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ABSTRACT

A major difficulty in interpreting coarse resolution satellite data in terms of land surface characteristics is unavailability of spatially and temporally representative ground observations. Under certain conditions rainfall has been found to provide an important proxy measure for surface (soil-litter-vegetation) characteristics, and thus a relation between satellite observations and rainfall might provide an indirect approach for relating satellite data to the surface characteristics. Observations show that in areas where vegetation growth is limited due to available water, *long-term average rainfall* could be a good predictor of productivity, fractional ground cover or leaf area index of vegetation in the absence of anthropogenic impact. The relation between rainfall over Africa and Australia and seven year average (1979-1985) polarization difference (PD) at 37 GHz from the scanning multichannel microwave radiometer (SMMR) on board the Nimbus-7 satellite is studied in this paper. *Quantitative* methods have been developed and used to screen (accept or reject) PD data considering antenna pattern, geolocation uncertainty, water contamination, surface roughness, and adverse effect of drought on the relation between rainfall and surface characteristics. Three rainfall data sets have been used in the present analysis (two data sets are for climatologic averages and one data set is for 1979-1985 averages), and no screening has been applied to these rainfall data. The screening methods applied to the PD data do not *a priori* assume the existence of a relation between PD and rainfall. The PD data has been screened considering *only* the location of rainfall stations, without any regard to rainfall amounts. *The present analysis based on quantitative data screening confirms a non-linear relation between rainfall and PD published previously.* The atmospheric effect on the rainfall-PD relation is considered and it is concluded that *atmospheric effect alone cannot explain* the observed relationship.

1. INTRODUCTION

All field and aircraft observations of microwave emission intensity over snow-free land surface and radiative transfer modeling have shown that the intensity at any polarization state for a prescribed angle of observation is determined most prominently by surface temperature, volumetric soil moisture, surface roughness and vegetation water content (Schmugge, 1985; Matzler, 1991; Jackson and Schmugge, 1991; Ferrazzoli *et al.*, 1992; Paloscia and Pampaloni, 1992). These studies have also shown that the rank ordering of the sensitivity of emission intensity to soil moisture, surface roughness and vegetation is determined primarily by the wavelength of observation: long wavelengths (say 21 cm) are more sensitive to soil moisture, while short wavelengths (say 1 cm) are more sensitive to surface roughness and vegetation cover. While most effort have been directed towards estimation of soil moisture using microwave observations, several recent studies have focused directly on relating these observations over agricultural fields to leaf area index and water content of crop canopies (Chukhlantsev and Shutko, 1990; Matzler, 1991; Jackson and Schmugge, 1991; Ferrazzoli *et al.*, 1992; Paloscia and Pampaloni, 1992).

Monitoring of land surface vegetation and quantification of its characteristics (such as biomass, leaf area index, stress and fractional cover) at regional and global scales are of significant importance for a quantitative understanding of natural and anthropogenic changes of land surface and land surface-atmosphere interaction through exchanges of energy, mass and momentum. While field observations to quantify vegetation characteristics through microwave observations are immensely valuable for development, clarification and validation of basic concepts and methodologies, satellite observations are indispensible for regional and global studies. The disparity of spatial scales involved in going from field observations (c. 100 m) to satellite data (c. 30 km) presents the major difficulty in directly transferring the methodologies developed through field observations to the satellite data. This disparity of spatial scales might be addressed through aircraft observations from different altitudes and large-scale field studies, but nevertheless remains an outstanding problem.

The feasibility of monitoring vegetation using passive microwave observations from satellites has been investigated by Hallikainen *et al.* (1988), Kerr and Njoku (1990), Choudhury (1989, 1990), Reutov and Shutko (1990), among others. These studies have shown that multifrequency dual-polarized observations can discriminate different vegetation types and monitor seasonal and interannual changes. Much progress has been made towards classification of land surface types using microwave observations from different satellites (Ferraro *et al.*, 1986; Neale *et al.*, 1990; Grody, 1991).

Choudhury (1989), Prince and Choudhury (1989), Smith and Choudhury (1990) and Tucker (1992) have studied the relation between rainfall and the difference of vertically and horizontally polarized brightness temperatures (polarization difference or PD) observed at 37 GHz by the scanning multichannel microwave radiometer (SMMR) on board the Nimbus-7 satellite. Simulations using radiative transfer models have shown that 37-GHz PD depends upon soil, litter and vegetation characteristics, such as fractional cover, leaf and stem area indices (Choudhury, 1990; Choudhury *et al.*, 1990). The spatial resolution of the SMMR 37-GHz data is about 25 km, and, in the absence of spatially and temporally representative data for vegetation, rainfall was considered as a proxy measure for surface characteristics. Several studies have shown that fractional ground cover, leaf area index and productivity of vegetation could be related to rainfall or soil moisture, in areas where water availability is the limiting factor for vegetation growth (Terborgh, 1973; Lieth, 1975; Grier and Running, 1977; Waring *et al.*, 1978; Eagleson, 1982; Eagleson and Tellers, 1982; Le Houerou, 1984; Eagleson and Segarra, 1985; Woodward, 1987). Eagleson (1982) has put forward a formal theory for ecologically optimum joint state of vegetation and soil towards which natural systems evolve in a given climate. Eagleson and Tellers (1982) showed that fractional vegetation cover is determined to a large extent by soil and climate, and Woodward (1987) has shown that leaf area indices of different vegetation types predicted from water balance computation using *climatologic rainfall* values are in accord with observations. Le Houerou (1989) notes that biomass productivity of rangelands is directly tied to rainfall for a given plant community or for a given geographical area *over a number of years*, but annual rainfall for a specific year is *not* a good predictor of productivity (the ratio of the coefficient of variations of biomass production and rainfall was found to be in the range 1.2 to 1.8). These studies suggest that the relation between rainfall and surface characteristics is better defined when considered over a number of years (when a steady state condition develops), although such a relation can be adversely affected by drought or anthropogenic impact, as discussed below.

Choudhury (1989) found a statistically significant non-linear relationship between the PD values averaged for 7 years (1979-1985) and climatologic mean rainfall for 76 locations over Africa and Australia. Choudhury had argued that it is desirable to consider average rainfall for several years because of the spatial variability of rainfall over the resolution area of PD (c. 25 km). For temporally coincident (1979-1985) PD and rainfall data over Botswana, Prince and Choudhury (1989) found that 7-year mean rainfall was more closely related to PD than for individual years. Smith and Choudhury (1990) found wide scatter (barely recognizable relationship) when temporally coincident (May 1986-April 1987) monthly values of rainfall and PD over Australia were plotted against each other. Any misregistration of PD pixel with respect to the location of rainfall station can also introduce scatter in the PD-rainfall analysis, particularly for monthly or annual values. Tucker (1992) found poor correlations for temporally coincident data July-October (1982-1985) at 41 locations over arid and semi-arid West Africa (Mali and Niger); the coefficient of determination ranged between 0.1 to 0.5 for individual years and 0.31 to 0.45 for 1982-1985 (July-October) average, depending upon the range of rainfall values considered in the regression. Tucker (1992) investigated the marked difference between the poor correlation he found for the temporally coincident rainfall and PD data sets and high coefficient of determination (0.88) reported by Choudhury (1989) by attempting to reproduce Choudhury's results. Tucker found wide scatter when all rainfall data less than 1600-mm annual value over Africa and Australia (159 locations) from Muller (1982) were plotted against 1979-1985 average PD. Choudhury had selected 76 locations for his analysis and the rainfall data for most of these locations were from Muller (1982). These 76 locations were selected subjectively considering, (1) the effects of exposed water (lakes, rivers and swamps) and surface roughness on PD (see p. 1579, 1585, 1588, 1592, 1599, in Choudhury, 1989), (2) high PD values in some of the coastal regions, which were assumed to be due to land/water mixed pixels (see p. 1601, in Choudhury, 1989), and (3) prior knowledge of drought over the Sahel zone of Africa (see p. 1601, in Choudhury, 1989). These considerations were not detailed while presenting the PD-rainfall relation, but were noted elsewhere within the paper (as annotated above). When Tucker screened the PD pixels for possible water contamination using a digital data base, only 25 of the original 159 stations were found to be further than 100 km from standing water of some sort, and the data for these 25 locations also did not show any clear relation between PD and rainfall. Tucker (1992) also found that PD pixels are apparently unaffected by inclusion of a river or water body within the pixel for his West African locations. Based on these findings Tucker (1992) concluded that the relation between PD and rainfall reported by Choudhury (1989) was based upon selective information and that PD is poorly correlated with rainfall.

Relation between 1979-1985 averaged PD and rainfall is reexamined in this paper. All rainfall data cannot be used for correlation with PD because, (a) factors other than vegetation affect PD values, and (b) relation between rainfall and surface characteristics under drought conditions (or anthropogenic pressure) could be much different from that in the absence of drought (or anthropogenic impact). Whereas Choudhury (1989) had subjectively selected rainfall stations for his analysis of PD-rainfall relationship, we have developed and used quantitative methods to screen (accept or reject) the PD data considering antenna pattern, geolocation uncertainty, exposed water, surface roughness and land surface change due to drought. The rationale and quantitative methods used for these screenings are discussed in the following section. The present analysis has been done using three rainfall data sets for Africa and Australia; two data sets are for climatologic mean rainfall, while one data set is concurrent with the PD data (1979-1985 averages). Climatologic rainfall data sets are from Muller (1982) except those over islands and from Legates and Willmott (1990). All rainfall data have been considered because there is no rationale for setting *a priori* an upper or a lower limit on rainfall amount for correlation with PD.

2. DATA AND METHODS

The SMMR on board the Nimbus-7 satellite was a conically scanning dual-polarized radiometric system which has provided global observations at six frequencies from December 1978 to August 1987. All observations were acquired at a constant incidence angle of 50° and at equator crossing times of local noon and midnight. Observations at two polarizations were coincident for 37-GHz frequency, while the observations for five other frequencies were acquired in alternate scans. The data analyzed in this paper are those acquired at local noon equator crossing time. From vertically and horizontally polarized brightness temperatures we have computed the polarization difference (PD), and the second lowest value of PD among all the PD values available within a month at any location are kept for analysis. This selection procedure for PD was applied to minimize the effects of soil moisture and clouds on the PD values. In addition to this second lowest PD we have kept the brightness temperatures associated with this PD. All brightness temperatures have been gridded into 0.25°x0.25° (latitude x longitude) cells by determining the radiometer beam center to be within this cell. (Note that the beam center for the brightness temperature data within a cell is not necessarily situated at the center of the cell). The geolocation uncertainty for the beam center has been estimated to be about 12 km. Any missing pixel in the global data set due to unrecorded (missing) orbits has been filled by spatial and temporal averaging. (These missing orbits were particularly significant for a few months during 1986.) The global monthly data set was subjected to a trend analysis to assess any systematic sensor degradation. This trend analysis showed a systematic decrease of PD by about 0.013 K per month. The data set used in the present analysis has been adjusted for this sensor degradation. The absolute accuracies of the brightness temperatures have not yet been established due to difficulties in the precise sensor calibration and determination of antenna temperatures (Hallikainen *et al.*, 1988; Choudhury, 1992). The PD values for 84 months (January 1979 to December 1985) at each location have been averaged (arithmetic mean) for correlation with the rainfall data.

The PD data needs to be screened before correlation with the rainfall data because, (a) factors other than vegetation affect PD, and (b) drought or anthropogenic impact can affect the relation between rainfall and surface characteristics. The data have been screened at three levels considering, (1) antenna pattern and geolocation uncertainty (Level 1), (2) surface roughness and exposed water (Level 2), and (3) systematic land surface change (Level 3). The rationale and quantitative methods used for these screenings are outlined below.

The screening methods applied to the PD data do not *a priori* assume the existence of any relation between PD and rainfall. The PD data has been screened considering *only* the location of rainfall stations; *rainfall amounts have not been used in any way for screening.*

Level 1: The way a microwave radiometer measures the radiative energy emitted from the Earth (which is conventionally reported in temperature units called brightness temperatures) and the accuracy with which this pattern of measurement can be located on the Earth, put some fundamental restrictions on the interpretation of radiometric measurements.

The instantaneous field-of-view (IFOV) 3-dB footprint of the SMMR 37-GHz radiometer was about 27x18 km. While the IFOV was 27x18 km, the effective field-of-view (EFOV) 3-dB beamwidth, taking into account the data integration time on board the satellite, was about 27x27 km. The antenna received 6 percent of the total radiative energy from the area determined by 3-dB beamwidth, and of the remaining 4 percent about 3 percent of the energy came from an area 2.5 times the area for 3-dB beamwidth and 1 percent from a much larger area. (These fractional energy received from different areas are determined by the radiometer antenna pattern.) Thus, about 70x70 km area contributed to 9 percent of the energy received by the SMMR 37-GHz antenna. This larger area contributing to the energy received by the antenna has a significant bearing on the interpretation of observations over radiometrically highly heterogeneous regions, like the coastal regions. Water is very cold when observed at horizontal polarization (brightness temperatures are typically 130-140 K as could be determined from Fresnel equation) and has a much higher polarization difference (about 60 K) as compared to land surface (horizontal brightness temperatures are typically 240-280 K and polarization difference 5-30 K). Thus, the antenna energy for 37-GHz observations over land with beam centers within 35 km of land/ocean boundary was a composite of energy received from land and water surfaces, recognizing that 9 percent of the energy received by the antenna was from 70x70 km area. Alternately, *two* 0.25°x0.25° *land pixels on the coastal areas will always have brightness temperatures (and PD) representing the energy received from both land and ocean surfaces.* These two land pixels are *radiometrically mixed pixels* due to the antenna pattern having signatures of both land and water, although water may not be present within these pixels. The rainfall data for all stations situated within two pixels from any ocean boundary would have to be excluded from correlation with PD because these PD values cannot be considered representative of only the land surface characteristics. The effect of water contamination due to antenna pattern may also appear in the third land pixel away from water boundary due to geolocation uncertainty of the PD data (as discussed below) and mismatch of the land/water boundary with the pixel boundary, in which case the first pixel bordering water would be a mixed pixel in the literal sense due to fractional coverage of both land and water.

Figure 1 shows the observed pixel values of SMMR 37-GHz PD for two regions over Africa containing land and ocean, illustrating the effect of water contamination of land pixels due to antenna pattern (radiometrically mixed pixels). Note that the PD values of two or three land pixels bordering water are systematically higher than those appearing further inland. As discussed above, the PD over water is about 60 K, while it is 5-30 K over land and consequently a radiometrically mixed pixel will have intermediate PD values. The effect of antenna pattern in increasing the PD value could be seen more clearly for vegetated surfaces bordering water compared to desert areas because of larger difference between the PD values for water (c. 60 K) and densely vegetated surfaces (c. 4-5 K) vs. deserts (c. 25-30 K). These high PD values bordering ocean cannot be considered representative of only the land surface characteristics, since the antenna received energy from both ocean and land. *These mixed pixels bordering ocean must be excluded from any study of land surface characteristics using the SMMR 37-GHz data.*

Now, consider the 0.25°x0.25° pixel in which a particular rainfall station is situated. The antenna beam center for the brightness temperatures which was gridded into this pixel may not actually be situated within this pixel because of the geolocation uncertainty of the beam center (c. 12 km). Similarly, the brightness temperatures whose beam centers were actually situated within this pixel got gridded into one of the neighboring pixels. Considering these misregistrations it is more appropriate to consider an average PD value of nine pixels (3x3 matrix) centered on the rainfall station rather than the PD value for the pixel containing the rainfall station. We have used an average value of nine PD pixels for correlation with the rainfall data.

The data screening due to proximity of a rainfall station to oceans and geolocation uncertainty for beam center (gridding error) is illustrated in figure 2. This figure shows a rainfall station which is situated three pixels away from any water pixel, 3x3 matrix centered on the rainfall station and radiometrically mixed pixels (two pixels bordering water pixels). In this figure there are no mixed pixels in the literal sense (pixels containing both land and water).

To screen the PD data for antenna pattern and geolocation uncertainty, we have used a digital data set (developed by H. W. Powell and Y. L. Chien from a contour plotting package called WOLF-PLOT resident on the IBM mainframe computer at Goddard) which identifies major water bodies and land mass into three surface categories, land, water and mixed (land/water) coastal region at 0.25° resolution registered to and used for processing the PD data (see fig. 1). We have rejected the PD data corresponding to all rainfall stations for which a water pixel can be identified within 9x9 matrix centered on the rainfall station (fig. 2). (The number of stations passing each screening is given in Table 3, further discussed below.) There was no observer bias or fine tuning involved in this screening. Also, this screening does not *a priori* assume the existence of a relation between PD and rainfall.

Tucker (1992) screened rainfall stations based on their distance "from water of any sort" as 45 and 100 km without stating the rationale for choosing these distances. We find from the above discussion that neither of these distances can be justified for the processed PD data used by Tucker.

Level 2: The PD data needs to be screened for variations introduced by rough terrain, built-up area and exposed water from rivers, lakes or dams.

Theoretical studies and field observations over bare soils have demonstrated that polarization difference decreases and horizontally polarized brightness temperature increases as the surface roughness increases, and an important parameter controlling the effect of roughness is the ratio of root mean square surface height and the wavelength of microwave radiation (Beckman, 1968; Schmugge, 1985; Choudhury, 1989). At coarse spatial resolution of the satellite data there could be a range of roughness scales (small-scale surface undulations to large topographic variations) and the relative impact of these scales on the brightness temperature has not yet been quantified. Nevertheless, from basic physical consideration, mountainous areas with little or no vegetation are expected to impact PD because PD is sensitive to the incidence angle (i.e., the angle between the direction of observation and normal to the surface). The incidence angle for mountainous areas is a spatially variable parameter due to changes in the surface slope (the effective incidence angle at any location could be greater or less than 50° depending upon slope and aspect of the location). Field observations at 37 GHz illustrating the sensitivity of brightness temperatures and PD to the incidence angle for bare and vegetated soils are shown in figure 3 (Wang *et al.*, 1982), and similar angular dependencies have been observed at other microwave frequencies (cf., Mo *et al.*, 1982). It is seen that PD depends strongly on the incidence angle for bare soils, while it is rather insensitive for vegetated soils. Surface roughness also introduces polarization mixing (which decreases the PD value) because the rectangular coordinate system needed to specify the polarization states cannot be defined uniquely due to variations in slope and aspect (Beckman, 1968; Choudhury, 1989). Thus, topographic variation can affect the magnitude of PD of individual pixels and can introduce pixel-to-pixel variations for bare or partially vegetated surfaces. A mountainous area will have a lower PD compared to a smooth surface when both surfaces are devoid of any vegetation due purely to surface roughness effect. However, this surface roughness on PD is expected to decrease as the terrain gets vegetated because of the diffuse nature of vegetation canopy which emits largely depolarized radiation (fig. 3 and Matzler, 1991). Although a quantitative method for detecting the effect of surface roughness on PD as a terrain changes from bare to densely vegetated has not yet been developed, *terrain roughness alone (as might be determined from a digital elevation model) should not be used as a sufficient condition for rejecting the PD data for roughness effect.* The complementary nature of the effects of surface roughness and vegetation on PD has been discussed by Choudhury (1989).

Exposed water within a pixel can decrease horizontal brightness temperatures and increase PD (Choudhury, 1989). The effect on PD of lakes and rivers within a pixel will be determined by the fractional area of water actually visible to the sensor (SMMR) from the incidence angle of 50° (Choudhury, 1989). For example, when the observations are being made perpendicular to a river lined with 10-m-high trees on the river banks, then the width of the river needs to be greater than about 12 m for SMMR to see any exposed water. Thus, the effective fractional area of exposed water could be much less than the fractional area determined from nadir observations. Consequently, to assess the effect of lakes and rivers on the observed brightness temperatures and PD using a digital database one will need additional information about the angle of observation with respect to the orientation of the water bodies and the nature of vegetation surrounding the water bodies. Also, calculations using equation (16) of Choudhury (1989) show that for forested areas, about 1.8 km^2, and for arid areas, about 2.9 km^2 of exposed water within a 0.25°x0.25° pixel needs to be visible to SMMR for PD to change by 0.15 K, which is about the rms error of PD. Thus, a river crossing a pixel needs to be 70-100 m wide (effective width visible to the sensor) to affect PD by about the rms error. Atmospheric effects could further increase the uncertainty to about 0.5 K in PD, which will increase the effective width of exposed water needs to be visible to the sensor for detectable effect. The fractional coverage of exposed water needs to be higher to achieve similar rms error when average PD value of 9 pixels (3x3 matrix) is considered for correlation with the rainfall data. These calculations show that *presence of any sort of water within a pixel should not be used as a sufficient condition for rejecting the PD data for water contamination.* Tucker (1992) had rejected rainfall stations based only on the proximity of the stations to "water of any sort," which, based on the above discussion, we think is inappropriate. Nevertheless, exposed water from many rivers, lakes and dams can have noticeable impact on PD.

The effects of surface roughness and exposed water on PD and horizontally polarized brightness temperature as discussed above are illustrated in figures 4 (a and b) using the SMMR 37-GHz observations. These figures show the pixel values of PD and horizontally polarized brightness temperature going across Air mountain within Sahara (fig. 4a) and across Zaire river and Lake Leopold II (fig. 4b). One can see that in going across the Air mountain the PD decreases and horizontally polarized brightness temperature increases, while going across exposed water the PD increases and the brightness temperature decreases. These are the expected effects of rough terrain and exposed water on PD and the brightness temperature.

The above discussion and examples provide the rationale for screening the PD data for effects of surface roughness and exposed water. If this screening is not done then the PD value corresponding to a rainfall station would be higher when the pixel is contaminated with water, and it will be lower when affected by surface roughness compared to the possible value in the absence of these effects. We have not yet been able to develop a method for detecting these effects on the SMMR data from theoretical consideration, and even when such a method is developed, it will almost certainly require fairly detailed quantitative data on surface characteristics (river width and surrounding vegetation height and density, etc.), which is not currently available. Recognizing the complementary nature of PD and horizontally polarized brightness temperature with respect to their responses to roughness and exposed water (fig. 4) we developed a data set of normalized polarization difference (NPD) as the ratio of PD and horizontally polarized brightness temperature. Pixel-to-pixel variations of roughness and fractional area of exposed water can introduce spatial variations in NPD, as could be determined from fig. 4. Thus, as an index for spatial variability we computed the ratio (V; variability index) of the highest and the lowest pixel values of NPD occurring within the 3x3 matrix centered on a rainfall station. Table 1 gives the calculated values of the variability index (V) for all rainfall stations in Africa from Muller (1982) which passed Level 1 screening, while examples of 3x3 matrix of NPD for several locations in Table 1 are shown in fig. 5 (see Table 3 for the number of stations rejected at this screening). Geographical setting of rainfall stations assessed subjectively from atlases (*The Times Atlas* and *National Geographic Atlas*) and rainfall values from Muller are also given in Table 1.

The effect of exposed water for Eala and Kinshasa (situated on the bank of Zaire river), Harar and Ar-Rusayris (situated close to large dams) and Tshibinda (situated close to Lake Kivu) is seen to produce about a factor of two variation in the 3x3 matrix of NPD and resulting in high values for V (fig. 5 and Table 1). The NPD value of the pixels affected by exposed water is higher compared to those not affected in fig. 5. Exposed water has less noticeable impact on the spatial variation of NPD and the resulting value for V for stations situated in arid regions (see Al Uqsur and Dunqulah in Table 1 and fig. 5). Effect of exposed water on NPD and V is also not clearly seen for many other stations, for example, Garissa, situated on the bank of Tana river (see Table 1 and fig. 5). Although we do not have information on river width at Al Uqsur, Dunqulah or Garissa, it is possible that the width at these locations is not sufficient to have a detectable impact on NPD and V. The calculated low values of V for Jima, Dagoretti and Morogoro situated in mountainous areas could be because of vegetation covering the terrain, recognizing the observed high rainfall values for these stations (900-1500 mm).

Examination of Table 1 and figure 5 also shows some limitations of screening rainfall stations using the variability index. We see that stations, like Bobo Dioulasso and Jos, situated away from mountainous areas or water bodies have fairly high V values. Both of these stations have fairly high rainfall and thus are expected to be densely vegetated. The 3x3 matrix of NPD for Bobo Dioulasso (fig. 5) shows a systematic north-to-south pattern of decreasing NPD values, possibly in response to the known rainfall gradient (Le Houerou, 1989). These examples show that factors other than surface roughness or exposed water can introduce spatial variations in NPD, leading to a high value for V.

Screening for roughness and exposed water could be achieved by setting a cutoff value for V to accept or reject a rainfall station, although we recognize the limitation that variations in soil and vegetation can also introduce spatial variability. The data in Table 1 provide some guidance for choosing a cutoff value (s) for V, although much caution is needed. Geographical setting of locations given in Table 1 (rough terrain or water bodies) has been assessed subjectively from atlases, and it was found that these settings could not be reproduced identically under repeated blind trials due partly to difference among atlases and the subjective nature of the assessment. Even when the geographic setting could be prescribed unequivocally, this setting alone does not completely describe the impact on PD; we need to consider the effective area of exposed water and vegetation covering on rough terrain. Keeping these cautions in mind, we note that about 2 percent of all rainfall stations have V values greater than 1.30, while 5 percent of the stations have V values greater than 1.20. In both of these cases the proportion of stations situated close to water or rough terrain is higher compared to stations situated away from such areas, which suggests that V index has some merit for screening rainfall stations situated in mountainous areas or close to water bodies.

The data in Table 1 is for isolated locations as given in Muller (1982). However, the present screening is attempting to identify rainfall stations situated close to rivers, lakes, and mountainous areas, which appear as spatial features rather than isolated points in a map. Therefore, we wanted to see whether screening using a cutoff value for V can identify spatial features related to rough terrain or exposed water.

A shaded map of pixel-by-pixel binary classification (accept or reject based on a cutoff V values of either 1.25 or 1.3) for Africa, Middle East, and parts of Europe are shown in figure 6. A V value was computed for each pixel in this map from 3x3 matrix of NPD centered on the pixel, except for those pixels for which a water pixel was detected within the 3x3 matrix (see Level 1 screening for detection of water pixels). In fig. 6 one can see that high V values generally appear in mountainous areas and close to water bodies. The appearance of spatial features in this figure may be compared with those found in atlases. Perhaps the most prominent feature is the appearance of Zaire river and its main tributaries (Ubangi and Kasai rivers). One can also see Tibesti, Air and Ahaggar mountains within Sahara, the mountainous area of the Eastern Desert, Namib Desert, Atlas-Saharien mountains in the Mediterranean northern Africa, the highlands of Ethiopia, and Kenya. Okavango Delta and Makagadikgadi salt pan in southern Africa appear clearly and also Lake Volta, Lake Kossou, and the entrance of Niger River in the Gulf of Guinea. Many rivers, for example Tana, Nile, Zambeze, and Orange, do not appear clearly in this figure. Regions around Kufra Oasis and Hamada de Tinrhert within Sahara are seen to have high values of V. *It is important to note in this figure that accept/reject criterion does not appear as randomly distributed points over this map and thus screening using a cutoff value of V is not likely to result in accepting or rejecting rainfall stations totally randomly. The present screening is fairly capable of identifying spatial features related to rough terrain and exposed water, which is the objective of this screening.*

We have used the variability index V to screen for surface roughness and exposed water, although we recognize its limitations. Since it is difficult to establish an unique cutoff value for V, we have studied two cases as: (a) rejecting the PD data for all rainfall stations for which V is greater than 1.249 (referred to below as Level 2A screening), and (b) rejecting the PD data for which V is greater than 1.20 (referred below as Level 2B screening). A comparison of results based on Level 2A and Level 2B screenings would provide an appraisal of the sensitivity of any relation between PD and rainfall to this data selection criterion. The Level 2B screening puts a more stringent restriction on the selection of rainfall stations (lower spatial variability), and the stations selected under Level 2B will be a subset of the stations selected under Level 2A. As the cutoff value of V is increased more stations situated close to water or in rough terrain will pass the screening and thus will appear as candidates in relating PD to rainfall; scatter in any relation between PD and rainfall is expected to increase with increasing cutoff value of V. There would certainly be some natural variabilities surrounding the rainfall stations and therefore a lower limit on the cutoff value of V associated with such variabilities. If one accepts the subjective designation of terrain characteristics surrounding the rainfall stations given in Table 1 (rough, water, and homogeneous) then the mean (standard deviation) of V values for stations situated in homogeneous area is found to be 1.175 (0.066). Thus, a cutoff value of V as 1.2 appears to be representative of the average variability in homogeneous areas.

Screening of rainfall stations has been done by calculating the index V considering only the location of rainfall stations; no other information has been used for screening. From the data in Table 1, which is for all stations in Africa from Muller (1982) passing Level 1 screening, one can verify that the variability index has no recognizable relation with rainfall. Although there is a clear rationale to screen rainfall stations due to roughness and exposed water, the present screening procedure is not totally satisfactory because spatial variations of vegetation or soil characteristics can also give high values of V, as discussed above.

Note that the nine PD (or NPD) values in the 3x3 matrix are not totally independent observations because of geolocation uncertainty and 70x70 km area contributing to 9 percent of the radiative energy received by the SMMR 37-GHz antenna, which introduce difficulty in interpreting standard deviation or coefficient of variation as reliable measures of spatial variability. Although the variability index, V, provides a quantitative approach for data screening, further research is highly desirable to differentiate natural variabilities of soils and vegetation from those due to topography and exposed water.

Level 3: It is rather well known that the Sahel and Sudan zones of Africa were under a severe, long-term drought during the period of our satellite data (Nicholson, 1985; Dennet *et al.*, 1985). The occurrence of drought can adversely affect soil, litter and vegetation so that the relation between rainfall and surface characteristics under drought conditions could be much different from that in the absence of drought. Anthropogenic causes can also affect rainfall-vegetation relationships (e.g., clearing of forested land to pasture or urban land significantly changes the surface characteristics without significant rainfall). *It is important to distinguish the areas affected by long-term drought or anthropogenic causes from the unaffected areas when rainfall is being used as a proxy for the surface characteristics.*

There is ample evidence that water deficit can affect vegetation physiological processes both on short- and long-time scales (hour to year) as discussed by Crafts (1968), Gates (1968), Zahner (1968), Levitt (1980), among others. The Sahel zone has experienced deficit rainfall since 1970. Several consecutive years of rainfall deficit can have a rather severe impact on the surface characteristics, particularly under anthropogenic pressure (Katz and Glantz, 1977; Hare, 1985; Williams and Calaby, 1985; Rapp, 1986; Le Houerou, 1989). Drought can desiccate land, induce accelerated soil erosion and disappearence of litter and can cause major changes in the vegetation characteristics (species composition, fractional cover and leaf and stem area indices). There have been heavy mortalities of woody vegetation in the Sahel zone north of the 16° latitude during the 1983-1985 drought (Le Houerou, 1989). Return of a year of excess rainfall following several years of rainfall deficit is not expected to restore immediately the surface characteristics; trees that died or litter decomposed during the drought period may require several years to be restored. Le Houerou (1989) wrote that under the current conditions of increasing anthropogenic pressure, the Sahel will probably never recover from the recent drought of 1970-1984. An implication of the recent Sahel drought together with the prevailing anthropogenic pressure is that the relation between rainfall and surface characteristics which existed before the drought may not be realized for many years in the future (perhaps never be realized). Changes in the surface characteristics may not be proportional to or synchronous with the changes of rainfall, and thus rainfall may not always provide a representation of vegetation even when averaged over a number of years.

Figure 7, from Choudhury and Nicholson (1992), show rainfall deficit percent (departure from climatologic mean), PD, and visible reflectance (derived from observations by the advanced very high resolution radiometer on board NOAA satellites) for two areas, respectively, within the Sahel and Sudan zones. Although one can see an overall trend of higher rainfall deficit being correlated with higher PD and visible reflectance, *there are major systematic inconsistencies in this correlation.* While maximum rainfall deficit for both regions occurred during 1984, the PD values attain their maximum during 1985 for both regions; the visible reflectance also attains its maximum value during 1985 for the Sudan zone, while it occurs during 1984 for the Sahel zone. Apart from this major inconsistency in the relation between rainfall deficit and independent satellite observations, one can also see that year-to-year changes of these satellite data are not proportional to the changes in the rainfall deficit. For example, rainfall deficit during 1986 over the Sudan zone is comparable to that during 1981, but PD during 1986 is comparable to that during 1984. Rainfall deficit over the area within the Sahel zone during 1986 is seen to be less than that during 1982, but both PD and visible reflectance during 1986 are higher compared to that during 1982. The adverse effect of drought on the surface characteristics is clearly seen in these two independent satellite observations. Drought over the Sahel and Sudan zones started in 1970 and continued through the study period, and much has been written on human suffering and large-scale changes of the land surface both due to drought and anthropogenic impact (Hare, 1985; Le Houerou, 1989). Here it is pertinent to note that the rainfall data during July-October, 1982-1985 in Mali and Niger used by Tucker (1992) for correlation with PD were under this drought condition over the Sahel and Sudan zones. Tucker (1992) had also analyzed rainfall data from Muller (1982) including stations within this drought affected area without any justification, even though the rainfall values given in Muller were known to be unrealistic for the period of satellite data. Choudhury (1989) had excluded stations situated within the Sahel and Sudan zones because of prior knowledge of drought, but no quantitative criteria was applied to the selected stations to determine the occurrence of drought, as being applied here. The poor correlation found by Tucker (1992) might be due to shorter time duration for his analysis, as has been noted above and found by Smith and Choudhury (1990) and Prince and Choudhury (1989). We find the correlation between PD and rainfall over the Sahel and Sudan zones to be substantially higher than that found by Tucker (1992) when 1979-1985 average rainfall data is considered (see below).

As a quantitative indicator for land surface change, we have computed the slope of the monthly PD values from January 1979 to December 1985 for all rainfall stations which passed the Level 2 screening. Then, we have rejected the stations for which the slope was not zero at 9-percent confidence level (Student's t test). *There is no firm rule for setting the confidence level for testing a hypothesis* (Acton, 1963). Thus, while screening could be achieved by setting any confidence level, *we had set the level at 9 percent without examining the result for any rainfall station so as to avoid any observer bias or fine tuning in this Level 3 screening.* The slope of the regression for all stations in Muller (1982) which passed the Level 2A screening but was rejected at Level 3 screening is given in Table 2 (see Table 3 for the number of stations passing Level 3 screening). This table also gives the results for screening at 99-percent confidence level for comparison purposes only. These rejected stations are seen to be generally situated in the drought affected areas of northern and southern Africa. Only two stations, Mut and Al-Kufrah, are seen to have negative slopes; the slope for Mut is not significantly different from zero, which is not the case for Al-Kufrah. A negative slope for these desert locations (see Table 1 for rainfall values) would signify anthropogenic impact towards irrigated crop production, and indeed, Libya is known to have invested a very significant income from oil towards irrigation using water from the Kufrah oasis (Metz, 1989). The higher the confidence level, the more stringent is the restriction for rejecting a station (see Table 2). By this screening we are choosing rainfall stations for which the surface characteristics have not changed systematically for the period of our satellite data. We are assuming that rainfall values for stations where the surface characteristics are in a steady state (zero slope for PD) might be considered to provide a proxy measure for such characteristics (Woodward, 1987; Le Houerou, 1989). Year-to-year fluctuation of rainfall amount about the long-term mean is less likely to introduce a systematic land surface change than a prolonged drought and/or anthropogenic impact (Williams and Calaby, 1985; Schlesinger *et al.*, 1990). Note that rainfall stations are being screened using the PD data considering only the station location and not the rainfall amount.

Trend analysis has been applied to rainfall data to demonstrate systematic changes of rainfall over the Sahel and Sudan zones (cf., Adejuwon *et al.*, 1990). We are applying trend analysis to the PD data to assess systematic changes of land surface, although recognizing that a general validity of trend analysis to detect land surface change due to drought or anthropogenic impact has not yet been demonstrated. The climatologic mean values of rainfall given in Muller (1982) do not allow one to assess the occurrence of drought for any location for the period of our satellite data. A screening based on PD data can be applied uniformly to all three rainfall data sets (described below).

The rainfall data used in the present analysis are climatologic mean values and also those concurrent with the PD data. All rainfall data for Africa and Australia from Muller (1982) have been considered except those for island locations. The total number of stations for Africa is 159 and for Australia is 39. A nominal check for the accuracy of station locations was made, which showed typographic errors for one location in Australia (Perth) and three locations in Africa (Tindouf, Adrar, and Luderitz). The number of stations passing different levels of screening are given Table 3.

The other climatologic mean rainfall data set used in this analysis is that of Legates and Willmott (1990). This data set was provided to us by Prof. Willmott (University of Delaware, Newark, USA), and contains mean monthly rainfall values as observed and also after rain gauge correction. To be consistent with Muller's data, we have used the observed rainfall data. We have used all rainfall data for Africa and Australia and no editing has been done to these data. The total number of stations for Africa and Australia are, respectively, 3406 and 618. The number of stations passing different levels of screening are given in Table 3.

Rainfall data for the period 1979-1985 for Africa were provided by Prof. S. E. Nicholson (Florida State University, Tallahassee, USA) and the data for Australia were acquired from

Bureau of Meteorology (Melbourne, Australia). Both of these rainfall data sets contain monthly rainfall. We have used rainfall data for all stations with complete records (i.e., data available for each month for 1979-1985) to compute 7-year average values. The total number of stations for Africa and Australia are, respectively, 216 and 4221. The number of stations passing different levels of screening are given in Table 3.

It should be noted that vastly different number of data values (or station locations) for Africa and Australia appearing in Legates and Willmott (1990) and the concurrent rainfall data sets, and both of these data sets are significantly more comprehensive than Muller (1982) with respect to the total number of stations when both continents are combined. While many locations are common in these data sets, there are also many differences, at least between the data sets of Legates and Willmott (1990) and the concurrent rainfall (see the number of station for Africa and Australia given in Table 3). Thus, to a degree, these data sets are independent. The data set of Muller (1982) was aimed to achieve as uniform a distribution as possible across the earth.

Most importantly, there was no bias on our part in the selection of either station locations or rainfall amount at these locations appearing in any one of these rainfall data sets, and no screening has been applied to any one of the rainfall data (all rainfall data have been used as described above). The quantitative methods of screening have been applied to the PD data considering only the location of rainfall stations; the rainfall amounts were kept "blind" for all screenings. No observer bias or fine tuning is involved in either Level 1 or Level 3 screenings. Uncertainty in the screening at Level 2 has been recognized and its effect will be addressed through sensitivity analysis. None of the screenings *a priori* assumed the existence of a relation between PD and rainfall. All PD data which pass these screenings will be used to assess possible relation between PD and the rainfall amount. The results are given the following section.

3. RESULTS AND DISCUSSION

Figures 8-13 show the scatterplots of PD and rainfall after different Levels of screening for the three rainfall data sets, and the results of statistical analysis based on the data passing Level 3 screening are given in Table 4.

Figure 8 (a-d) show scatter plots of PD and rainfall over Africa and Australia as given in Muller (1982). The rainfall values are climatologic mean and not concurrent with the period of PD data (1979-1985). These figures show rainfall values up to 1750 mm, although we have analyzed the data for all stations except those on the islands. Figure 8 (a-d) show, respectively, the data without any screening (for Africa only), after Level 1, after Level 2A and after Level 3 screening. The number of stations at each level of screening are given in Table 3. The scatter decreases in going from fig. 8a to 8d.

Figure 8a shows the data for Africa before Level 1 screening, and much of the scatter in this figure is due to inclusion of stations situated close to ocean which have high PD values, as has been illustrated in figure 1. This scatter is considerably reduced by exclusion of coastal stations (Level 1 screening) as seen in figure 8b. The results of excluding stations due to effects of surface roughness and exposed water on PD (Level 2A screening) are shown in figure 8c, while the results after exclusion of stations due to land surface change (Level 3 screening) are shown in figure 8d.

The data in figure 8d suggest a highly non-linear relation between rainfall and PD. Choudhury (1989) had found a statistically significant ($r^2 = 0.88$) relation between PD and rainfall (P in mm) as:

$$PD = 6.2 + 20.3 \exp(-0.0035 P) \qquad (1)$$

When the data in fig. 8d (36 stations for Africa and 4 stations for Australia) were subjected to a linear regression with exponential rainfall function as in eqn. (1), exp (-0.0035 P), the result was:

$$PD = 5.2 + 20.6 \exp(-0.0035 P) \qquad (2)$$

with the explained coefficient of variation (r^2) being 0.91 and standard error of estimate being 2.1 K. The slopes of eqns. (1) and (2) do not differ, but intercepts do differ at 9-percent confidence level under t test.

Figure 9 (a-c) show scatterplots of PD and climatologic rainfall from Legates and Willmott (1990), in sequence, after Level 1 (fig. 9a), after Level 2a (fig. 9b) and after Level 3 (fig. 9c). This climatologic rainfall data set is significantly more comprehensive compared to that of Muller (1982), as is apparent from Table 3. When the data in figure 9c (726 station from Africa and 158 stations from Australia) was subjected to a linear regression analysis with the exponential rainfall function the result was (see Table 4 for statistics):

$$PD = 5.5 + 20.6 \exp(-0.0035 P) \qquad (3)$$

with the explained coefficient of variation (r^2) of 0.84 and standard error of estimate of 1.7 K.

Figure 10 (a-c) show scatter plots of PD and rainfall averaged for the period 1979-1985, in sequence, after Level 1 (fig. 10a), Level 2A (fig. 10b) and Level 3 (fig. 10c) screenings. The number of stations at each level of screening are given in Table 3. Unlike figures 8 and 9, both PD and rainfall values are averaged for the same period in figure 10. We have analyzed all available data, although these figures show the data values up to 1750 mm rainfall. A comparison of figs. 10b and 10c shows a significantly larger number of data values from Australia with rainfall less than 500 mm remain after Level 3 screening. This is because the data base for Australia is eight times larger than that for Africa at Level 2A screening (Table 3) and also semi-arid regions of Australia have not been under a drought condition similar to that for the Sahel and Sudan zones of Africa. When the data in figure 10c (54 stations for Africa and 654 stations for Australia) were subjected to a linear regression analysis with exponential rainfall function the result was (see Table 4):

$$PD = 5.1 + 20.1 \exp(-0.0035 P) \qquad (4)$$

with the explained coefficient of variation (r^2) being 0.81 and standard error of estimate being 1.30 K. The slopes of eqns. (1) and (4) do not differ, but intercepts do differ at ?-percent confidence level. The intercept and the slope of eqns. (2) and (4) do not differ at ?-percent confidence level.

The results presented in figure 8 (c and d), figure 9 (b and c), and 10 (b and c) are for rainfall stations which have the spatial variability index (V) less than or equal to 1.249 (see Level 2 screening in previous section). When the Level 2 screening was done by setting a lower value of V, namely 1.20 (Level 2B) then the number of paired (PD and rainfall) data points decreased, and this selected data is a subset of that selected with the higher cutoff for the V value. Corresponding to figure 8 (c and d) we have figure 11 (a and b) for Muller's data showing the scatter plot when the rainfall stations were selected with V less than or equal to 1.20 (Level 2B screening). A linear regression analysis of data values in figure 11b (28 stations for Africa and 3 for Australia) with exponential rainfall function gave:

$$PD = 5.0 + 22.6 \exp(-0.0035\ P) \qquad (5)$$

with $r^2 = 0.96$ and standard error of estimate 1.52 K. The slopes of eqns. (1) and (4) do not differ, but intercepts do differ at 9-percent confidence level. The slopes and intercepts of eqns. (4) do not differ at 9-percent confidence level from those appearing in eqns. (2) or (3).

Similarly, we obtain figure 12 (a and b) under the Levels 2B and 3 screening corresponding to figure 9 (b and c) for climatologic rainfall data of Legates and Willmott (1990). Regression analysis of data in figure 12b (573 stations from Africa and 115 stations from Australia) gave (see Table 4):

$$PD = 5.3 + 21.1 \exp(-0.0035\ P) \qquad (6)$$

with the explained coefficient of variation (r^2) of 0.84 and standard error of estimate of 1.6 K.

Similarly, we obtain figure 13 (a and b) corresponding to figure 10 (b and c) for the concurrent data sets of PD and rainfall under the Levels 2B and 3 screenings. Regression analysis of data values in fig. 13b (43 stations for Africa and 507 stations for Australia) gave (see Table 4 and figure 14):

$$PD = 5.1 + 20.5 \exp(-0.0035\ P) \qquad (7)$$

with $r^2 = 0.82$ and standard error of estimate 1.28 K. Neither the slope nor the intercept differ from those appearing in eqn. (4) at 9-percent confidence level. The intercept and slope of eqn. (4) do not differ from those appearing in eqn. (7) at 9-percent confidence level.

A linear model for PD vs. exp (-0.0035 P) was assumed by Choudhury (1989) and in the above analysis. To check the adequacy of such a model, fig. 15 shows the plot of residuals (the difference of observed and predicted PD corresponding to any rainfall value) against the predicted PD based on eqn. (7). These residuals do not show any systematic pattern of scatter about the zero value, illustrating no obvious defect in the model. Also, the normality assumption for linear regression would require 6 percent of the standardized residuals to be within -1 and +1, while 9 percent of the residuals to be within -2 and +2. In the present case, we find that 7 percent of standardized residuals are within -1 and +1, while 9 percent to be between -2 and +2. Thus, the data satisfy fairly well the normality assumption of linear regression.

The correlation coefficients for all cases are significant at better than one percent level, and the slope and intercept of the regression for different rainfall data sets (two climatologic and one concurrent) and for different screenings do not differ at 9-percent confidence level. Thus, the relation between PD and rainfall is not distinguishable for different climatologic rainfall and 1979-1985 average rainfall data sets. The slope of the regression line do not differ, but the intercept do differ at 9-percent confidence level from those calculated by Choudhury (1989). *The present analysis based on quantitative methods for data selection on three rainfall data sets (two climatologic and one concurrent) confirms the non-linear relation between PD and rainfall obtained by Choudhury (1989) with highly significant correlations.* The present analysis disputes poor correlation between PD and rainfall found by Tucker (1992).

The calculated high correlation ($r^2 > 0.8$) between PD and rainfall and statistically indistinguishable nature of the relations obtained using both climatologic rainfall and 1979-1985 average rainfall do suggest that the magnitude of PD could be used as an estimator for surface characteristics determined by the rainfall amount averaged over a number of years. Analyses presented by Eagleson and Tellers (1982), Woodward (1987), Le Houerou (1989), among others, show that long-term average rainfall could be a major determinant of such surface characteristics as fractional ground cover, productivity and leaf area index. Recognizing the unavailability of quantitative data for surface characteristics at coarse spatial resolution of PD, the relation established here between PD and rainfall (averaged over several years) could provide a starting point for relating PD to surface characteristics. Choudhury (1990, 1991) has suggested that fractional ground cover could be an important surface characteristic determining PD (see also fig. 2.6A in Shmida, 1985).

It is unfortunate that several stations in the concurrent rainfall data set with rainfall less than 200 mm got rejected under Levels 2 and 3 screenings. While true deserts are considered to be areas receiving less than 100 mm rainfall (long-term average per annum), the transition area receiving 100-400 mm rainfall is quite sensitive to anthropogenic pressure, which can lead to large-scale major changes of the land surface (Schlesinger *et al.*, 1990). It will be desirable to have more long-term average rainfall data in the range 0-200 satisfying the screening criterion for a better definition of the rainfall-PD relationship.

4. ATMOSPHERIC EFFECTS ON RAINFALL-PD RELATION

The above analysis showed that a statistically significant non-linear relation exists between long-term average rainfall and PD such that PD decreases as rainfall increases. These PD values are as observed by the satellite and thus include atmospheric effect. Although both cloud and water vapor in the atmosphere affect the satellite data, the magnitude of the atmospheric effect is determined primarily by the total precipitable water vapor, W (Choudhury *et al.*, 1992). Since it is commonly recognized that W is low (c. 15 mm) over low rainfall areas and high (c. 45 mm) over high rainfall areas (Tuller, 1968), there is an implicit correlation between the magnitude of the atmospheric effect that is associated with the PD at a particular rainfall value. (Note however that locations of high precipitable water are not always the locations of high rainfall, and interannual variation of rainfall could be larger than that for precipitable water). An important question therefore is, can the relation between PD and rainfall arise purely due to the atmospheric effects contained in the PD data?

The PD value at the surface (PD_S) is approximately related to PD as (Choudhury *et al.*, 1992):

$$PD_S = PD \exp(2t/m) \qquad (8)$$

where t is the optical thickness of the atmosphere and m is the cosine of the incidence angle of the radiometer (50°). The optical thickness can be calculated as (Choudhury *et al.*, 1992; Matzler, 1992; Westwater *et al.*, 1990):

$$t = 0.037 + 0.0021\,W + 0.16\,L \qquad (9)$$

where W is precipitable water vapor (mm) and L is cloud liquid water content (mm).

From eqn. (8) and (9) one can see that PD_S is always greater than PD and the relative increase of PD is higher over the humid areas with cloudy skies as compared to the arid areas with clear skies. If the relation between PD and rainfall is purely due to atmospheric effects, then PD_S will be independent of rainfall. (Note that there is no obvious physical basis to postulate that PD is related to rainfall per se; our hypothesis is that PD is related to some surface characteristics which is determined by long-term rainfall.)

Radiosonde data for precipitable water corresponding to the location of rainfall stations used in the present analysis are not available so as to arrive at an atmospherically corrected relation between rainfall and PD (i.e., a relation between PD_S and rainfall). (The relative humidity data given in Muller (1982) cannot be used directly to calculate precipitable water because of strong diurnal variation of humidity.) Nevertheless, a first-order assessment of the magnitude of the atmospheric effect for clear skies (L=0) can be performed using surface observations of vapor pressure (NOAA Monthly Climatic Data of the World, Asheville, North Carolina) and empirical relations between vapor pressure and precipitable water (Monteith, 1961; Idso, 1969; Ben Mohamed and Frangi, 1983). This assessment for a selected number of stations is given in Table 5. The ratio (PD_S / PD) at the low end of the rainfall is about 1.23, while at the high end of the rainfall it is about 1.48. These results show that the atmospheric effect essentially decreases the range of PD_S in going from the low to the high end of the rainfall compared to that for PD. From eqns. (7-9) we calculate the ratio [PD (P=0) / PD (P=2000)] = 5.0, while [PD_S (P=0) / PD_S (P=2000)] = 4.1. Considering this 2-percent reduction in the range of polarization difference we conclude that atmospheric correction to PD should generally be performed for a quantitative interpretion of PD-rainfall relation in terms of surface characteristics.

The above calculations of atmospheric effect on PD did not consider the effect of clouds, and one may suggest that low PD values observed over the rainforest areas are due to very dense clouds. Such a possibility is very unlikely considering the data shown in figures 1 and 4b. If low PD values over rainforest are due to dense clouds then such clouds would have to appear systematically two or three pixels away from the ocean coast (fig. 1) and such clouds would have to dissipate systematically over the Zaire river and Lake Leopold II (fig. 4b). We are not aware of any fundamental physical principle governing such systematic occurrences of dense clouds and indeed, METEOSAT and AVHRR observations do not show such systematic occurrences of dense clouds. Also, one can calculate from eqns. (7-9) that the cloud liquid water content (L) would have to be about 2.8 mm for [PD_S (P=0) / PD_S (P=2000)] = 1, and this liquid water content needs to occur at the spatial scale of 37-GHz observations for the period 1979-1985. The compositing procedure for PD (i.e., the second lowest value occurring during a month) would require a common occurrence of cloud liquid water content *higher* than 2.8 mm. A cloud liquid water content of 2.8 mm occurring regularly (in a temporal sense; e.g., for each month for seven consecutive years in the context of present analysis) at the spatial resolution of PD data (c. 25 km) has not yet been documented for non-precipitating clouds, and the observed values are generally less than 0.3 mm (Grody *et al.*, 1980; Prabhakara *et al.*, 1983; Takeda and Liu, 1987; Jones and Vonder Haar, 1990; Lojou *et al.*, 1990; Curry *et al.*, 1990; Matzler, 1992). Thus, atmospheric effects *cannot* explain eqn. (7), although these effects should be considered for a quantitative interpretation of this equation in terms of land surface characteristics. A more critical discussion of atmospheric effects on seasonal and interannual variations of PD may be found in Choudhury *et al.* (1992).

5. ANALYSIS FOR SAHEL AND SUDAN ZONES

The nature of drought over the Sahel and Sudan zones and its possible impact on the relation between PD and rainfall have been discussed above. Figure 7 showed that both PD and visible reflectance increased with increasing rainfall deficit, although there are some systematic differences in their relationships for interannual variations. Tucker (1992) found poor correlations (r^2 value 0.31 and 0.45 depending upon rainfall range) for linear regressions between PD and rainfall for 41 locations in Niger and Mali with the average data for July-October, 1982-1985. The correlation (r^2) for individual years ranged 0.10-0 to 51.

A scatter plot of PD and rainfall (exp(-0.0035 P)) for *all* rainfall stations within 12°N-19°N with complete records for 1979-1985 which passed Level 1 screening (33 stations) is shown in fig. 16. A linear regression analysis of the data in fig. 16 gave $r^2 = 0.87$, with slope and intercept being, respectively, 22.2 and 9.8. The correlation between PD and rainfall is substantially higher than that found by Tucker (1992). This figure also shows the relation derived for data in figs. 13 and 14 (eqn. 7). The PD values over this drought affected region are seen to be consistently higher than those expected from eqn. 7 (the intercepts differ at 9-percent confidence level). The data values in this figure are for a much larger area than those of Tucker (1992), but the number of data points is less than that for Tucker because a majority of stations did not have complete rainfall records for 1979-1985. The data values in fig. 16 have not been subjected to Level 2 screening, and thus the higher PD values in figure 16 could be suggested to be because of systematic water contamination of the PD data. Indeed, one can see from Table 1 that many of the stations situated within this area would be rejected under Level 2 screening. However, an examination of the station locations for the data appearing in fig. 16 showed that exposed water is not likely to be the factor contributing to consistently higher values of PD seen in this figure (see also fig. 7). These high PD values are most likely the result of land surface change due to drought. This figure provides some indirect evidence that the relation between rainfall and surface characteristics under drought conditions could be much different from that in the absence of drought, which needs to be further studied.

There could be several reasons for poor correlations found by Tucker (1992) and high correlation between PD and rainfall reported above using *all* rainfall stations with complete records. It has been noted that changes in the surface characteristics may not be proportional to or synchronous with the changes in rainfall (fig. 7). Monthly and annual values of rainfall are much less representative of the surface characteristics than the rainfall values averaged over a number of years (Le Houerou, 1989). Perhaps more important is the question of spatial representativeness of monthly and annual rainfall values of Sahelian stations in relation to the spatial resolution of the PD data (c. 25 km). Observations show that seasonal total rainfall can differ by 180 mm at a distance of 10 km as illustrated in figure 17 (Lebel *et al.*, 1992), and variograms of seasonal total rainfall for 1990 and 1991 over 100x100 km area around Niamey (Niger) after accounting for the north-south rainfall gradient show that the rainfall values become uncorrelated at a distance of 10-30 km as illustrated in figure 18 (Lebel *et al.*, 1991; Taupin *et al.*, 1992). Certainly, such high spatial variability of rainfall is expected to introduce much scatter when PD is plotted against seasonal total rainfall observed at station locations and thus can result in poor correlations. Choudhury (1989) and the present analysis considered the relation between rainfall and PD averaged over a number of years, since a relation between rainfall and surface characteristics is much better defined when averaged over a number of years, as noted by Le Houerou (1989). The poor correlations between PD and rainfall reported by Tucker (1992) could be due to the spatially unrepresentative nature of the rainfall values as compared to the PD data for short time durations.

The results of analysis based on three rainfall data sets and also concurrent data over the Sahel and Sudan zones presented above clearly demonstrate that long-term average PD is highly correlated with the average rainfall.

6. SUMMARY AND CONCLUSIONS

Interpretation of coarse resolution satellite data in terms of surface characteristics presents considerable difficulty because of a lack of spatially and temporally representative data for surface characteristics. Under certain limited circumstances rainfall may be used as a proxy measure for surface (soil-litter-vegetation) characteristics, and it is in this regard that a relation between PD and long-term rainfall was sought by Choudhury (1989) and in this paper. If a statistically significant relation can be found between PD and rainfall, then such a relation could provide a starting point for relating PD to appropriate surface characteristics.

All rainfall data cannot be used to correlate with PD because, (1) relation between rainfall and surface characteristics under drought conditions (or anthropogenic impact) could be much different from that in the absence of drought (or human interference; natural vegetation being replaced by agricultural crops), and (2) factors other than soil, litter and vegetation affect PD. Quantitative methods were developed and used in this paper to screen the PD data considering antenna pattern, geolocation uncertainty, exposed water, surface roughness, and systematic land surface change. Rainfall data considered in this study were two data sets of climatologic mean values and one data set concurrent with the PD data (1979-1985) for Africa and Australia. These three rainfall data sets are to a degree, independent data sets. All rainfall data have been used in the present analysis and no screening has been applied to the rainfall data. Selection of rainfall stations for correlation with PD has been done considering *only* the location of rainfall stations, and the screening methods did not *a priori* assumed the existence of any relation between PD and rainfall. There was no observer bias or fine tuning involved at Level 1 (effects of antenna pattern and geolocation uncertainty on PD) and Level 3 (effects of systematic land surface change due to natural or anthropogenic causes on PD) screenings. Uncertainty at Level 2 screening (effects of small water bodies and surface roughness on PD) has been recognized and was addressed through sensitivity analysis. Whereas Choudhury (1989) had used subjectivity for these screenings in the selection of rainfall stations, we have used quantitative methods in the present study.

The present analysis gave statistically significant ($r^2 > 0.8$) non-linear relationships between PD and rainfall (climatologic and 1979-1985 average), although the intercepts and the slopes of these relations were not different at 9 percent significance level (Student's t test). The slopes of the present relations generally did not differ, but the intercepts did differ at 9-G28 percent confidence level from the relationship obtained previously by Choudhury (1989). An analysis of the residuals showed no obvious defect in the assumed linear model for the relation between PD and exponential transform of rainfall. Based on the calculated coefficient of determination obtained in this study, a hypothesis of no relation between PD and rainfall can be rejected at better than 9 percent confidence for all three rainfall data sets. The results of present analysis contradict "weak relation" between PD and rainfall found by Tucker (1992). However, the total number of stations passing all screening levels is about 1 percent of the original data base, which clearly shows the limited region over which PD was directly related to rainfall. This limited region of applicability is somewhat biased because about 4 percent of the stations in the climatologic rainfall (Muller) and about 6 percent of the stations in the concurrent rainfall data sets got rejected at Level 1 screening for being situated close to ocean or major lakes, although these rejected fractions are substantially higher than the fraction of coastal areas for these continents. We did not investigate the capability of the derived PD-rainfall relationship to predict long-term average rainfall from the 1979-1985 average PD data, and until such capability is tested against an independent rainfall data set one should not use the relation between PD and rainfall as a predictor of rainfall. We note that there is no obvious physical basis to postulate that PD is related to rainfall per se; our hypothesis is that PD is related to some surface characteristics determined by long-term rainfall. By evaluating the atmospheric effect on PD, we concluded that *atmospheric effect alone cannot explain* the observed relation between PD and rainfall, although this effect should be considered for a quantitative interpretation of the relation in terms of surface characteristics.

The present analysis was limited to only Africa and Australia. It will be interesting to evaluate long-term average rainfall data from other locations (continents) where snowcover is not an important consideration and the data satisfy the screening criterion to assess the generality of the present relationship between PD and long-term average rainfall. Further evaluation and research are also needed for the screening methodologies used in this study (in particular the screening methodology for rough terrain and exposed water from rivers and lakes; the Level 2 screening). Then, we need to understand the relation between PD and rainfall in terms of appropriate surface characteristics.

The global monthly data set of 37-GHz polarization difference from January 1979 to August 1987 from Nimbus-7 SMMR observations and from July 1987 to December 1990 from DMSP SSM/I observations has been archived for public distribution. This data could be acquired by writing to: Polarization Difference Vegetation Index, Pilot Land Data System, Code 934, Data Management Systems Facility, NASA/ Goddard Space Flight Center, Greenbelt, MD 20771, USA.

7. ACKNOWLEDGEMENTS

Dr. C. Prabhakara of the Climate and Radiation Branch of Goddard Space Flight Center provided the initial idea and approach for using spatial variability to screen for mountainous and water contaminated pixels. We have also benefitted from other discussions with Dr. Prabhakara.

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CAPTIONS TO THE FIGURES:

Figure 1 (a and b). Pixel values of 37-GHz polarization difference (PD) and surface designation for two regions in Africa containing land and water (ocean) bodies. The surface designation is based on a digital data set which identifies water, land/water mix and land pixels at a spatial resolution of 0.25°. Note that two land pixels and often the third pixel bordering water (going perpendicular to ocean/land interface) have systematically higher PD values compared to those situated further inland. The first land pixel bordering water is generally a mixed pixel in the literal sense (fractional coverage of land and water). High PD values for inland pixels bordering water are generally due to the antenna pattern (radiometrically mixed pixels).

Figure 2. Schematic representation of water pixels, radiometrically mixed pixels (two pixels bordering water) and 3x3 matrix of pixels centered on a rainfall stations. Level 1 screening determines the location of water pixel within the 9x9 matrix centered on a rainfall station using a digital land surface data describing land, land/water mixed and water pixels at 0.25° resolution (see fig. 1).

Figure 3. Field observations of 37-GHz brightness temperatures and polarization difference over dry bare soil (a and c) and over grass at leaf area index (L) of 1.7 (b and c). Note the strong dependence of polarization difference on the incidence angle for bare soil and a lack of such dependence for vegetated surface. Such field observations and theoretical studies provide the rationale for screening PD due to effects surface roughness, which has a significant impact on PD values over desert areas (see text for the quantitative methods used to screen at Level 2).

Figure 4. (a) Pixel values of PD and horizontally polarized brightness temperature across Air mountain within the Sahara, and (b) across Zaire river and Lake Leopold II (Lac Mai-Ndombe). Note in (a) that PD decreases and the brightness temperature increases in going across topographic variation (surface roughness effect), while in (b) PD increases and the brightness temperature decreases in going across water bodies. These differing responses of PD and brightness temperature to surface roughness and exposed water are consistent with field observations and theoretical studies. The ratio of PD and horizontal polarization difference (normalized polarization difference or NPD) has been used to screen PD values due to effects of topographic variation and exposed water (see Table 1 and discussion for Level 2 screening).

Figure 5. The 3x3 matrix of normalized polarization difference (NPD) for several locations in Africa from Muller (1982). Other pertinent data for these locations may be found in Table 1. The ratio of the highest and lowest NPD within each 3x3 matrix centered on rainfall stations is used for Level 2 screening. The effect of substantial exposed water within a pixel visible to SMMR would be to increase the NPD value compared to neighboring pixels without exposed water.

Figure 6. Binary classification [accept (dark shade) or reject (light shade)] map of Africa, Middle East and a part of Europe based on pixel-to-pixel calculation of the variability index (V) of either 1.25 (a) or 1.3 (b). High V values (light shade) are seen to appear generally in mountainous areas (rough terrain) with little vegetation and for exposed water due to rivers, lakes, swamps, etc. This variability index is used for Level 2 screening.

Figure 7. Annual average values of rainfall deficit percent (departure from climatologic mean calculated using all reporting stations within the region), PD, and visible reflectance (derived from observations by the advanced very high resolution radiometer on board NOAA satellites) for two areas within the Sahel and Sudan zones of Africa. Note that (1) interannual variation of these satellite data are not proportional to the corresponding variation of rainfall deficits, and (2) the occurrence of highest rainfall deficit during 1984 does not match the occurrence of the highest PD or reflectance for the Sudan zone, although the highest values for both of these satellite data occur during 1985. These independent satellite observations provide evidence for land surface change which may not be proportional to or synchronous with rainfall variations particularly under drought conditions. Relation between rainfall and surface characteristics under drought conditions could be much different from that in the absence of drought. The slope of the monthly PD values for 1979-1985 was tested for non-zero value to assess any systematic land surface change (Level 3 screening).

Figure 8. Scatter plot of PD and climatologic rainfall values for Africa (filled circle) and Australia (open square) from Muller (1982) for (a) data values for Africa before any screening, (b) after Level 1 screening done to exclude stations situated close to large water bodies, (c) after Level 2A screening done to exclude stations for which the PD values are affected by surface roughness and exposed water (lakes and rivers), and (d) after Level 3 screening done to exclude stations with systematic land surface change

(temporal trend determined from linear regression). Quantitative methods used for each screening are discussed in the text. Each screening has been done considering only the location of rainfall stations; the rainfall values have not been used for screening any data. None of the screening methods have *a priori* assumed the existence of any relation between PD and rainfall.

Figure 9. Scatter plot of climatologic rainfall data set from Legates and Willmott (1990) of PD and rainfall for Africa and Australia for (a) after Level 1 screening, (b) after Level 2A screening, and (c) after Level 3 screening.

Figure 10. Scatter plot of concurrent data sets of PD and rainfall for Africa and Australia for (a) after Level 1 screening, (b) after Level 2A screening, and (c) after Level 3 screening.

Figure 11. Scatter plot of climatologic rainfall (from Muller) and PD for (a) after Level 2B screening, and (b) after Level 3 screening. Note that these data values are a sub-set of those appearing in figure 8 (c and d).

Figure 12. Scatter plot of climatologic rainfall (from Legates and Willmott) and PD for (a) after Level 2B screening, and (b) after Level 3 screening. Note that these data values are a sub-set of those appearing in figure 9 (c and d).

Figure 13. Scatter plot of concurrent data sets of PD and rainfall for (a) after Level 2B screening, and (b) after Level 3 screening. Note that these data values are a sub-set of those appearing in figure 10 (b and c).

Figure 14. Scatter plot of PD and exponential transform of rainfall (exp (-0.0035 P)) for all data points which have passed the screening criterion (Levels 1, 2B and 3). The results of regression analysis are given in the text (eqn. 7).

Figure 15. Scatter plot of residuals and predicted PD corresponding to the data in fig. 14. This figure shows that there is no obvious defect in the assumption of a linear model for PD vs. exp (-0.0035 P). The data for Africa and Australia are shown by the same symbol.

Figure 16. Scatter plot of PD and rainfall (exp (-0.0035 P)) for all stations within 12°N-19°N having complete rainfall records for 1979-1985 which passed Level 1 screening. This figure also shows the relation derived from data in figure 14 (eqn. 7). Systematically

higher values of PD for the rainfall stations within this region are most likely due to land surface change resulting from a rather prolonged drought, which need to be further studied and confirmed. Note the high correlation between PD and rainfall, which is significantly at variance from poor correlation reported by Tucker (1992).

Figure 17. Detailed map of the 1990 seasonal cumulative rainfall over an area close to Niamey, Niger. A difference of 183 mm is observed over a distance less than 10 km.

Figure 18. Variograms of seasonal total rainfall after accounting for the north-south rainfall gradient over 100x100 km area around Niamey (Niger) for (a) 1990 season, and (b) 1991 season. Seasonal total rainfall observed at a rainfall station is not likely to be representative of the average rainfall at the spatial resolution of the PD data. Tucker (1992) had used these spatially un-representative rainfall data to find poor correlations between July-October averages of PD and rainfall for individual years.

POLARIZATION DIFFERENCE (K) x 10

```
         9°E                                                     12°E
          I                                                        I
           WATER                      LAND
3°N       --- --- 480 274 064 044 044 043 043 043 043 043
          --- --- 472 218 054 045 045 042 044 043 045 042
          --- --- 471 200 051 044 047 046 046 046 045 044
          --- --- 468 178 050 046 045 044 046 045 045 045
          --- --- 369 113 048 049 047 045 044 045 045 045
          --- 451 210 063 049 047 047 047 046 047 047 046
          --- 374 139 067 048 049 047 045 046 043 044 043
1°N       --- 456 234 086 051 048 047 044 044 044 044 040
```

SURFACE DESIGNATION (--- Water; /// - Mixed*; 111 - Land)

```
3°N       --- --- /// 111 111 111 111 111 111 111 111 111
          --- --- /// 111 111 111 111 111 111 111 111 111
          --- --- /// 111 111 111 111 111 111 111 111 111
          --- --- /// 111 111 111 111 111 111 111 111 111
          --- --- /// 111 111 111 111 111 111 111 111 111
          --- /// /// 111 111 111 111 111 111 111 111 111
          --- /// 111 111 111 111 111 111 111 111 111 111
1°N       --- /// /// 111 111 111 111 111 111 111 111 111
           9°E                                            12°E
```

Mixed* (Fractional Coverage of Land and Water)

Figure 1a

POLARIZATION DIFFERENCE (K) x 10

	10°W I											7°W I
7°N	050	049	049	048	046	044	046	046	043	043	044	053
	047	049	048	045	046	045	045	044	041	042	050	071
	052	049	045	044	043	043	042	044	042	042	048	074
	089	051	044	043	042	042	043	044	042	042	042	041
	266	087	048	044	043	041	042	042	041	041	042	041
	466	295	098	049	043	041	042	044	041	043	045	042
	---	474	299	112	056	044	044	045	044	045	045	045
	---	---	485	365	201	085	052	046	045	047	045	043
	---	---	---	---	456	327	187	089	063	053	055	079
	---	---	---	---	---	494	447	354	245	150	174	296
	---	---	---	---	---	---	---	---	480	435	445	498
4°N	---	---	---	---	---	---	---	---	---	---	---	---

SURFACE DESIGNATION (--- Water; /// - Mixed*; 111 - Land)

7°N	111	111	111	111	111	111	111	111	111	111	111	111
	111	111	111	111	111	111	111	111	111	111	111	111
	111	111	111	111	111	111	111	111	111	111	111	111
	111	111	111	111	111	111	111	111	111	111	111	111
	///	111	111	111	111	111	111	111	111	111	111	111
	///	///	111	111	111	111	111	111	111	111	111	111
	---	///	///	111	111	111	111	111	111	111	111	111
	---	---	///	///	111	111	111	111	111	111	111	111
	---	---	---	---	///	///	111	111	111	111	111	111
	---	---	---	---	---	///	///	///	111	111	111	111
	---	---	---	---	---	---	---	---	///	///	///	///
4°N	---	---	---	---	---	---	---	---	---	---	---	---
	10°W											7°W

Mixed* (Fractional Coverage of Land and water)

Figure 1b

9 X 9 MATRIX OF 37 GHz POLARIZATION DIFFERENCE PIXELS

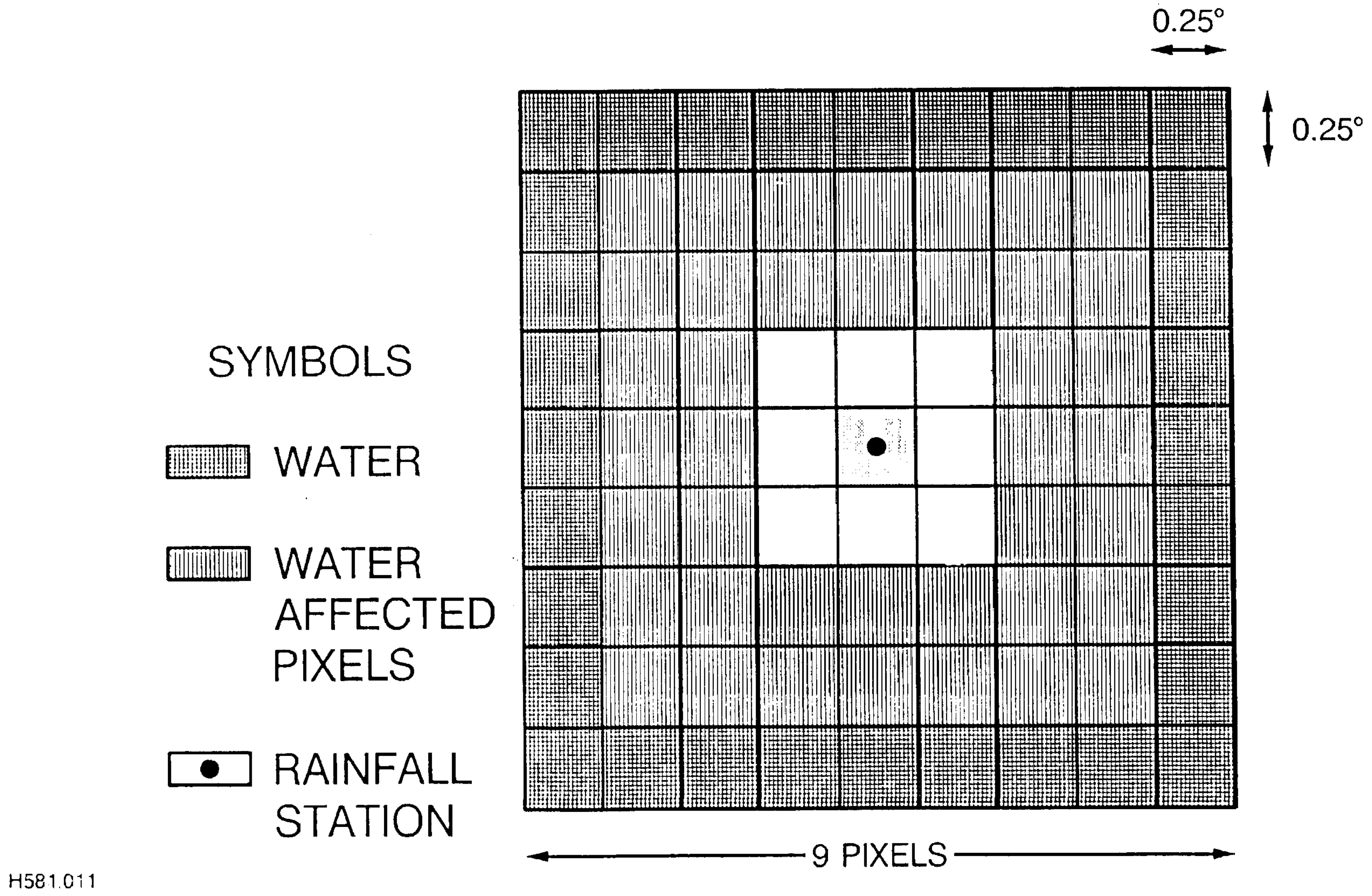
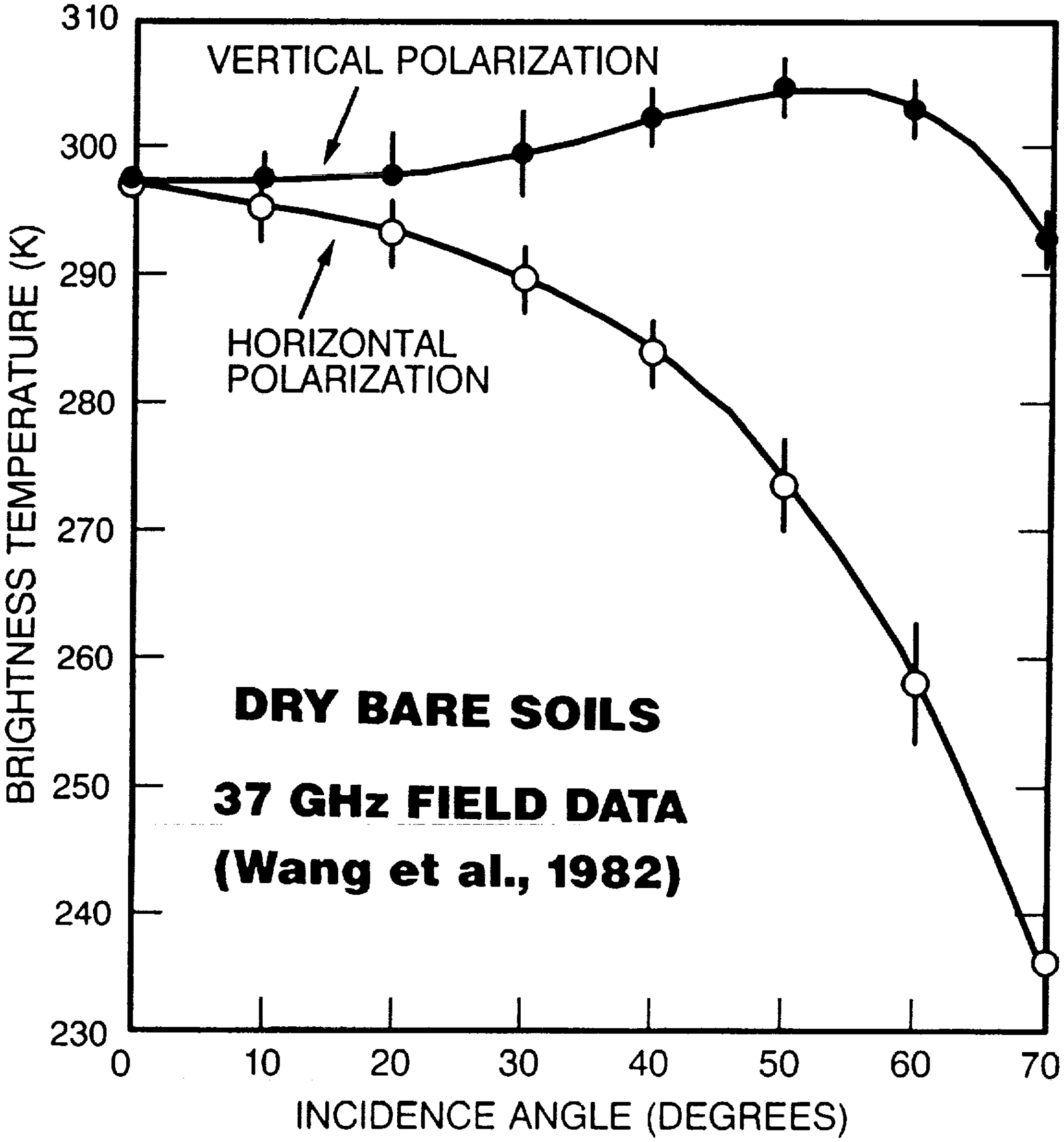
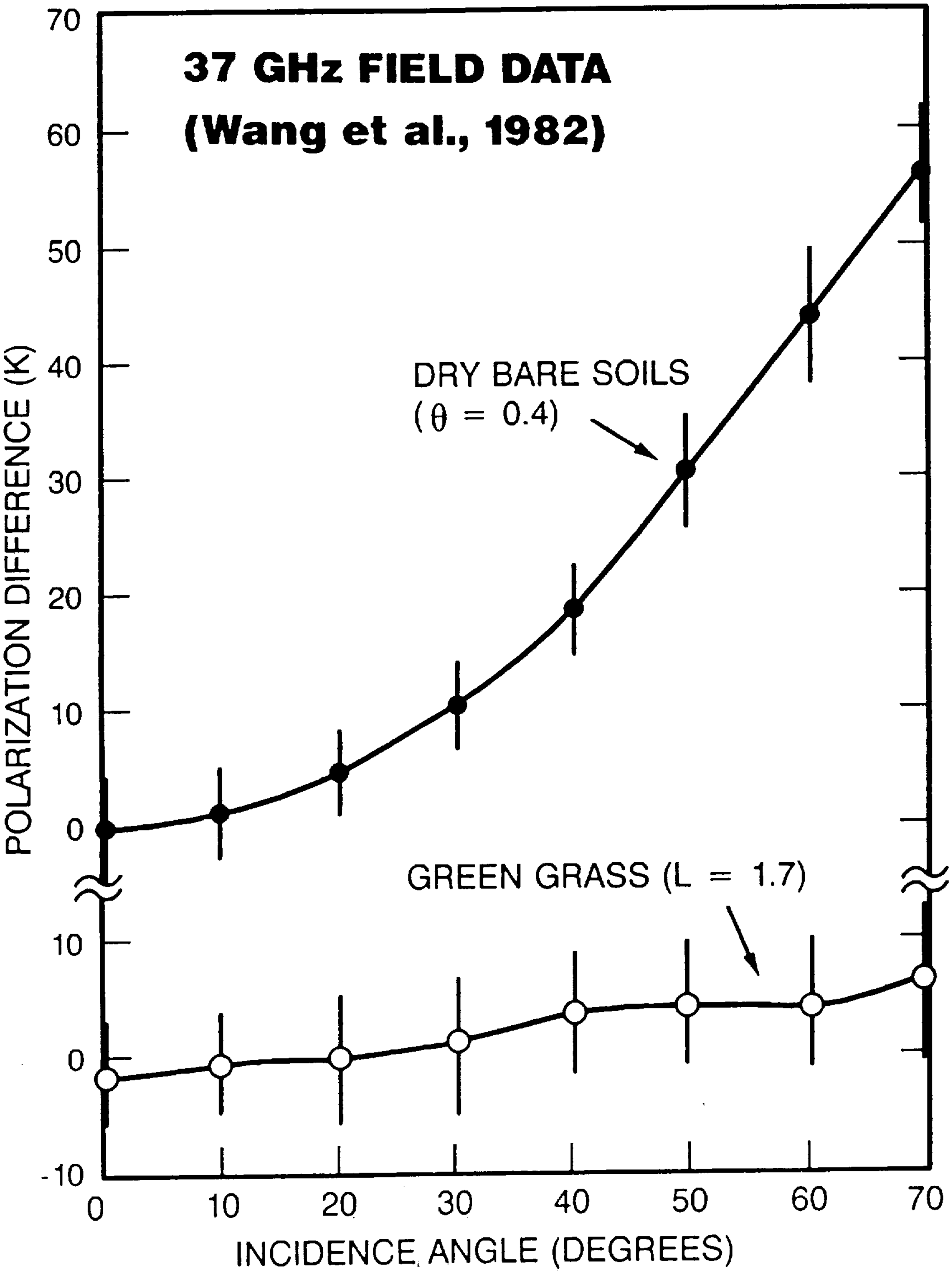


Figure 2



310
300
290
280
270
260
250
240
230
0
10
20
30
40
50
60
70
BRIGHTNESS TEMPERATURE (K)
INCIDENCE ANGLE (DEGREES)
VERTICAL POLARIZATION
HORIZONTAL POLARIZATION
DRY BARE SOILS
37 GHz FIELD DATA
(Wang et al., 1982)

Figure 3a



37 GHz FIELD DATA
(Wang et al., 1982)
DRY BARE SOILS
(θ = 0.4)
GREEN GRASS (L = 1.7)
POLARIZATION DIFFERENCE (K)
INCIDENCE ANGLE (DEGREES)
70
60
50
40
30
20
10
0
10
0
-10
0
10
20
30
40
50
60
70

Figure 3b

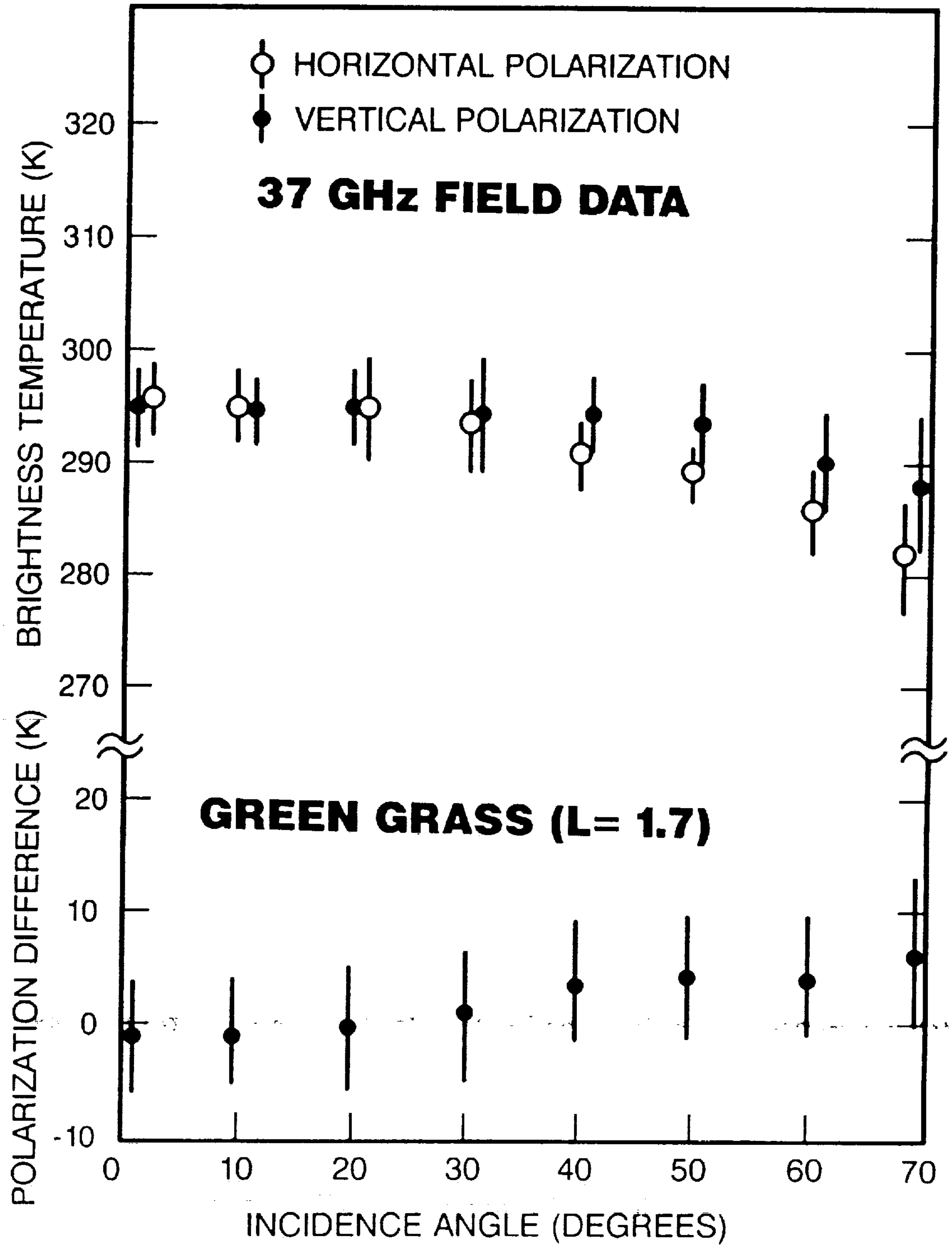

HORIZONTAL POLARIZATION
VERTICAL POLARIZATION
37 GHz FIELD DATA
GREEN GRASS (L= 1.7)
BRIGHTNESS TEMPERATURE (K)
POLARIZATION DIFFERENCE (K)
320
310
300
290
280
270
20
10
0
-10
0
10
20
30
40
50
60
70
INCIDENCE ANGLE (DEGREES)

Figure 3c

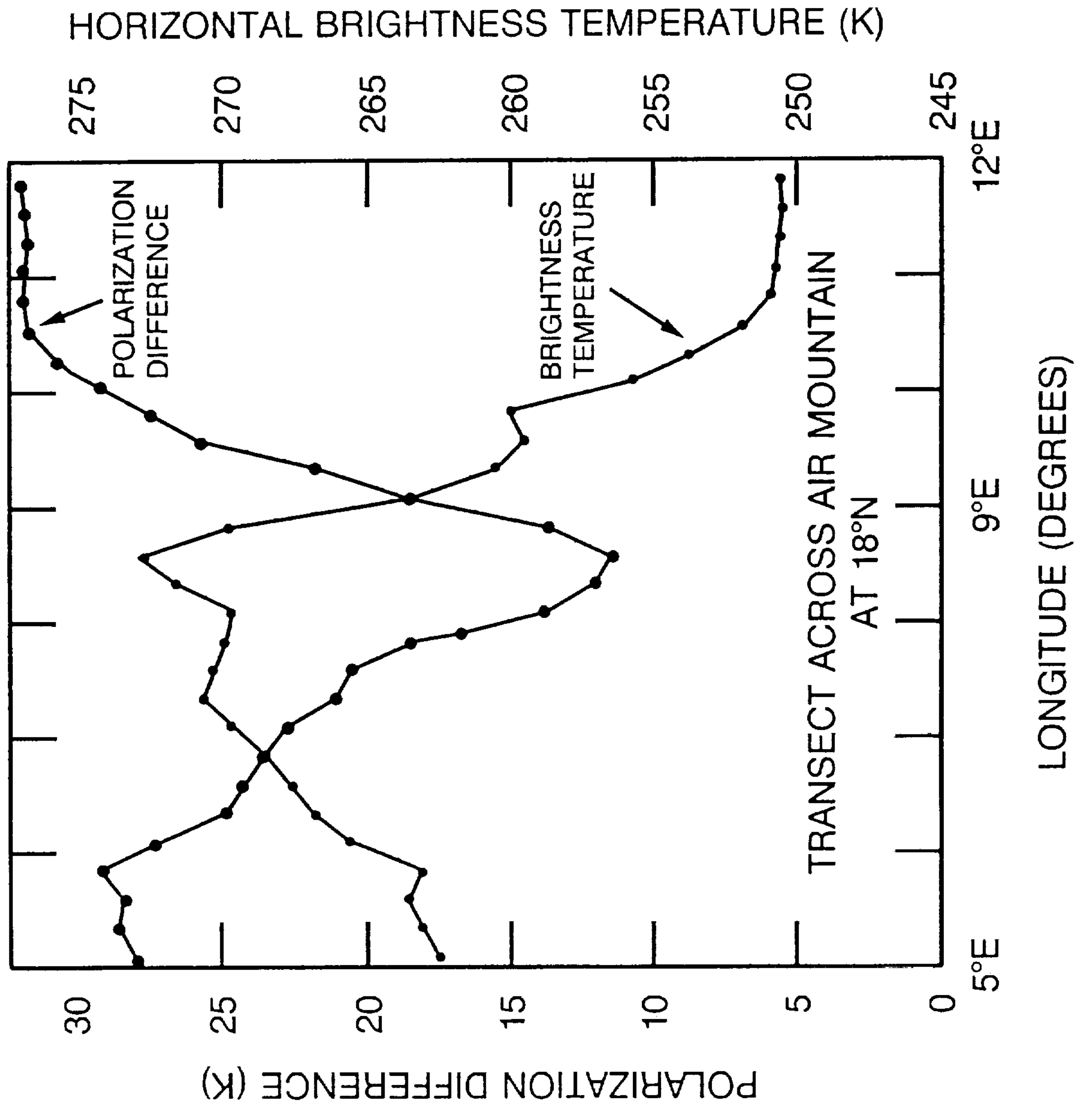
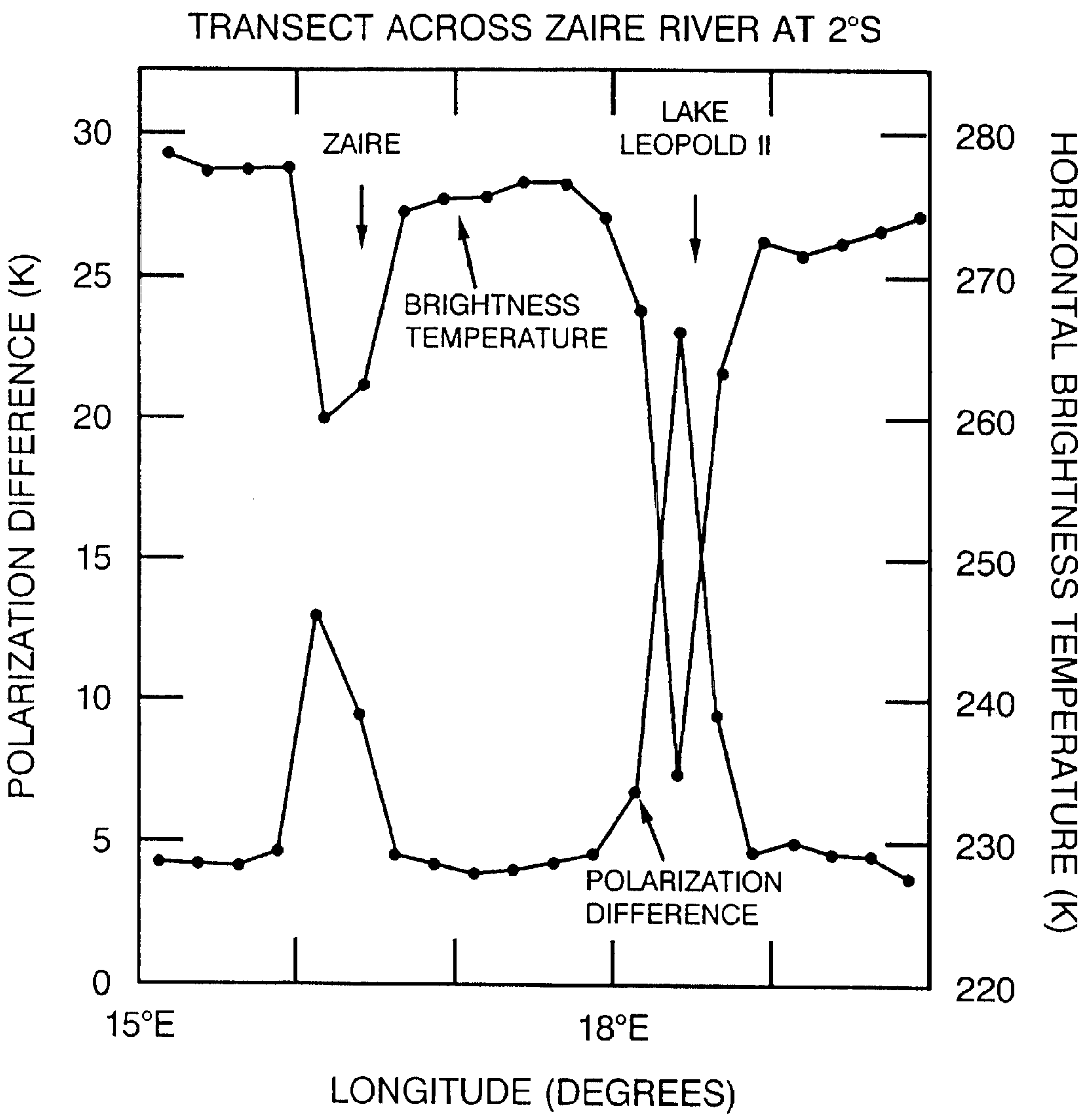

HORIZONTAL BRIGHTNESS TEMPERATURE (K)
275
270
265
260
255
250
245
POLARIZATION DIFFERENCE
BRIGHTNESS TEMPERATURE
TRANSECT ACROSS AIR MOUNTAIN AT 18°N
POLARIZATION DIFFERENCE (K)
30
25
20
15
10
5
0
5°E
9°E
12°E
LONGITUDE (DEGREES)

Figure 4a



J581.008

Figure 4b

3x3 NORMALIZED POLARIZATION DIFFERENCE MATRIX (x3000)

Adrar

319	313	305
333	314	300
338	310	289

Sabahah

341	295	257
257	240	231
224	222	216

Mut

293	262	265
293	270	264
282	281	265

Al-Uqsur

236	208	208
236	203	204
247	224	207

Dunqulah

282	283	293
295	304	320
285	302	326

Garissa

082	089	089
084	090	091
085	092	094

Eala

100	121	065
117	106	072
108	063	061

Tshibinda

071	241	350
065	119	105
059	063	066

Harar

058	059	076
054	058	106
060	057	069

Addis Abeba

072	074	074
082	084	083
085	088	094

Jima

057	059	055
057	055	056
056	055	052

Al-Kufra

277	307	329
306	324	335
332	346	332

Bobo Dioulasso

090	094	089
084	084	080
076	073	071

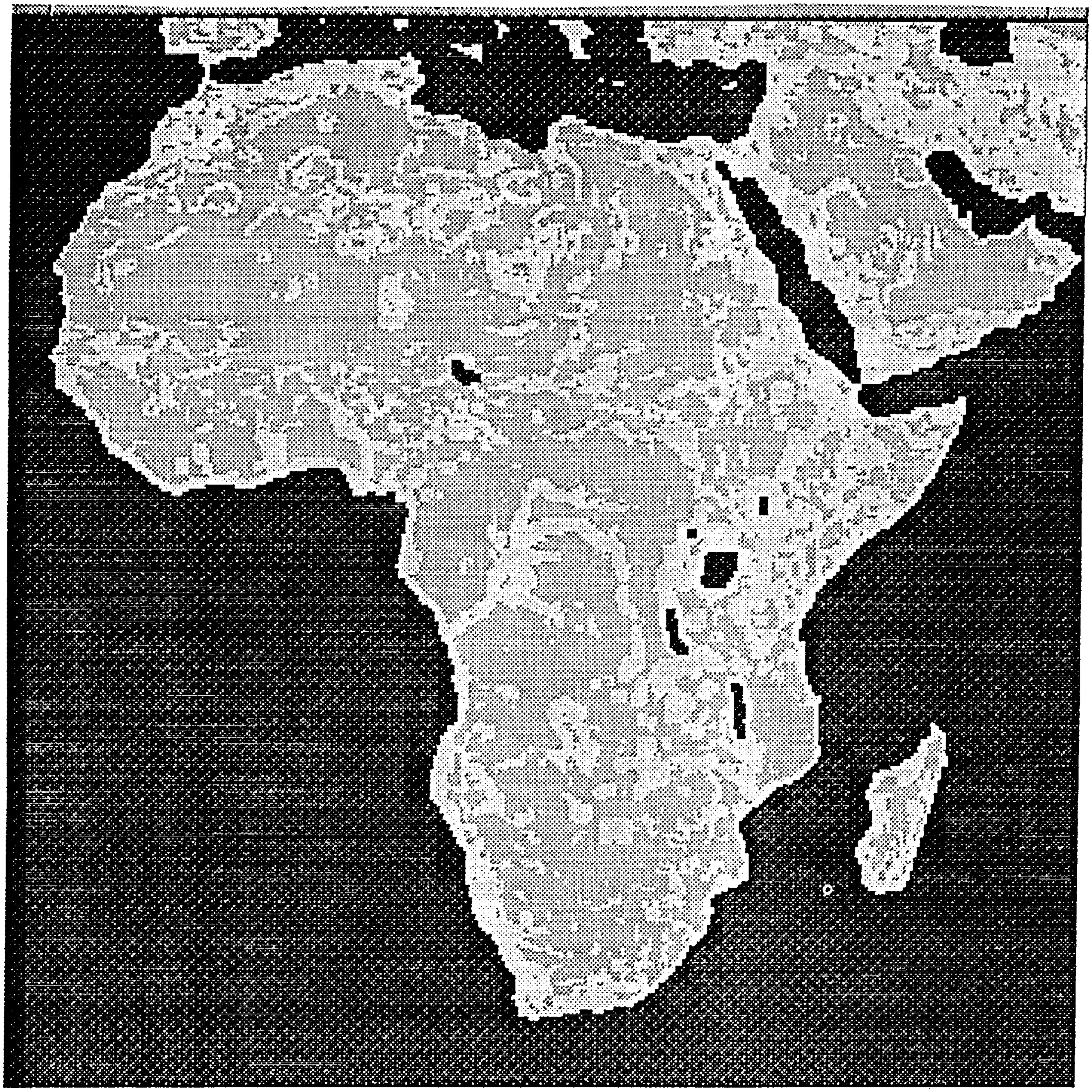
Ar-Rusayris

078	093	075
078	130	091
074	110	103

Kinshasa

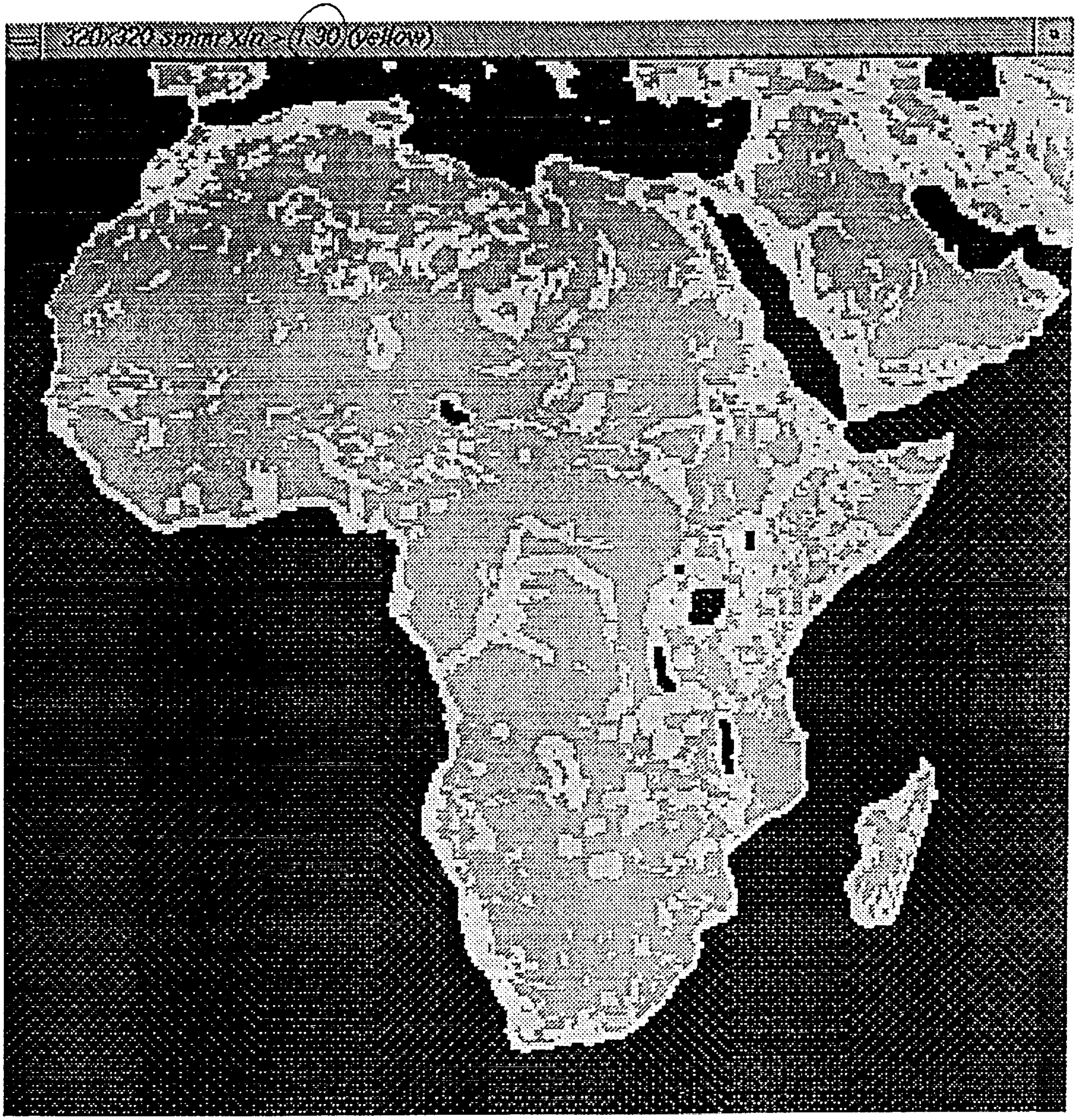
078	162	116
070	083	063
061	052	052

Figure 5



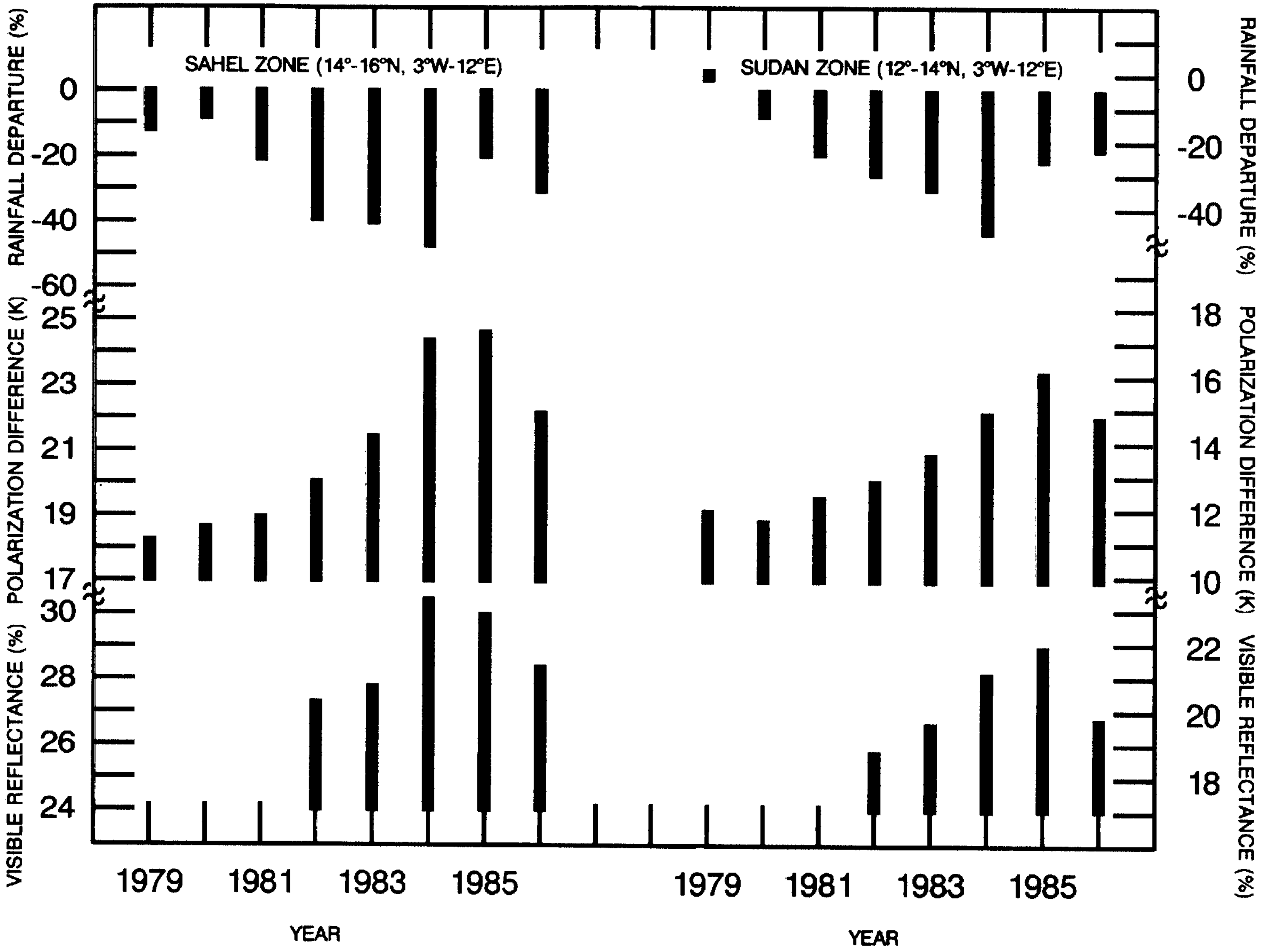
V=1.25

Figure 6a



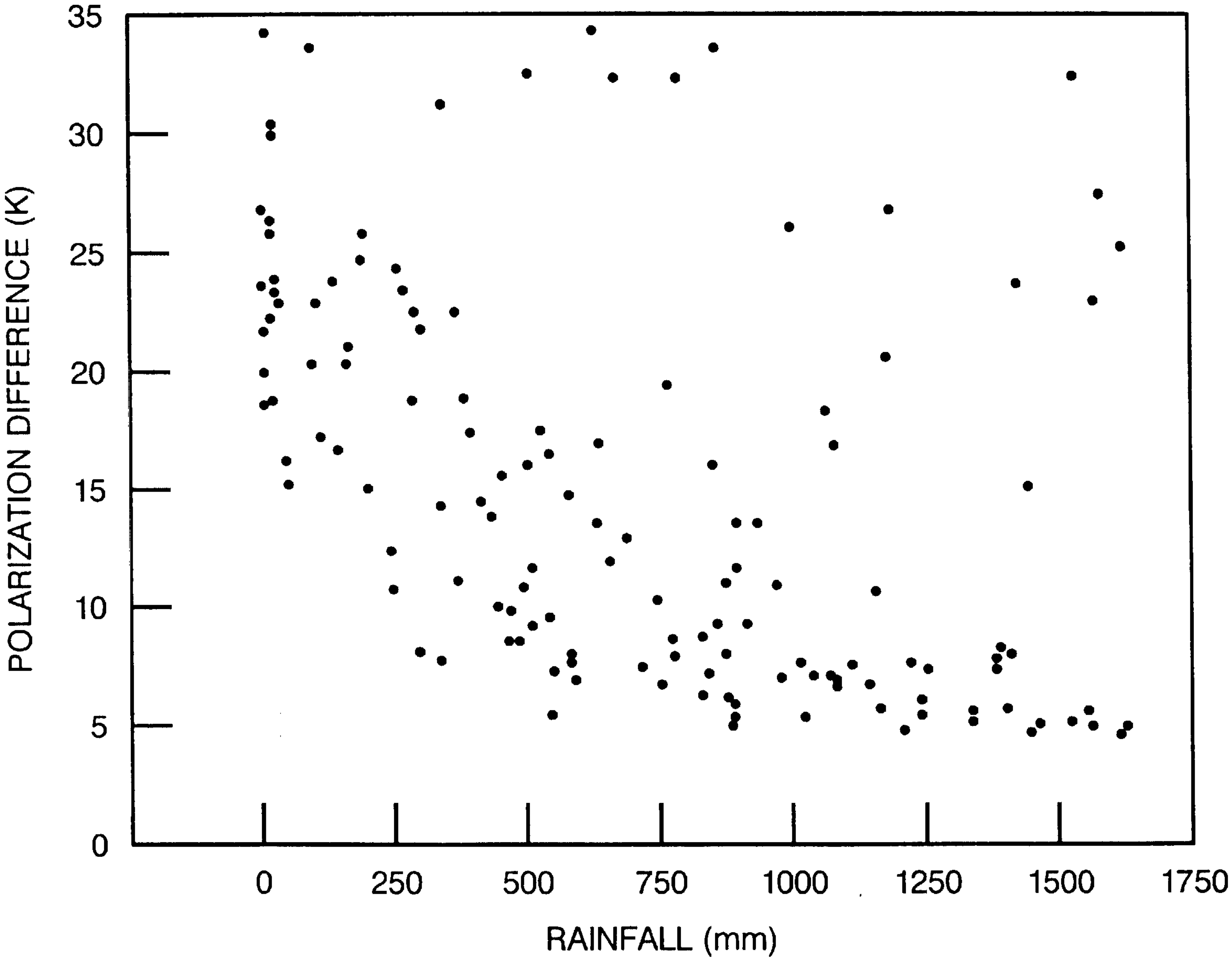
V=1.3

Figure 6b



L763.001

Figure 7



K581.001

Figure 8a

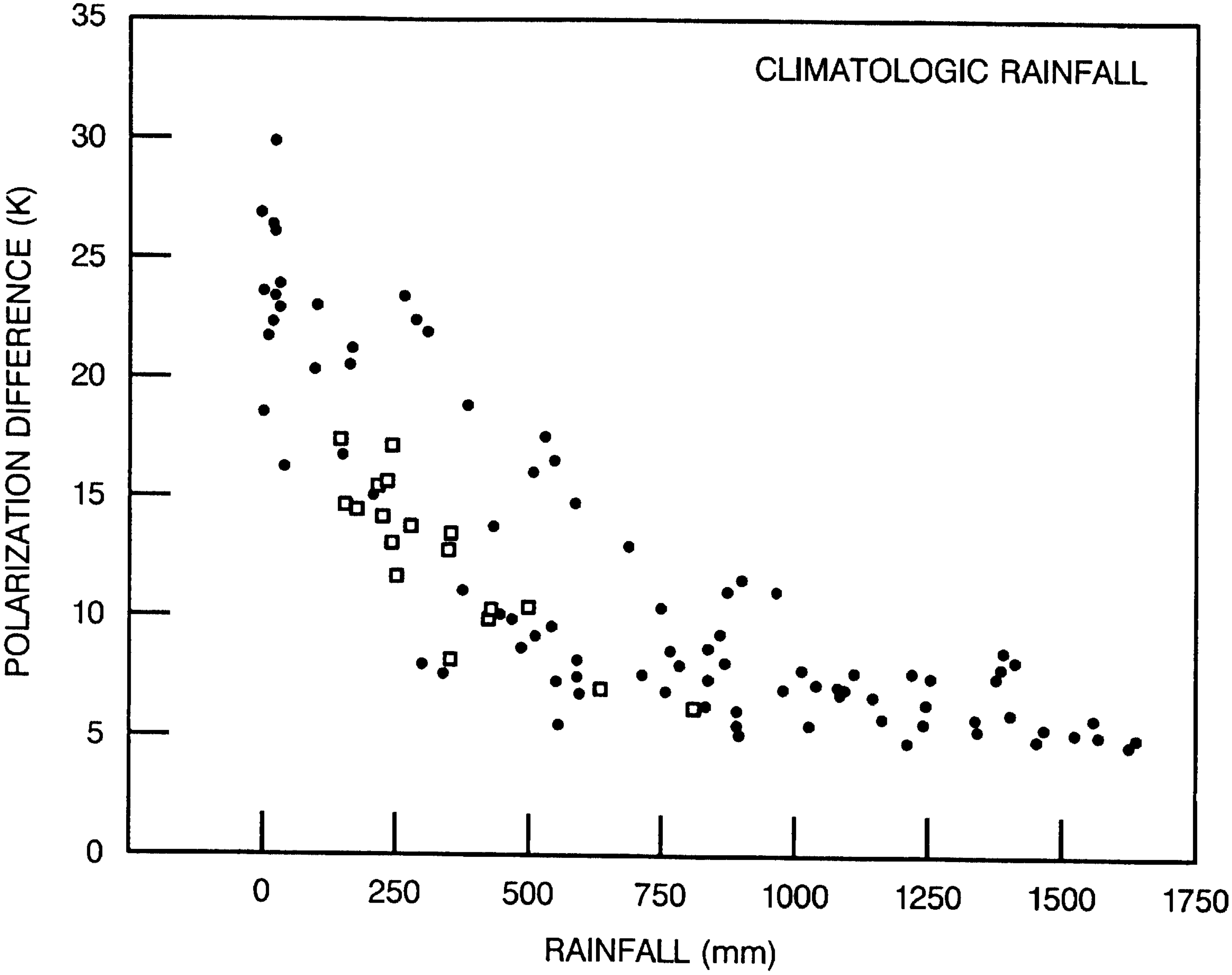
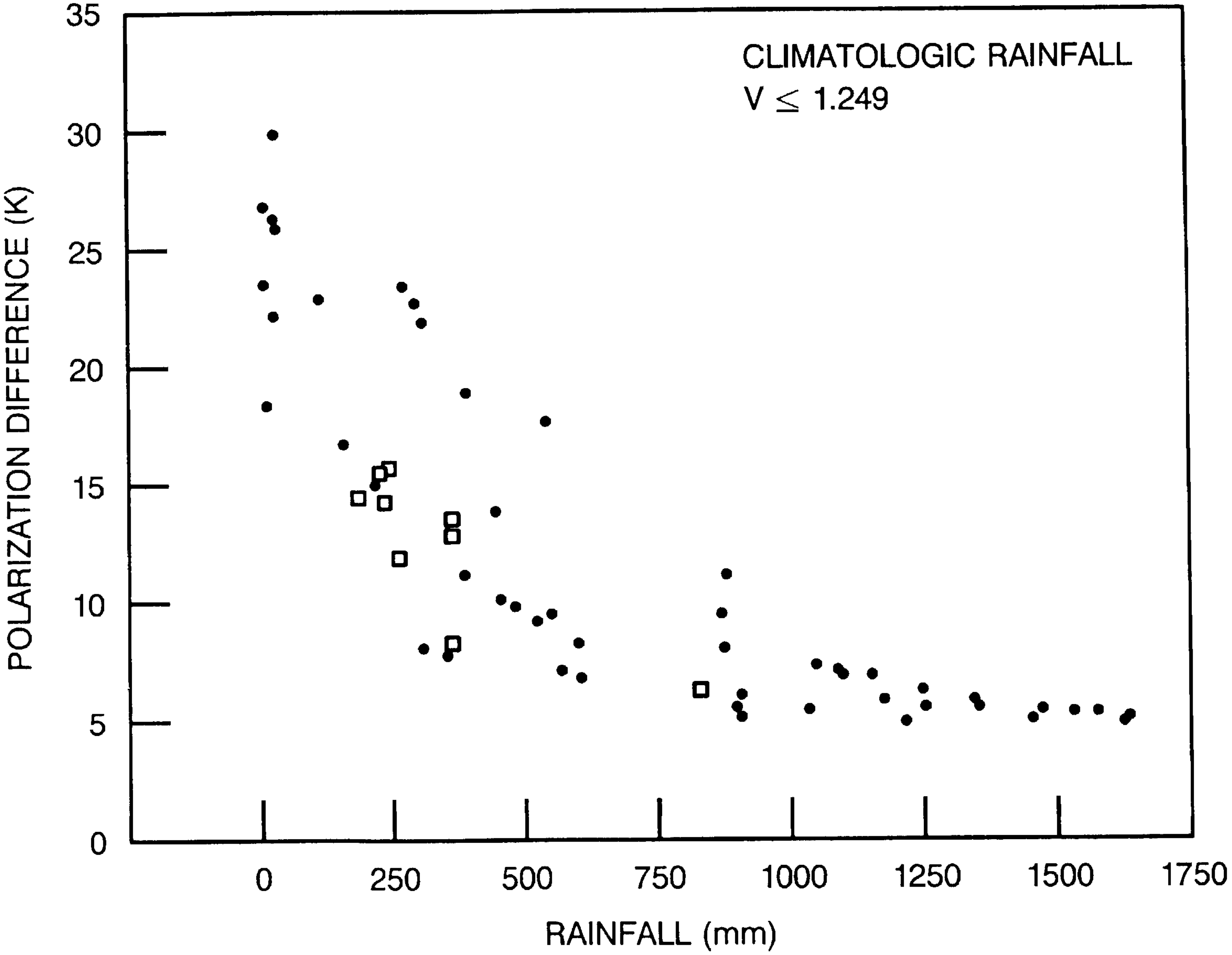


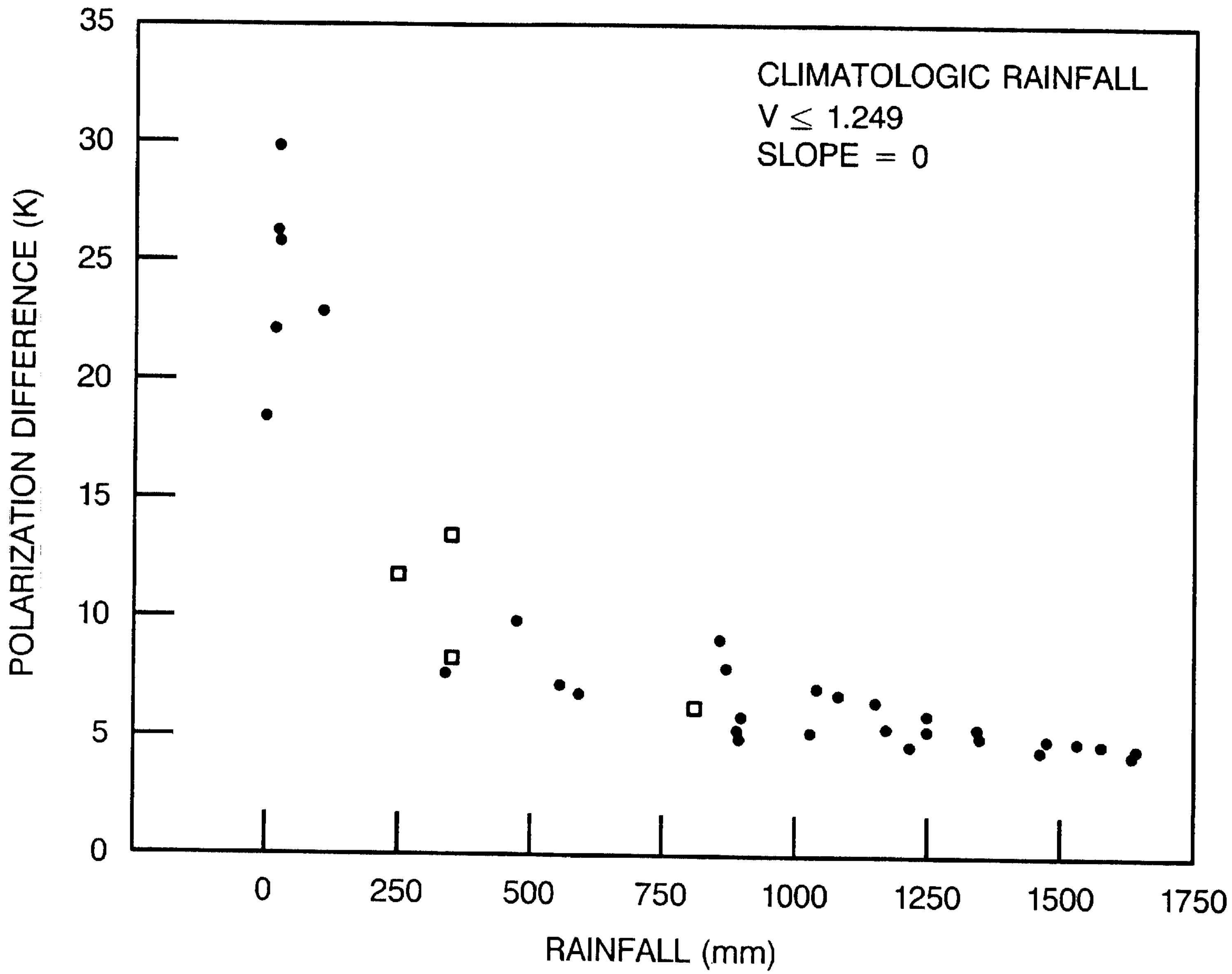
Figure 8b

K581.002



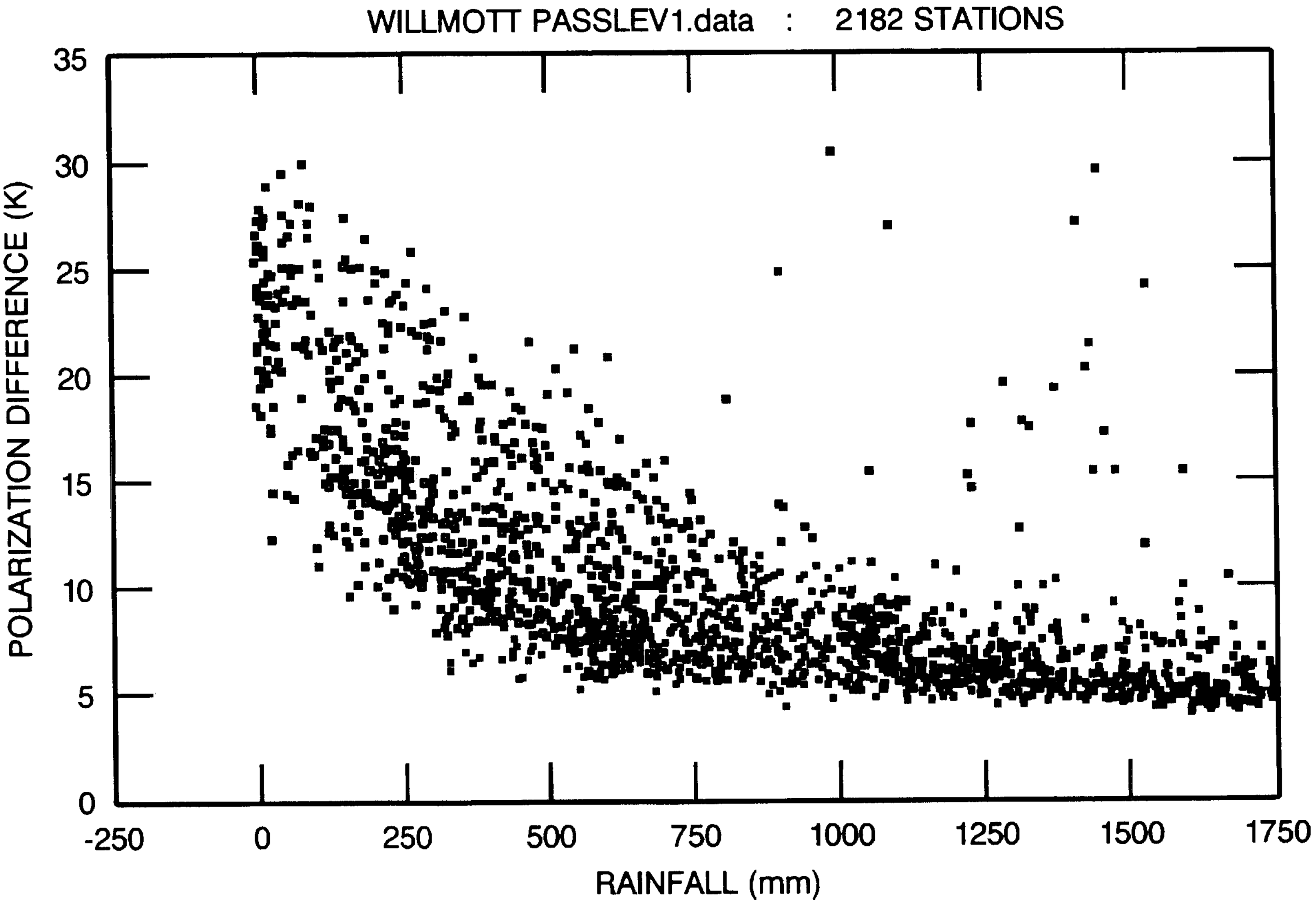
K581.003

Figure 8c



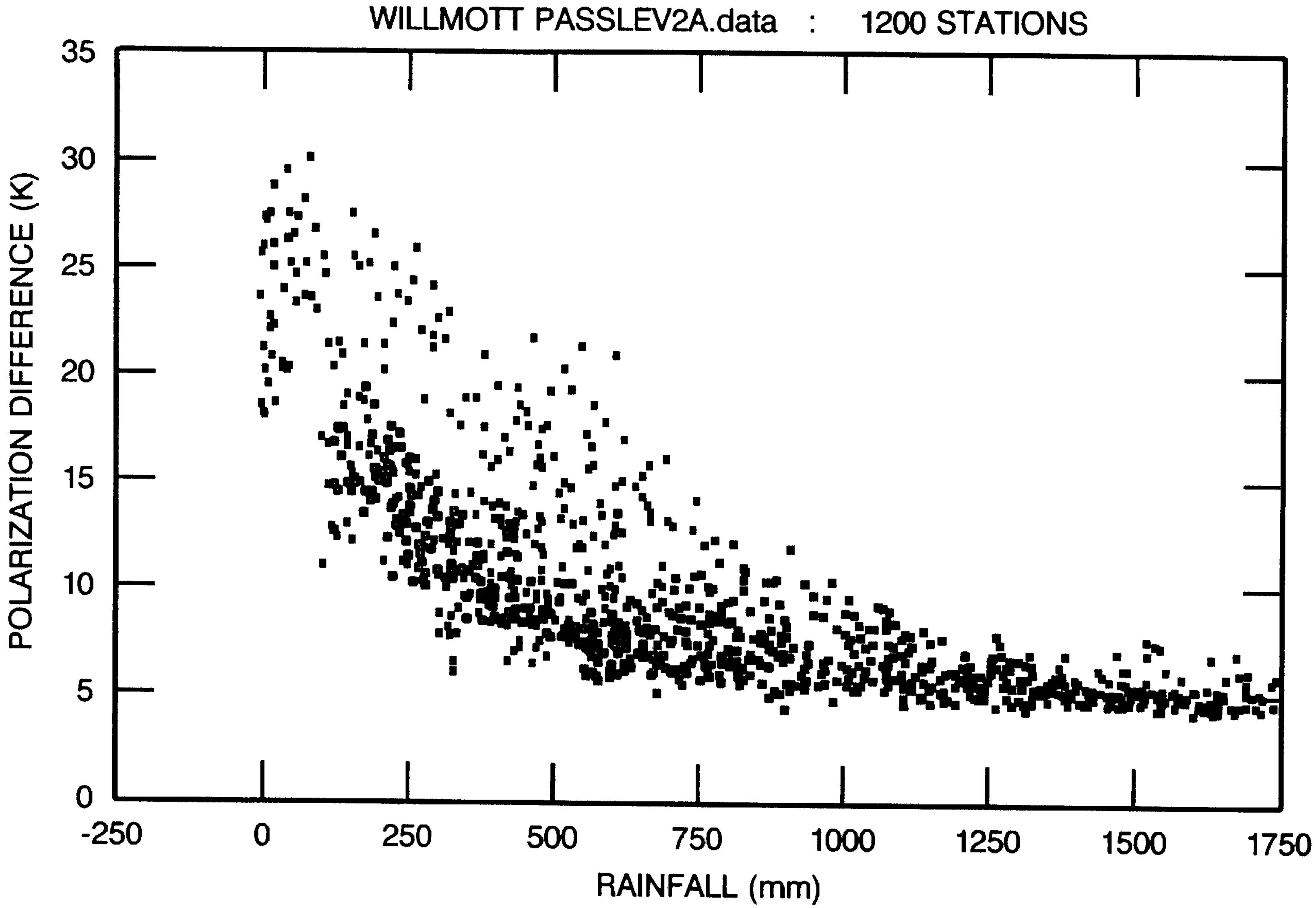
K581.004

Figure 8d



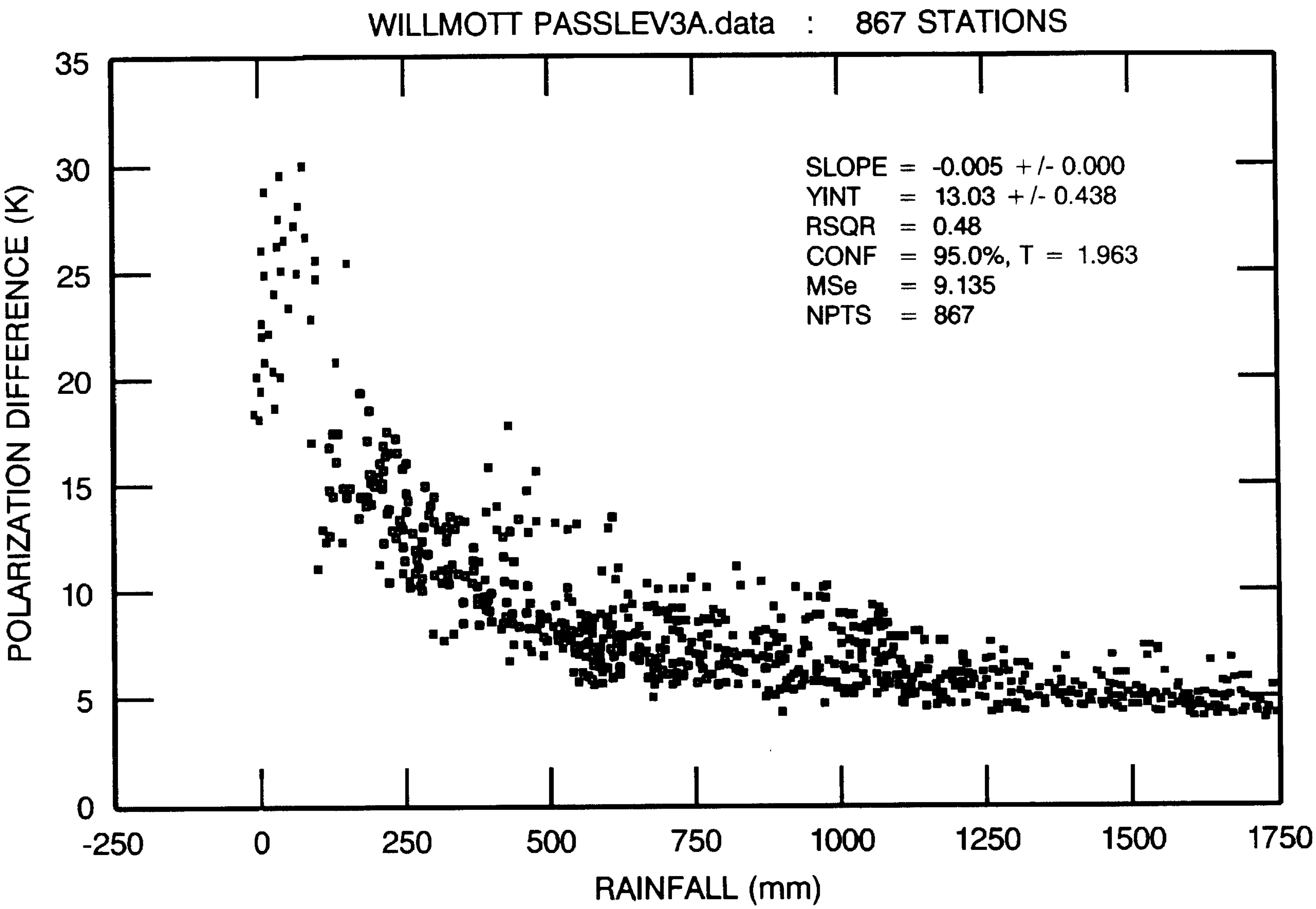
L763.002

Figure 9a



L763.003

Figure 9b



L763.004

Figure 9c

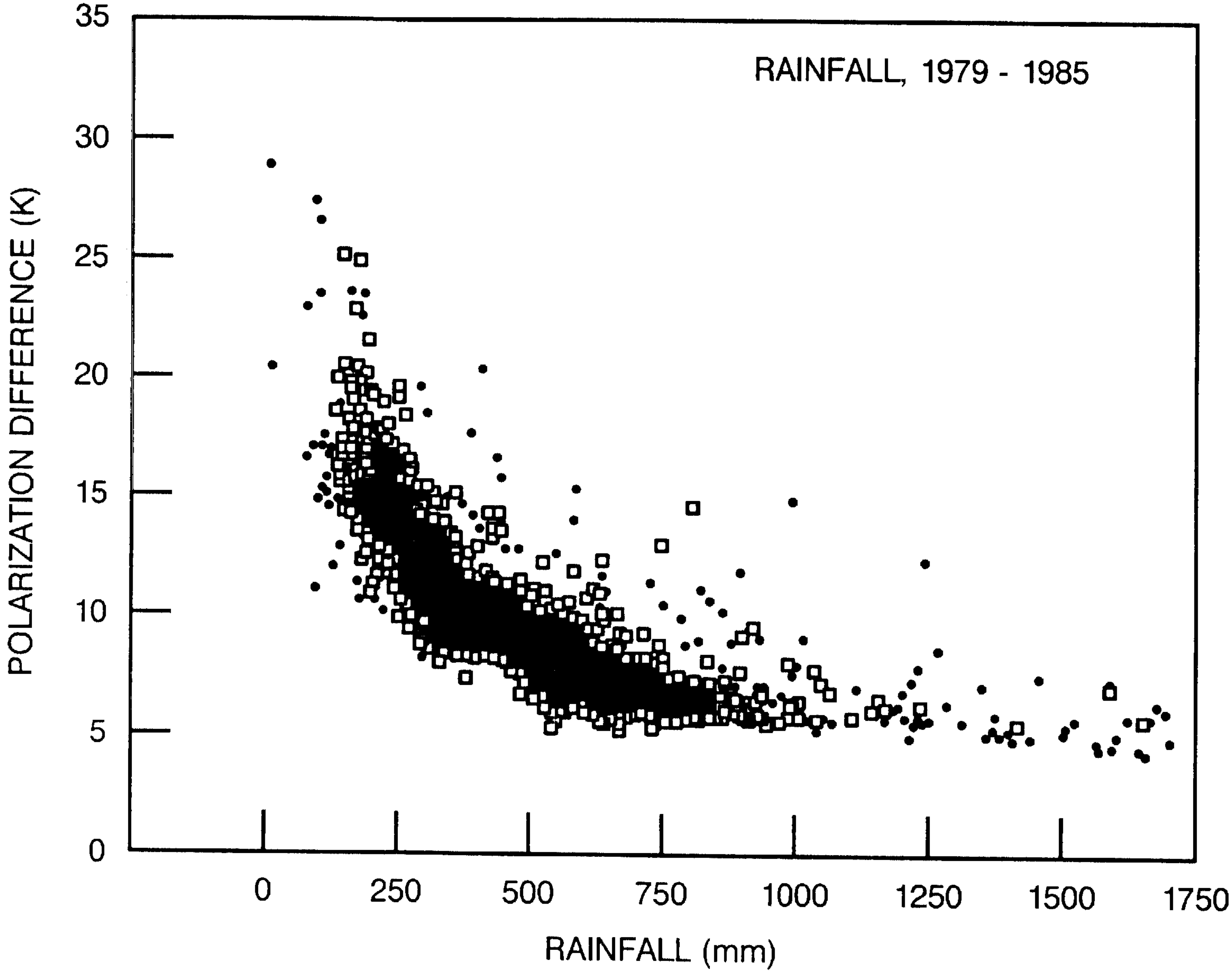
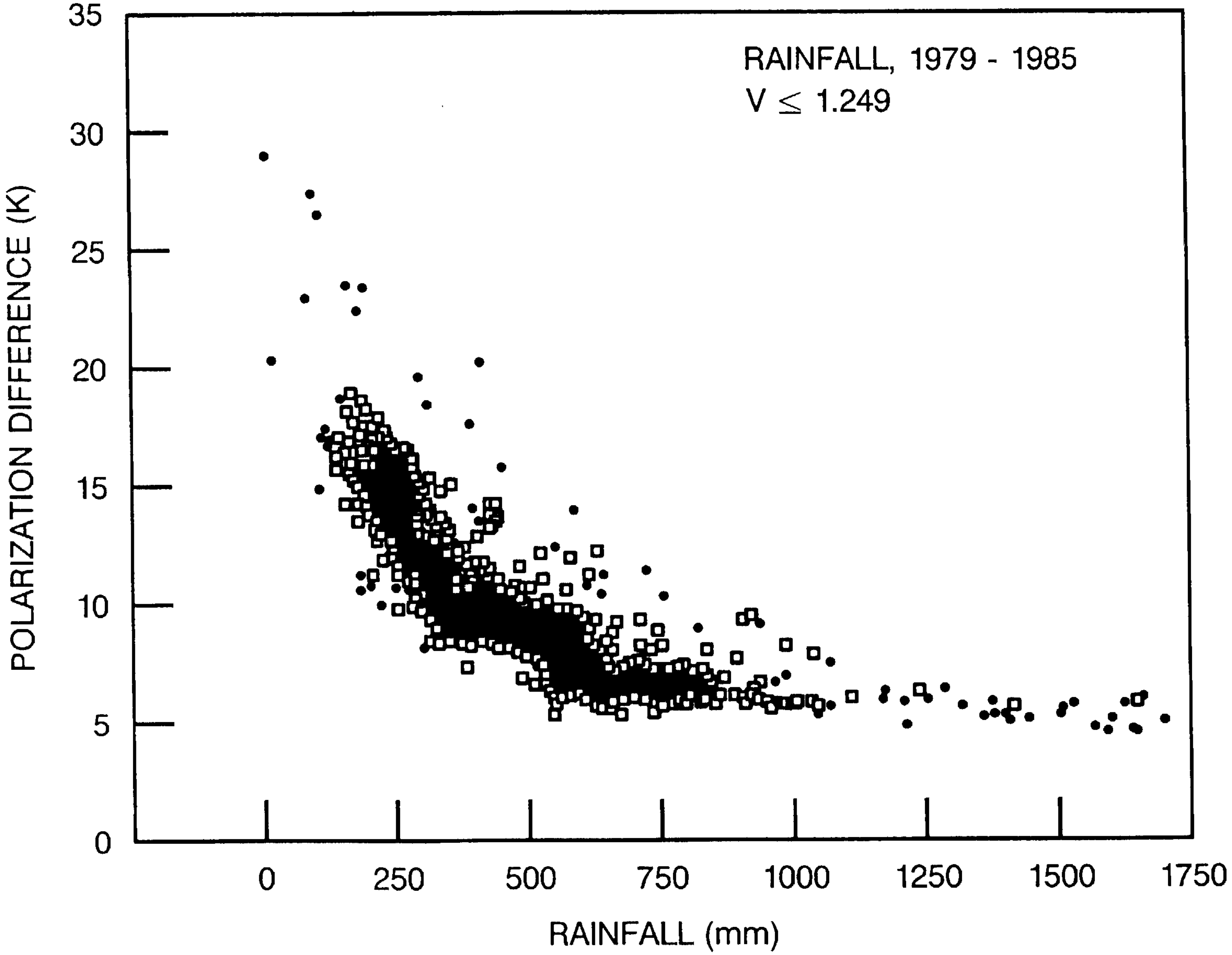


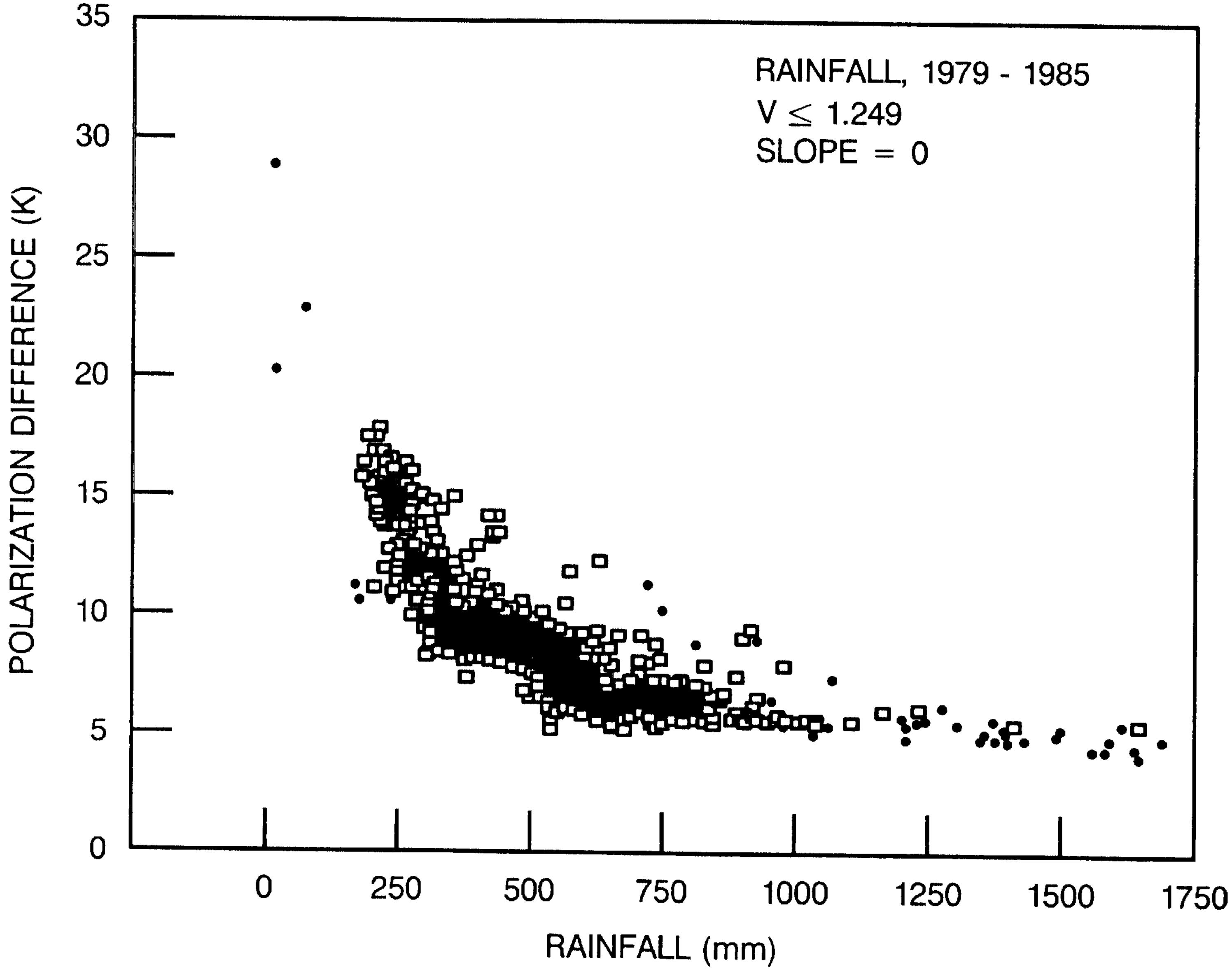
Figure 10a

K581.005



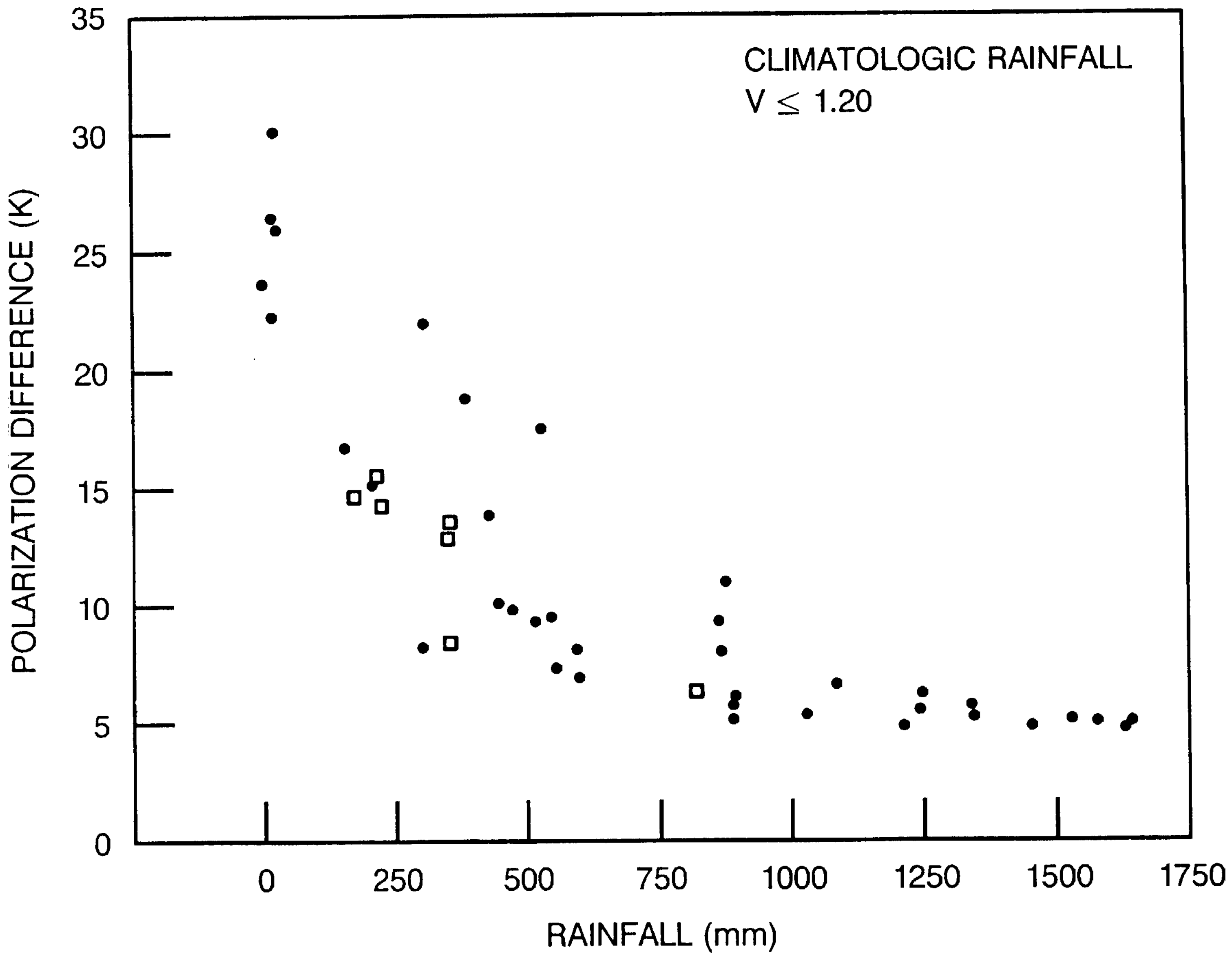
K581.006

Figure 10b



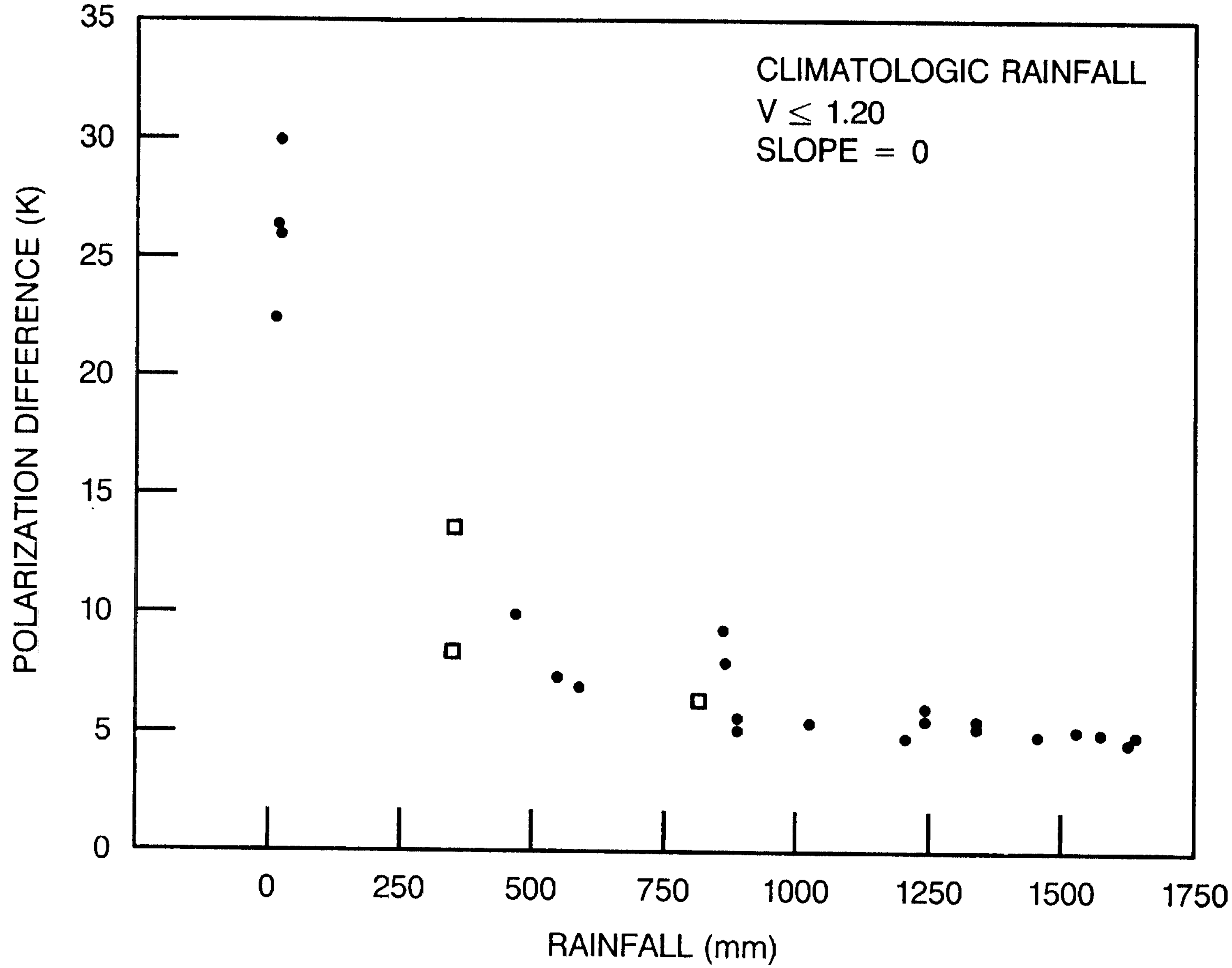
K581.007

Figure 10c



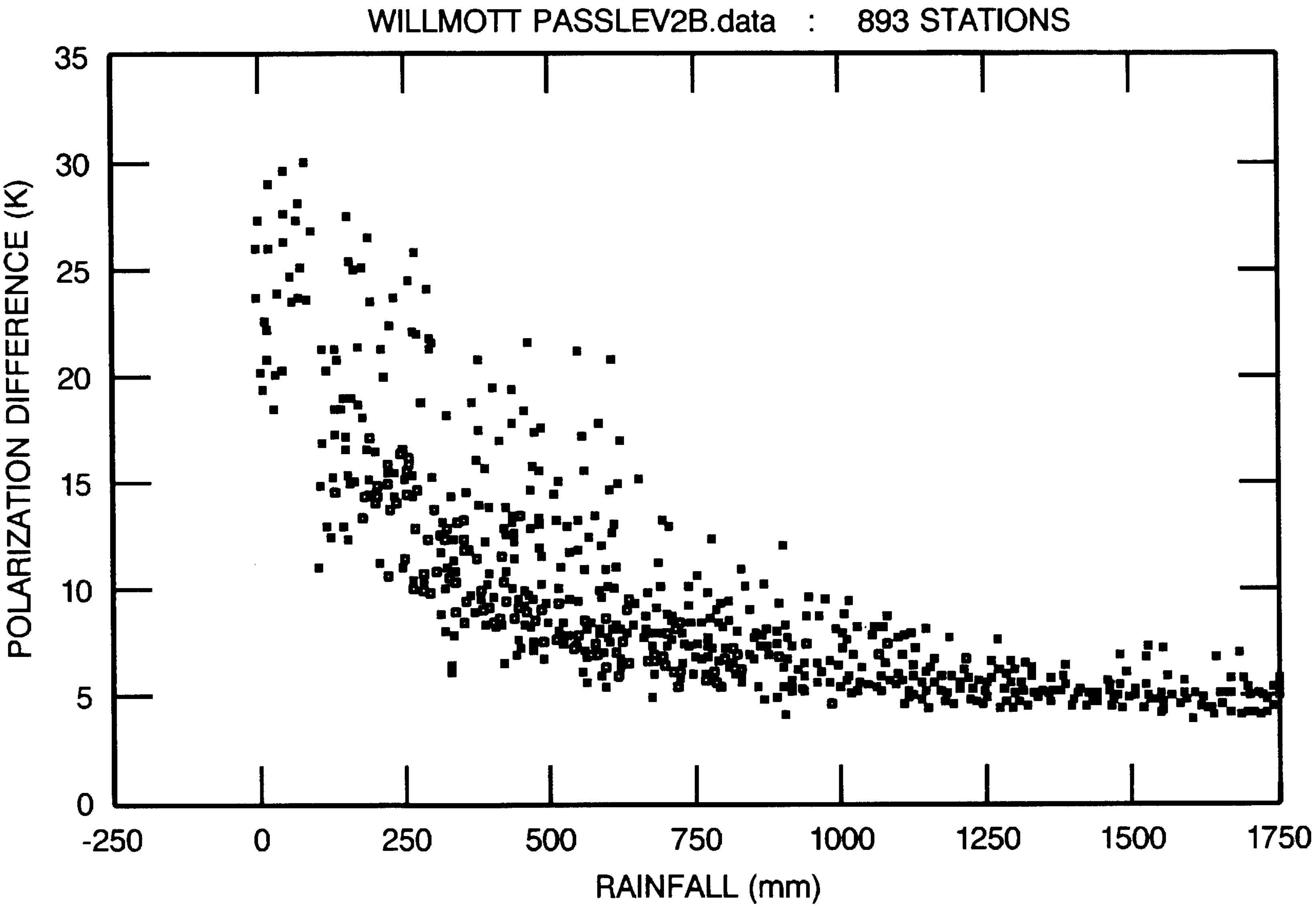
K581.008

Figure 11a



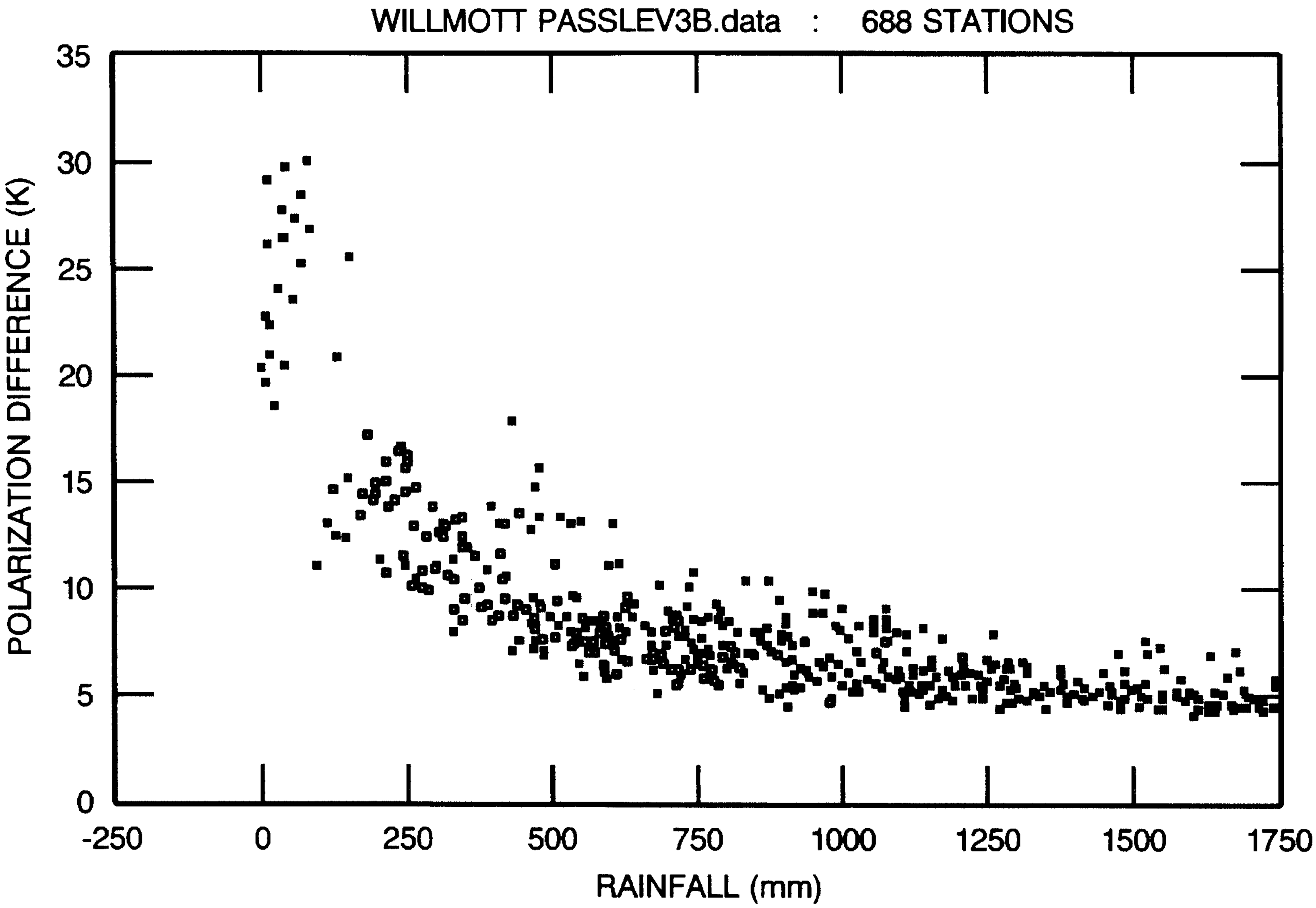
K581.009

Figure 11b



L763.005

Figure 12a



L763.006

Figure 12b

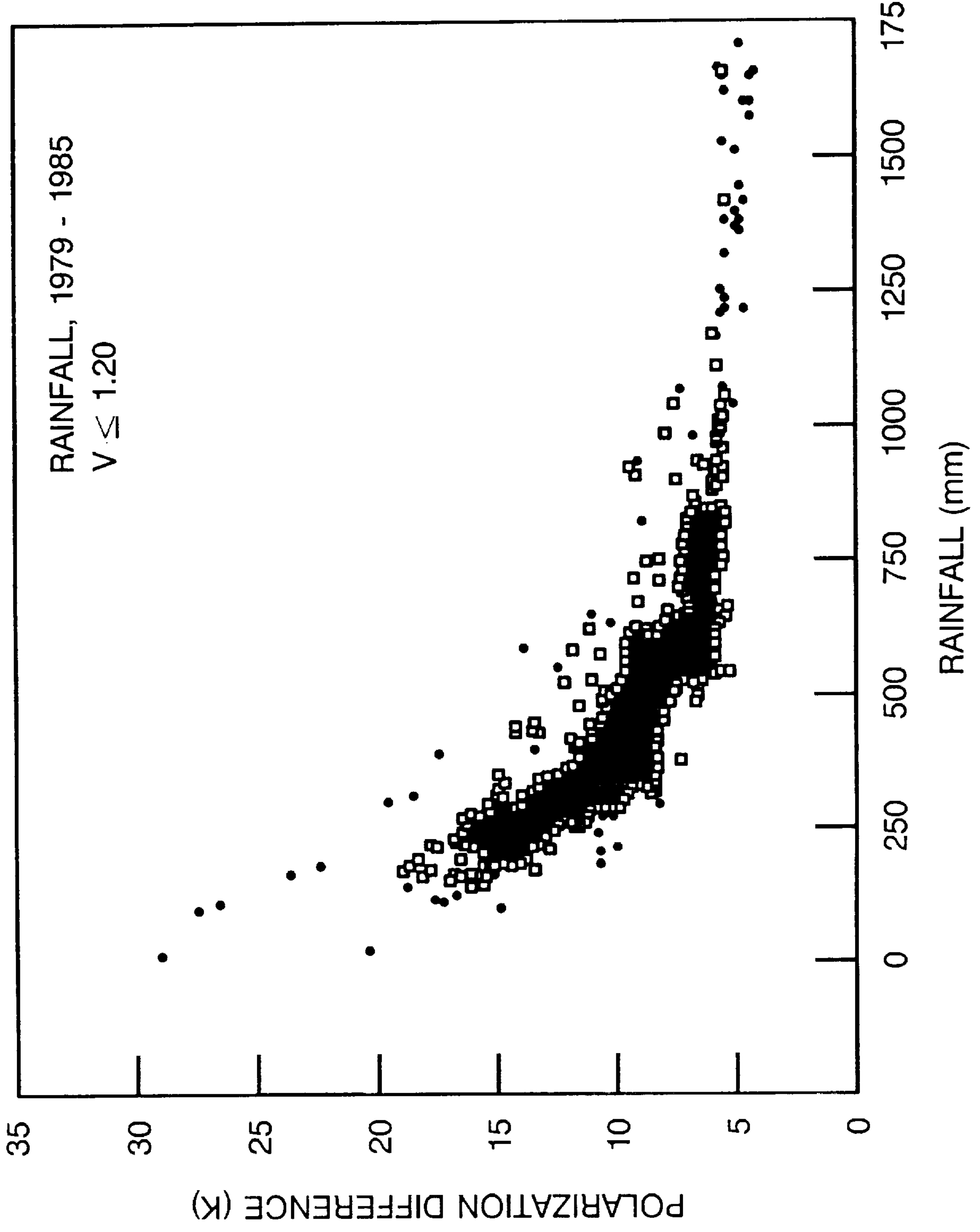
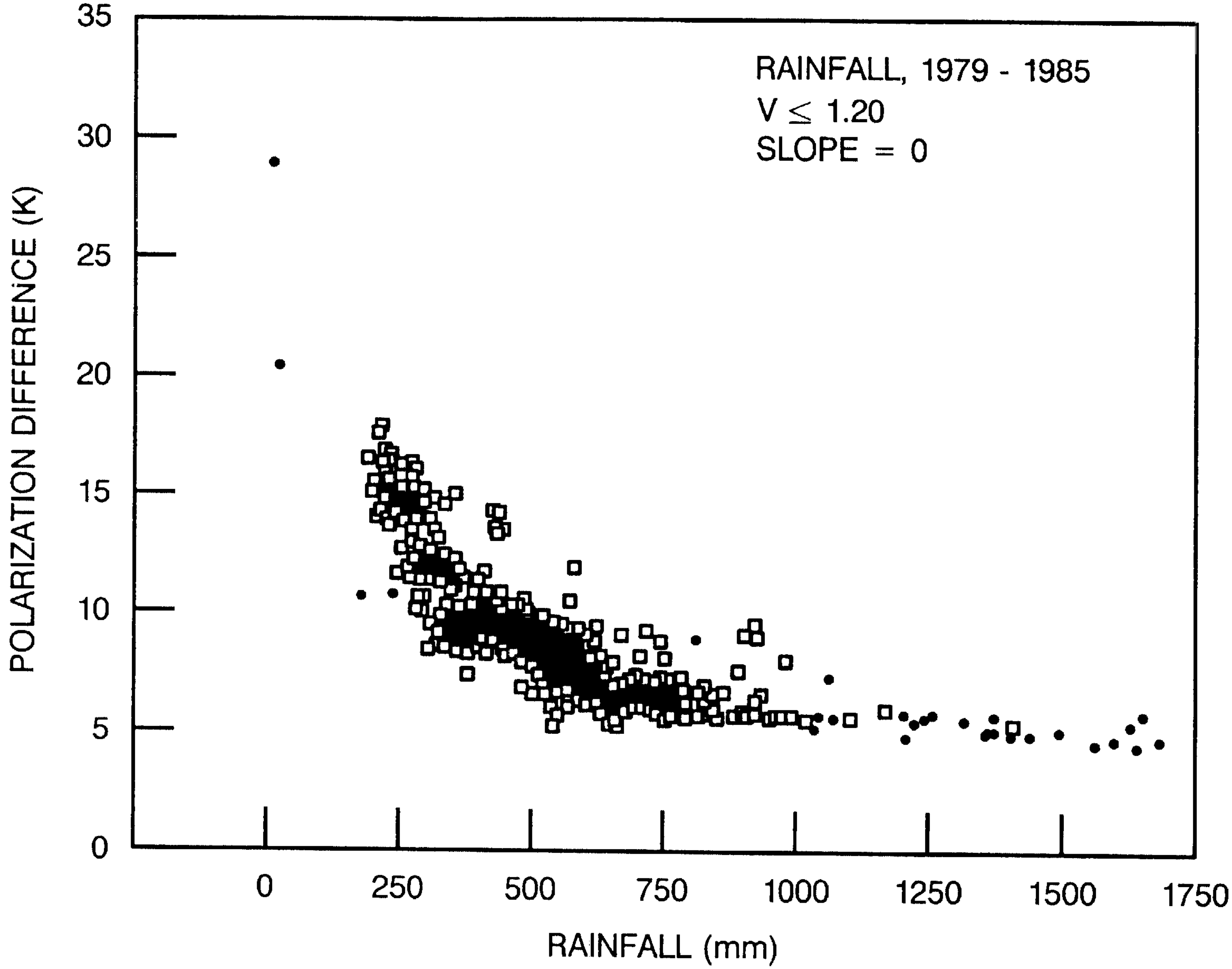


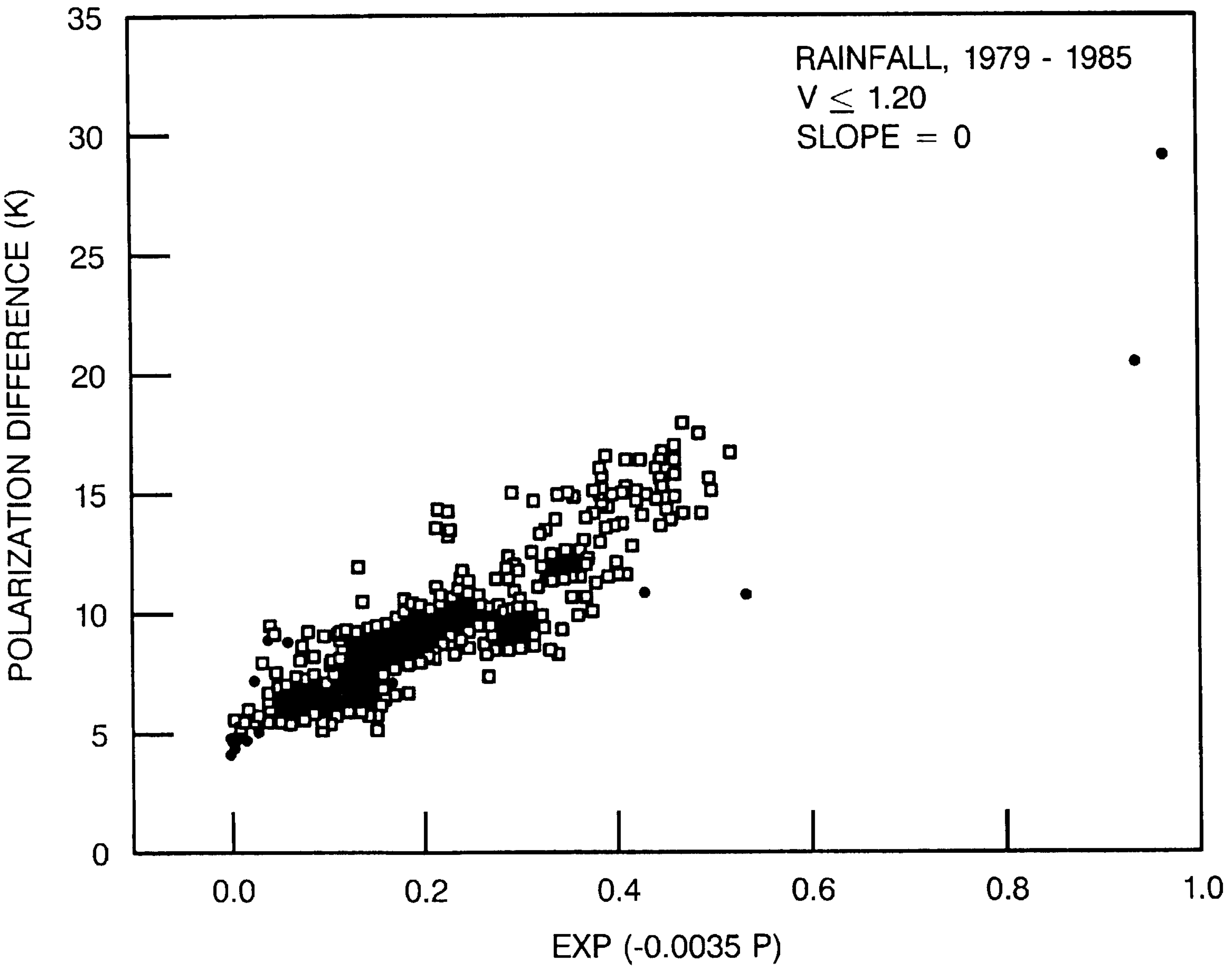
Figure 13a

K581.010



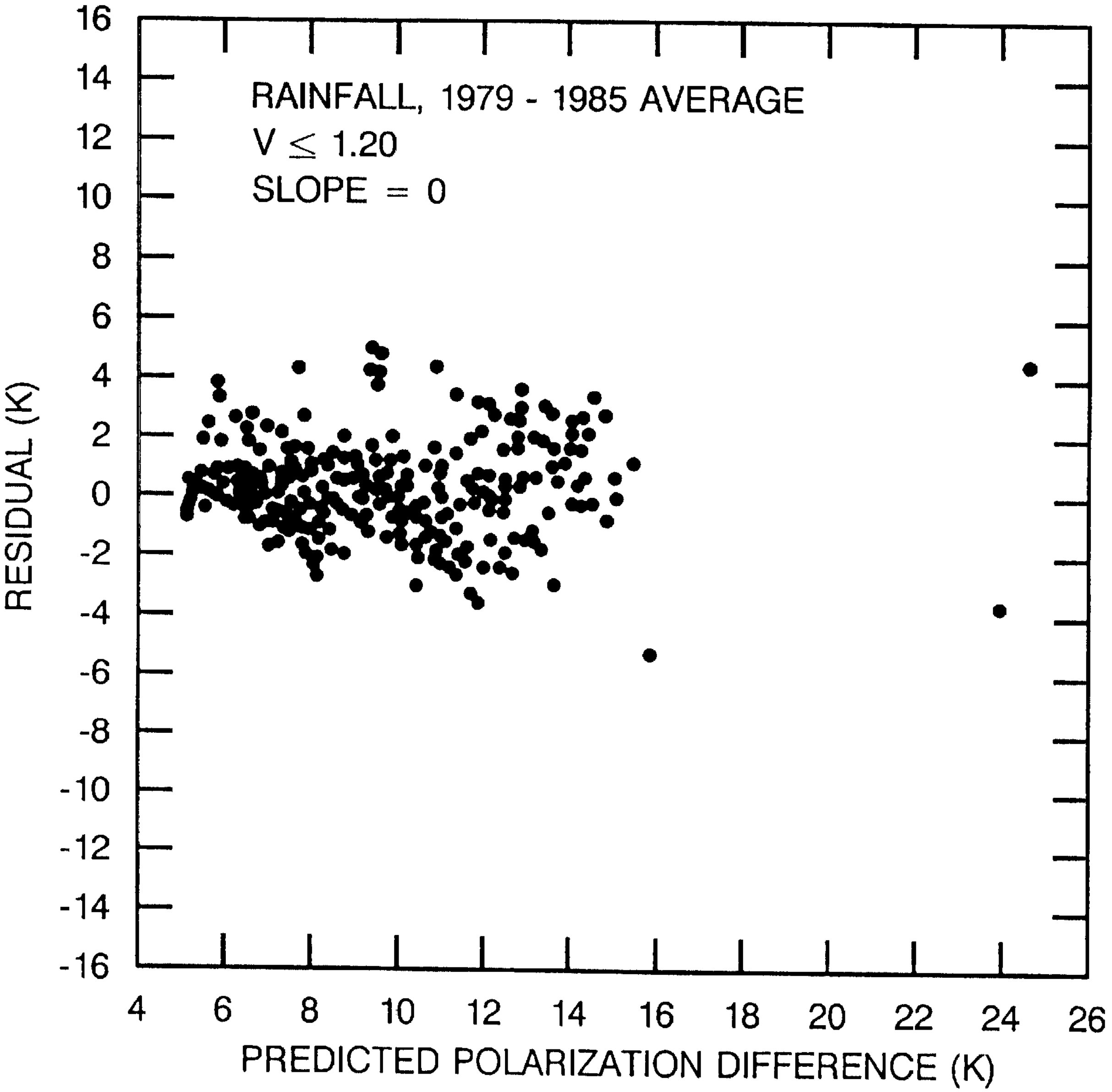
K581.011

Figure 13b



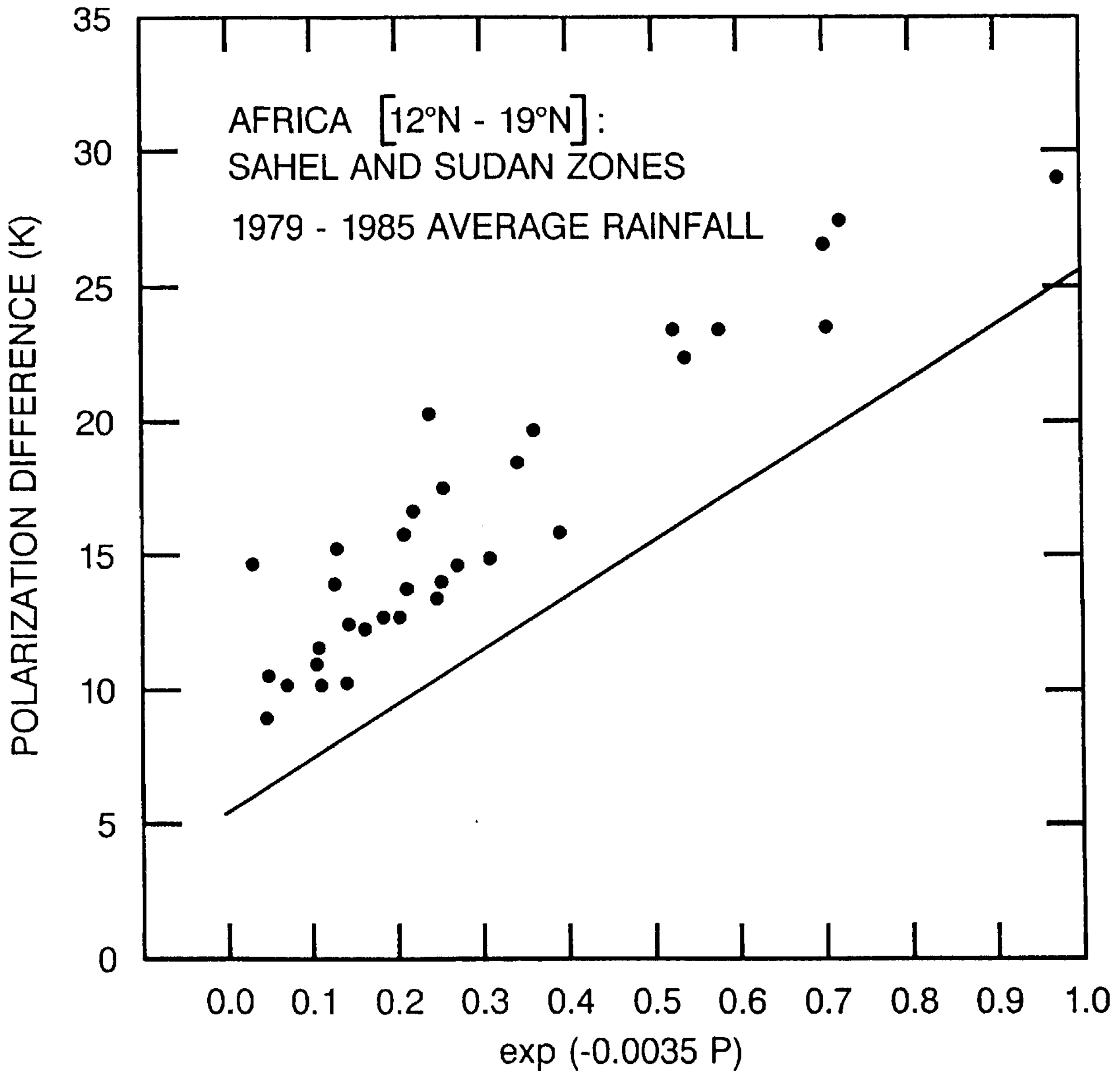
K581.012

Figure 14



A701.003

Figure 15



A701.004

Figure 16

SEASONAL TOTAL RAINFALL, 1990

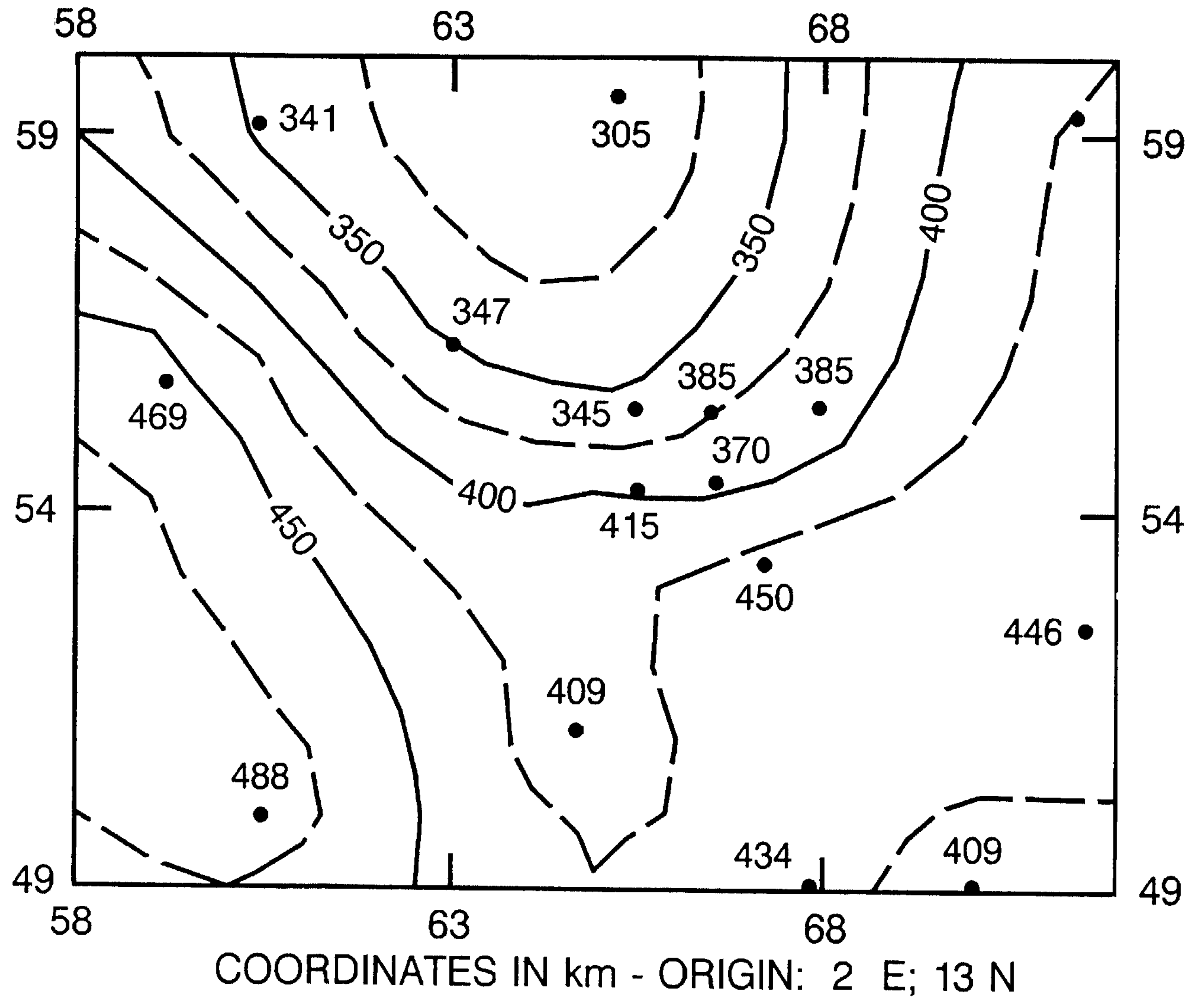
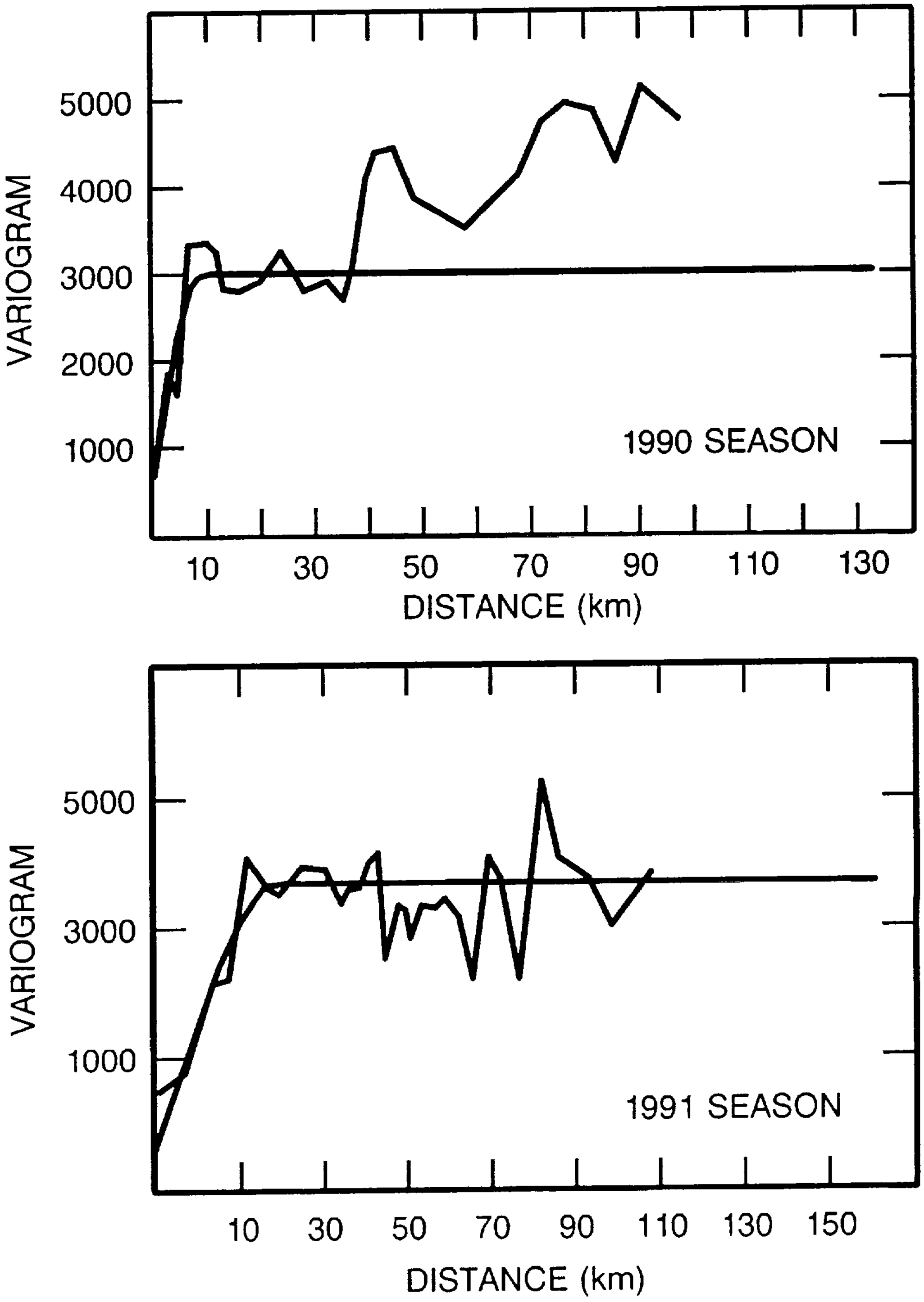


Figure 17

VARIOGRAMS OF SEASONAL TOTAL RAINFALL OVER THE SAHEL



D701.002

Figure 18

Table 1. The index of spatial variability (V) computed as the ratio of the highest and the lowest values of the normalized polarization difference (NPD) occuring within the 3x3 matrix centered on some of the rainfall stations in Africa (Muller, 1982). This variability index in used for Level 2 screening for roughness and exposed water. Geographical setting of the location (mountainous area/ close to water bodies) as assessed subjectively from The Times and National Geographic Atlases of the World is given in the Comment column, although these settings were found not to be repeatable identically in different trials.

Station Name	Latitude/Longitude	Rainfall (mm)	Variability Index (V)	Comment
Gafsa	34.4°N/8.9°E	160	1.726	Rough
Ghudamis	30.1°N/9.7°E	27	1.272	"
Zauia el Kahla	28.1°N/6.7°E	29	1.480	"
Tindouf	27.7°N/8.1°W	33	1.275	"
Sabahah	27.0°N/14.5°E	8	1.579	"
Tamanrasset	22.7°N/5.5°E	44	1.544	"
Tessalit	20.2°N/1.0°E	96	1.283	"
Addis Abeba	9.0°N/38.8°E	1256	1.306	"
Jima	7.7°N/36.9°E	1529	1.135	"
Enugu	6.5°N/7.6°E	1784	1.103	"
Bouar	5.9°N/15.6°E	1572	1.135	"
Negelli	5.1°N/39.4°E	550	1.291	"
Dagoretti	1.3°S/36.9°E	1086	1.086	"
Morogoro	6.8°S/37.7°E	892	1.192	"
Kamina	8.7°S/25.0°E	1343	1.111	"
Mongu	15.3°S/23.2°E	972	1.747	"
Tananarive	18.9°S/47.5°E	1393	1.461	"
Umtali	19.0°S/32.7°E	756	1.500	"
Windhoek	22.6°S/17.1°E	370	1.205	"

Station Name	Latitude/Longitude	Rainfall (mm)	Variability Index (V)	Comment
Mahalatswe	23.1°S/26.8°E	511	1.160	"
Keetmanshoof	26.6°S/18.1°E	147	1.161	"
Mokhotlong	29.3°S/29.1°E	586	1.307	"
Al Uqsur (Luxor)	25.7°N/32.7°E	1	1.217	Water
Dunqulah	19.2°N/30.5°E	23	1.156	"
Gao	16.3°N/0.1°W	270	1.225	"
Al-Khartoum	15.6°N/32.5°E	164	1.468	"
Kayes	14.4°N/11.4°W	746	1.545	"
Mopti	14.5°N/4.2°W	543	1.276	"
Abeche	13.8°N/20.8°E	505	1.252	"
Niamey	13.5°N/2.1°E	584	1.264	"
Sokoto	13.0°N/5.3°E	689	1.286	"
Kano	12.1°N/8.5°E	873	1.152	"
Ar Rusayris	11.9°N/34.4°E	770	1.757	"
Bougouni	11.4°N/7.5°W	1078	1.246	"
Harar (Haratu?)	9.7°N/36.8°E	889	1.963	"
Malakal	9.6°N/31.6°E	783	1.250	"
Garoua	9.3°N/13.4°E	1015	1.471	"
Moundou	8.6°N/16.1°N	1228	1.338	"
Makurdi	7.7°N/8.6°E	1405	1.393	"
Waw	7.7°N/28.1°E	1145	1.227	"
Juba	4.9°N/31.6°E	982	1.292	"
Bangui	4.4°N/18.6°E	1560	1.423	"
Yangambi	0.8°N/24.5°E	1828	2.114	"
Eala	0.0°N/18.3°E	1794	1.984	"

Station Name	Latitude/Longitude	Rainfall (mm)	Variability Index (V)	Comment
Garissa	0.5°S/39.6°E	298	1.146	"
Tshibinda	2.3°S/28.7°E	1833	5.932	"
Kinshasa	4.3°S/15.3°E	1378	3.115	"
Kasama	10.2°S/31.0°E	1245	1.143	"
Nova Lisboa	12.8°S/15.7°E	1386	1.746	"
Nova Freixa	14.8°S/36.9°E	889	1.085	"
Lusaka	15.4°S/28.3°E	837	1.869	"
Wankie	18.4°S/26.5°E	592	1.200	"
Maun	20.0°S/23.4°E	471	1.136	"
Upington	28.4°S/21.3°E	204	1.123	"
Adrar	27.9°N/0.3°W	18	1.170	Homogeneous
Mut	25.5°N/29.0°E	1	1.118	"
Al-Kufrah	24.2°N/23.4°E	2	1.249	"
Atar	20.5°N/13.1°W	106	1.243	"
Bilma	18.7°N/13.4°E	22	1.171	"
Largeau	18.0°N/19.2°E	30	1.152	"
Nema	16.6°N/7.5°W	288	1.230	"
Zinder	13.9°N/9.0°E	529	1.152	"
Al Fashir	13.6°N/25.3°E	304	1.124	"
Al-Ubayyid	13.2°N/30.1°E	383	1.128	"
Ouagadougou	12.4°N/1.5°W	897	1.257	"
Kandi	11.1°N/2.9°E	1042	1.229	"
Bobo Dioulasso	11.1°N/4.3°W	1113	1.324	"
Birao	10.3°N/22.8°E	860	1.125	"
Mamou	10.3°N/12.1°W	1963	1.094	"

Station Name	Latitude/Longitude	Rainfall (mm)	Variability Index (V)	Comment
Jos	9.9°N/8.9°E	1414	1.291	"
Tamale	9.3°N/0.9°W	1089	1.254	"
Bouake	7.7°N/5.0°W	1210	1.163	"
Bria	6.5°N/22.2°E	1636	1.038	"
Yubo	5.4°N/27.5°E	1455	1.059	"
Batauri	4.6°N/14.4°E	1625	1.102	"
Bongabo	3.1°N/20.5°E	1810	1.109	"
Gulu	2.8°N/32.3°E	1470	1.208	"
Mitzic	0.8°N/11.6°E	1842	1.114	"
Tabora	4.0°S/32.8°E	892	1.161	"
Kananga	5.9°S/22.4°E	1572	1.157	"
Teixeira	10.7°S/22.2°E	1341	1.172	"
Lubumbashi	11.6°S/27.5°E	1244	1.200	"
Ndola	13.0°S/28.6°E	1169	1.211	"
Cangamba	13.7°S/19.9°E	1027	1.088	"
Blantyre	15.7°S/35.0°E	834	1.267	"
Mupa	16.1°S/15.9°E	712	1.253	"
Tsumeb	19.2°S/17.7°E	553	1.118	"
Bulawayo	20.1°S/28.6°E	589	1.181	"
Ghanzi	21.7°S/21.6°E	553	1.143	"
Messina	22.3°S/30.0°E	340	1.208	"
Pietersburg	23.8°S/29.4°E	485	1.250	"
Gaborone	24.7°S/25.9°E	541	1.155	"
Kimberly	28.8°S/24.8°E	431	1.144	"

Table 2. Results of trend analysis for monthly polarization difference data for 1979-1985. Regression slopes and confidence limits for all stations in Africa from Muller (1982) which passed Level 2A screening, but was rejected at Level 3 screening. Stations with stars will not be rejected at 99.9 percent confidence level. Latitude/logitude for these locations may be found in Table 1.

Location Name	Slope	Confidence Limit	
	(K / month)	99%	99.9%
Mut (**)	-0.009	0.008	0.010
Al-Kufrah	-0.025	0.008	0.010
Nema	0.036	0.025	0.032
Gao	0.075	0.044	0.057
Zinder	0.064	0.045	0.058
Al-Fashir	0.070	0.033	0.043
Al-Ubayyid	0.090	0.037	0.048
Kano (**)	0.024	0.019	0.025
Garissa	0.031	0.013	0.017
Dagoretti	0.016	0.010	0.013
Bulawayo	0.025	0.019	0.025
Ghanzi	0.045	0.032	0.041
Windhoek	0.039	0.025	0.032
Mahalatswe	0.064	0.022	0.028
Gaborone	0.071	0.022	0.028
Keetmanshoof	0.040	0.017	0.022
Upington	0.057	0.021	0.027
Kimberly	0.051	0.023	0.030

Table 3. Number of rainfall stations passing at different levels of data screening for different rainfall data sets.

Screening Level	Number of Stations	
	Africa	Australia
Muller (1982) Climatologic Data:		
Data Base	159	39
Level 1	95	18
Level 2A	54	9
Level 3	36	4
Level 2B	42	7
Level 3	28	3
Legates and Willmott (1990) Climatologic Data:		
Data Base	3046	618
Level 1	1875	307
Level 2A	1023	177
Level 3	726	158
Level 2B	767	126
Level 3	573	115
1979-1985 Average Data:		
Data Base	216	4221
Level 1	178	1398
Level 2A	100	817
Level 3	54	654
Level 2B	76	636
Level 3	43	507

Table 4. Results of statistical analysis between PD and exponential transform of rainfall (exp (-0.0035 P)) for data passing Level 3 screenings for different rainfall data sets. The confidence range for slope and intercept at 99 percent level is given in the parenthesis, together with standard error of estimate (SEE), coefficient of determination (r^2) and number of data values (N). Further datails about the data and screenings are given in the text.

Screening	Slope	Intercept	SEE	r^2	N
Muller (1982) Climatologic Data:					
2A + 3	20.6 (2.8)	5.2 (0.2)	2.1	0.91	40
2B + 3	22.6 (2.5)	5.0 (0.9)	1.5	0.96	31
Legates and Willmott (1990) Climatologic Data:					
2A + 3	20.6 (0.8)	5.5 (0.2)	1.7	0.84	884
2B + 3	21.1 (0.9)	5.3 (0.2)	1.6	0.84	688
1979-1985 Average Data:					
2A + 3	20.1 (0.9)	5.1 (0.2)	1.3	0.81	708
2B + 3	20.5 (1.1)	5.1 (0.2)	1.3	0.82	550

Table 5. Atmospheric effect on the SMMR 37-GHz polarization difference for selected rainfall stations. Station name, latitude/longitude, climatologic rainfall, surface vapor pressure, precipitable water vapor calculated from the surface vapor pressure (Ben Mohamed and Frangi, 1983) and the ratio of polarization difference at surface and at satellite (PD_S/PD) are given.

Name	Lat./Long.	Rainfall (mm)	Vapor Pressure (kPa)	Precipitable Water (mm)	Ratio
Adrar	27.9°N/0.3°W	18	0.70	14	1.23
Kufra	24.2°N/23.3°E	2	0.69	14	1.23
Ouagadougou	12.4°N/1.5°W	897	1.82	31	1.37
Bobo Dioulasso	11.2°N/4.3°W	1113	1.80	30	1.36
Mitzic	0.8°N/11.6°E	1842	2.49	43	1.48
Upington	28.4°S/21.3°E	204	0.85	16	1.25
Tennant Creek	19.6°S/134.2°E	351	1.02	18	1.26
Giles	25.0°S/128.3°E	174	0.83	16	1.24
Charleville	26.4°S/146.2°E	498	1.22	21	1.29
Enugu	6.5°N/7.6°E	1784	--	45*	1.51
Bria	6.5°N/22.2°E	1636	--	32*	1.38
Bangui	4.4°N/18.6°E	1560	--	35*	1.41
Bongabo	3.1°N/20.5°E	1810	--	35*	1.41
Tshibinda	2.3°S/28.7°E	1833	--	32*	1.38
Kinshasa	4.3°S/15.3°E	1378	--	40*	1.46

* from Tuller (1968)

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13. ABSTRACT *(Maximum 200 words)*

A major difficulty in interpreting coarse resolution satellite data in terms of land surface characteristics is unavailability of spatially and temporally representative ground observations. Under certain conditions rainfall has been found to provide a proxy measure for surface characteristics, and thus a relation between satellite observations and rainfall might provide an indirect approach for relating satellite data to these characteristics. Relationship between rainfall over Africa and Australia and 7-year average (1979-1985) polarization difference (PD) at 37 GHz from scanning multichannel microwave radiometer (SMMR) on board the Nimbus-7 satellite is studied in this paper. Quantitative methods have been used to screen (accept or reject) PD data considering antenna pattern, geolocation uncertainty, water contamination, surface roughness, and adverse effect of drought on the relation between rainfall and surface characteristics. The rainfall data used in the present analysis are climatologic averages and also 1979-1985 averages, and no screening has been applied to this data. The PD data has been screened considering only the location of rainfall stations, without any regard to rainfall amounts. The present analysis confirms a non-linear relation between rainfall and PD published previously.

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