy season as rainfall predictor

4.2.1. Niamey, Niger

The first example comes from Niamey, the capital of Niger, located in the southwest corner of the country along the Niger River somewhat east of the border of Burkina Faso (see Figure 9). Figure 10 shows the rainfall occurrences in the 30-

year period of 1954-1983. This is not the entire record available for Niamey, but it is the period of special interest for this presentation, for two reasons:

(1) It matches the period of records available from Bouza, Niger, which is the other West Africa example to be discussed in detail. This permits direct comparisons of the two locations.

(2) In 1971 (arguably, as early as 1968), a major reduction in rainfall took place throughout the Sahelian zone. For 50 years before, the rainfall averaged markedly higher. To include the entire longer record would distort the averages in a way that would mask the effects of the recent climatic shift. The 30-year record creates a reasonable balance, with 17 years before the climatic shift and 13 years after.

Figure 10 is a scatter diagram in the form of a "rainfall flag", relating seasonal rainfall amount to date of onset of the monsoon. It is not crop specific, but the major food crop in the area is pearl millet, although many other crops and cultivars having different maturities are grown. Onset is defined as 40 mm of rainfall stored in the surface soil - a somewhat stringent requirement due to the high evaporation rates and temperatures. A year with an early onset is expected to have longer dry spells in the beginning of the rainy season, which might affect the crop negatively. Therefore, the onset definition uses a 'critical date', before which onset is not allowed, unless a more demanding criterion is satisfied: for each day before the critical date, an extra 2 mm of stored rainfall are required. For example with a critical date of May 30 and a potential onset date of May 20, 40 + 10*2 = 60 mm of stored rainfall are required.

The final rainfall date in this instance is identified by summing daily rainfall backward in time from the last rainfall event in October (November rainfall seldom occurs and is not considered for this purpose) until a total of 10 mm or more

is reached. That date is taken to be the final rain date in the season for practical purposes. This procedure avoids the problem of, say, reasonable rainfall to Sept 10, then nothing until Oct 20 when a final rainfall of 2.0 mm occurs. Effectively, this would be outside of the cropping season.

The final rain date changes from year to year, but less than the date of onset. Figure 10 displays a horizontal scale at the top labeled Monsoon Cropping Season Duration, which means number of days from onset to final rain date, inclusive. Because of the relatively small changes in final rain date, the durations shown are approximate as noted in the figure. For the same reason, the intensities are also approximate when related to any given data point, but are correct overall and are representative.

The Niamey rainfall in Figure 10 may be viewed as a single record or as two separate records, one from 1954 to 1970, and the other from 1971 to 1983. We will do both, starting with the view that it is a single record. This means the open circle and blackened circle data points are each representative of one year in the record and are all to be viewed equally. The shading in the lower portion of the flag is to be ignored and the whole is to be seen as one.

Overall, Figure 10 provides an excellent example of the ways in which seasonal rainfall characteristics are impacted by date of onset. It is clear that the range of expected rainfall amounts as well as the duration of the rainy period are both diminishing with each day that onset is delayed. Table 3 provides details on median values of the agriculturally pertinent characteristics, first for the 30-year record as a whole, then as if it were two separate records - one confined to years that, in fact, had early onset, and the other containing late-onset years. Note that this division of the record is not the same as that described.

The first line in Table 3 provides an overall look at Niamey rainfall. It shows that onset may occur as early as May 28 or as late as July 21, a span of 55 days.

The median date in this range is June 20. The final rain date (not in the table) has a lesser range, and more importantly, a strong tendency to cluster around the median date of September 26. The median cropping season rainfall amount is 494 mm, ranging from as little as 275 mm to as much as 771 mm. Median duration of the rainy period is 99 days, but the actual duration has ranged from 71 to 154 days. This will be dealt with shortly in more detail. Intensity of rainfall at Niamey has a median value of 4.68 mm/day, with a range from 3.02 to 8.08 mm/day.

However, if we divide the Niamey rainfall record into two records, simply on the basis of whether onset occurs before the median date or thereafter, major differences are revealed in all of the season characteristics of interest to the farming community. These differences may be seen in the second and third lines of Table 3 which contain characteristics of early versus late seasons, respectively.

First, we see that the median rainfall amount in early seasons is high (590 mm), whereas that of late seasons is very low (351 mm). To the farmer, this means emphasis on different crops and provision of different levels of inputs. It means different land preparation and tillage practices, probably different row spacings and certainly different plant populations.

Next, we see that the median season duration is much longer (113 days) in early seasons than late ones (82 days). This again calls for emphasis on different crops and cultivars with different maturities. Rainfall intensities at Niamey have also been higher (median values) in early than late seasons, by nearly one millimeter per day, being 4.91 mm/day (0.19 in/day) in early seasons versus 4.07 mm/day (0.16 in/day) in late seasons.

In most instances, rainy period duration correlates with date of onset much better than does rainfall amount. Sivakumar (1987) quantifies the duration relationship for 57 locations in Niger (including Niamey) and Burkina Faso. In each case, the rainfall records used were more than 25 years long, ranging from 26 to 78 years.

Thirty of the stations analyzed are in the drier zone more to the north, with 27 in Niger and 3 in Burkina Faso. The mean annual rainfall here ranges from 330 to 640 mm. Throughout this zone the correlations are excellent, with coefficients (r) ranging from 0.81 to 0.95. An additional 27 stations (all in Burkina Faso) in the zone more to the south have higher rainfall means from 650 to 1160 mm. Here the correlations are somewhat lower, but still very good. All are statistically significant at the 1% level, with correlation coefficients ranging from 0.52 to 0.90.

Stewart (1987a) finds virtually the same correlation between duration and date of onset at Niamey as does Sivakumar (op cit). This is of interest because the latter used somewhat different criteria for both date of onset and final rain date. Additionally, he analyzed 78 years of record whereas Stewart analyzed only 30 years.

One important difference between the onset definitions of Stewart and Sivakumar is, that in Stewart's case, the predictor is the onset date and in Sivakumar's case the onset date plus one month! In the latter definition, a possible onset is prevented from being a false one, up to one month afterwards. It is a false one if there is a long dry spell within this first month. This difference in definition might explain why Sivakumars correlation coefficients on average are better than ours for the eleven Sahelian locations, presented later in this paper.

The relationship developed by Stewart is presented in Figure 11 in the form of a "rainfall duration flag." An example of how information of this type can be interpreted to assist farmers in selecting crops and cultivars to emphasize in seasons with different onset dates is based on the figure.

Crop/Cultivar Selection Based on Predicted Duration

Using the duration versus onset information to guide farmers requires consideration of (a) lengths of growing seasons (maturities) of different crops and cultivars in the planning site environment, (b) rapidity of planting (no. of days it

takes to plant following onset), (c) soil depths and water holding capacities, (d) crop coefficients for estimation of water requirements, and (e) evaporative rates through the season.

The goal of the planning exercise is to select crops/cultivars that will reach maturity within the rainy period, or within a time period following the final rain date but before completely running out of extractable soil water. The first question is: What is the assured duration of the rainy period in relation to date of onset?

The assured, or minimum, duration of the rainy period on any given onset date is defined by the lower boundary of the flag in Figure 11, which is drawn through all of the lowest data points in the record. Of course the actual duration may range anywhere from the number of days indicated by the lower boundary up to that indicated by the upper boundary of the flag. However, Figure 11 shows that the season durations at Niamey tend to lie in the lower half of the flag. Five of the 30 years analyzed, (i.e. one year in six) are on the lower boundary, and another five years are within four days of the lower boundary, so the risk of overestimating season duration climbs quickly as one increases the estimate above the minimum.

For sake of illustration, let us assume that planting can be accomplished within five days after onset. We will estimate rainy period duration to be the lower boundary value plus five days. From germination onward, this makes our effective estimate the lower boundary value. Two-thirds of seasons will be of longer duration and one-third shorter than estimated, but only slightly shorter. If we further assume that the soil can (and will) store sufficient extractable water to provide the minimum needs of the crop in the final 20 days before maturity, then our illustrative case takes the form created by the three shaded bands across the flag in Figure 11. First, there is the middle band representing traditional millets around Niamey which require a growing period of 100 to 110 days. If, in fact, it is 110 days, and the

soil holds water for the final 20 days, the rain should not cease until 90 days into the growing period, i.e. 90 days after crop germination. This is conservative because the actual growing period may be only 100 days. However, the conservatism is somewhat offset by risking the five planting days. The conclusion is that traditional millets should be deemphasized, and shorter maturity cultivars should be substituted to ensure the family food supply, if onset of the rainy season occurs later than the date when the lower boundary of the flag equals 90 days duration. In our illustration, this is the case when onset is after June 15.

On the other hand, when onset is quite early and the lower boundary of the duration flag equals or exceeds 110 days (June 4 or earlier), the indication is that longer maturity crops can and probably should be grown. Such crops require more water as well as a longer rainy period, but hold the potential for higher yields and more desirability and value in the marketplace, which are needed to break the poverty syndrome.

This illustration of crop selection based on the duration versus date of onset relationship is not intended to be definitive as it stands. It is just one example of a field application of the new information about rainfall. However, little additional information would be required to adapt it for use on the ground in providing guidance to farmers. The principal need is to conform the recommendations to the major soil types of the area, which will differ in their depths and water holding capacities. Thus, a shallow sandy soil would require emphasis on shorter term, food insurance crops at an earlier onset date than would a deeper soil with loamy or clayey texture.

4.2.2. Broadening the Findings

Relationships of rainfall amount and duration such as those at Niamey, Niger are found throughout the Sahelian zones. The application of these findings to

farm-level decision making is further enhanced by the broader, better known climate relationships of the area. Table 4 provides a first look at the broader aspects of the situation and an initial blending of the longer known information with that more recently developed.

In Table 4, information is shown for 11 locations in Sub-Saharan West Africa (see Figure 9), including the one already discussed. Four countries are involved, from Senegal on the west reaching the Atlantic Ocean, eastward through Mali and Burkina Faso to Niger. All 11 locations lie in the belt between 11° and 17 °N latitude, above which is virtually rainless desert. Table 4 lists the locations by latitude in descending order from north to south. The northernmost location is Podor, Senegal, at 16° 38′, and the southernmost is Boromo, Burkina Faso, at 11° 44′. These are also the driest and wettest locations, respectively, with long-term, mean rainfall amounts (prior to 1971) of 292 mm at Podor and 957 mm at Boromo.

The intermediate nine locations have intermediate rainfall, increasing with descending latitude. This relationship of annual rainfall to latitude is well known and much documented. The relation is nearly perfect for 8 of the 11 locations that lie to the east in Niger (3), Burkina Faso (3), eastern Mali (1) and northern Senegal (1). More westerly locations in Senegal (Nioro) and Mali (Kayes, Kolokani) follow a similar pattern but with approximately 35-50% higher rainfall at a given latitude. The mean rainfall figures at all locations prior to 1971 may be seen in column 3, Table 4.

Table 4 shows the results of additional analyses on the long-term rainfall records (all years) of when onset of the monsoon for cropping purposes has occurred at the 11 locations. Columns 5, 6 and 7 respectively, show the earliest dates of onset, the dates by which 50% of all years had onset, and the latest dates. Since it is always possible to have a freak onset event, which might throw the "earliest" and "latest" onset columns out of line, it is most informative to look at the

50% onset dates. There we see a nearly clear progression of onset, starting early in the south at Boromo and 80 days later reaching Podor in the north. The reader should not infer that this type of progression occurs cleanly each year. These are long term means, and in any given year, the progression of the monsoon front can be erratic, making it difficult to predict the onset at a given location from the onset of a location more to the south. Correlation analysis of onsets at different locations show this. Even locations close to each other often show bad correlation. There are a few exceptions, so possibly predictions of this kind can be made locally.

Unlike the onset, the recession or withdrawal of the monsoon occurs (on average) almost simultaneously at all latitudes being discussed. There is a mild tendency for later withdrawal in the south, perhaps four days later than in the north. Thus in 50% of years, the monsoon rains depart at 17 °N latitude by Sept 24, and at 11 °N latitude by Sept 28.

Figure 12 provides a graphical representation of the relationship of onset to latitude, based on columns 5, 6 and 7, Table 4. The vertical scale shows north latitude in degrees and minutes, from 11° to 17°, inclusive. The horizontal scale is a calendar showing both ordinary dates and day of year (days are numbered from one on January 1). The onset dates from each of the 11 locations are drawn in at the appropriate latitude, in each case showing the earliest date of onset analyzed from the long term rainfall record, the 50% date and the latest date. The three dates for each location are linked by dashed lines.

The shaded area of Figure 12 represents the result of regression analyses in which the three sets of onset dates are related to latitude mathematically. The purpose of the analyses is to enable estimation of the dates of onset for any other location not analyzed, in the Sub-Saharan zones covered. Estimates of earliest onset dates would be based on the line forming the left side of the shaded area. Fifty percent onset dates would be based on the heavy line up through the

middle of the shaded area, whereas the line on the right side estimates latest onset dates. For example, the three arrows dropped from 13° N latitude in the figure indicate that locations at that latitude should have earliest onset on May 13, 50% onset by June 14 and latest onset by July 24. Such estimates are shown for 11 °N latitude through 17 °N latitude in the last three columns of Table 8. These estimates derive from the same types of regression analyses that were used to construct Figure 12.

The relationships of principal interest - those of (1) cropping season rainfall amount and (2) duration versus date of onset - are quantified by regression equations for all 11 locations in Table 5. Whenever data were sufficient, the above relationships were analyzed separately for the years prior to 1971 and 1971 onward. In each case, the degree of closeness or fit of the relationship is represented by the coefficient of variation (r^2).

In Table 5, we see the following:

1. A strong relationship exists between rainfall season duration and date of onset at all 11 locations. This is shown by r^2 values that range from a low of 0.46 in recent years (since 1971) at Bouza, Niger, to a high of 0.85 in years before 1971 at Kolokani, Mali. Statistically speaking, these are all highly significant relationships at the 1% level. Practically speaking, these are all highly useful relationships upon which to base advice to farmers on crop types and cultivars to emphasize in their plantings in different seasons.

2. A less strong but equally valid and useful relationship exists between cropping season rainfall amount and date of onset. Coefficients of variation (r^2) range from a low of .07 at Nioro in the years before 1971 to a high of 0.73 at Bouza since 1971.

3. The relationship between rainfall amount and date of onset is nearly always useful for guiding farm decisions even when the r^2 values are low. For example, at

Kaya, Burkina Faso, before 1971, the r^2 was only 0.11. The probability of season rainfall amount being less than 600 mm is 15% with an onset on April 30 (the earliest onset date in the historical record), whereas it is 66% with an onset on July 24 (the latest onset date in the record). Expressed differently, if a year with less than 600 mm seasonal rainfall is arbitrarily defined as a bad year, only 1 or 2 years out of every 10 are bad when onset is on April 30 and as much as 6 or 7 out of every 10 are bad when onset is on July 24.

4.2.3. Impact of the climatic change.

4.2.3.1. Niamey, Niger

Returning to Figure 10, the lower shaded portion of the flag is seen to contain all of the data points representing the more recent years from 1971 onward. Earlier years (1954-1970) are in the unshaded portion of the flag and also the upper part of the shaded area, in effect creating two separate flags that overlap each other. The two flags each show clear relationships between farm-relevant rainfall characteristics and date of onset, in fact, each of these relationships is stronger than when considering the whole as a single record. The important point made by the shading and separation into two records is that past rainfall (1954-70) was markedly better in every respect than current rainfall (1971 on). This has continued to be true since 1983 but additional data are required for definitive relationships.

Table 6 duplicates Table 3, but only covers Niamey rainfall as it used to be, i.e. prior to 1971. Table 7 characterizes Niamey rainfall as it is today and may be tomorrow. Whereas average annual rainfall over the 50-year period 1921-70 was 594 mm, and in the more recent 17 years of that period (1954-70) was 603 mm, it then fell to 504 mm in the 13-year period 1971-83. The significance of this change is elaborated below.

There has been a general shift to later onset of the monsoon, of

approximately 11 days, from a median date of June 12 in the pre-1971 period to June 23 thereafter. Compounding this problem is a slight tendency for earlier recession of the monsoon, from Sep 26 before 1971 to Sep 24 thereafter. These shifts have reduced the median rainy period duration from 107 days before 1971 to 93 days in recent years. The relative drop in rainfall amount for cropping has been greater, with median values of intensity falling sharply, from 5.16 mm/day before 1971 to 4.20 mm/day thereafter.

The effects of the climatic change on early-onset seasons is important, but not dramatic. In the present period, onset is a bit later, resulting in a reduction in rainy period duration of one week (median), from 112 to 105 days. There has been a corresponding and relatively larger reduction in cropping season rainfall amount from 603 mm to 508 mm, which has reduced median intensity from 5.16 mm/day to 4.66 mm/day.

Late-onset seasons have suffered much more from the climatic change, not simply in relative terms but in absolute reduction in rainfall amount. Prior to 1971, late seasons tended to be like early seasons, except greatly shortened in duration. The result was a short season with daily rainfall (average) greater than that in early seasons. Now the situation is much different. In the period from 1971 onward, late seasons have been somewhat earlier in onset and, therefore, of somewhat longer duration than before, but the total rainfall and average intensity have declined catastrophically. Median late-season rainfall amount used to be 480 mm but now is only 306 mm. The average intensity formerly was 5.44 mm/day and is presently only 3.45 mm/day. These facts mean that the traditional ways of farming in late seasons require radical change, just for the sake of survival. Because the traditions have been developed in the better rainfall period from 1922 to 1970, the need presently is to provide farmers with the rainfall information and ways to deal with it - particularly in seasons that start late.

In Figure 11 the first thing to notice is that the years before 1971 and the more recent years all fall nicely into the same pattern - unlike Figure 10 where they effectively form two different flags (albeit overlapping). This reflects the fact that the changes, that took place at Niamey in 1971 were in the amount of rainfall and in the onset dates, but not significantly in the final rain dates. Figure 10 shows the change in amount of rainfall relative to onset date. Figure 11 shows that onset dates since 1971, except for two in May, are clustered in the late, middle period from June 11 to July 11. Pre-1971 onsets tend to cluster both earlier and later than that, from June 1-12 and from July 6-21, with only one of the 17 years between (on June 20). Whether or not the new tendency for onset to occur in the mid-June to early July period persists remains to be seen, because it is not clear whether it is simple coincidence or has some physical cause.

4.2.3.2. Bouza, Niger

The second location, that is discussed in more detail, is Bouza, Niger - more northerly than Niamey and, therefore, closer to the Sahara Desert and drier. It shows that at Bouza the impact of the climatic shift at the start of the 1970s is greater than at Niamey, absolutely as well as relatively. Figure 13 shows a still more startling separation than seen in Figure 10 for Niamey - more nearly complete and of greater magnitude. As at Niamey, the Bouza rainfall flags show that rainfall amount declines with later onset. But the lower shaded area, labeled "Today's Flag," shows that the reduction in expected rainfall (compared to 1954-70) with any given date of onset is severe, ranging from approximately 160 mm with the earliest onset (June 12) to about 170 mm with the latest onset (August 16) for an average of 165 mm.

There are three important differences between Figure 13 and Figure 10. First, the range of dates of onset in Figure 13 (Bouza) is from June 12 to August 16, markedly later than at Niamey on average. However, onset has been earlier at

Bouza in some individual years. Second, the scales showing approximate monsoon cropping season duration at the top and bottom of the figure are not identical. The lower scale, representing "today's" situation, shows that the rainy period duration associated with any given date of onset has decreased by about 10 days as compared with the pre-1971 situation. More detail on this will come with discussion of Figure 14. Third, Figure 13 shows that 1974 was an exception at Bouza, with high rainfall , near the top of the former pattern. In practical terms, this is of little consequence because it stands alone. However, if it happens in several years, then reevaluation of the situation would be in order.

Figure 14 shows the rainfall duration flag for Bouza, equivalent to that seen in Figure 11 for Niamey. But again there are noteworthy differences. First, the duration of rains at Bouza is much less than at Niamey, ranging from about 20 to 100 days, versus approximately 70 to 150 days at the latter. The average is about 50 days longer at Niamey. Second, the lower shaded portion of Figure 14 shows that the climatic shift of 1971 strongly affected season duration.

Until 1970, data from all years at Bouza were in the upper clear portion of the flag, meaning the expected duration is greater. Since 1971, of the total of 12 years (1971-83, with 1982 missing), eight years have formed a completely different and poorer pattern (shaded) including one year with no onset at all (1977). The other four years remain in the pre-1971 pattern. The practical meaning of this is that since 1971, in two out of every three years, the monsoon has withdrawn from the area approximately 10 days earlier on average than previously.

It is the earlier recession of the monsoon at Bouza that required two different duration scales for "yesterday's" versus "today's" flags in Figure 13. This shift is also responsible for there being two lines in the figure labeled 4 mm/day intensity. And with reference to rainfall intensities, note that they ranged mostly from 4 to 7 mm/day, comparable to Niamey before 1971, after which

they have ranged from 2 to 4 mm/day, much less than at Niamey, and, as previously indicated, over a much shorter season.

The inescapable conclusion is that although Bouza was at least a marginal crop production area before 1971, it is no longer suited to that usage. If crops are attempted in today's rainfall conditions, only those grown in seasons with onset by mid-July offer any reasonable hope of satisfactory production.

4.2.3.3. Senegal, Mali, Burkina Faso and Niger.

Column 4 in Table 4 shows mean rainfall from 1971 onward at 10 of the 11 locations for which data are available at this writing - plus an estimate for the remaining one (see footnote of table). These are limited data with different numbers of years at different sites. The post-1970 rainfall means are not offered as precise values, but simply as representative of the situation now being faced by farmers of the region. As more data become available, improved analyses will be made.

Table 8 shows estimates of mean annual rainfall at each parallel both before 1971 and from 1971 onward. Rainfall figures used in the analyses are those shown earlier in Table 4. The estimates of rainfall in columns 2 and 3, Table 8, were in turn used to estimate the percentages by which rainfall has been reduced in this region in the years from 1971 onward.

The estimates of percentage reduction in rainfall in column 4, Table 8 do not form a linear function with latitude, as do rainfall amounts and dates of onset. Instead, we see small reductions of 10% or less in the wetter southern areas, becoming ever greater percentagewise (and also in absolute rainfall amount) as one proceeds to the drier northern latitudes. Detailed examples of this phenomenon were discussed earlier for Niamey and Bouza, at latitudes 13° 29′ N and 14° 25′ N respectively. Niamey rainfall has fallen from 603 mm before 1971 to 504 mm thereafter - a drop of 99 mm or 16.4%. Bouza started at 489 mm and fell to 313

mm - a drop of 176 mm, or 36% .

An other interesting phenomenon is that the r^2 values for the onset versus season rainfall amount relationship have increased markedly since 1971 at five of the six locations where data are available. The recent mean is 0.51 whereas the pre-1971 mean was 0.24.

5. Botswana SAT

Botswana is a land locked country situated in Southern Africa. It has experienced food deficits in the recent past. Major improvements in agricultural management in Botswana are required to increase its production. During the period 1979 -1984, the average farmer's yield for sorghum was 175 kg/ha. Even large commercial farms frequently record yields less than 500 kg/ha. The low productivity is a result of physical, biological and economic factors. In the traditional agricultural system, there is little or no application of chemicals or hybrid seed. Because of the low and variable rainfall, water availability is the limiting resource; therefore, the farmer is not willing to risk the additional expense of fertilizer and chemicals. Development of on-farm water resources for securing adequate water availability during the growing season has been identified as one of the key factors to increased agricultural production.

The annual rainfall in Botswana is 650 mm in the north to 250 mm in the southwest (Figure 15). In general 90% of the rainfall is received in the period October to April. The rainy season is November to January. The rainfall is unimodal with a peak during January. Thus the climate borders on being arid subtropical. However, the Botswana climate and agriculture provide an illustration of an agroclimatological approach to dryland agriculture.

In order to illustrate the moisture and thermal regimes of Botswana, Virmani (1985) studied the agrometeorological features of two contrasting locations to

evaluate variability of rainfall and the thermal regime. Mahalapye is located in eastern Botswana with a mean annual rainfall of about 500 mm, while Tsabong is located in southern Botswana with a mean annual rainfall slightly above 250 mm. At Mahalapye the rainy, pre- and post-rainy, and dry seasons are well defined. The rainy season extends from November to March. During this period in terms of thermal regime some 400 thermal units are accumulated.

The data for Tsabong showed that the rainy season there was not well defined. The rainfall has a tendency towards bi-modality with the first peak in December and the second in February. However, the amount of rainfall received in any of the months is less than 50 mm which meets only a fraction of the PE needs.

Virmani's analysis based on the rainfall and thermal regimes of about 30 locations of Botswana have indicated that areas receiving above 400 mm mean annual rainfall follow the trend of rainfall distribution and thermal exhibited by Mahalapye station, and areas receiving less than 400 mm mean annual rainfall exhibit rainfall and thermal characteristics as those of Tsabong.

5.1. Crop production potential of different regions of Botswana

High potential areas:

This region is located in northern Botswana with mean annual rainfall of at least 550 mm. In order to estimate potential for productivity a sorghum yield model (SORGF) was run using climatic data of Kasane. It showed that under medium management conditions (adequate fertilization, 60-70,000 plants/ha) sorghum yields in excess of 4 tons/ha can be achieved in 5 years out of every 10 in this agroecological zone. Three years in every ten years will record a crop failure (less than 500 kg/ha), while in two years out of every ten years the sorghum yields may be around 1000 - 2000 kg/ha.

The results also showed that for a 120 - 130 day sorghum cultivar the drought stress in deep soils of the region is likely to be encountered at GS3 stage, while in the shallow soils, it will be encountered both at GS2 and GS3 stages. Maize is likely to do well in deeper/fertile soils. In terms of moisture conservation and crop management agronomic research, some agenda points for research are:

(1) Increased emphasis on insitu soil moisture conservation through efficient weed control, deep ploughing, stubble mulch farming, micro-watershed water harvesting by growing crops on ridges and establishment of key lines for providing a reference point for farmers to follow contour cultivation.

(2) Inter-cropping of maize and sorghum may be tried in soils with high (150 mm) moisture storage capacity, and intercropping of millet and sorghum in soils with medium (100 mm) moisture storage capacity.

(3) Adequate fertilization with nitrogen and phosphorous is essential to optimize rainfall use efficiency. Research on split application of nitrogen fertilizer and basal application of P in relation to crop phenology and soil moisture is essential.

medium potential areas:

This region of Botswana receives between 400 and 550 mm annual rainfall. Two main soils predominate this region, the Aeronosols in the west and the Alfisols in the east. Since the water holding capacities of these soils are quite different, the issues related to crop production in this region would vary with the soil type. We are, therefore, presenting the agenda points for improved soil moisture conservation separately for the two soil groups:

(1) Aeronosol areas: In this region, our model simulation results for crops show that the probability of harvesting a crop of sorghum yielding over 1000 kg/ha under adequate management conditions is one in every three years. The risks to dependable crop production are high. In addition, in-situ soil moisture conservation is not

likely to be of much help because of the low moisture holding capacity of the soil. The yields in drylands can be stabilized by providing irrigation.

(2) Alfisol areas: In the Alfisol region which is located in the Francistown - Mahalapye - Gaborone transect of the eastern Botswana, the application of improved land and water management techniques is likely to help stabilize and increase crop production. In the current dryland farming system, it is possible to mature a sorghum crop in three or four years out of every ten. Some suggestion for improved dryland farming are:

1. In soils with 150 mm available water storage capacity in the root profile, zonal water harvesting systems may be tried. Such a practice has been successful in stabilizing yields of millet crop at Bellary station of the All India Coordinated Dry-land Agriculture Research Project of the Indian Council of Agriculture Research (Randhawa and Venkateswarlu 1968).

2. Watershed based water harvesting/recycling system that has been developed at ICRISAT in Hyderabad, India may prove useful for stabilizing dryland production. A part (30 - 50 %) of the watershed can be left bare or uncultivated. this uncultivated land is treated to encourage runoff which could be stored in a reservoir. The stored water could be applied to the cultivated area of the watershed. Our simulation results showed that moisture from rainfall plus irrigation from the reservoir would be adequate for six to seven years in every ten to successfully mature a sorghum crop using Mahalapye climatic data. Under adequate fertilization and with proper agronomic management yields in excess of 3000 kg/ha could be expected. There would be two to three years in every ten when the rainfall would be too meager to mature a crop of sorghum. Under this system water will have to be lifted out of the reservoir and applied uniformly over the cultivated area.

low potential areas:

A very large part of Botswana (about 50 % of the total area of the country) where rainfall is 400 mm or less forms a low crop production region of the country. It is not suitable for arable farming. Development of pasture based programs should be taken up in this region.

5.2. The relationship between onset of rains versus season duration and rainfall amount.

We selected the three locations of Francistown, Mahalapye and Gaborone, to evaluate the relationship between onset of the growing season versus the duration of it and onset versus growing season rainfall amount have been analyzed, using the same definitions as have been used for the Sahel analysis. The three locations have about the same mean annual rainfall (Figure 15).

The results of the analysis are shown in Table 9. In the regression equations, the day of year should be used to calculate expected duration and amount. If the onset is so late that it falls in the beginning of the next year, then the day of year + 365 should be used. For example, one year in Francistown the onset is on January 15. The expected duration equals a1 - b1*(15+365) = 536 - 1.24*380 = 65 days.

The correlations seem to be as useful as in the Sahel, because both for onset versus duration and onset versus amount the r^2's are of about the same magnitude. Even Gaborone is not as hopeless as it looks . When two extremely abnormal years (1957 and 1959) of the thirty years are left out of the regression analysis, the r^2 for the onset - duration correlation increases to .76 and for the onset - amount correlation to .25!

In Botswana, the rainfall is less concentrated in the rainy season than it is in the Sahel. A larger percentage of the rain falls outside the rainy season. In addition, the season duration is significantly longer, compared to Sahelian locations with

about the same mean annual rainfall, like Bouza and Dori. Thus, the season rainfall intensity (= amount/duration) in Botswana is rather low. This suggests that long dry spells have a higher probability of occurrence and that the growing season, although longer, will be less reliable.

6. Summary and conclusions

6.1. Role of Agroclimatic Studies

The studies reported in this chapter improve our understanding of the agro-climatic environment, and summarize the state of the knowledge on the subject. They also provide broad indications of directions of interventions for growth and stability of agriculture in this agroclimatic region. However, they relate to some selected locations, and it is important to extend such studies, to cover larger areas and a greater variety of farming systems in the SAT.

The logical and practical means to facilitate the agroclimatic approaches, requires the development both of hardware and of software, as well as an expanded data base. The prospects for achieving this now appears quite encouraging. In Sahelian Africa a large amount of international effort is expended in collecting weather data and in monitoring crop conditions and providing warning for food shortage. Remotely sensed data especially aircraft would provide important information. In India, the government is giving major emphasis to computerization of agricultural information systems, which contain rainfall data for over 350 locations, information on soils for different regions, data on crop and resource-centered technologies available with central and regional research/development organizations, and information from farm surveys. In the section on Indian study therefore we have emphasized inter- year and intra-year variations in rainfall for understanding need for and direction of introducing greater flexibility in cropping strategies for improved crop production. New farming systems based on agroforestry or agropas-

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toral systems are suggested in areas of high risk of droughts to cope with rainfall variability.

6.2. Sub-Saharan agriculture

In this region early warning of weather conditions is critical because the growing season is very short and most of the cropping is done by several farmers with limited means producing staple cereal (millet) of low value. In this paper a new methodology termed 'Response Farming' is described. It is based on rainfall records of several Sahelian stations. The potential for its application in the Sahelian and Sudan bioclimatic regions are evaluated. The farm manager makes a series of decisions throughout the season from planting, fertilization, thinning, cultivation, weeding and harvest. By being given an expectancy of the rainfall pattern, he can make decisions as to the crop, planting density, and fertilization that will optimize his economic output.

The attempt has been made to predict essential characteristics of the approaching monsoon season, and to match crop decisions, farm practices and levels of inputs to expected rainfall. The key point is that an early onset of the rainy season means a longer growing season and a higher total amount of rainfall whereas delayed onset of the rainy season means a shorter growing season and less than average rainfall. Sivakumar (op cit.) suggests that by a careful choice of crops (e.g., millet gives high yields in years when planting is delayed) the crop yields can be increased and stabilized.

Since about 1970 the rainfall has dropped considerably in the Sahel, most dramatically in the northern parts.

6.3. Botswana

The agroclimatic analyses presented here delineate areas of high- , medium- , and low productivity. Suggestions for testing various improved land, water, and

crop management practices for increasing and stabilizing agricultural production are discussed. The agroclimatic survey shows that about half the country is not suitable for arable agriculture. The concept of advance prediction of growing season duration and seasonal rainfall amount from the date of onset of the rainy season has been tested for Botswana. The analysis show that here too, as in the Sahel, the date of onset of the growing season could be used for predicting the expected length of the growing season.

6.4. Outlook for future

Current indications are that in the semi-arid areas the rainfall variability is on the increase. This would lead to changes in the length and the quality of the growing season. The improved farming systems of the future would have to be more flexible and broad-based. The research available today shows that in the Indian SAT, food production can be increased through improved technology. The agronomist and the agroclimatologist will have to work together to make strategic and tactical decisions for the farmer for adopting cropping systems and crop management practices as of the onset and progress of the rainy season. The results of application of improved practices in the farmers' fields managed by researchers have consistently showed that crop yields of major rainfed cereals and grain legumes can be easily increased to 1500 - 2000 kg/ha against their average yield of 300 - 800 kg/ha.

In Africa food production increases in the next decade may mainly come by increasing land area under cultivation. However the situation in the Sahel and other SAT area of West Africa is less promising. In the end, it should be mentioned that the productivity of traditional agriculture is declining, and that the threat of serious food shortages is rising in the rainfed semi-arid tropics but potential for increased food production does exist. By a proper evaluation of the agroclimatic resources and by transferring and adapting improved technologies, the yet under exploited potential of semi-arid tropical regions can be realized for sustained and improved

agriculture.

7. References.

Hargreaves, G.H. and Zohrab A. Samani. 1986. *World water for agriculture - precipitation management.* International Irrigation Center, Department of Agricultural and irrigation Engineering Center, Utah State University. 617 p.

Huda, A.K.S. and S.M. Virmani. 1987. *Effects of variations in climate and soil water on agricultural productivity.* In Parry M.L. et al. (eds.), The impact of Climatic Variations on Agriculture. Reidel, Dordrecht, The Netherlands.

Robertson, G.W. 1976. *Dry and wet spells.* UNDP/FAO Tun Razah Agriculture Research Centre, Sungh: Tekam, Malaysia, Project field Report, Agrometeorology A-6, 15 p.

Sivakumar, M.V.K. 1987. *Predicting rainy season potential from beginning of rains in the Sahelian and Sudanian climatic zones of West Africa.* Proceedings, INRAN-ICRISAT-TROPSOILS-USAID-USDA Workshop on Soil and Water Management systems for Rainfed Agriculture in the Sudan-Sahelian zone, Niamey, Niger. January 11-16, 1987. 17p.

Stewart, J. Ian. 1987a. *Potential for response farming in sub-Saharan Africa.* Proceedings, INRAN-ICRISAT-TROPSOILS-USAID-USDA Workshop on soil and Water Management Systems for Rainfed agriculture in the Sudano-Sahelian Zone, Niamey, Niger. January 11-16 1987. 26p.

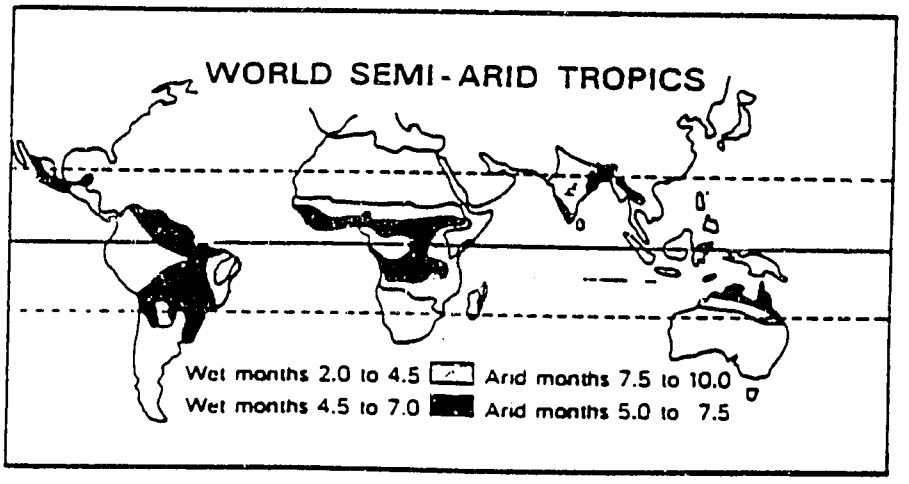
Troll, C. 1965. *Seasonal climates of the earth.* In Rodenwaldt, E. and H.J. Jusatz (eds.), World Maps of Climatology, 2nd Edn. Springer-Verlag, Berlin, pp. 2-25.

Virmani, S.M., M.V.K. Sivakumar, and S.J. Reddy. 1982. *Rainfall probability esti-*

mates for selected locations in semi-arid India. Research Bulletin No. 1 (2nd enlarged Edition), ICRISAT, Patancheru, A.P. 502 324, India.

Virmani, S.M. 1985. *Agroclimatic assessment of Botswana: an agenda for dryland farming research.* Mimeo (for limited circulation). pp. 22. ICRISAT, Patancheru, A.P., 502 324, India.

Figure 1: Distribution of semi-arid tropics of the world, according to classification proposed by Troll (1965).



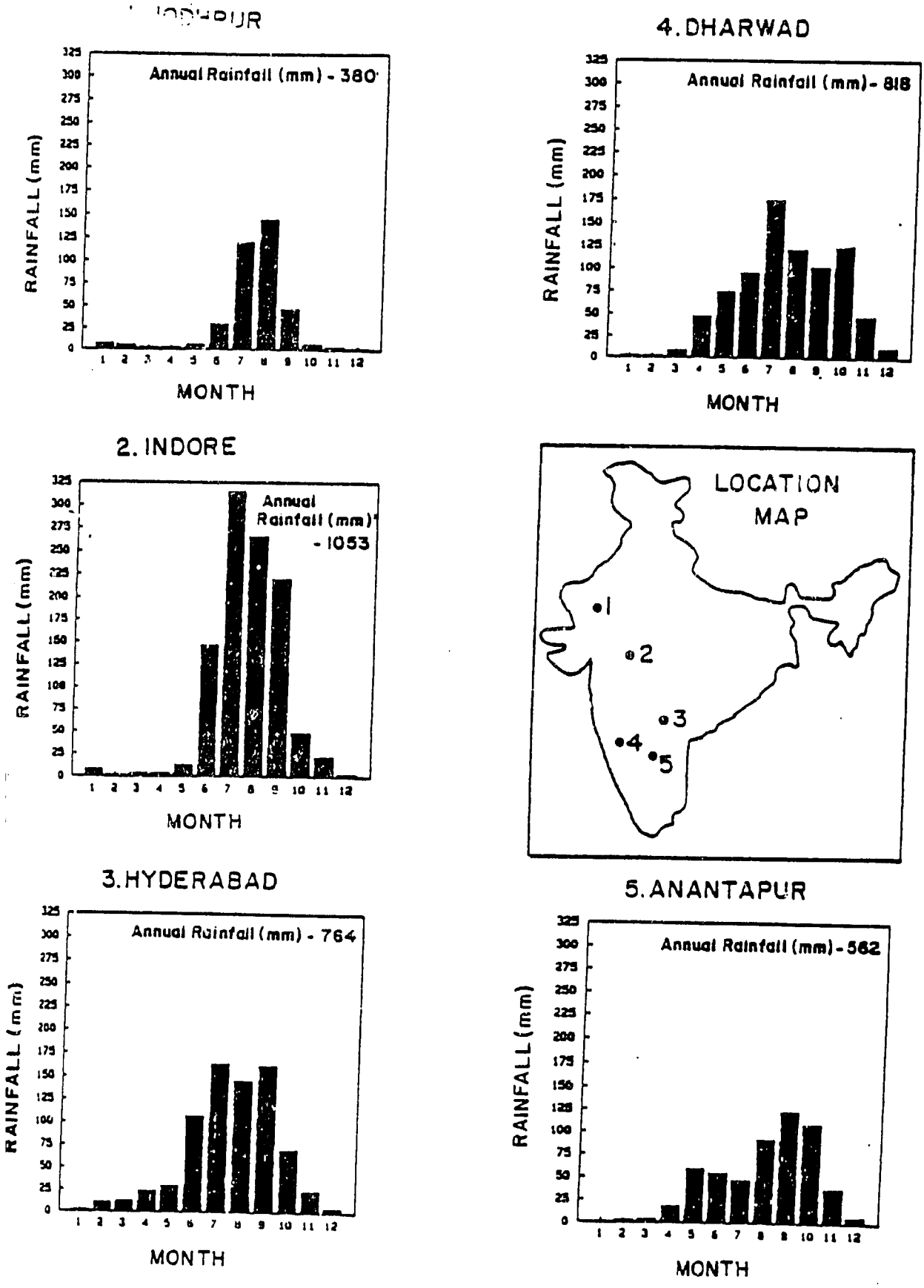


Figure 2: Mean monthly rainfall at 5 representative SAT stations in India.

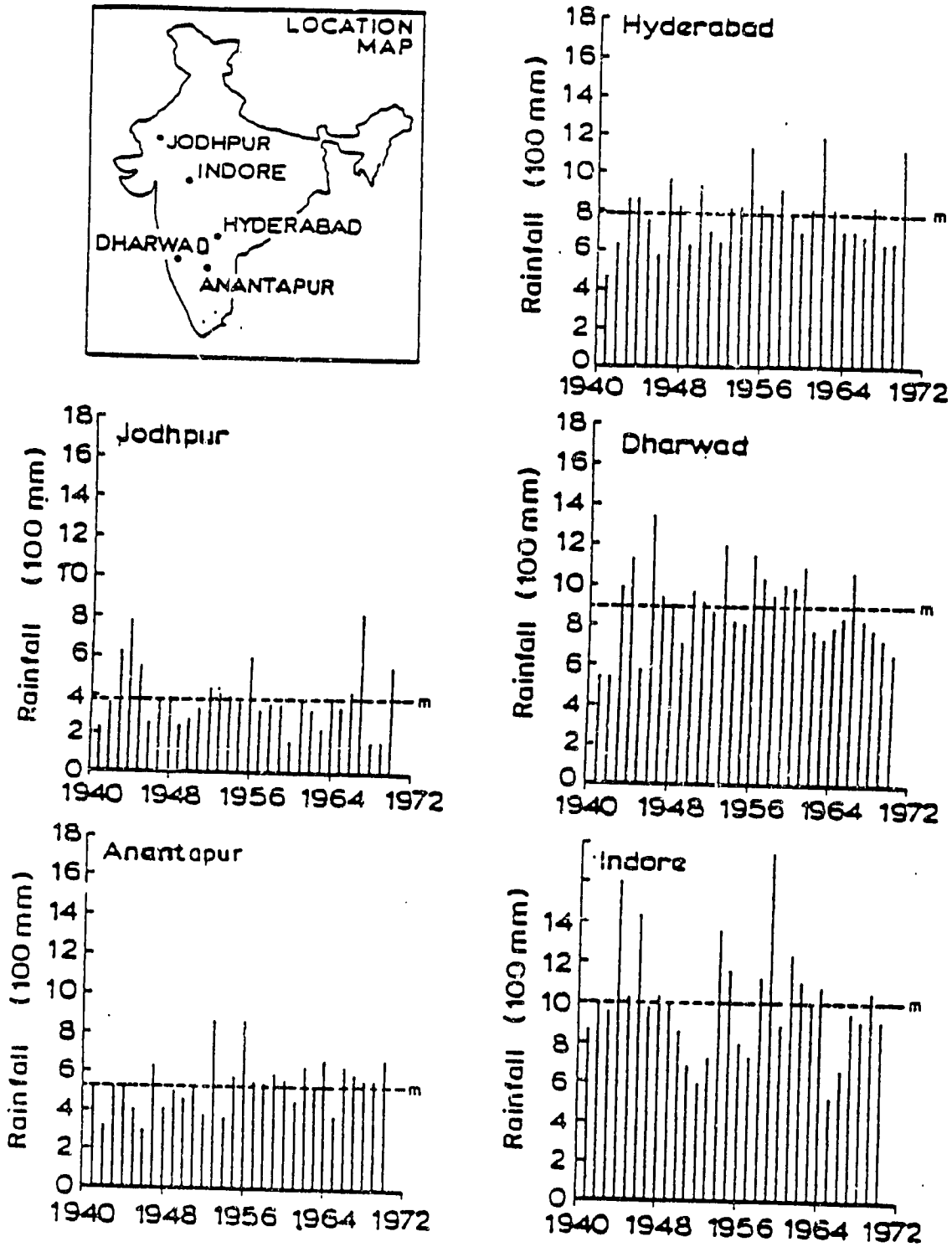


Figure 3: Annual rainfall for five locations during 1941 - 1970. m = mean annual rainfall.

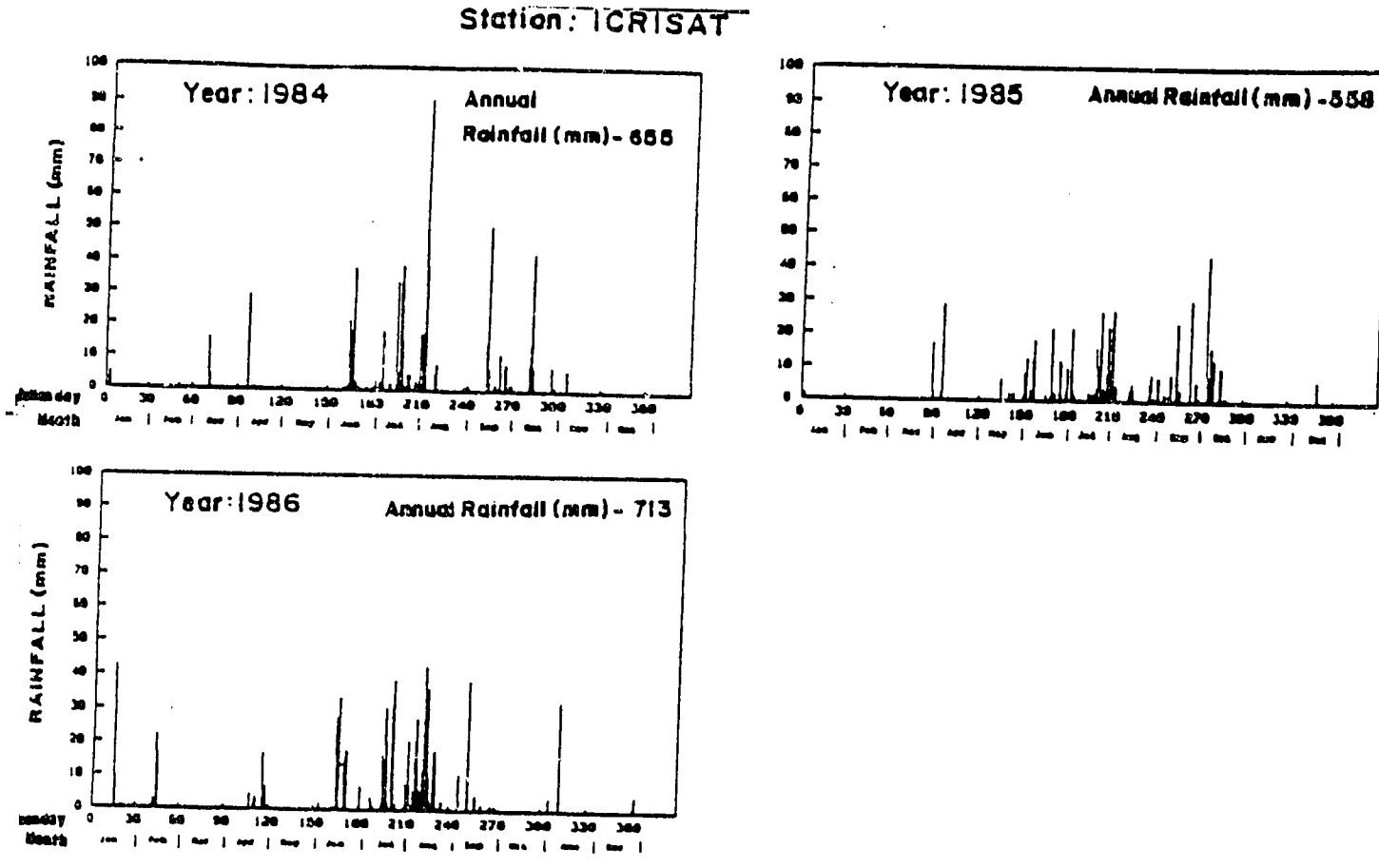


Figure 4: Daily rainfall recorded in the years 1984,1985 and 1986 at the ICRISAT Center, Patancheru located near Hyderabad (India). Note that during the core rainy season there are periods of relatively low rainfall e.g., Aug 1984/85 and Sep 1986.

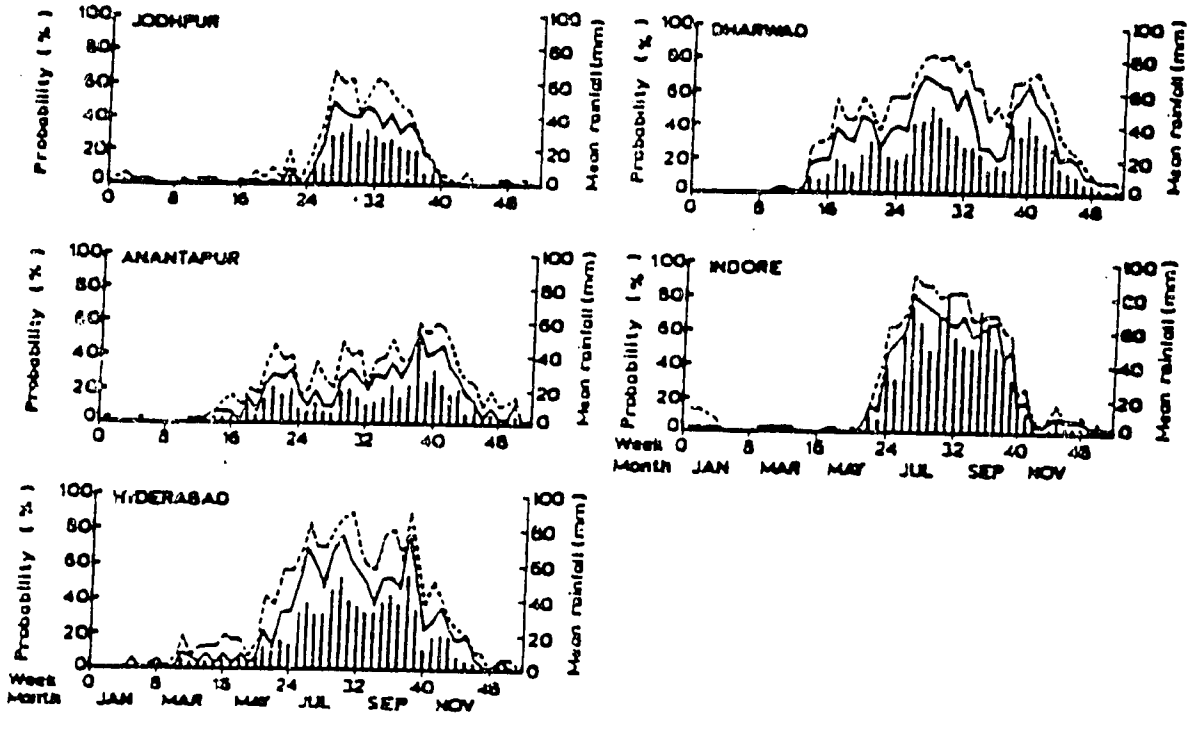


Figure 5: Mean weekly rainfall distribution (vertical lines) and the probabilities of receiving at least 10 mm (dashed lines) and 20 mm (solid lines) rainfall in a week for 5 locations. Data base 1941 -1970.

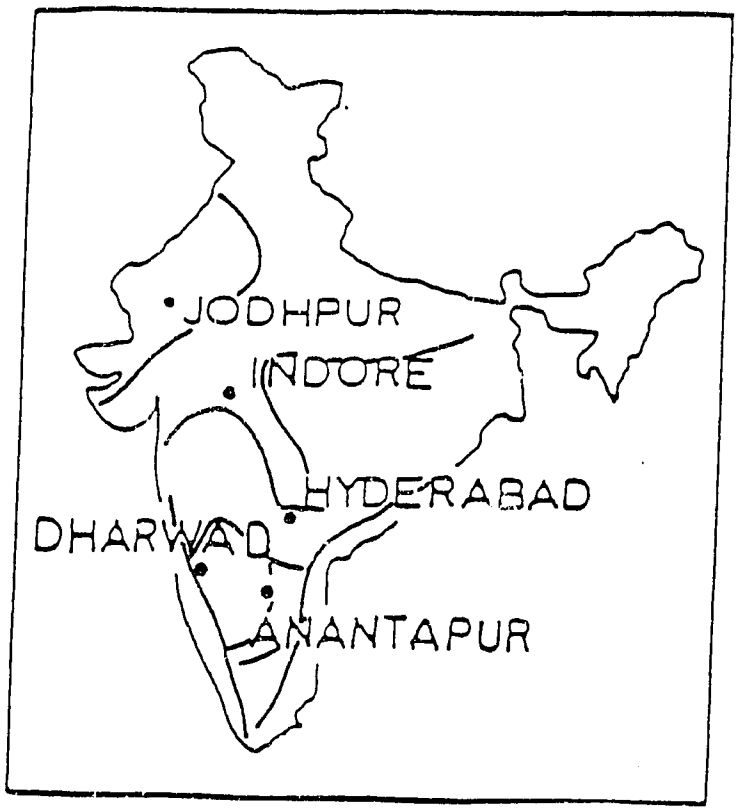
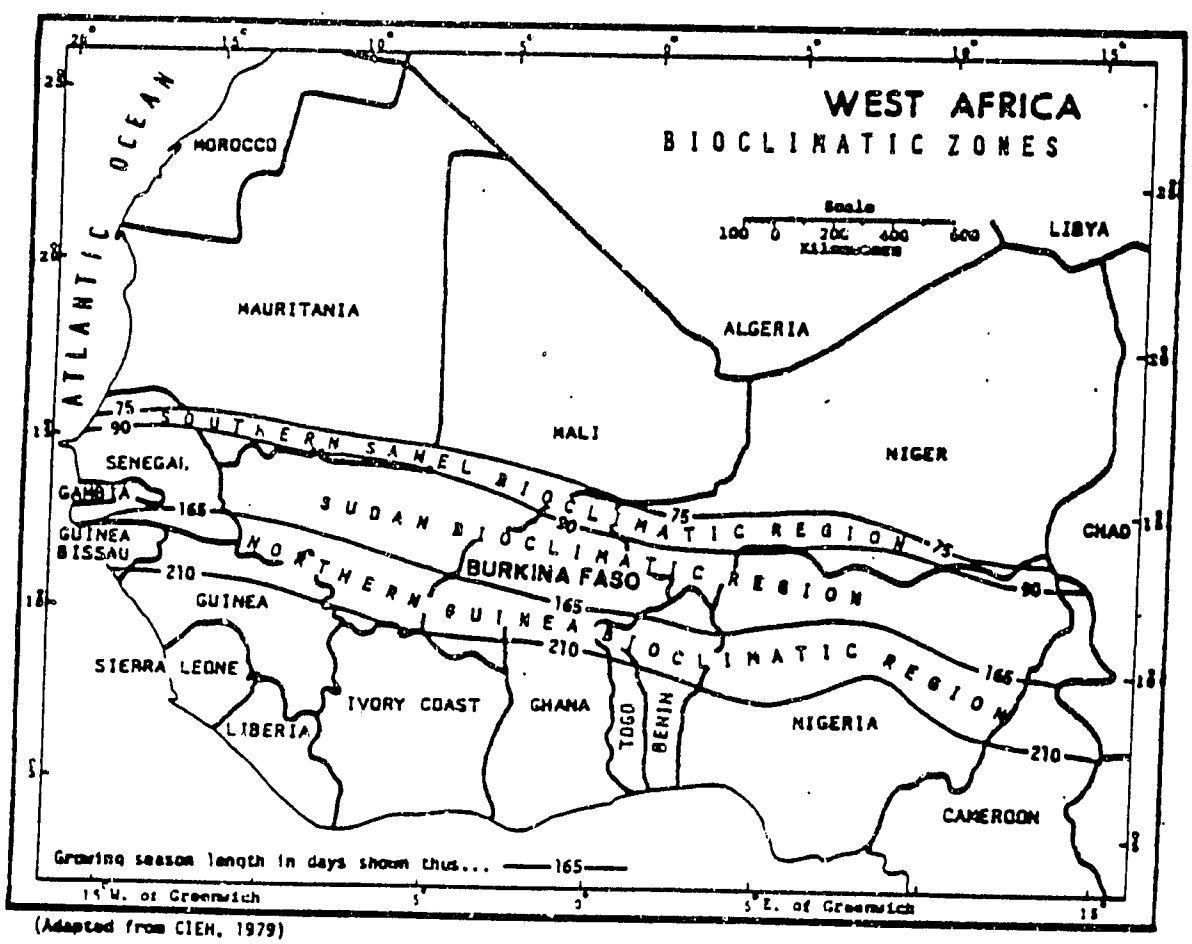


Figure 6: An approximate area of similarity of the agroclimatic regions of India to the 5 selected representative stations based on climatic clusters prepared by Gadgil 1987. The cropping systems and land and water management technology developed at the research institutions located can be tested and adapted in isoclimatic regions in which these stations are located.



(Adapted from CIEH, 1979)

Figure 7: Bioclimatic regions in West Africa.

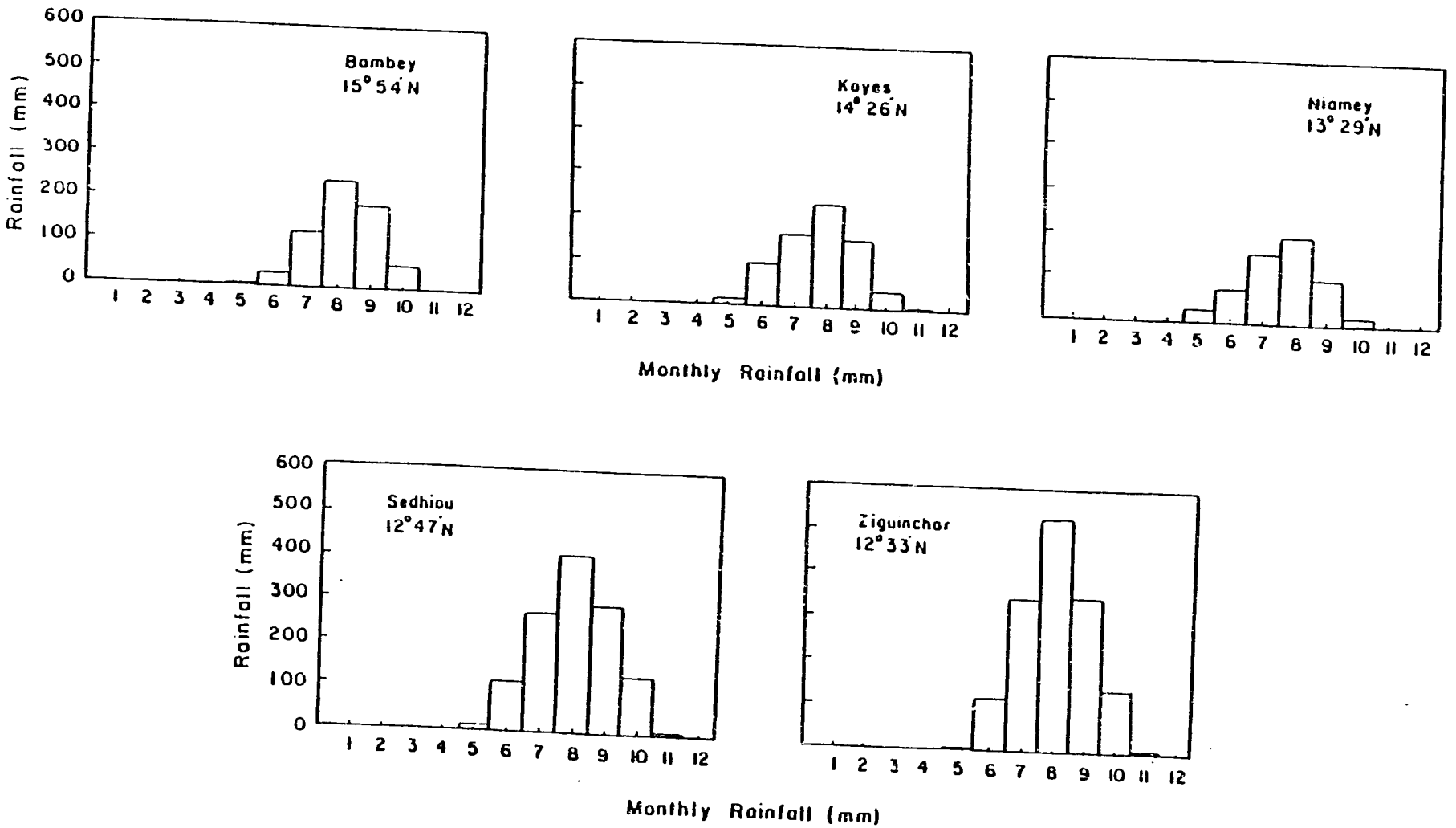
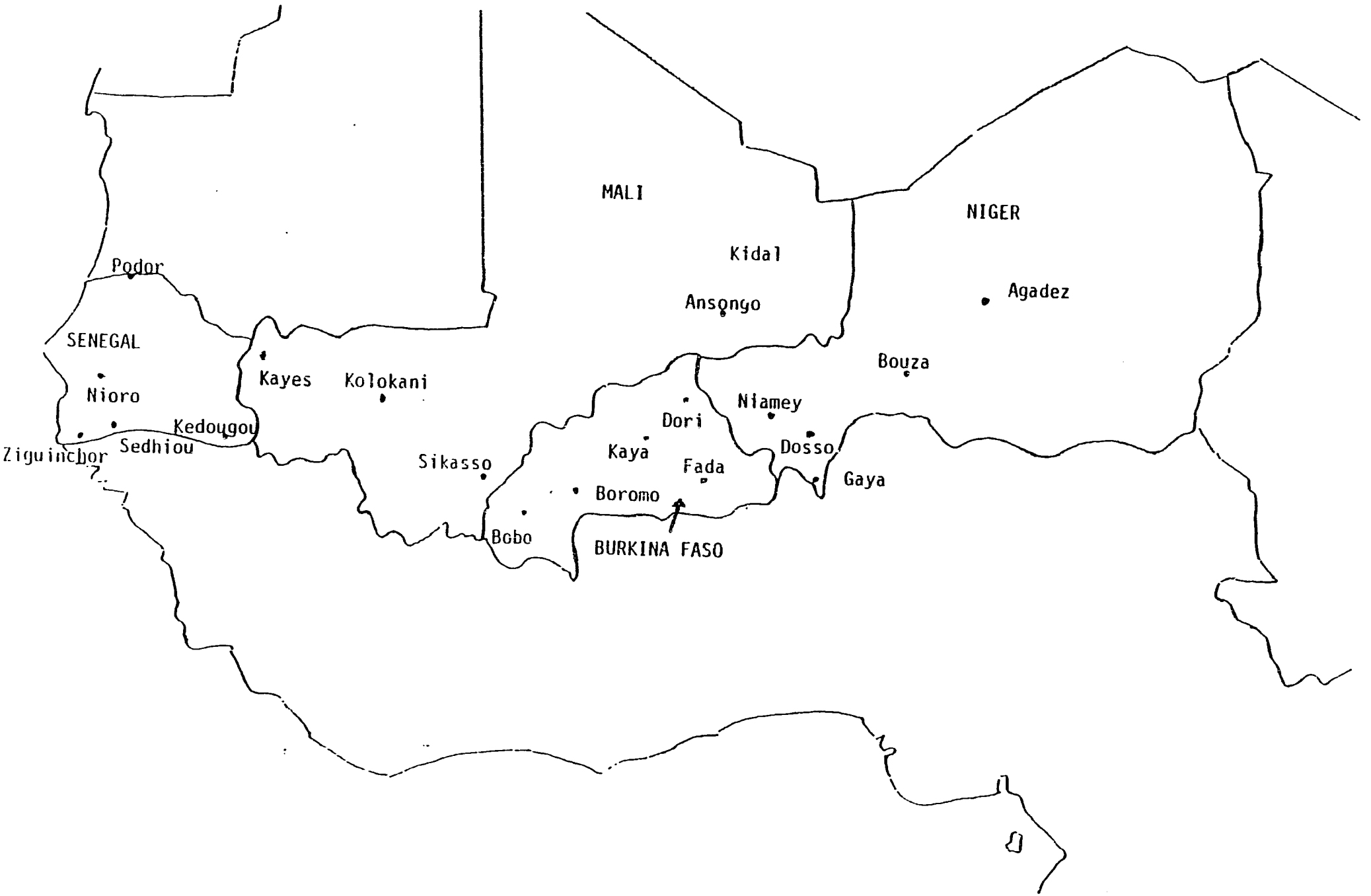


Figure 8: Distribution of monthly rainfall in 5 selected locations of Sahelian West Africa.

Figure 9: Location of Sahelian rainfall stations used in this paper.



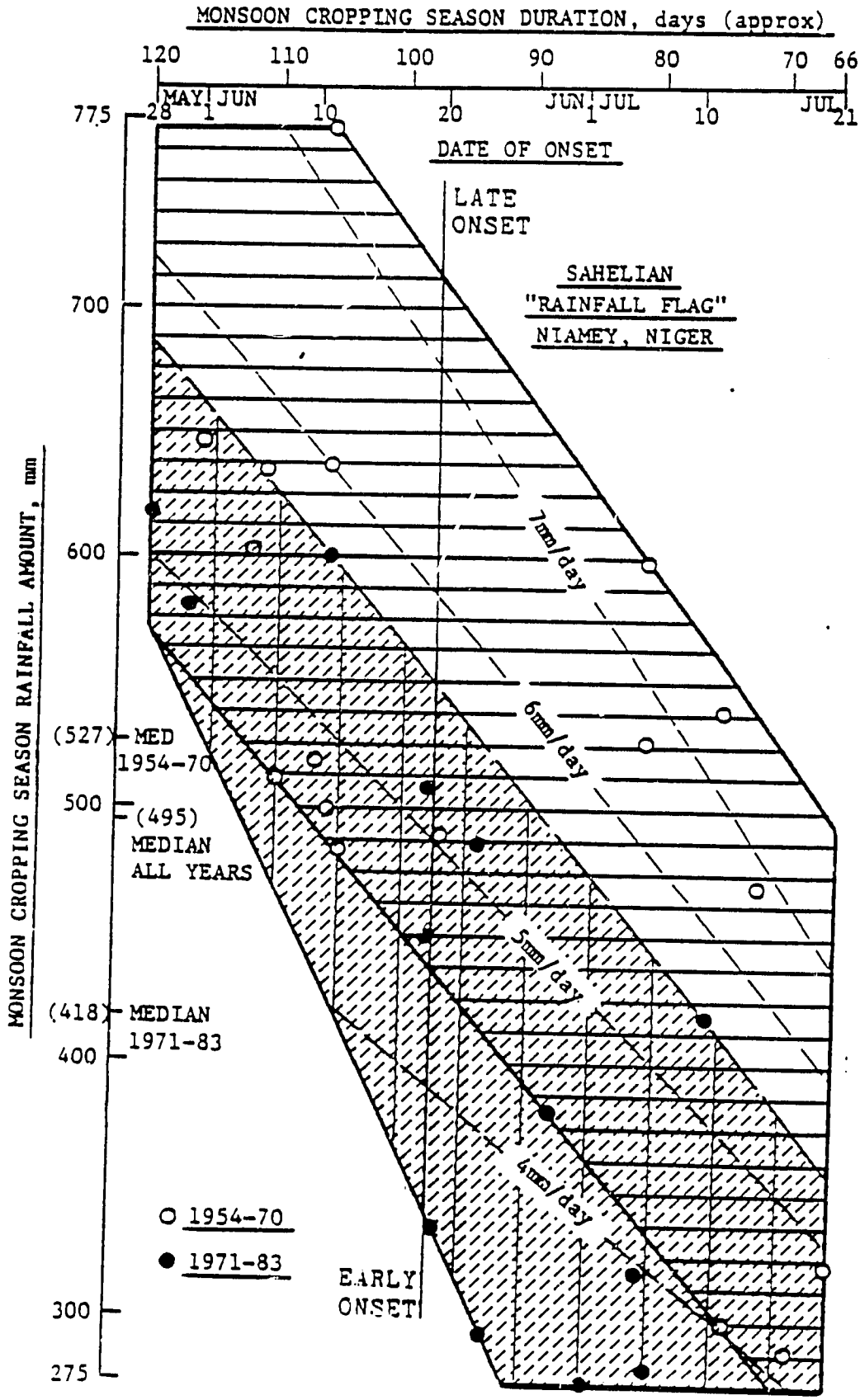


Figure 10: 30 year relationships of monsoon rainfall amount, duration and intensity to date of onset Niamey, Niger. Note effects of climatic shift from 1971 onward.

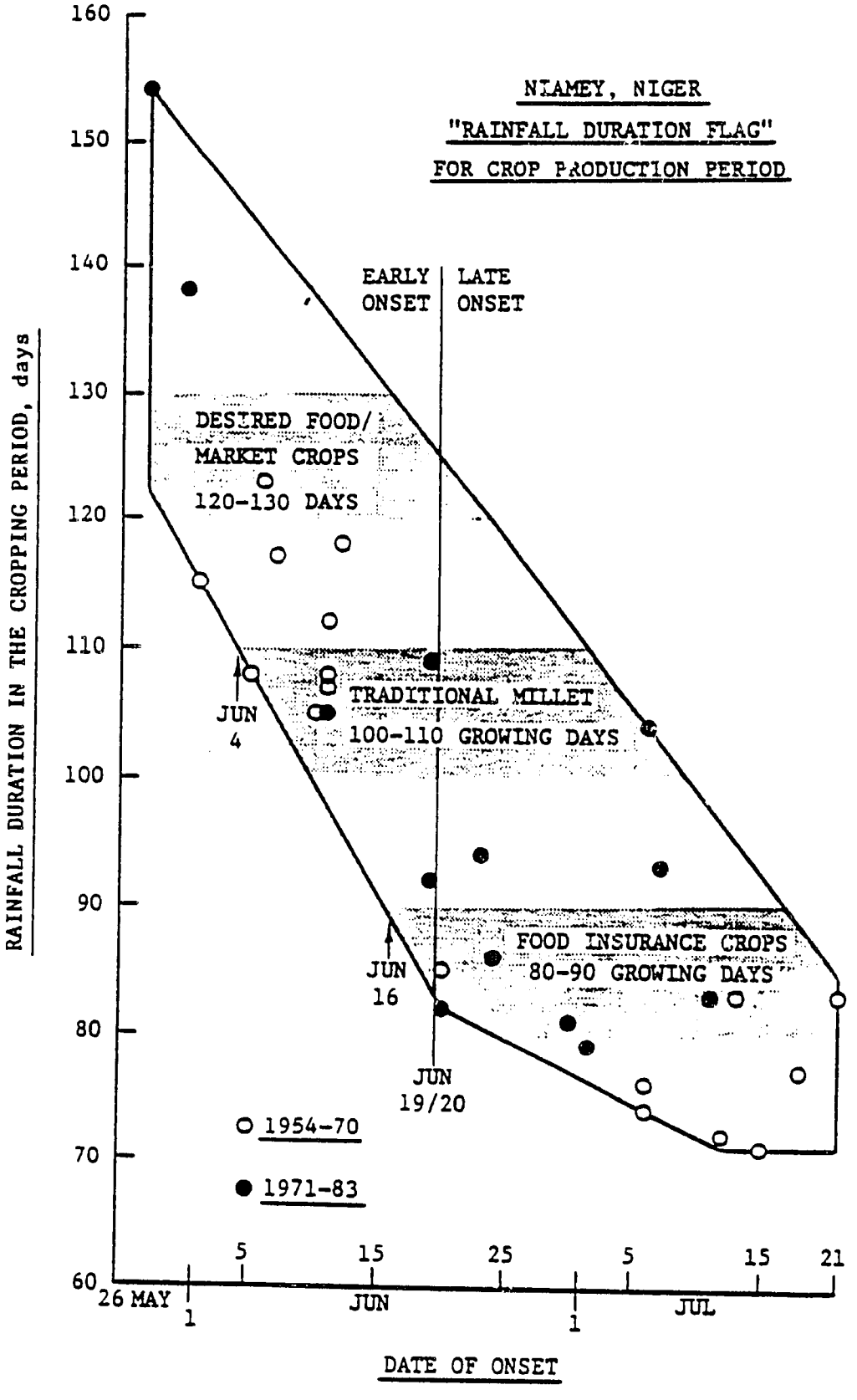


Figure 11: Duration of monsoon cropping season rainfall, as related to date of onset. Illustrative example of crop and cultivar selection based on this relation.

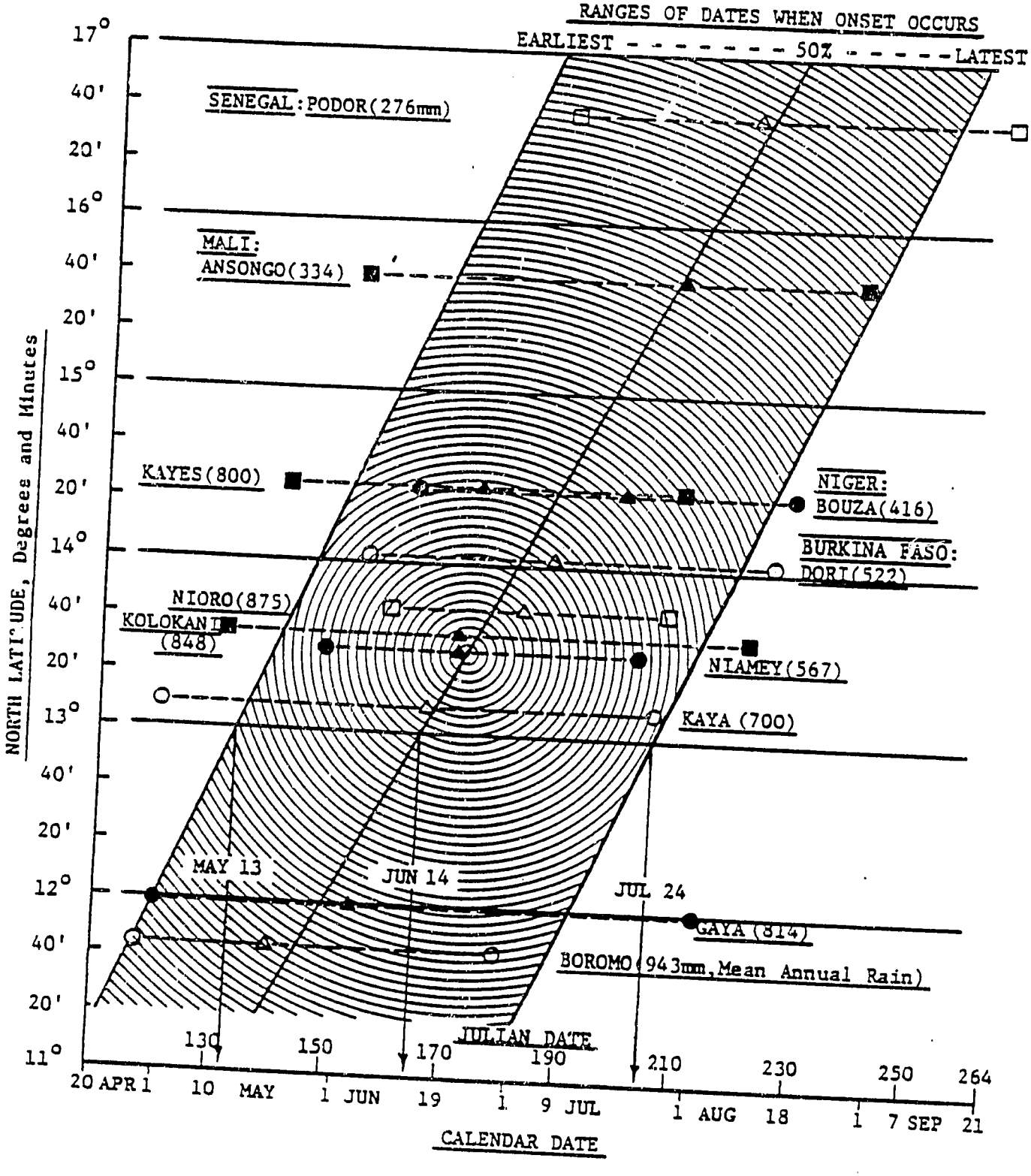


Figure 12: Western Africa, Sudano-Sahelian zone: ranges of dates of onset of the monsoon cropping season, shown as a function of latitude. Senegal, Mali, Burkina Faso and Niger.

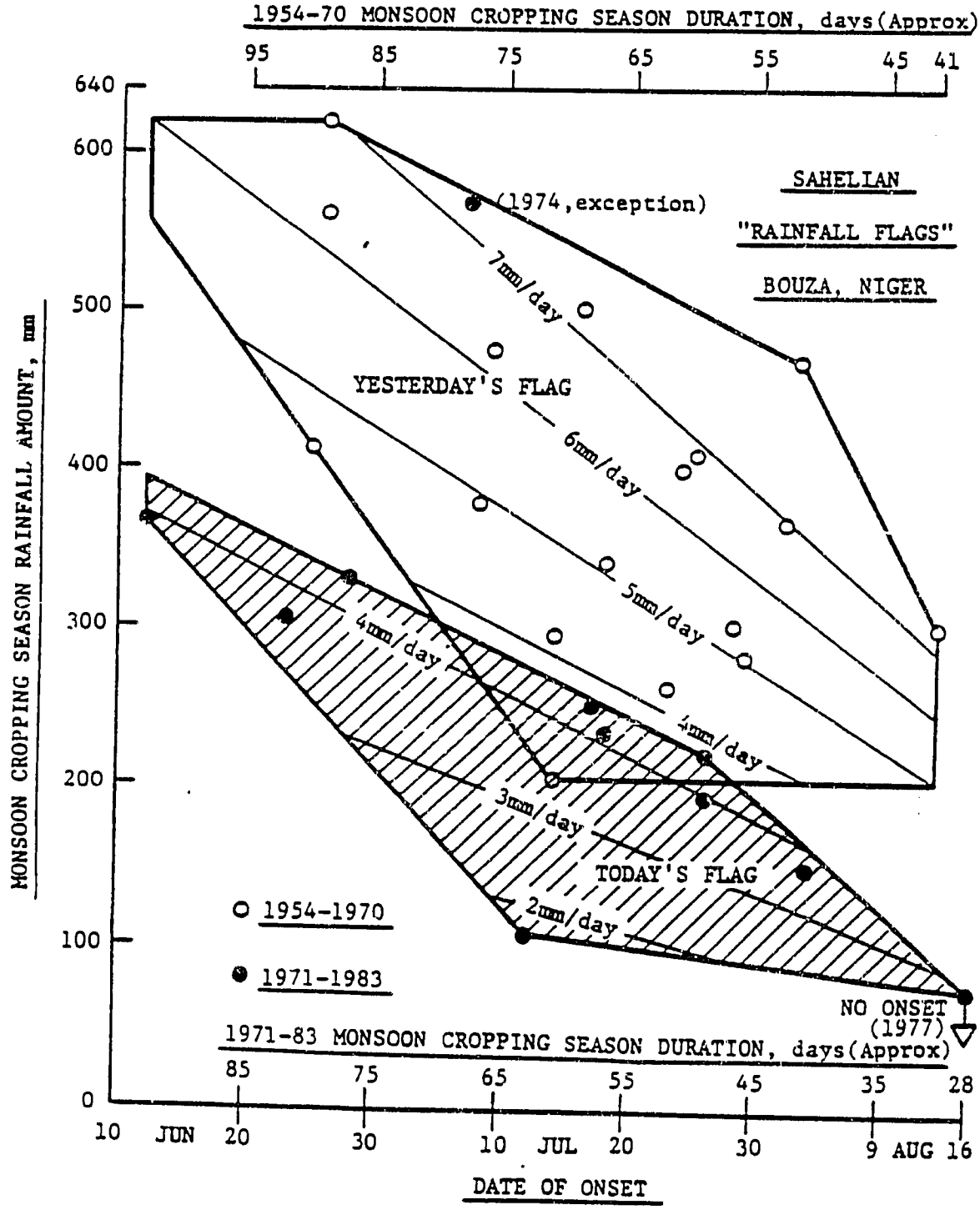


Figure 13: Two rainfall flags over Bouza, Niger. The upper flag shows how the monsoon season rainfall amount, duration and intensity related to the date of onset prior to 1971. The lower flag (shaded) shows the effects of the climatic shift in subsequent years.

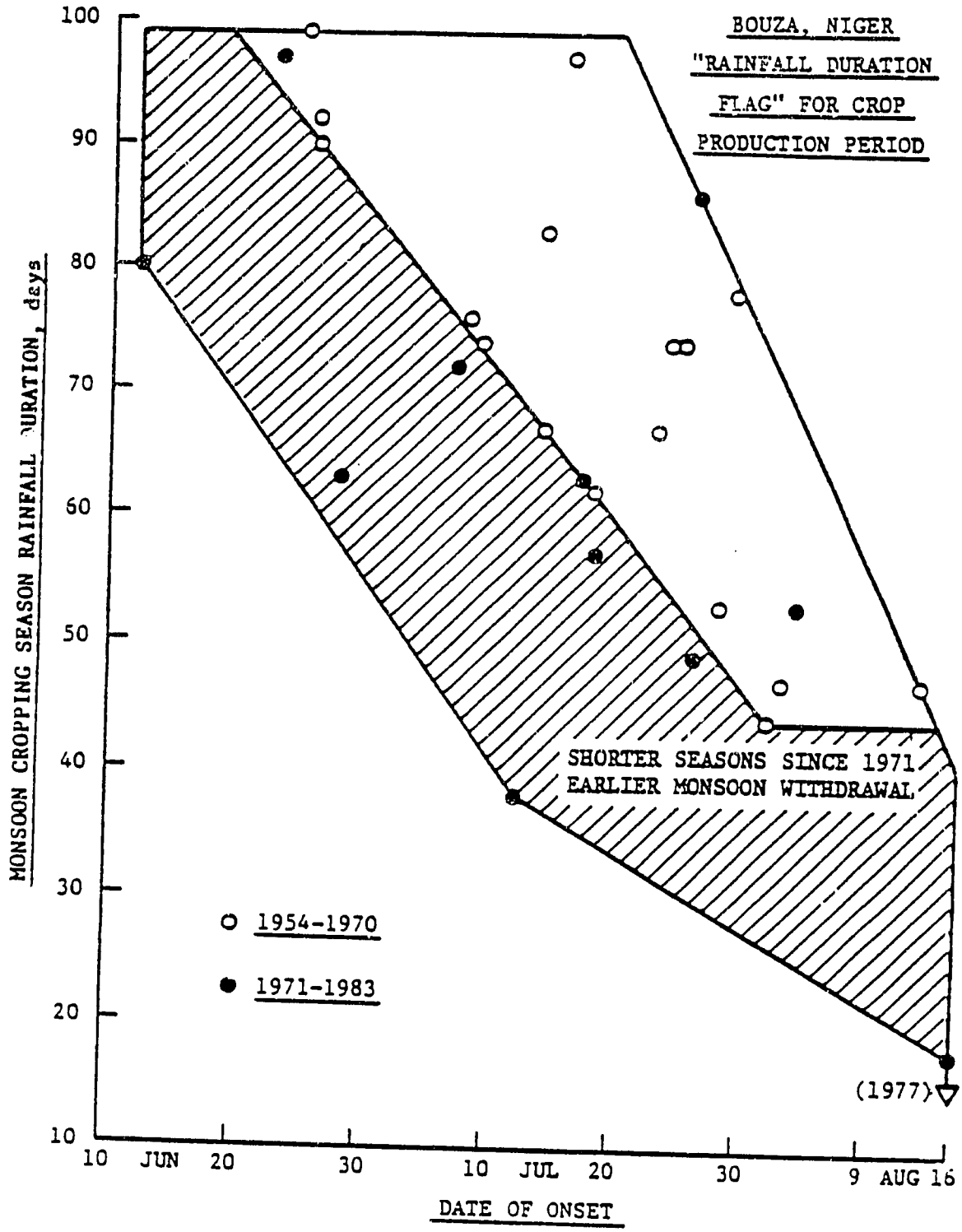


Figure 14: Duration of the monsoon rainy period for crop production, as related to date of onset at Bouza, Niger. Shaded area shows climatic shift since 1971, manifested by earlier recession of the monsoon. Bouza, Niger, 1954 - 83.

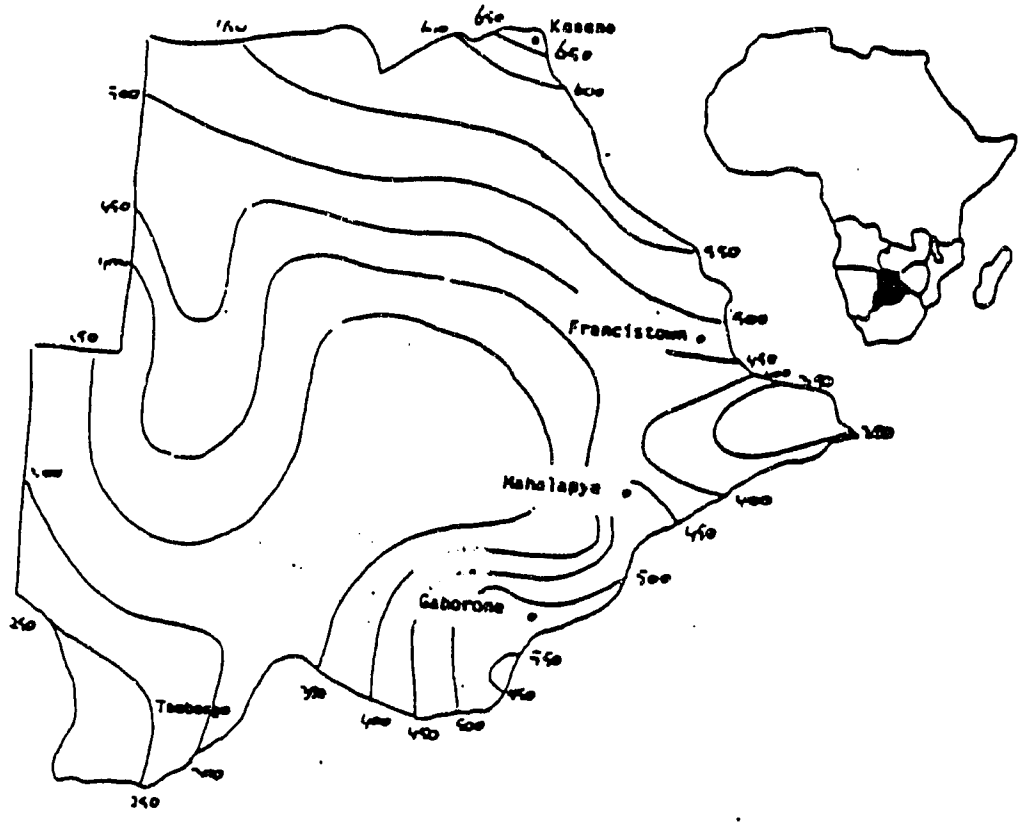


Figure 15: Location of the selected Botswana rainfall stations used in this paper and mean annual rainfall in Botswana.

Table 1. Mean monthly rainfall (mm) and potential evapotranspiration (PE) at some selected locations in the semi-arid tropics.

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Hyderabad	Rainfall	2	11	13	24	30	107	105	147	163	71	25	6	704
(India)	PE	110	130	182	198	220	196	140	136	119	124	104	99	1758
17°27'N; 78°28'E														
Bangalore	Rainfall	3	10	6	46	117	80	117	147	143	185	54	16	924
(India)	PE	117	130	166	158	157	127	116	114	109	105	98	103	1500
12°58'N; 77°35'E														
Dakar	Rainfall	0	1	0	0	0	10	87	220	164	58	2	3	546
(Senegal)	PE	142	134	160	173	165	165	159	141	143	149	149	151	1831
14°44'N; 17°30'W														
Niamey	Rainfall	0	0	0	0	26	77	159	201	101	15	0	0	580
(Niger)	PE	163	165	207	202	215	204	157	131	135	172	154	141	2046
13°29'N; 02°10'W														
Debre-Zeit	Rainfall	11	25	41	58	45	88	231	229	110	18	6	4	866
(Ethiopia)	PE	101	107	129	129	131	109	97	97	99	114	106	100	1319
08°44'N; 39°02'E														
Nairobi	Rainfall	63	34	81	107	130	24	7	11	21	62	188	116	844
(Kenya)	PE	135	143	151	116	102	93	90	95	106	124	113	117	1385
01°19'S; 36°55'E														
Morogoro	Rainfall	94	104	167	208	96	27	15	10	17	27	54	73	892
(Tanzania)	PE	137	124	132	103	92	85	92	106	123	149	143	143	1429
06°50'S; 37°39'E														
Motopos	Rainfall	123	99	68	26	7	3	0	1	4	26	85	130	572
(Zimbabwe)	PE	129	108	114	97	76	49	57	102	142	178	139	131	1322
20°23'S; 28°30'E														
Katherina	Rainfall	234	246	195	44	6	3	3	1	7	31	90	152	1012
(Australia)	PE	155	125	138	149	144	135	146	170	188	234	218	194	1997
14°28'S; 132°20'E														

Source: India Meteorological Department, Climatological Tables of Observatories in India, 1931-1960.

Food and Agriculture Organization of the United Nations, Agroclimatological Data for Africa. FAO Plant Production and Protection Series No.22, 1984.

World Meteorological Organization, Climatological Normals for Climat and Climatship Stations for the Period 1931 - 1960. WMO No.117. T.P.52, 1971.

Month	Mean PE (mm)	Standard deviation (mm)	Co-efficient of variation (%)
January	85	27	32
February	103	24	23
March	151	23	15
	Prerainy hot season		
April	177	21	14
May	207	33	16
	Rainy season		
June	174	34	19
July	132	27	20
August	122	21	18
September	122	18	15
	Postrainy cool season		
October	119	15	12
November	90	19	21
December	78	25	32
Annual	1556	196	13

Table 2: Potential evapotranspiration (PE) statistics for 169 locations in rainfed areas of India.

NO. YEARS	ONSET PERIOD	MONSOON CROPPING SEASON RAINFALL MEDIAN VALUES			
		ONSET (date)	AMOUNT (mm)	DURATION (days)	INTENSITY** (mm/days)
30	ALL, May 28-Jul 21	6-20	494	99	4.68
14	EARLY, to Jun 19	6-10	590	113	4.91
16	LATE, Jun 20 on	7-06	351	82	4.07

* 30 year record from 1954 to 1983 inclusive.
** Intensity from actual data, not calculated from median amount duration.

Table 3: Niamey, Niger: Median values of monsoon cropping season rainfall characteristics, including date of onset and consequent rainfall amount, duration and intensity. Presented first for all years*, then for early onset versus late onset years.

Location	North Latitude	Mean annual to 1970	Rainfall mm 1971 on	Ranges of onset dates		
				Earliest	50%	Latest
Podor (S)**	16° 38'	292	156	7-07	8-08	9-21
Ansongo (M)	15° 40'	334	(214)*	6-02	7-27	8-27
Kayes (M)	14° 26'	749	546	5-21	6-23	7-28
Bouza (N)	14° 25'	489	313	6-12	7-18	8-16
Dori (BF)	14° 02'	536	455	6-04	7-06	8-13
Nioro (S)	13° 44'	875	590	6-08	7-01	7-26
Kolokani (M)	13° 35'	848	724	5-11	6-20	8-09
Niamey (N)	13° 29'	603	504	5-28	6-20	7-21
Kaya (BF)	13° 09'	700	673	4-30	6-15	7-24
Gaya (N)	11° 59'	829	774	4-30	6-03	8-01
Boromo (BF)	11° 44'	957	875	4-27	5-20	6-28

* Estimated using the relations shown in column 4, Table 4.

** Countries are Senegal (S), Mali (M), Niger (N) and Burkia Faso (BF).

TABLE 4 Eleven locations in four countries of Sub-Saharan Africa listed by latitude from the dry north with a late monsoon to the relatively wetter south where the monsoon arrives earlier. Mean annual rainfall to 1970, then for 1971 onward. Ranges of onset dates showing earliest, 50% of years and latest onsets.

STATION	DATA* BASE (YRS)	MEAN ANNUAL RAINFALL (mm)	---------MONSOON R= a1 + b1(Onset) (a1)	(b1)	R2	CROPPING SEASON------ DUR= a2+b2(Onset) (a2)	(b2)	R2
PODOR	46	292	1190	-4.31	(.44)	269	-0.98	(.56)
	6	156	- - - - - - - - - -			- - - - - - - - - -		
ANSONGO	40	334	851	-2.98	(.41)	295	-1.14	(.73)
	ND	(214)**	- - - - -ND- - - - -			- - - - - ND - - - - -		
KAYES	41	749	- - - - - - - -		-(.10)	275	-0.95	(.52)
	3	546	- - - - - - - - - -			- - - - - - - - - -		
BOUZA	17	489	1149	-3.89	(.17)	270	-1.00	(.65)
	12	313	1037	-4.14	(.73)	218	-0.80	(.46)
DORI	43	536	1347	-4.76	(.38)	274	-0.98	(.64)
	9	455	1135	-3.99	(.58)	298	-1.12	(.68)
NIORO	33	875	- - - - - - - -		-(.10)	296	-1.04	(.70)
	4	590	- - - - - ND - - - - -			- - - - - ND - - -		
KOLOKANI	41	848	1550	-4.73	(.28)	289	-1.03	(.85)
	3	724	- - - - - ND - - - - -			- - - - - ND - - -		
NIAMEY	17	603	1382	-4.95	(.47)	269	-0.98	(.83)
	13	504	1693	-7.32	(.62)	334	-1.35	(.64)
KAYA	48	700	- - - - - - - -		-(.12)	284	-1.01	(.71)
	8	673	- - - - - - - -		-(.05)	308	-1.18	(.69)
GAYA	36	829	- - - - - - - -		-(.10)	289	-1.07	(.80)
	13	774	1505	-5.16	(.51)	298	-1.14	(.82)
BOROMO	45	957	- - - - - - - -		-(.06)	301	-1.14	(.78)
	9	875	1391	-4.24	(.59)	282	-0.95	(.77)

* Upper number is years to 1970, lower number is years from 1971 onward.

** Estimated value - annual rainfall data unavailable.

Note: In regression equations in headings section, R=rainfall (mm), DUR is duration (days) and Onset is the JULIAN date of onset of the monsoon cropping season. R2 is the coefficient of variation.

TABLE 5 - Eleven locations in Sub-Saharan Africa, described in Table 4. Regression equations showing how monsoon cropping season rainfall amount and duration relate to the date of onset (see footnote).

NO. YEARS	ONSET PERIOD	MONSOON CROPPING SEASON RAINFALL MEDIAN VALUES			
		ONSET (date)	AMOUNT (mm)	DURATION (days)	INTENSITY* (mm/days)
17	ALL, Jun 01-Jul 21	6-12	519	107	5.16
9	EARLY, to Jun 16	6-10	603	112	5.16
8	LATE, Jun 17 on	7-12	480	76	5.44

* Intensity from actual data, not calculted from median amount duration.

Table 6: Niamey, Niger: Past situation - median values of monsoon cropping season rainfall characteristics, including date of onset and consequent rainfall amount, duration and intensity. Presented first for all years from 1954 - 71 (17 years), then for early onset years (9) versus late onset years (8).

NO. YEARS	ONSET PERIOD	MONSOON CROPPING SEASON RAINFALL MEDIAN VALUES			
		ONSET (date)	AMOUNT (mm)	DURATION (days)	INTENSITY* (mm/days)
13	ALL, May 28-Jul 11	6-23	418	93	4.20
7	EARLY, to Jun 23	6-19	508	105	4.66
6	LATE, Jun 24 on	7-04	306	84	3.45

* Intensity from actual data, not calculted from median amount duration.

Table 7: Niamey, Niger: Current situation - median values of monsoon cropping season rainfall characteristics, including date of onset and consequent rainfall amount, duration and intensity. Presented first for all years from 1971 - 83 (13 years), then for early onset years (7) versus late onset years (6).

LATITUDE NORTH	ESTIMATED RAINFALL, mm PRE-1971	1971 ONWARD	% REDUCTION 1971 ONWARD	ESTIMATED ONSET DATES EARLIEST	50%	LATEST
17o	177	32	81.9	7-04	8-16	9-16
16o	310	182	41.3	6-21	7-31	9-03
15o	444	331	25.5	6-08	7-15	8-20
14o	577	481	15.1	5-26	6-30	8-07
13o	711	630	11.4	5-13	6-14	7-24
12o	844	780	7.6	4-30	5-29	7-11
11o	977	929	4.9	4-17	5-14	6-27

TABLE 8 - Generalized values for monsoon cropping season onset date and mean annual rainfall amounts for latitudes 11 to 17N in Burkina Faso, Niger, eastern Mali and the northernmost area of Senegal. Rainfall amounts are shown to 1970 and from 1971 onward, with percentage reductions of the latter.

	Gaborone	Francistown	Mahalapye
Number of years	30	49	53
Mean onset (Julian date)	321	338	333
DURATION			
R2	.15	.82	.78
a1	346	536	432
b1	.67	1.24	.91
Mean (days)	130	118	127
AMOUNT			
R2	.09	.25	.31
a2	973	1485	1147
b2	1.76	3.25	2.28
Mean (mm)	407	386	388

Table 9: Three locations in Botswana, described in Figure 15. Regression equations showing how monsoon cropping season rainfall amount and duration relate to the date of onset.

Appendix 2: Detailed description of the definition of onset date.

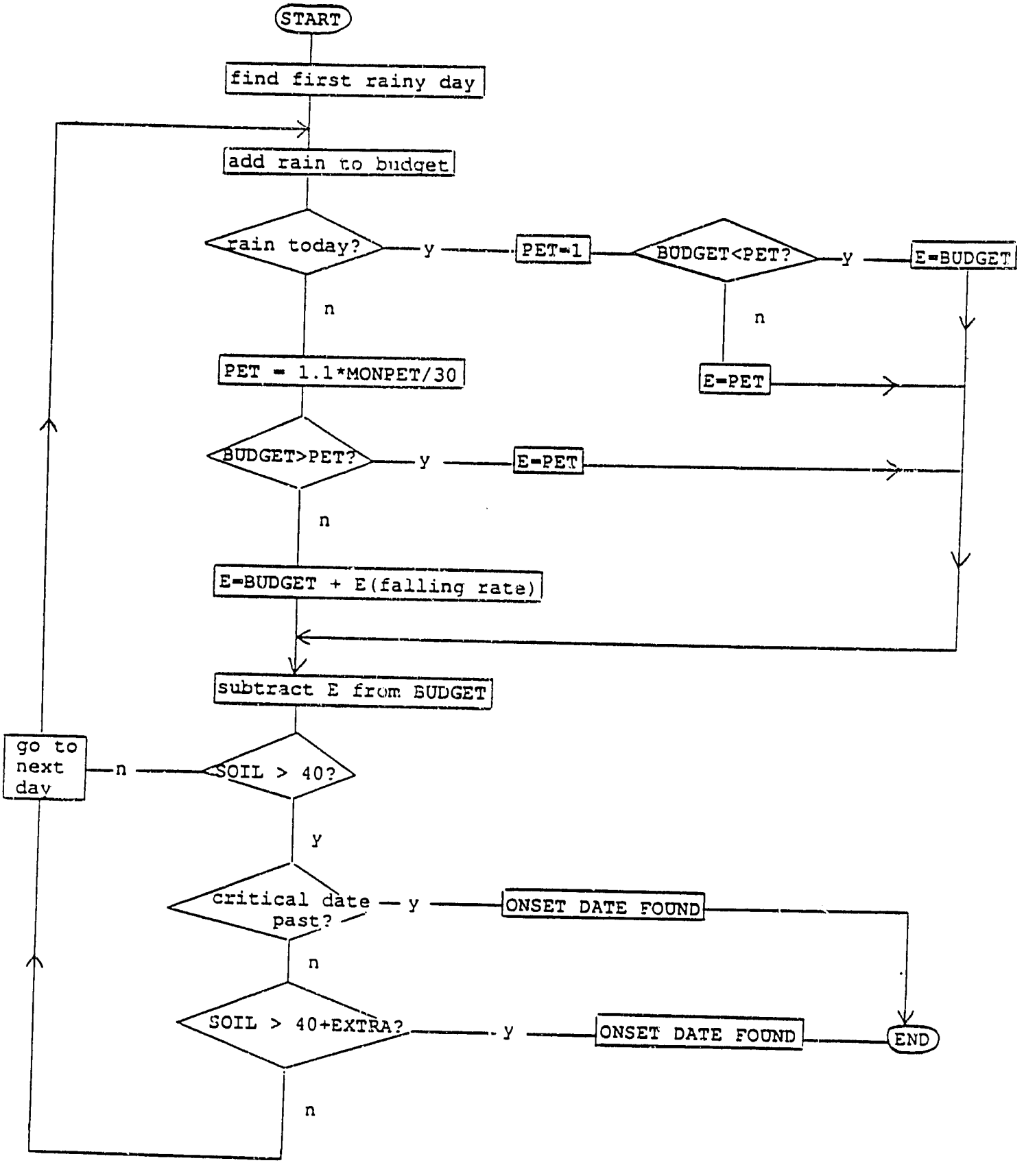
Input data used to determine the onset date are daily rainfall and monthly potential evapotranspiration (PET) (Virmani,1980). The soil moisture content is determined by that of the previous day plus today's rainfall minus today's evaporation (E). Daily PET = (monthly PET)*1.1/30 on a dry day and 1 mm on a rainy day. A water budget is calculated which equals rain minus E and has a maximum U. Water of this budget can be evaporated freely: E equals PET if the budget ≥ PET. When all of the budget has been evaporated, the soil starts limiting the evaporation and from now on the evaporation is calculated according to the 'falling evaporation rate' equation (Steiner, 1979; Jaafer, 1978):

$$E = C*\sqrt{t} - C*\sqrt{t-1}.$$

C soil dependent constant
t number of days into the falling evaporation rate phase

The flowchart on the next page (symbols used are listed at the end of this appendix) schematically shows the onset definition. A computer program listing (Pascal) is given in this appendix and also a detailed output sample of this program. The output sample shows that on day 156 the soil is refilled with water to a higher level than at the first rainy day (RAIN > DEPLETION), so t is set back to 1. At the end of day 157 0.7 mm of water is left in the budget. This is evaporated the next day plus an additional amount in the falling rate phase of $C*\sqrt{t} - C*\sqrt{t-1} = 2.4*\sqrt{1} = 2.4*\sqrt{1-1} =$ 2.4, giving a total evaporated amount (E) of 3.1 mm.

On day 160 there is a rain of 2 mm of which 1 mm is evaporated the same day, leaving a budget of 1 mm. The 2 mm rain did not refill the soil enough (RAIN < DEPLETION), so t is not set back to 1. On day 161 the remainder of the budget is evaporated plus an amount in the falling rate phase (still using the 'old' t), since PET (7.3 mm) > BUDGET (1 mm): $C*\sqrt{t} - C*\sqrt{t-1} = 2.4*\sqrt{4} - 2.4*\sqrt{4-1} = 0.6$, making a total of 1.6 mm. On day 192 the soil moisture content exceeds 40 mm, so this is the date of onset.


START
find first rainy day
add rain to budget
rain today?
y
PET=1
BUDGET<PET?
y
E=BUDGET
n
n
PET = 1.1*MONPET/30
E=PET
BUDGET>PET?
y
E=PET
n
E=BUDGET + E(falling rate)
subtract E from BUDGET
go to next day
n
SOIL > 40?
y
critical date past?
y
ONSET DATE FOUND
n
SOIL > 40+EXTRA?
y
ONSET DATE FOUND
END
n

Pascal computer program to determine the onset date of the rainy season.

```
(* This program finds the onset- and end date of the rainy season. Input
data are daily rainfall and monthly potential evapotranspiration.

constants:
criterium        when the soil moisture-content exceeds this value, the
                 onset date is found.
u                threshold value, above which soil determined evaporation
                 starts.
c                soil dependent constant in equation for falling evaporation
                 rate.
extra_per_day    constant that determines the amount of soil moisture that
                 has to be exceeded, when having an onset before the critical
                 date.

variables:
soilmoist        moisture content of the soil.
rain[day]        rainfall on this day. (1 = january 1)
it               number of days in falling evaporation rate.
it_on            flag' to indicate it has to be updated every day.
monpet           monthly potential evapotranspiration.
pet              daily potential evapotranspiration.
e                actual evapotranspiration.
budget           water that can be evaporated freely. u is the maximum of
                 budget.
depletion        soil moisture that is lost by evaporation. (depletion =
                 cumulative e minus rain).
crit_date        critical date; date before which onset is not allowed, except
                 a few exceptions.*)


program onset(input,output);

type line = array [1..16] of char;

const
   criterium = 40;
   u = 9;
   c = 2.4;
   extra_per_day = 2;

var
  raindata, onset_data, pot_evap:text;
  onset_found, it_on: boolean;

  rain: array[1..365] of real;
  monpet: array[1..12] of real;
  amount,soilmoist,e,pet,budget,depletion,intensity,backsum:real;
  i,mnth,it,onset,endd,duration,crit_date,julian,day,year: integer;

  inp,out,station,current:line;
```

```
begin
argv(1,inp);
(* BEGIN: Make the output filename out of the input file name, extension
is ons *)
for i := 1 to 14 do out[i] := inp[i];
i := 1;
while out[i] <> '.' do i := i+1;
i := i+1;
out[i] := 'o';
i:=i+1;
out[i] := 'n';
i := i+1;
out[i] := 's';
(* END: Make the output filename out of the input file name, extension
is ons *)

for i := 1 to 13 do current[i] := ' ';
i:=1;
while inp[i] <> '.' do begin
  current[i] := inp[i];
  i:= i+1;
end;
writeln(current); (* this is the current station *)
reset(raindata,inp);
reset(pot_evap,'pet.dat');
rewrite(onset_data,out);

(* BEGIN: read monthly evapotranspiration *)
repeat
  for i := 1 to 13 do station[i] := ' ';
  for i := 1 to 13 do read(pot_evap,station[i]);
  read(pot_evap, crit_date);
  for i := 1 to 12 do read(pot_evap, monpet[i]);
  readln(pot_evap);
until (station = current); (* leave loop when values of current station are read *)
(* END: read monthly evapotranspiration *)

writeln('  pet values for 12 months for location ',station);
for mnth := 1 to 12 do write(monpet[mnth]:5:0);
writeln;
for day := 1 to 365 do rain[day] := 0;

while not eof(raindata) do begin
for day:=1 to 365 do readln(raindata,year,julian,rain[julian]);
for day:=1 to 365 do rain[day] := rain[day]/10;
(* find first rainy day and then set values *)
(* begin searching for rainy days on march 1 *)
soilmoist := 0;
it:=1;
depletion := 0;
onset_found := false;
day := 60;
```

```
while (day <= 365) and (rain[day] =0) do day := day+1;
(*the first wet day in the season is found*)

while (not onset_found) and (day <= 365) do begin
  if day <= 150 then mnth := 5;
  if (day > 151) and (day <= 180) then mnth :=6; (*june*)
  if (day > 181) and (day <= 211) then mnth :=7; (*july*)
  if (day > 212) and (day <= 242) then mnth :=8; (*august*)
  if (day > 243) and (day <= 272) then mnth :=9; (*september*)
  if (day > 273) and (day <= 303) then mnth :=10; (*oktober*)
  if (day > 304) and (day <= 334) then mnth :=11; (*november*)

  budget := budget + rain[day];
  if budget < 0 then budget := 0;
  if budget > u then budget := u;


  if rain[day] > 0 then pet := 1 else pet := 1.1*(monpet[mnth]/30);

  if budget > pet then e := pet (* e is weather determined *)
  else begin
    (* e is, at least partly, soil determined *)
    it_on := true;
    e := c*sqrt(it) - c*sqrt(it-1) + budget;
    if e > pet then e := pet;
  end;

  if rain[day] > depletion then begin
    it_on := false; (* soil is satisfied with water *)
    it := 1;
  end;

  (* e can never exceed the available moisture *)
  if soilmoist +rain[day] <= e then e := soilmoist +rain[day];

  budget := budget - e;
  if budget < 0 then budget := 0;
  if budget > u then budget := u;

  depletion := depletion - rain[day];
  if depletion < 0 then depletion := 0;
  depletion := depletion + e;
  soilmoist := soilmoist + rain[day] - e;
  if soilmoist < 0 then soilmoist := 0;

  (* BEGIN: Check if onset date is there *)
  if soilmoist >= criterium then begin
    if day >= crit_date then begin
      onset := day; (*date of onset is found*)
      onset_found := true;
    end
    else begin
      if soilmoist >= ((crit_date-day)*extra_per_day + criterium) then begin
        onset := day; (*date of onset is found*)
```

```
        onset_found := true;
      end;
    end;
  end;
  (* END: Check if onset date is there *)

  if it_on then it := it + 1;
  day := day+1;
end; (* while (not onset_found) and (day <= 365) *)

(* BEGIN: Find end date *)
day := 304; (* start searching for end date from november 1 *)
backsum := 0;
repeat
  day := day - 1;
  backsum := backsum + rain[day]; (*backward summation of rainfall*)
until backsum > 10;
endd := day; (* enddate is found*)
(* END: Find end date *)

amount := 0;
(*summation of season rainfal amount *)
for day := onset + 1 to endd do amount := amount + rain[day];
amount := soilmoist + amount; (* add the soil moisture content at onset to this sum *)
duration := endd - onset + 1;
intensity := amount/duration;
if onset_found then begin
  writeln(onset_data, year,onset:4,endd:4,duration:4,amount:6:0,intensity:5:1);
  writeln(year,onset:4,endd:4,duration:4,amount:6:0,intensity:5:1);
end
else begin
  writeln(onset_data,year,' sorry, no onset this year ');
  writeln(year,' sorry, no onset this year ');
end;
end; (* while not eof(raindata) *)

end.
```

Detailed output of the computer program, determining the date of onset.

	input							output
day of year	rain (mm)	MONPET (mm)	PET (mm)	BUDGET (mm)	DEPLETION (mm)	t (days)	E (mm)	SOIL (mm)
145	0.0	224.0	8.2	0.0	16.9	63	1.0	0.0
146	2.5	224.0	1.0	1.5	15.4	64	1.0	1.5
147	0.0	224.0	8.2	0.0	16.9	65	1.5	0.0
148	0.0	224.0	8.2	0.0	16.9	66	0.0	0.0
149	0.0	224.0	8.2	0.0	16.9	67	0.0	0.0
150	0.0	224.0	8.2	0.0	16.9	68	0.0	0.0
151	0.0	224.0	8.2	0.0	16.9	69	0.0	0.0
152	0.0	200.0	7.3	0.0	16.9	70	0.0	0.0
153	0.0	200.0	7.3	0.0	16.9	71	0.0	0.0
154	0.0	200.0	7.3	0.0	16.9	72	0.0	0.0
155	0.0	200.0	7.3	0.0	16.9	73	0.0	0.0
156	26.0	200.0	1.0	8.0	1.0	1	1.0	25.0
157	0.0	200.0	7.3	0.7	8.3	1	7.3	17.7
158	0.0	200.0	7.3	0.0	11.4	1	3.1	14.6
159	0.0	200.0	7.3	0.0	12.4	2	1.0	13.6
160	2.0	200.0	1.0	1.0	11.4	3	1.0	14.6
161	0.0	200.0	7.3	0.0	13.0	4	1.6	13.0
162	0.0	200.0	7.3	0.0	13.6	5	0.6	12.4
163	0.0	200.0	7.3	0.0	14.1	6	0.5	11.9
164	0.0	200.0	7.3	0.0	14.6	7	0.5	11.4
165	0.0	200.0	7.3	0.0	15.0	8	0.4	11.0
166	5.0	200.0	1.0	4.0	11.0	9	1.0	15.0
167	0.0	200.0	7.3	0.0	15.4	10	4.4	10.6
168	0.0	200.0	7.3	0.0	15.8	11	0.4	10.2
169	13.0	200.0	1.0	8.0	3.8	12	1.0	22.2
170	0.0	200.0	7.3	0.7	11.1	13	7.3	14.9
171	0.0	200.0	7.3	0.0	12.1	14	1.0	13.9
172	7.5	200.0	1.0	6.5	5.6	15	1.0	20.4
173	0.0	200.0	7.3	0.0	12.4	16	6.8	13.6
174	0.0	200.0	7.3	0.0	12.7	17	0.3	13.3
175	20.2	200.0	1.0	8.0	1.0	1	1.0	32.5
176	0.0	200.0	7.3	0.7	8.3	1	7.3	25.2
177	0.0	200.0	7.3	0.0	11.4	1	3.1	22.1
178	0.0	200.0	7.3	0.0	12.4	2	1.0	21.1
179	0.0	200.0	7.3	0.0	13.2	3	0.8	20.3
180	0.0	200.0	7.3	0.0	13.8	4	0.6	19.7
181	20.2	200.0	1.0	8.0	1.0	1	1.0	38.9
182	0.0	180.0	6.6	1.4	7.6	1	6.6	32.3
183	0.0	180.0	6.6	0.0	11.4	1	3.8	28.5
184	0.0	180.0	6.6	0.0	12.4	2	1.0	27.5
185	0.0	180.0	6.6	0.0	13.2	3	0.8	26.7
186	0.0	180.0	6.6	0.0	13.8	4	0.6	26.1
187	0.0	180.0	6.6	0.0	14.4	5	0.6	25.5
188	0.0	180.0	6.6	0.0	14.9	6	0.5	25.0
189	6.4	180.0	1.0	5.4	9.5	7	1.0	30.4
190	0.0	180.0	6.6	0.0	15.3	8	5.8	24.6
191	0.0	180.0	6.6	0.0	15.7	9	0.4	24.2
192	19.5	180.0	1.0	8.0	1.0	1	1.0	42.7

Symbols used in this appendix.

BUDGET	water that can be evaporated freely. U is the maximum of the budget.
C	soil dependent constant in equation for falling evaporation rate.
E	actual evaporation.
EXTRA	(critical date - actual date)*constant
DEPLETION	amount of water that the soil lost through evaporation and gained through rainfall, since the first rainy day.
MONPET	monthly potential evapotranspiration.
PET	daily potential evapotranspiration.
SOIL	moisture content of the soil.
U	when U mm has been evaporated freely, evaporation in the falling rate starts.
t	number of days in falling evaporation rate.