THE IMPACTS OF WEATHER ON SUGARCANE PRODUCTION IN THE MUMIAS SUGAR ZONE OF WESTERN KENYA

BY

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Declaration

I hereby declare that this dissertation is my original work and has not been presented for a degree in this or any other university.

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Abstract

This study sought to understand the existing trend in selected weather variables and investigate the effect of these variables on annual yield of sugarcane in the Mumias sugarcane growing region of Western Kenya. The weather-yield relations were investigated using two sugarcane varieties CO 421 and CO 945 under same growing conditions at Mumias Sugar Company nucleus estate in Mumias district. Two weather datasets were used; one comprising of daily rainfall, temperature and radiation data from 1981 to 2008 and another comprising of 40-year mean monthly data from 1968 to 2008 of the same variables. The yield data set comprised of yields at field level for the period between 1984 and 2008. Trend analysis for both the weather and yield data was done using the Mann-Kendall and Sen Statistics. The influence of different weather-related variables on sugarcane yield was investigated using correlation and regression analysis.

Analysis of the trends in the observed weather records indicated an increase in the mean monthly minimum temperature during all the months of the year with the magnitude of change ranging between 0.05°C and 0.08°C per year. The records also showed an increasing trend in the mean monthly maximum temperatures which was significant during the months of July and August with a magnitude of 0.03°C for both months. Rainfall records did not indicate any significant trends. Trend analysis of the yield data showed a general decreasing trend in the yields in both the varieties, with variety CO 421 showing a slower decline than CO 945. Analysis on the interaction of the selected weather variables on sugarcane yields in the two varieties showed that CO 945 was more sensitive to weather variables than CO 421.

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List of abbreviations

AEZ	Agro-Ecological Zone
AIC	Akaike's Information Criteria
ANOVA	Analysis of variance
APSIM	Agricultural Production System Simulator
AR (1)	Auto-regressive (1) covariance structure
C_3 plants	Group of plants that use Rubisco to make a three-carbon as the first stable product of carbon fixation before entering the Calvin cycle of photosynthesis
C_4 plants	Group of plants that use Phosphoenolpyruvate- Carboxylase to make a four-carbon molecule in the first step of photosynthesis,
CIRAD	French Agricultural Research Center
CMS	Central Meteorological Station
CO 421	Sugarcane variety from Coimbatore, India predominant in the Kenya sugar industry
CO 945	Sugarcane variety from Coimbatore, India. Mostly grown in the Mumias sugar zone
CS	Compound symmetry covariance structure
FAO	Food and Agriculture Organization of the United Nations
FM	Filter Mud
GDD	Growing Degree Days
ICIPE	International Center of Insect Physiology and Ecology
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
KESREF	Kenya Sugar Research Foundation

KARI	Kenya Agricultural Research Institute
LAI	Leaf Area Index
LSD	Least Significant Difference
ML	Maximum Likelihood
MIVQUE0	Minimum Variance Quadratic Unbiased Estimation
MSC	Mumias Sugar Company
MOSICAS	French Sugarcane simulation model
NPK	Nitrogen, Phosphorus, Potassium
PAR	Photosynthetically Active Radiation
PER	Plant Extension Rate
Q-CANE	Queensland sugarcane simulation model
REML	Restricted or Residual maximum likelihood
RMSE	Root Mean Square Error
RUE	Radiation Use Efficiency
SAS	Statistical Analysis System
SSE	Sum of Squared Errors
SST	Sum of squared Totals
TCH	Tonnes of cane per hectare
TRS	Total recoverable Sugar
TSH	Tonnes of Sugar per hectare
UN	Unstructured covariance structure
VC	Variance components covariance structure
WUE	Water Use Efficiency

Dedication

To my dear son Neville

"If you believe in yourself and have dedication and pride - and never quit, you'll be a winner.

The price of victory is high but so are the rewards".

Paul Bryant

CHAPTER 1

1.0 INTRODUCTION

This chapter presents a brief introduction on the sugarcane industry in Kenya, the objectives, justification and description of the site of this study.

Sugarcane (*Saccharum officinarum*) cultivation in Kenya dates back to 1922 in the Ramisi area of the Coast province. Today, the sugar sub-sector provides direct and regular employment for about 40,000 workers and indirectly employs thousands of casual workers on farms as weeders and cane cutters among others. Sugarcane growing is a major source of income to over 150,000 smallholders, (Kenya Sugar Board, 2009). The sugar sector acts as an input supplier for other manufacturing concerns and as marketing and distribution agent for sugar and sugar by-products. Sugar also acts as a foreign exchange earner and if produced in large quantities can save on import expenditure. It is also a major food item in the household budget of the average Kenyan. Refined sugar is an essential raw material in food processing, confectioneries, beverage manufacture, soft drinks and pharmaceutical industries among others. In Kenya today, the demand for sugar across these competing uses outweighs domestic production. There is a national sugar deficit of 200,000 metric tonnes, (Kenya Sugar Board, 2009).

The area under cane is currently estimated at over 169,000 hectares, with an estimated annual production of approximately 520,000 tonnes. Approximately 156,000 hectares of the land under cane is owned by out-grower farmers while the rest 14,000 hectares is nucleus estate plantations owned by the millers, (Kenya Sugar Board, 2009). The major problems facing the sugar industry in Kenya range from factory processing inefficiency to low productivity, poor management, distortions of prices in the sugar market, persistent droughts, wild and deliberate fires, inadequate credit facilities, and under-funding for sugarcane development This scenario is further compounded by the conflicting land use priorities, especially those geared towards staple food production thereby diminishing the available land for sugarcane growing amongst the small-holder farming communities. This variable production is also exacerbated by the low levels of farm input used owing to the poor economic resource base of the subsistence farmers in sugarcane growing areas.

Sugarcane production in Kenya remains to be the preserve of the perceived high potential areas where the productivity is highly dependent on weather, which in turn determines both the quantity and quality of the harvested sugarcane crops. The former is readily measured as yield, or the mass harvested per unit area typically reported as tonnes per hectare, while the latter is more difficult to measure directly. An understanding of the weather influences on sugarcane yield and quality constitutes a basis for explaining the variability of sugarcane yields using weather and climate variability. This, in addition, paves way for forecasting sugarcane production using observed weather variables. These relationships may also guide the processes of adjusting management decisions based on weather forecasts, and projecting the economic impacts of future climate changes. A quantitative relationship between sugarcane productivity and weather variables is necessary. Such a quantitative relationship requires development of appropriate forecasting models with the crop yield as the dependent variable and various weather variables for example, growing season rainfall and average monthly temperature as the predictor variables.

Recent assessments of weather impacts on sugarcane production elsewhere have employed different techniques; some have relied heavily on process-based crop simulation models, which emphasize physiological controls on plant growth, (Martine, et al., 1999), correlations, (Kuhnel, 1996; Greenland, 2005), and regression trees, (Liu and Bull, 2001, Ferraro, et al., 2009). Despite the worldwide growing interest in sugarcane-weather interactions, Kenya seems to lag behind as evidenced by the scarcity of literature on works done regarding quantification of the weather effects on sugarcane productivity in Kenya.

Agricultural systems and sugarcane productivity in particular are influenced by an array of edaphic, plant and atmospheric factors which operate singly or in combination to determine the yields. An understanding of such complex interactions calls for appropriate tools and methodology to analyze the interrelationships between crop performance and productivity and the physical as well as biological factors that determine crop growth and development.

Crop simulation models are appropriate tools for handling the complexity and variability that arise from a combination of a complex system involving many interactions, and operating under a highly variable weather regime. They can enable a quick and effective investigation of a wide range of production scenarios over varying climatic and soil conditions. Comprehensive crop simulation models for sugarcane have been developed and validated for several areas in the world. Some well-known models include Canegro model, (Inman-Bamber, 1991); the APSIM sugarcane model, (Keating, et al., 2003); QCANE, (Liu and Bull, 2001); and MOSICAS (Martine, et al., 1999). However none of these models has been calibrated for Kenyan varieties and growing conditions.

In the absence of a simulation model, empirical models offer the next best option for such studies. Empirical models that rely on past observations of weather and crop production offer the potential to capture effects of some poorly understood processes. However, empirical models have limited predictive power in situations with no historical analogue or when future climate changes exceed the extremes of past observations. Despite these limitations, empirical models can be important tools for understanding the historical relationship between past weather variation and crop production.

1.1 Objective of the Study

The overall objective of this study was to investigate the impacts of weather variability on sugarcane productivity in the Mumias sugarcane growing zone of western Kenya.

1.1.1 Specific objectives

The specific objectives were;

(i). To determine the temporal characteristics of the past temperature and rainfall
(ii). To determine the temporal characteristics of sugarcane yields
(iii). To determine the relationships between selected weather variables and sugarcane productivity

1.2 Justification of the study

A lot of presumptions have been made regarding the decreasing sugarcane yield in the sugar industry. Weather fluctuations have been associated with this decrease in sugarcane yield, (KESREF, 2009; Kenya Sugar Board, 2009) yet no study has been conducted to quantify to what extent this presumption is true.

This study sought to address the knowledge gap by evaluating the relationships between weather and sugarcane yields in Kenya through quantification of weather effects on the yield of two (2) sugarcane varieties cultivated in the Mumias Sugar Zone of Western Kenya.

This study adopted an empirical approach, but one that implicitly incorporates within-growing-season variability of some weather variables. The results of this study will either confirm or refute the claims that recent decline in sugarcane yields are because of climate and weather variability.

1.3 Study Site

This study was carried out in the Mumias sugarcane growing zone of the Butere-Mumias district of Western province of Kenya. The focal point for this study was the Mumias Sugar Company nucleus estate, shown in Figure 1.

1.3.1 Agro-ecological features of the study site

Mumias Sugar Company is located in Butere-Mumias district, at latitude 0°20'11N, Longitude 34°29'21E and at an altitude of 1268 meters above mean sea level. This district has an area of 939.3 km^2. Out of this area, approximately 75.6% of the total area or 710 km^2 is suitable for crop and livestock production. This area lies within the Lower Midlands humid Agro-

Ecological Zone (AEZ LM 1) and is well suited for sugar cane commercial cultivation. The nucleus estate in Mumias Sugar Company covers approximately 3400 hectares. The nucleus estate has been under cane cultivation since 1976. The major soil types at the nucleus are – mostly Humic acrisols which are lower middle level upland soils mainly well drained, moderately deep, dark yellowish-brown to dark reddish brown sandy clay to clay soils with an acid humic topsoil, (Jaetzold, et al., 2005).

1.3.2 Climatology of the study area

The study area experiences a bi-modal rainfall pattern with long rains being received between March and July and short rains between received between August and October. The average annual rainfall ranges between 1400mm and 2600mm.The mean annual temperature over Mumias ranges between 14 to 30 degrees Celsius. The seasonal rainfall patterns in this area are mainly controlled by the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ), a broad low pressure zone, in which the northeast and southeast trade winds of the two hemispheres meet. It passes over the equator twice a year conferring the bimodal pattern of rainfall that characterizes this region. In April the region is under the southeast monsoons from the Indian Ocean and is the source of almost 50% of the rain received over the country including the study region. In January, the north east monsoons which are hot and dry are usually quite intense and deprive the region of rainfall. Their retreat in March marks the onset of the long rainy season. From about July, the time when the southwest trade winds are strong, high winds, referred to as the Congo air stream penetrate through equatorial Africa and produce convectional storms, their influence is felt mostly in the western parts of Kenya and gives rise to the second weak rainfall peak in the study region between June and August.

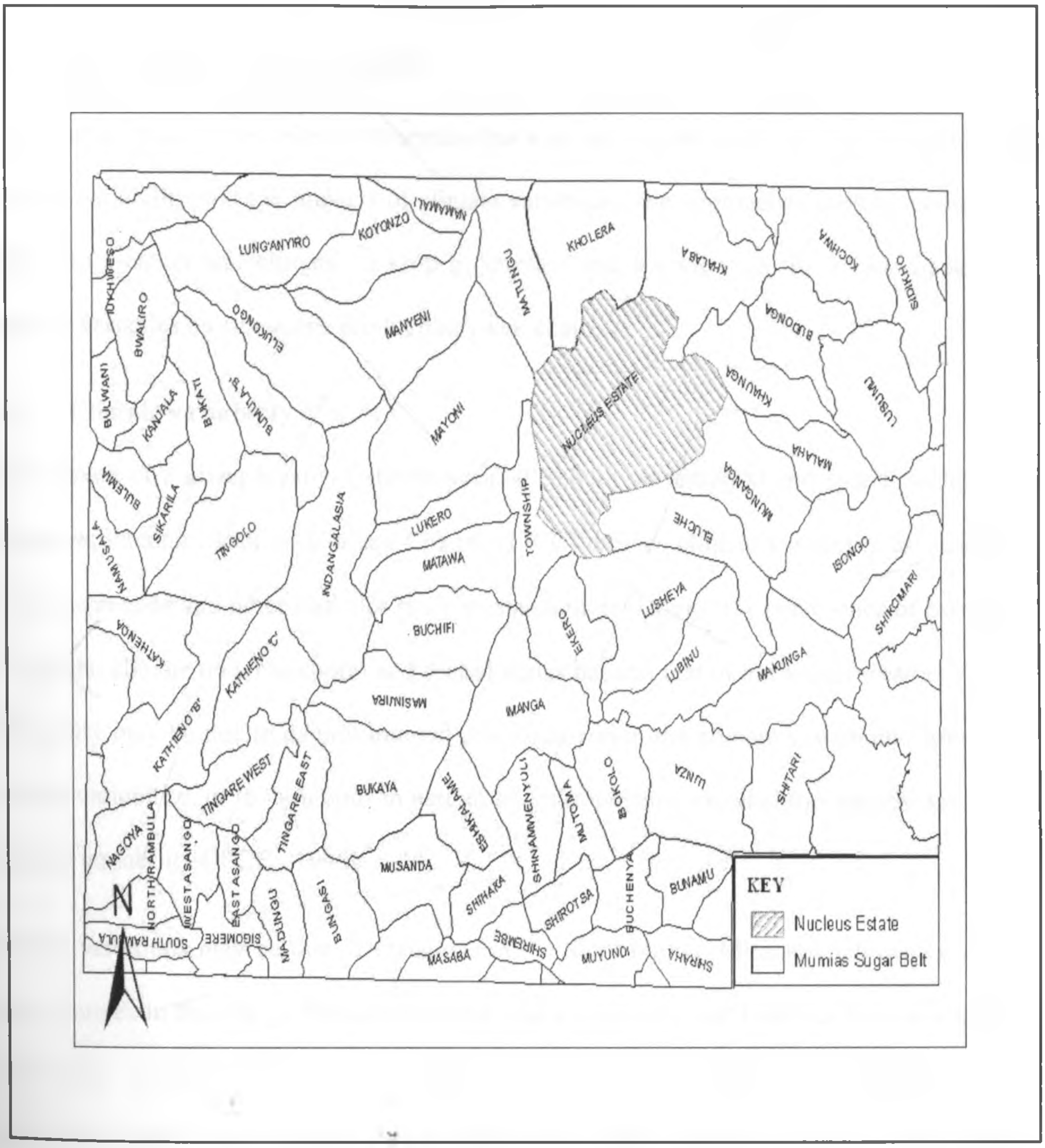

Figure 1: Map of Mumias Sugar growing zone (belt). Shaded is the Mumias Nucleus Estate (Personal communication Mumias Sugar Company survey office)

CHAPTER 2

2.0 LITERATURE REVIEW

This chapter presents the relevant literature that was used in the study; it presents a review of climate variability and the impacts of climate variability, the approaches used to assess the effects of weather and climate on crop production and a review on the effects of specific weather variables on sugarcane production value chain.

2.1 Climate variability

The climate of a given locality exhibits variability both on temporal and spatial scales. The Intergovernmental Panel on Climate Change (IPCC) defines climate variability as variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system also known as internal variability, or to variations in natural or anthropogenic external forcing also known as external variability (IPCC , 1996).

Internal variations may be due to variations in the Sun's output, Milankovitch cycles, small-scale changes in the energy balance between heat received by and heat lost from the surface of the earth. While external variability may be due to volcanic eruptions and human induced greenhouse effect largely due use of fossil fuel combustion, land use change, and agriculture these changes in concentration of greenhouse gases are projected to lead to regional and global changes in temperature, precipitation and other weather variables. This can ultimately result in global changes in soil moisture, an increase in global mean sea level, and prospects for more severe extreme high-temperature events, floods and droughts in many locations, (IPCC , 1996; Salinger, et al., 2000).

2.1.1 Impacts of climate variability and change

The impacts of the projected global warming to the agriculture sector depend on the nature of the agricultural system. For example, a crop response to enhanced carbon dioxide enrichment is physiologic class dependent. Crops such as wheat, rice, and soybeans that belong to C_3 group of plants (plants that use Rubisco to make a three-carbon as the first stable product of carbon fixation before entering the Calvin cycle of photosynthesis) respond readily and enhance their productivity due to increased Carbon-dioxide (CO_2) levels. On the other hand, the C_4 group of plants (plants that use phosphoenolpyruvate carboxylase to make a four-carbon molecule in the first step of photosynthesis), such as maize, sorghum, sugarcane, and millet are more efficient photo synthetically than C_3 crops at the present levels of CO_2, and therefore tend to be less responsive to enriched carbon dioxide concentrations (Chen, et al., 1996). At the same time, associated weather effects, such as higher temperatures, changes in rainfall and soil moisture, and increased frequencies of extreme meteorological events, could either enhance or negate potentially beneficial effects of enhanced atmospheric CO_2 on crop physiology and productivity.

Global warming will also extend the length of the potential growing season of crops. In middle and higher latitudes, however, in warmer, lower latitude regions, increased temperatures may accelerate the rate at which plants release CO_2 in the process of respiration, resulting in less than optimal conditions for net growth, (Ryan, 1991). If night time temperature minima rise more than do daytime maxima, as is expected from greenhouse gas induced warming projections, heat stress during the day may be less severe than otherwise, but increased night time respiration may also reduce potential yields. Another important effect of high temperature is accelerated physiological development, resulting in hastened maturation and reduced yield. Higher temperatures may cause a shift in patterns of photosynthetic limitation in higher plants, (Sage and Kubien, 2007).

Agriculture is strongly influenced by the availability of water. Climate change will modify rainfall, evaporation, runoff, and soil moisture storage. Changes in total seasonal precipitation or in its pattern of variability are both important. The occurrence of moisture stress during critical phases of crop development such as flowering and fruit formation will adversely affect yields. Increased evaporation from the soil and accelerated transpiration in the plants themselves will cause moisture stress, thereby calling for introduction of crop varieties with greater drought tolerance. Intensified evaporation will increase the hazard of salt accumulation in the soil in saline soils.

Higher air temperatures following global warming will also lead to increased soil temperatures, which are likely to speed up the natural decomposition of organic matter and to increase the rates of other soil processes that affect soil fertility. This may lead to faster than normal release of nutrients and thus loss to the atmosphere or through leaching. However, additional application of fertilizers may be needed to counteract these processes and to take advantage of the potential for enhanced crop growth that can result from increased atmospheric CO_2. This can come at the cost of environmental quality since additional use of chemical fertilizers may adversely impact water and air quality. The continual cycling of plant nutrients such as carbon, nitrogen, phosphorus, potassium, and sulfur in the soil-plant-atmosphere system is also likely to accelerate in warmer conditions, enhancing CO_2 and nitrous oxide (N_2O) greenhouse gas emissions. Where they occur, drier soil conditions will suppress both root growth and decomposition of organic matter, and will increase vulnerability to wind erosion, especially if winds intensify. An expected increase in convective rainfall caused by stronger gradients of temperature and pressure and more atmospheric moisture may result in heavier rainfall when and where it does occur. Such extreme precipitation events can cause increased soil erosion.

The other possible effect of global warming is the creation of conditions that are more favorable for the proliferation of insect pests especially in warmer climates. The altered wind patterns may change the spread of both wind-borne pests and of the bacteria and fungi that are the agents of crop diseases. In addition, crop-pest interactions may shift as the timing of the development stages of both hosts and pests are altered in the face of the changing climate (Manning and Tiedemann,1995; Gregory, et al., 2009).

2.2 Interactions between weather and crop yields

Some of the weather variables that influence crop yields are radiation, temperature and rainfall. These have been highlighted by a number of investigations on the quantitative relationships between observed weather and actual crop yield over the past century. Some studies (Andresen, et al., 2001; Lobell and Asner, 2003) have shown that gains in grain yield after World War II may have been due, in part, to the milder climate experienced from about 1955 to 1975.

Several approaches have been utilized in studying these interactions between weather and crop yields. Some studies have relied on correlation analysis (Lobell and Asner, 2003; Peng, et al., 2004), single or multivariate regression analysis (Chmielewski and Potts, 1995; Landau, et al., 2000; Tao, et al., 2006; 2008). Others like Chmielewski and Kohn (1999; 2000) used factor analysis, whereas Chmielewski and Potts (1995) included a probability analysis in the form of frequencies of yield events given particular weather events.

Crop simulation models (Thompson, 1986) and a combination of both statistical and mechanistic modeling techniques have also been used to analyze the weather impacts on crop yields (Lobell, et al., 2005)

In sugarcane, studies using both direct and indirect measures of the effects of the weather variables on yields have been done. Direct measures have either been through the use of process-based crop simulation models, which emphasize physiological controls on plant growth (Martine, et al., 1999; Cheeroo-Nayamuth, et al., 2000); or empirically through the use of correlations, (Kuhnel, 1996; Greenland, 2005); regression trees, (Liu and Bull, 2001; Ferraro, et al., 2009) and regression, (Brüggemann, et al., 2001). Whereas most empirical studies have used average-growing-season weather variables, Greenland (2005), demonstrated that sugarcane yields cannot be explained by average-growing-season weather factors but by within-growing season variation. This, of course, is one reason why computer-simulation crop models, which use daily data and time steps, are more commonly employed at present and also the reason why the phenological approach was used in this study.

The indirect measures of weather effects such as the timing of crop ratooning and harvest as well as the year of harvest have been extensively analyzed (Higgins, et al., 1998; McDonald and Lisson, 1999; Lawes, et al., 2002).

2.3 Specific effects of weather variables on sugarcane productivity

2.3.1 Temperature

Establishing relationships between sugarcane yield and temperature is important in trying to understand the associated impacts of weather variability and possible climate change. Temperature derivatives such as the thermal-time or growing degree days (GDD) are a measure of accumulated heat and could help explain the temperature effects on crop growth, development and final productivity better than raw temperature data. GDD is commonly used as a driving variable for plant development processes and represents the strong relationship between the rate of underlying biochemical processes and temperature. It is calculated using the following Equation (1).

$$GDD = \left[\frac{T_{max}+T_{min}}{2}\right] - T_{base} \qquad \text{..................} (1)$$

Where;

T_{max} is the day's maximum temperature

T_{min} is the day's minimum temperature

T_{base} is the base temperature

The base temperature is the lower threshold of temperature below which the bio-physiological processes in an organism stop. The GDD determines the duration a crop takes to complete a phenological phase.

In general, temperature is a weather variable that conditions the processes of plant growth and development. High temperatures inhibit plant growth by inhibiting net photosynthesis and enzyme activation, (Crafts-Brandner and Salvucci, 2004). In sugarcane, leaf area development is especially important because the rate of leaf area increase is relatively slow. Leaf area development is critical in the establishment of a full leaf canopy to maximize interception of solar radiation and achieve high crop productivity. Leaf appearance in sugarcane is influenced by temperature to a large extent. The rate of emergence of individual leaves is highly dependent on temperature (Inman-Bamber, 1994; Bonnet, 1998; Campbell, et al., 1998). Although the leaf appearance intervals were influenced by temperature they are also cultivar specific (Inman-Bamber, 1994; Bonnet, 1998). Leaf appearance leads to the formation of the crop canopy and as such sugarcane canopy development is governed primarily by temperature (Inman-Bamber, 1994). Singels and Donaldson, (2000), showed that temperature in terms of GDD explained most of the variation in canopy development due to crop start date. Canopy development in ratoon crops is more rapid than in plant crops (Robertson, et al., 1996) because more buds are available to produce primary shoots and the buds are closer to the surface than in a plant crop. Canopy development differs amongst cultivars (Singels and Donaldson, 2000) and is influenced by row spacing and planting density (Singels and Smit, 2002). This implies that canopy development could be controlled to some extent by manipulating the interaction between these factors. For example, cultivars with slow canopy development but with other desirable traits could be planted at higher densities and started in warmer rather than in colder months. This could enhance radiation capture and yield.

2.3.2 Solar radiation

Solar radiation influences plant growth and development through its influence on the thermal environment of plants, plant photomorphogenesis, and the plant photosynthetic activities. Intercepted solar radiation is therefore very important to crop growth and development. Once a sufficient plant canopy has developed, and water and nutrients are not limiting, solar radiation intercepted and its subsequent conversion to biomass ultimately determines the productive potential of a given environment.

Radiation Use Efficiency (RUE) is defined as above-ground biomass produced per unit of global radiation intercepted and is a measure of photosynthetic efficiency of the plant. In sugarcane values between 1.72g MJ^{-1} -1.75g MJ^{-1} for the first sugarcane crop and 1.59g MJ^{-1} for the first ratoon have been reported (Muchow, et al., 1994; Robertson, et al., 1996). Singels and Smit (2002) found that RUE values ranged from 1.72 to 1.25 g MJ^{-1} for a sugarcane plant crop of cultivar NCo376, depending on row spacing and hypothesized that biomass productivity may be increased by either maximizing radiation interception or increasing radiation use efficiency of the crop plant, or both.

In sugarcane, the fraction of biomass accumulated converted into stalks is of economic importance and it increases with an increase in aboveground biomass and is also affected by water stress, temperature and cultivar, (Robertson, et al., 1996; Inman-Bamber, et al., 2002).

2.3. 3 Water

Like other crops, sugarcane is quite sensitive to water stress encountered during its growth cycle. The crop is resilient to water stress during early expansive growth however water stress at the late canopy development and stalk elongation phase decreased sugarcane and sucrose yields considerably (Robertson, et al., 1999; Inman-Bamber, et al., 2008). Water stress has been found in one study to reduce total biomass gain by 19%, leaf biomass including tops by 37%, stalks by 14% and increased sucrose mass gain by 27%. It decreased whole plant photosynthesis by 18% and fiber accumulation by 31% (Inman-Bamber, et al., 2008). In another study by Koonjah, et al., (2000), the Plant Extension Rate (PER) was first affected, followed by light interception and then the rate of photosynthesis. Drought affects sugarcane canopy formation by imposing leaf senescence, changing leaf appearance and shoot senescence. Leaf senescence responding the most, followed by leaf appearance rate and shoot senescence (Smit and Singels, 2006), Water deficit during the tillering phase, while having large impacts on leaf area, tillering and biomass accumulation, has little impact on final yield. This was primarily due to the length of time required to impose significant water deficit when the canopy is small, the comparatively small amount of biomass accumulation lost through water deficit, and the ability of the crop to produce leaves and tillers at a rapid rate if subsequently well-watered thereafter. On the other hand, water deficit imposed when the canopy was well-established with a leaf area index greater than 2 has a more deleterious impact on final yield of total biomass, stalk biomass, and stalk sucrose. Reductions in millable stalk biomass could be solely explained by reductions in total biomass. Similarly, greater than

97% of the variation in final cane or sucrose yield could be explained by variation in stalk biomass. (Robertson, et al., 1999 (2)).

2.3.4 Other effects of weather along the sugarcane production value chain

2.3.4.1 Soil compaction

Knowledge of the attendant weather factors that affect compaction can be used to minimize the compactive effect of agricultural machinery on soils. Soil compaction reduces porosity, which is an important parameter affecting root development, gas exchange rates, nutrient availability and the hydraulic properties of soils. The degree, to which soils will compact when a force is applied is primarily dependent on the amount of soil water and other factors including clay content, organic matter content, number of passes, axle load, and size, type, shape and inflation pressure of the tyres (Van Antwerpen, et al., 2000; Braunack, et al., 2006). Such knowledge is critical for guiding planning planting and harvesting times to merge routine management and operation of sugarcane activities with appropriate weather conditions in order to avoid field operations during periods when the soil is wet.

2.3.4.2. Fertigation

Because sugarcane plants cannot fully utilize nitrogen and potash fully under reduced light intensity and duration, application of nitrogen during cloudy periods should be avoided. This is because sugarcane plants cannot utilize the applied nitrogen and potash fully when the intensity as well as duration of light reduced this is due to the low transpiration rates during such days.

2. 3.4.3. Post harvest losses

The time lag between cutting-to-crushing, and other factors such as ambient temperature, humidity, cane variety, period of storage, activities of soluble invertases in cane, maturity status are responsible for post harvest decline in sugar recovery. Some studies have shown that cane starts to lose weight by drying out as soon as it is harvested. The percentage loss varies widely with temperature, humidity, wind speed, variety and method of storage. The loss in cane weight is more in the case of chopped cane than whole-stalk cane as observed after 72 hours of storing (Solomon, 2000; Uppal, et al., 2008; Siddhant, et al., 2009).

2.4 Regression model building and model selection

This section presents a review of methodology that was used in the regression analysis of the generalized yield data and the basis of choosing the Akaike's Information Criterion (AIC) as the method of selecting the best regression model.

2.4.1 Regression Using SAS Proc Mixed

The SAS Proc Mixed is a procedure based on mixed model methodology that has been widely used for longitudinal data analyses since its release in 1992. SAS Proc Mixed is a flexible program suitable for fitting multilevel models, hierarchical linear models, and individual growth models. It provides for convenient modeling of the covariance structure using Random and Repeated statements, with the 'Random' statement often used to model between-subject variation and the 'Repeated' statement often used to model within-subject variation.

SAS Proc Mixed has been used previously to study of water use efficiencies in sorghum (Tolk, 2003), characterize spatial variability of soil properties and irrigated corn yields across years (Schepers, et al., 2004); study el Niño – southern oscillation influences on soybean yields (Fraisse, et al., 2008). In sugarcane, it has been used extensively (Glaz, et al., 2004; Lingle, 2004; Viator, et al., 2008; Viator, et al., 2011). Sugarcane trials are best analyzed using SAS Proc Mixed because of the ratooning nature of the crop.

The SAS Proc Mixed sets up a mixed model which may contain both fixed and random effects. Fixed effects are factors for which the only levels under consideration are contained in the coding of those effects whilst random effects are factors for which the levels contained in the coding of those factors are a random sample of the total number of levels in the population for that factor. Effects may sometimes be classified as fixed or random depending on the experimental design. A variable represents a fixed effect if the levels of that variable included in the data either represent all the possible levels or inference is to be made only for those levels. If the levels of a variable in the data represent a random sample from a larger population of possible levels, then that variable is treated as a random effect.

There are four assumptions in Proc Mixed namely;

(i). Random effects and error terms are normally distributed with means of zero.

(ii). Random effects and error terms are independent of each other.

(iii). The relationship between the response variable and predictor variables is linear.

(iv). Variance-covariance matrices for random effects and error terms exhibit structures in Proc Mixed, (Dickey, 2008).

Proc Mixed has three options for the method of estimation. These are: Maximum Likelihood (ML), Restricted or Residual maximum likelihood, (REML, which is the default method) and Minimum Variance Quadratic Unbiased Estimation (MIVQUE0). ML and REML are based on a maximum likelihood estimation approach. They require the assumption that the distribution of the dependent variable (error term and the random effects) is normal.

With repeated measures analysis of variance, measurements made the same subject are likely to be more similar than measurements made on different individuals. That is, repeated measures are correlated. For an analysis to be valid, the covariance among repeated measures must be modeled properly. The four most commonly used covariance structures in Proc Mixed are compound symmetry (CS), unstructured (UN), and auto-regressive (1) (AR (1)) and the variance components (VC).

SAS Proc Mixed has methods for determining the correct degrees of freedom for the estimates, to correct for the downward bias. Kenward-Rogers is a more general degree-of-freedom procedure. For designs with missing data, the Kenward-Rogers is recommended, (Moser, 2004).

2.4.2 Model selection

Several techniques exist to find the best linear model; these include minimizing the Root Mean Square Error (RMSE), maximizing coefficient of determination (R^2), forward selection, backward elimination and stepwise regression.

Generally a good linear model should have a low RMSE and a high R^2 close to 1. However, these model diagnostics alone are insufficient to determine the best model.

The RMSE is a function of the number of observations n and the number of parameters p and is shown in Equation (2).

$$\mathrm{RMSE} = \sqrt{\frac{\mathrm{SSE}}{n-p}} \qquad \text{.. (2)}$$

The RMSE is calculated for all possible subset models. Using this technique, the model with the smallest RMSE is declared the best linear model. This approach does include the number of parameters in the model; so additional parameters will decrease both the numerator and denominator.

The R^2 is the percentage of the variability of the dependent variable that is explained by the variation of the independent variables. Therefore, the R^2 value ranges from 0 to 1. R^2 is a function of the Sum of Squared Totals (SST) and the Sum of Squared Errors (SSE) and is shown in Equation (3).

$$R^2 = 1 - \frac{\mathrm{SSE}}{\mathrm{SST}} \qquad \text{.. (3)}$$

The R^2 is calculated for all possible subset models. Using this technique, the model with the largest R^2 is declared the best linear model. However, this technique has several disadvantages. First, the R^2 increases with each variable included in the model. Therefore, this approach encourages including all variables in the best model although some variables may not significantly contribute to the model. This approach also contradicts the principal of parsimony that encourages as few parameters in a model as possible

Information Criteria is a measure of goodness of fit or uncertainty for the range of values of the data. In the context of multiple linear regression analysis, information criteria measures the difference between a given model and the “true” underlying model. Akaike’s Information

Criteria (AIC) is a function of the number of observations (n), the SSE and the number of parameters (p), as shown in Equation (4).

$$\mathrm{AIC} = \mathrm{n}.\mathrm{In}\left(\frac{\mathrm{SSE}}{\mathrm{n}}\right) + 2\mathrm{p} \quad \ldots\ldots\ldots\ldots (4)$$

The first term in Equation (4) is a measure of the model lack of fit while the second term is a penalty term for additional parameters in the model. Therefore, as the number of parameters p included in the model increases, the lack of fit term decreases while the penalty term increases. Conversely, as variables are dropped from the model the lack of fit term increases while the penalty term decreases. The model with the smallest AIC is deemed the best model since it minimizes the difference from the given model to the true model.

CHAPTER 3

3.0 DATA AND METHODOLOGY

This Chapter presents the data and methodology used to analyze the research problem in this study.

3.1 Data

The data used in this study comprised of two weather data sets and sugarcane crop yield data. The sub-sections that follow give a description of these data sets.

3.1.1 Weather data

The weather data sets used in this study were a 28-year (1981-2008) historical rainfall, radiation, temperature and wind data on daily timescales and another dataset comprised of monthly means of the same variables for a 40-year period (1968-2008) obtained from the Central Meteorological Station (CMS) at the Mumias Sugar Company. However, some of the data such as radiation was estimated using sunshine hours of the meteorological station using appropriate methodology presented in Section (3.2.2). This is because this was not routinely measured at the meteorological station.

3.1.2 Crop data

This study considered sugarcane yield expressed in metric Tons of Cane per Hectare (TCH) of land planted. This data was used to analyze the effect of a wide array of weather factors on sugarcane yield while maintaining other sugarcane production factors such as soil type, crop variety, and spatial variability constant. Crop yield data for the high-yielding variety CO 421 that has dominated the sugarcane growing areas in Kenya and CO 945 that has been widely cultivated in the Mumias zone for the period 1984 to 2008 were used in this study.

3.1.3 Metadata

The conditions under which the foregoing crop and weather data were observed that included field number, size, planting date, harvesting date, incidences of fires and fields prematurely harvested to pave way for other infrastructural developments such as roads were also considered owing to the perennial nature of the sugarcane crop.

3.1.4 MOSICAS model

The MOSICAS model, (Martine, et al., 1999), was developed by the French Agricultural Research Center (CIRAD) and has been used in Guadeloupe, Brazil, Morocco and Reunion islands to simulate sugarcane yields under various scenarios. This model was used to calculate various within-the-season weather parameter summaries received by each crop treatment. These indices are calculated on the basis of weather and plant factors and were used as factors in the correlation and in the regression model.

3.2 Methodology

This section presents the methods that were used to analyze the specific objectives of this study.

3.2.1 Data Quality Control

It is important to establish the homogeneity of any meteorological data before using it in any study. The single mass curve was used to check on homogeneity of the temperature and rainfall data. The single mass curves were obtained by plotting cumulative records of temperature or rainfall against time. A straight line indicates a homogenous record whereas heterogeneity can be indicated by significant deviations from the straight line.

The missing minimum temperature entries were 0.25% of the total record, the missing maximum temperature entries were 0.3% of the total record, while the missing rainfall records were 0.29% of the total record. In this study missing data values were very few and thus they were estimated using the simple arithmetic mean method prescribed by Allen, et al. (1998).

Extensive editing of the yield records was necessary to provide data suitable for electronic manipulation and statistical analysis. Unrepresentative observations were excluded from the investigation using the following prior criteria:

- Exclusion of all crop cycle types with less than 30 observations.
- Exclusion of all yield data from fields less than 1 hectare to minimize the error of extrapolating yield to 1 hectare.
- Exclusion of all harvested due to cane fires or to pave way for infrastructural developments such as roads.
- Fields which had been harvested below or above recommended age were removed.

The final database was then screened of observations that were outliers. 4% of the fields were removed. The acceptable yield values were those between the maximum potential yields of the varieties under study (200 TCH) and an average yield (55 TCH) obtained from field data. A total of four hundred and fifty four (454) field entries were retained for analysis.

3.2.2 Estimation of Non-measured Agrometeorological data

Some parameters such as radiation and reference crop evapotranspiration are not routinely measured at the Mumias meteorological station, and were therefore estimated using appropriate empirical equations as discussed in sections 3.2.2.1 and 3.2.2.2 respectively.

3.2.2.1 Solar Radiation (R_s)

Solar radiation, R_s, was estimated using the Angstrom formula which relates solar radiation to extraterrestrial radiation and relative sunshine duration as given by Allen, et al., (1998) in Equation (5).

$$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a \qquad \text{……………………………………………………………… (5)}$$

Where

R_s solar or shortwave radiation [MJ m^{-2} day^{-1}],

n actual duration of sunshine [hour],

N maximum possible duration of sunshine or daylight hours [hour],

n/N relative sunshine duration [-],

R_a extraterrestrial radiation [MJ m^{-2} day^{-1}],

a_s regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n = 0),

a_s+b_s	fraction of extraterrestrial radiation reaching the earth on clear days (n = N).

R_s is expressed in the above equation in MJ m^{-2} day^{-1}. Because no calibration has been carried out for improved a_s and b_s parameters, the recommended values $a_s = 0.25$ and $b_s = 0.50$ were used. The actual duration of sunshine, n, is recorded with a Campbell Stokes sunshine recorder.

3.2.2.2 Reference Crop Evapotranspiration (ET_0)

Potential reference evapotranspiration was subsequently calculated by the FAO Penman–Monteith equation (Allen, et al. 1998) given by Equation (6);

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad \text{...} \; (6)$$

Where;

ET_o	reference evapotranspiration [mm day^{-1}],
R_n	net radiation at the crop surface [MJ m^{-2} day^{-1}],
G	soil heat flux density [MJ m^{-2} day^{-1}],
T	air temperature at 2 m height [°C],
u_2	wind speed at 2 m height [m s^{-1}],
e_s	saturation vapour pressure [kPa],
e_a	actual vapour pressure [kPa],
$e_s - e_a$	saturation vapour pressure deficit [kPa],
Δ	slope vapour pressure curve [kPa $°C^{-1}$],
γ	psychrometric constant [kPa $°C^{-1}$].

Equation (6) requires wind speed. Where wind speed data was missing, a value of $2m/s^2$ was used as a suitable estimate as recommended by Allen, et al. (1998).

3.2.3 Determination of temporal characteristics of the weather data

This section presents the statistical methods used in the analysis of the temporal characteristic of the weather data used in this study.

3.2.3.1 Test for monotonic trends

In analyzing the historical data for possible trends, the null hypothesis, $H_{0,}$ that there was no trend in the population from which the meteorological data set was drawn, was formulated. The alternative hypothesis, $H_{1,}$ was that a trend exists in the data being studied.

3.2.3.2 Mann-Kendall Test

In this study, the Mann-Kendall test was used for monotonic trend analysis, while the Sen's method was used to assess the magnitude of the change. The Mann-Kendall non-parametric test was first proposed by Mann in 1945 and Kendall in 1975 derived the test statistic distribution. This test has been widely used to test randomness against trend. It is robust to the influence of extremes and performs well with skewed variables due to its rank-based procedure. It is also insensitive to missing values.

The Mann-Kendall test is applicable in cases when the data values X_i of a time series can be assumed to obey Equation (7).

$$x_i = f(t_i)\varepsilon_i \qquad \text{.......} \qquad (7)$$

Where; f (t_i) is a continuous monotonic increasing or decreasing function of time and the residuals ε_i can be assumed to be from the same distribution with zero mean and a constant variance. It is therefore assumed that the variance of the distribution is constant in time. The essence in this study was to test the null hypothesis of no trend, H_o, i.e. the observations x_i are randomly ordered in time, against the alternative hypothesis, H_1, where there is an increasing or decreasing monotonic trend. In this computation the statistical test uses the normal approximation (Z statistics).

The Mann-Kendall test statistic S was calculated using the Equation (8)

$$S = \sum_{k=1}^{n-i} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \qquad \text{...} \quad (8)$$

Where; x_j and x_k are the annual values in years j and k, $j > k$, respectively, and

$$\operatorname{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases} \qquad \text{...} \quad (9)$$

First the variance of S is computed by the following equation which takes into account the fact that ties may be present, Equation (10):

$$\mathrm{VAR}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5) \right] \qquad \text{.........................} \quad (10)$$

Where q is the number of tied groups and t_p is the number of data values in the p^{th} group.

The values of S and VAR(S) are used to compute the test statistic Z as shown in Equation (11);

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & \text{if } S < 0 \end{cases} \qquad \text{.........} (11)$$

The presence of a statistically significant trend is evaluated using the Z value. A positive (negative) value of Z indicates an upward (downward) trend. The statistic Z has a normal distribution. To test for either an upward or downward monotonic trend (a two-tailed test) at α level of significance, H_0 is rejected if the absolute value of Z is greater than $Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is obtained from the standard normal cumulative distribution tables.

For the four tested significance levels the following symbols are used in the analysis:

*** if trend at $\alpha = 0.001$ level of significance

** if trend at $\alpha = 0.01$ level of significance

* if trend at $\alpha = 0.05$ level of significance

\+ if trend at $\alpha = 0.1$ level of significance

The significance level 0.001 means that there is a 0.1% probability that the values x_i are from a random distribution and with that probability a mistake may be made when rejecting H_0 of no trend. Thus the significance level 0.001 means that the existence of a monotonic trend is very probable. In addition, the significance level 0.1 means that there is a 10% probability that we make a mistake when rejecting H_0.

The non-seasonal Mann-Kendall test was used. The Mann-Kendall test on each of the months was computed separately. Hence, January data are compared only with January and February only with February. No comparisons were made across monthly boundaries.

3.2.3.3 Sen's Method

To estimate the true slope of an existing trend as change per year, the Sen's non-parametric method was used. This method requires a time series of equally spaced data. Sen's method proceeds by calculating the slope as a change in measurement per unit change in time, as shown in Equation (12).

$$Q = \frac{x_{\imath}-x_{i}}{\imath-i} \qquad \text{(12)}$$

Where;

Q = slope between data points $x_{i'}$ and x_i

$x_{i'}$ = data measurement at time i'

x_i = data measurement at time i

i' = time after time i

The Sen's method was used in this study since the trend was assumed to be linear. This meant that f (t) in Equation (7) could be expressed as Equation (13).

$$f(t) = Qt + B \qquad \text{(13)}$$

Where;

Q is the slope and B is a constant

To get the slope estimate Q in Equation (12), first the slopes of all data value pairs were calculated using Equation (14).

$$Q_i = \frac{x_j - x_k}{j-k} \qquad \text{.......................} (14)$$

Where j>k

If there are n values x_j in the time series, then there will be as many as $N' = n(n-1)/2$ slope estimates Q_i. The Sen's estimator of slope is the median of these N values of Q_i. The N values of Q_i are ranked from the smallest to the largest and the Sen's estimator is;

$$Q = Q_{[(N'+1)]/2} \quad \text{If } N' \text{ is odd} \qquad \text{.......................} (15)$$

$$Q = \frac{1}{2}\left(Q_{[N'/2]} + Q_{(N'+2)/2}\right) \text{ If } N' \text{ is even} \qquad \text{.......................} (16)$$

A 100(1- α) two-sided confidence interval about the slope estimate was obtained by the non-parametric technique based on the normal distribution. This method is valid for n as small as 10 unless there are many ties.

The confidence interval was computed at two different confidence levels; $\alpha = 0.01$ and $\alpha = 0.05$, resulting in two different confidence intervals.

At first C_α was computed. Equation (17);

$$C_\alpha = z_{1-\alpha/2}\sqrt{VAR(S)} \qquad \text{.......................} (17)$$

Where, VAR(S) has been defined in Equation (10) and $Z_{1-\alpha/2}$ is obtained from the standard normal distribution.

Next M1 = (N′ - Cα)/2 and M2 = (N′ + C_α)/2 were computed. The lower and upper limits of the confidence interval, Q_{min} and Q_{max}, are the M^{th} largest and the $(M2 + 1)^{th}$ largest of the N ordered slope estimates Q_i. If M1 is not a whole number the lower limit is interpolated. Correspondingly, if M2 is not a whole number the upper limit is interpolated.

To obtain an estimate of B in Equation (13) the n values of differences xi – Q_{ti} were calculated. The median of these values gave an estimate of B. The estimates for the constant B of lines of the 99% and 95% confidence intervals were calculated by a similar procedure.

The SAS program used for the Mann Kendall and Sen's estimate analysis was adopted from Winkler (Winkler, 2004) and the graphics done using the MAKESENS excel macro adopted from Salmi, et al., (2002)

3.2.3.4 Analysis of weather variability

To test for increasing or decreasing variability in temperature and rainfall data, a test of unequal variances was done by dividing the data into two sub samples. Sample 1 has 20 years (n_1) and sample 2 has 20 years (n_2). The null hypothesis is that there is no change in the variability while the alternate hypothesis is that there is a change in the variability.

$H_0: \sigma_1^2 = \sigma_2^2$ (Assumption of equal variances satisfied)

$H_1: \sigma_1^2 \neq \sigma_2^2$ (Assumption of equal variances violated)

Where;

σ_1^2= variance of the mean for subpopulation 1

σ_2^2= variance of the mean for subpopulation 2

The F-statistic is used to test the statistical significance in the difference in the variances of the means of the sub-populations.

$$F = \frac{\sigma 1}{\sigma 2} \qquad \text{(18)}$$

Where $\sigma 1$ is the larger variance and $\sigma 2$ is the smaller variance. Under H_0 , F has F-distribution with v_1 and v_2 degrees of freedom, where v_1 (n_1-1) is the degree of freedom associated with the larger variance, and v_2 (n_2-1) is the degrees of freedom associated with the smaller variance.

3.2.4 Determination of the temporal characteristic of the past sugarcane production data

This was done by performing trend analysis of the historical data using the same techniques as ones described in the weather time series analysis above.

3.2.5 Investigation of linkages between the weather variables and sugar cane yields

A phenological approach was used to account for the within growing season weather variation of weather variable. Both the weather and yield data were inputted in the MOSICAS model to get outputs at 30-day intervals. These outputs were then grouped and divided into 4 phenological phases. Sugarcane phenological phases considered were: germination phase, tillering phase, grand growth phase and maturity phase. The choice of phenological phase duration was adopted from (Allen, et al., 1998) and customized based on personal discussions with Agronomist at MSC (Mutonyi, 2008) and Research Agronomist at KESREF (Abayo, 2008) since no specific studies have been done in Mumias to establish these phases. The

Hawaiian region was chosen since it closely represented the crop duration within the phases in the Kenyan sugar industry. Table 1 below shows the phenological lengths that were adopted in this study for both the plant and ratoon crops.

Table 1: Length in days of crop development stages for sugarcane in different climatic regions. (Adopted from Allen et. al. 1998)

Crop	Duration of phenological phase in days					Region
	Germination	Tillering	Grand growth	Maturation	Total	
Sugarcane, virgin	35	60	190	120	405	Lower Latitudes
	50	70	220	140	480	Tropics
	75	105	330	210	720	Hawaii, USA (adopted for Mumias)
Sugarcane, ratoon	25	70	135	50	280	Low Latitudes
	30	50	180	60	320	Tropics
	35	105	210	70	420	Hawaii, USA (adopted for Mumias)

3.2.5.1 Classification of variables

The variables that were considered in this study were categorized into three classes, namely those ones related to precipitation, temperature and those that are related to radiation as described in the 5 classes that follow below;

Class 1: Rainfall related variables

These included the total rainfall during the various growth stages of sugarcane as given below:

Raingerm: rainfall at establishment (germination)

Raintill: rainfall at tillering phase

Raing: rainfall at the grand growth phase

Rainmat: rainfall at maturation phase

Class 2 Growing degree days

This class consisted of total growing degree-days for different growth stages of sugarcane computed from the mean temperature values of the area weather data calculated using a base temperature of 16°C. The variables that arose include:

Sddgerm: number of accumulated degree days at germination

Sddtill: number of accumulated degree days at tillering phase

Sddg: number of accumulated degree days at the grand growth phase

sddmat: number of accumulated degree days at maturation phase

Class 3. Radiation related variables

This class consisted of study variables described as follows:

Pargerm: Total photo synthetically active radiation received at germination

Partill: Total photo synthetically active radiation received at tillering phase

Parg: Total photo synthetically active radiation received at grand growth phase

Parmat: Total photo synthetically active radiation received at maturation phase

Class 4. Mean minimum temperature related variables

This class consisted of study variables described as follows:

Mmingerm: Mean minimum temperature at germination

Mmintill: Mean minimum temperature at tillering phase

Mming: Mean minimum temperature received at grand growth phase

Mminmat: Mean minimum temperature at maturation phase

Class 5. Mean Maximum temperature related variables

This class consisted of study variables described as follows:

Mmaxgerm: Mean maximum temperature at germination

Mmaxtill: Mean maximum temperature at tillering phase

Mmaxg: Mean maximum temperature received at grand growth phase

Mmaxmat: Mean maximum temperature at maturation phase

3.2.5.2 Correlation Analysis

Before the correlation analyses were done, the SAS PROC ANOVA procedure was used to analyze the effects of variety and crop class in the cane yield. The means were separated using the student Neumann Kohl's test.

The variables for each phenological stage outlined in Section (3.2.5.1) were then correlated with the sugarcane crop yield to identify the variables with significant influence on sugarcane yields. The Pearson's correlation coefficient used for this analysis is given as Equation (19)

$$r = \frac{n\sum xy-(\sum x)(\sum y)}{\sqrt{\left(\sum x^2-\frac{(\sum x^2)}{n}\right)\left(\sum y^2-\frac{(\sum y^2)}{n}\right)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

Where, r is the Pearson correlation coefficient, x and y are the variables being correlated and n is the number of pairs of the correlated variables.

A significance test is performed to determine if an observed value of a statistic differs enough from a hypothesized value of a parameter to draw the inference that the hypothesized value of the parameter is not the true value. The hypothesized value of the parameter is called the "null hypothesis." A significance test consists of calculating the probability of obtaining a statistic as different from the null hypothesis (given that the null hypothesis is correct) than the statistic obtained in the sample. If this probability is sufficiently low, then the difference between the parameter and the statistic is said to be statistically significant. The significance test for Pearson's r was computed using the student-t test as in Equation (20);

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

with N - 2 degrees of freedom, r is Pearson's correlation and N is the number of pairs of scores that went into the computation of r. The significance of the correlation coefficient was determined from the t-statistic. The probability of the t-statistic indicates whether the observed correlation coefficient occurred by chance if the true correlation is zero.

A total of seven (7) correlation analyses were performed; (i) weather variables and yield of Variety CO 421 in the plant crop (ii) weather variables and yield of variety CO 421 combined ratoon crops, (iii) weather variables and yield of variety CO 945 plant crop, (iv) weather variables and yield of variety CO 945 combined ratoon crops (v) a general correlation where there was no separation in terms of variety or crop class, (vi) correlation of weather variables on yield with crop class as the classifying variable, (vii) correlation of the weather variables on yield with the variety as the classifying variable.

3.2.5.3 Regression Analysis

Regression analysis was done to quantitatively identify the weather signal in the annual sugarcane yield. Sugarcane yields were regressed on the variables that gave significant correlation coefficients with sugarcane yields. The aim was to develop a regression model based on weather variables that that could be used to explain the sugarcane yield variation. A total of 5 regression analyses were performed as follows;

(i). Variety CO 421 plant crop

(ii). Variety CO 421 combined ratoon crops

(iii). Variety CO 945 plant crop

(iv). Variety CO 945 combined ratoon crops (v). A generalized regression for both varieties and across crop classes

For regressions (i), (ii), (iii) and (iv), the SAS PROC REG was used. The linear regression equation that was used is given in Equation (21);

$$Y_{exp} = a + b_1x_1 + b_2x_2 + b_3x_3 \dots\dots\dots b_nx_n \qquad \dots\dots (21)$$

Where;

Y_{exp} is the expected crop yield value for a given set of X_i values.

b_1 is the regression coefficient/estimated slope of a regression of Y on X_1, if all of the other X variables could be kept constant, and so on for b_2, b_3,

a is the y-intercept

The best model was selected based on the model with the least AIC

Since the measurements in the data in regression (v) had some aspect of repeatedness, the SAS Proc Mixed was used. The equation for the mixed linear regression is given by Equation (22);

$$y = X_\beta + Z_\gamma + \varepsilon \qquad \dots\dots (22)$$

Where;

β = fixed effects parameter estimates

X = Fixed effects

Z = random effects parameter estimates

γ = random effects

ε = errors

Because all variables were significant either when the correlations were made by variety or crop class, they were all used in the model building. Variety and crop class were treated as class variables.

The model was developed using the following steps;

1. Using REML and a complex mean model an appropriate covariance structure was selected. REML is recommended to select a covariance structure and to estimate the covariance parameters because it provides unbiased estimates of the covariance parameters. The variance components, compound structure, autoregressive (1) and unstructured variance structures were tested. The unstructured structure had the least AIC therefore was used in this analysis.
2. Using ML and the selected covariance structure, a parsimonious mean model was selected by removing unnecessary terms one at a time. Model selection for linear mixed-effects model was done using AIC. The variables were manually removed using the backwards stepwise method. Among all possible models considered, the one with the smallest value of AIC was considered to be the best model.
3. The final model was then refitted using REML.

CHAPTER 4

4.0 RESULTS AND DISCUSSION

This chapter presents the results obtained from this study.

4.1 Data quality

The single mass curves of minimum and maximum temperatures and precipitation showed that the data was homogeneous. Figures (2), (3) and (4) show samples of the mass curves for maximum temperature, minimum temperature and rainfall respectively.

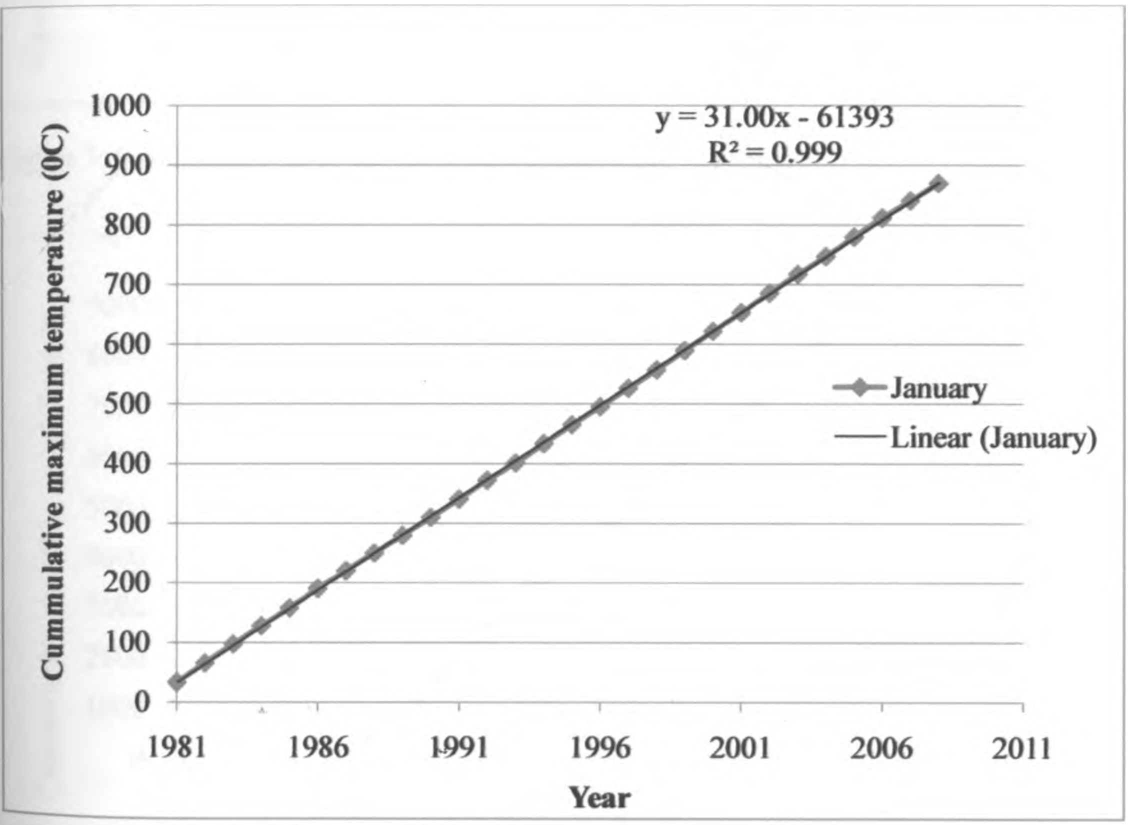

Figure 2: Single mass curve for maximum temperature in January

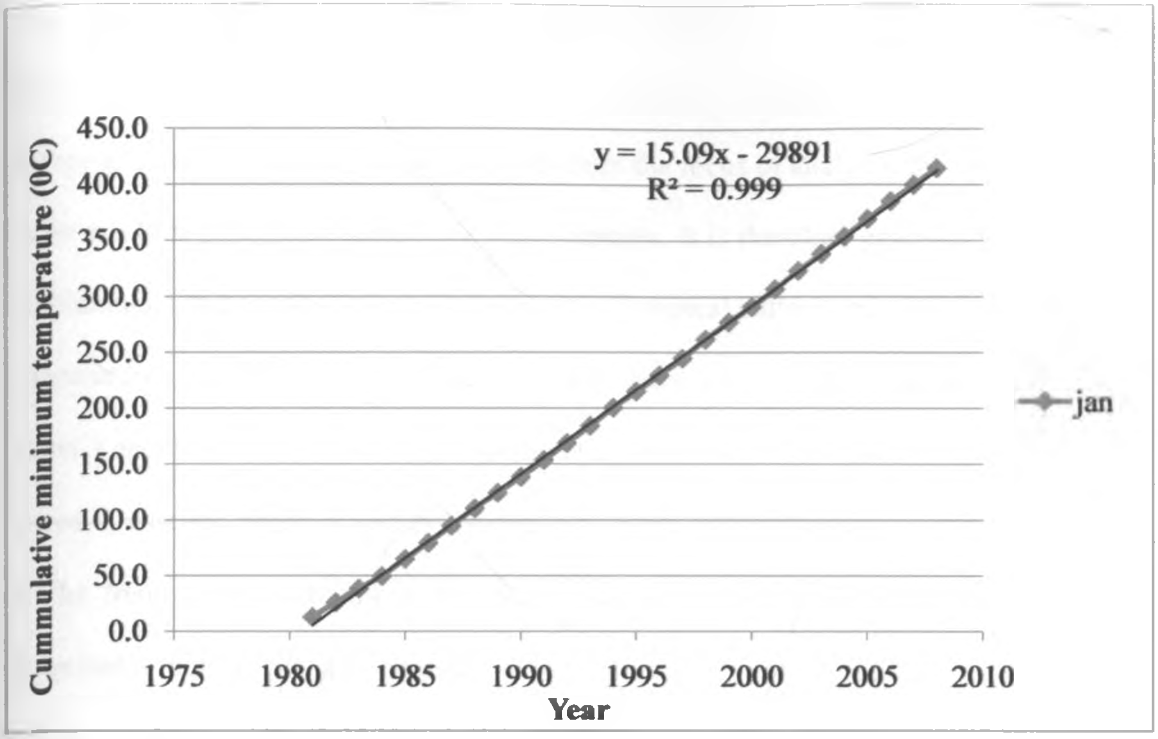

Figure 3: Single mass curve for minimum temperature in January

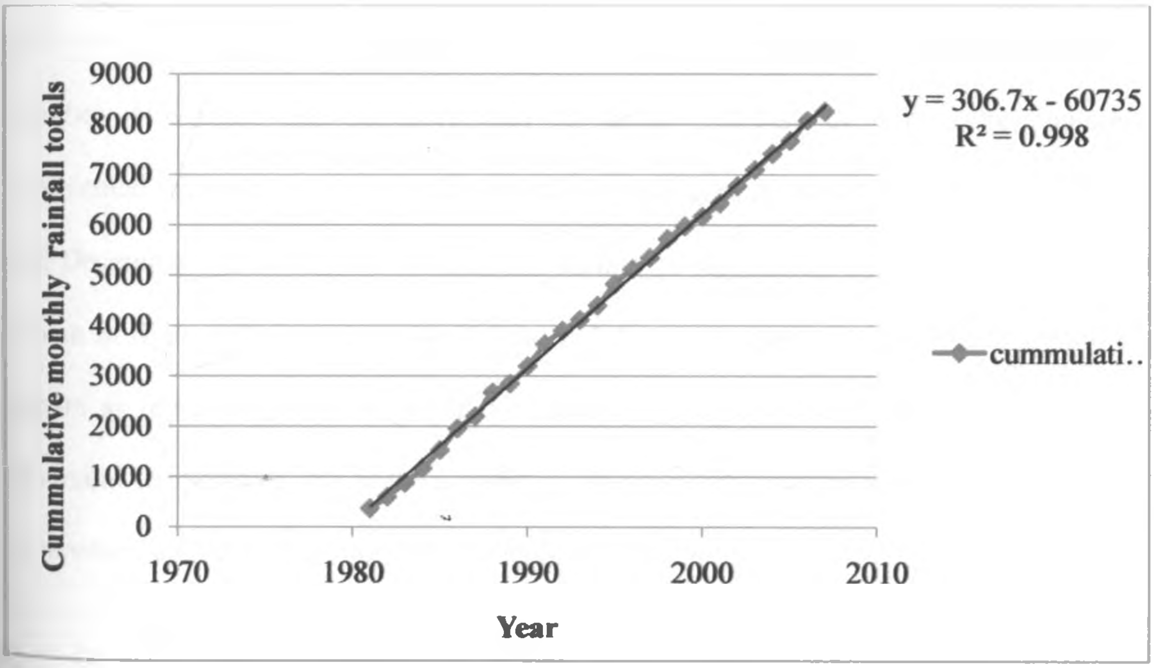

Figure 4: Single mass curve for rainfall in April

4.2 Trends analysis of the weather data

Detection of changes and trends in weather variables is important in climate variability and change analysis. While averages have often been the focus of analysis, the use of mean values alone can hide significant patterns in these changes. It is therefore essential to analyze trends in minimums and maximum values separately. Temporal patterns of minimum and maximum temperature, as well as monthly rainfall totals were analyzed and are presented here. The Mann-Kendall statistics was used. Positive values of the Mann Kendall statistic indicate an increase, whereas negative values indicate a decrease in temperatures over time. The strength of the trend is proportional to the magnitude of the Mann-Kendall Statistic with large magnitudes indicating a strong trend.

4.2.1 Trend analysis results for mean monthly minimum temperatures

The results show a significant positive trend during all the months of the year at the $\alpha= 0.05$ level of significance. The magnitude of this increasing trend is greatest in the months of October, November and January; with an annual increase of 0.08°C per annum and represented with the graph for January as shown in Figure (5) followed by March, September and December with a 0.07°C increase per annum as represented by the graph for March as shown in figure (6). February, April, June and August had an annual increase of 0.06°C per annum as represented by the graph for February in figure (7) and the smallest increase in minimum temperature was in the months of May and July with an annual increase of 0.05°C as represented in the graph for May in figure (8).

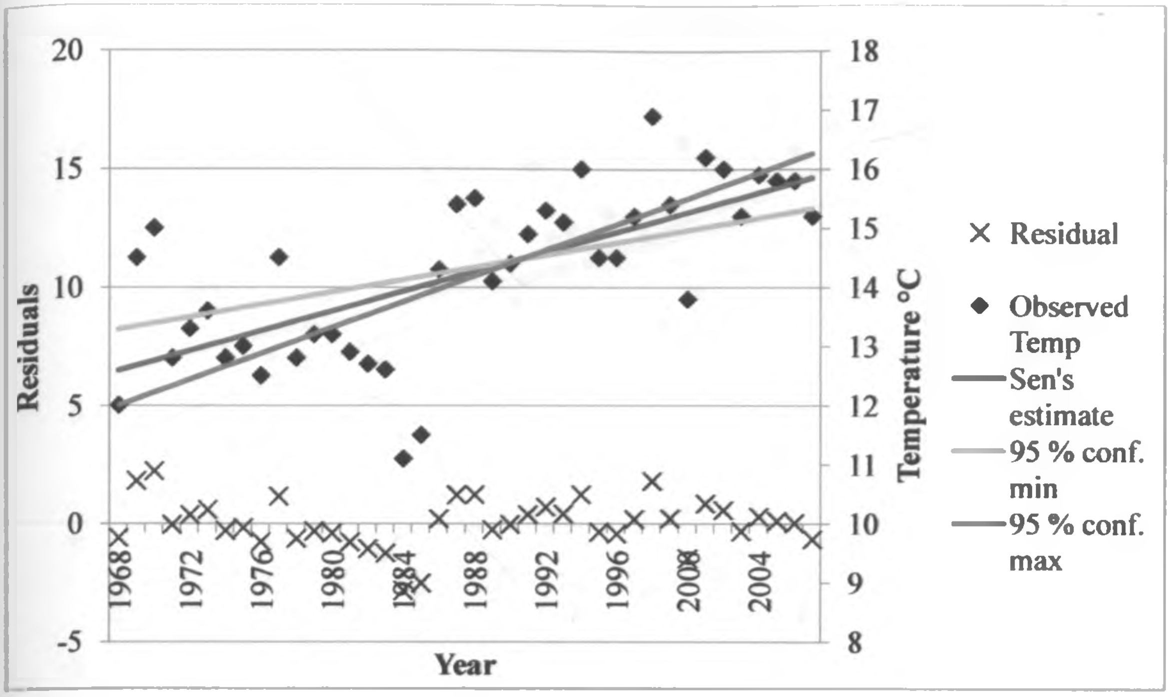

Figure 5: Sen's slope for minimum temperature in January

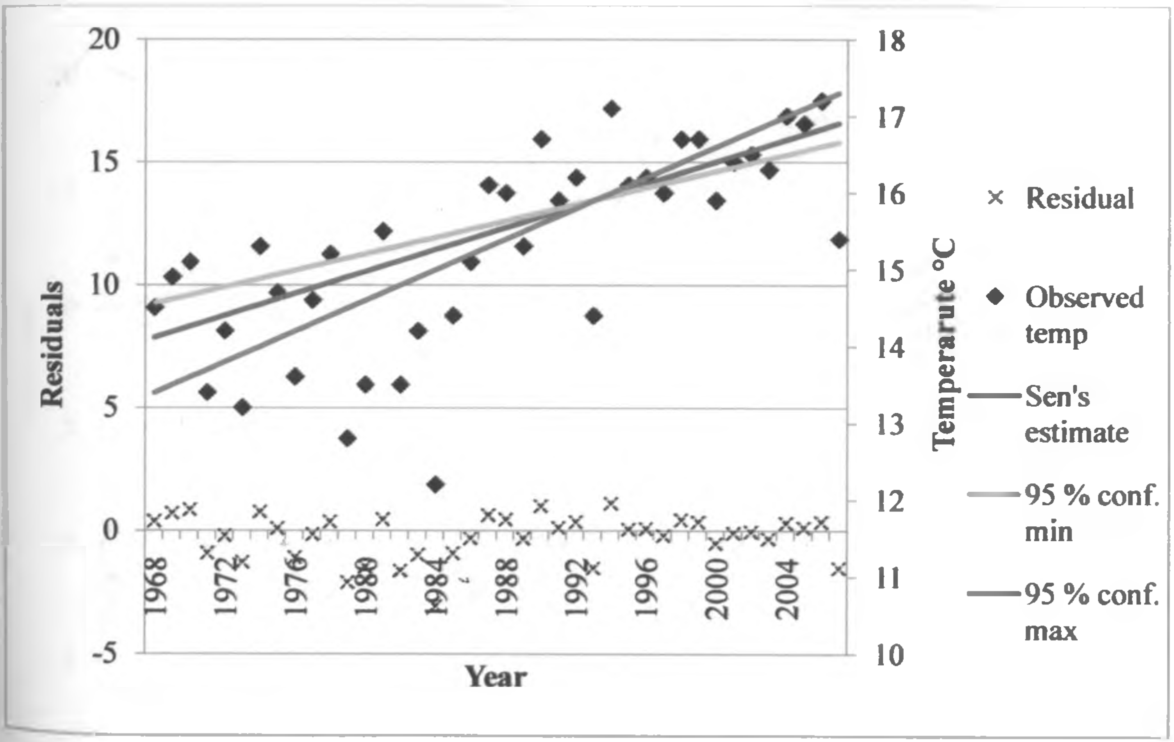

Figure 6: Sen's slope for minimum temperature in March

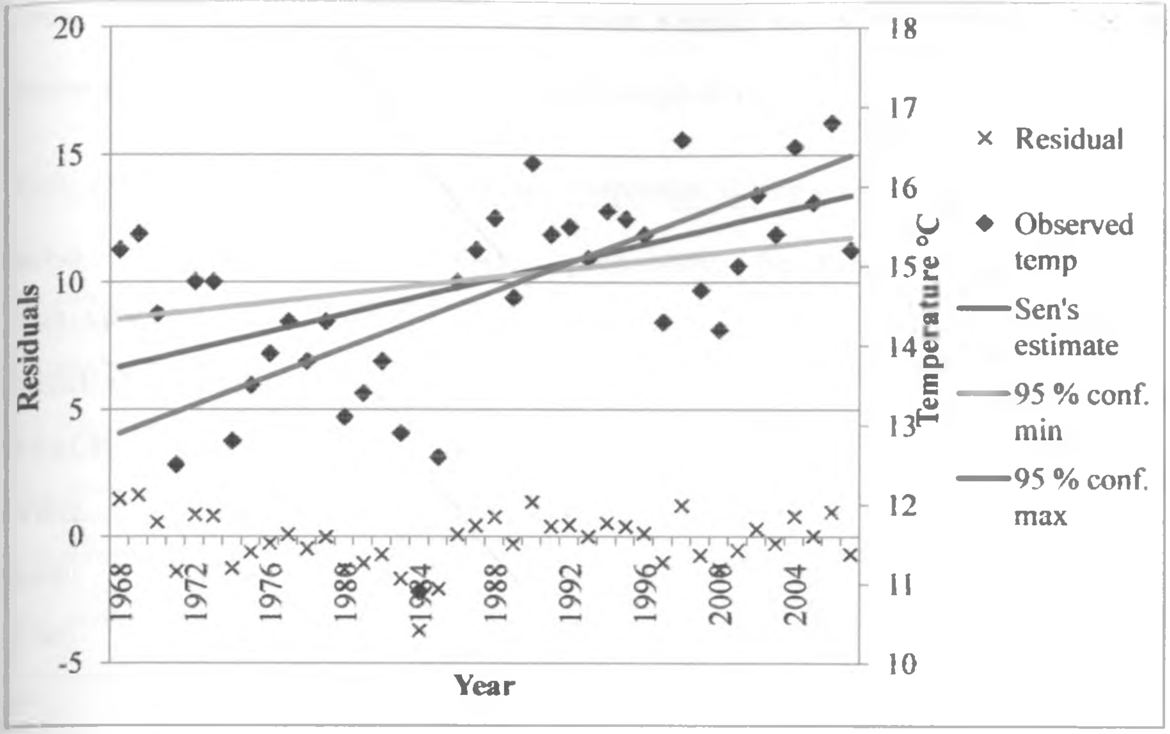

Figure 7: Sen's slope for minimum temperature in February

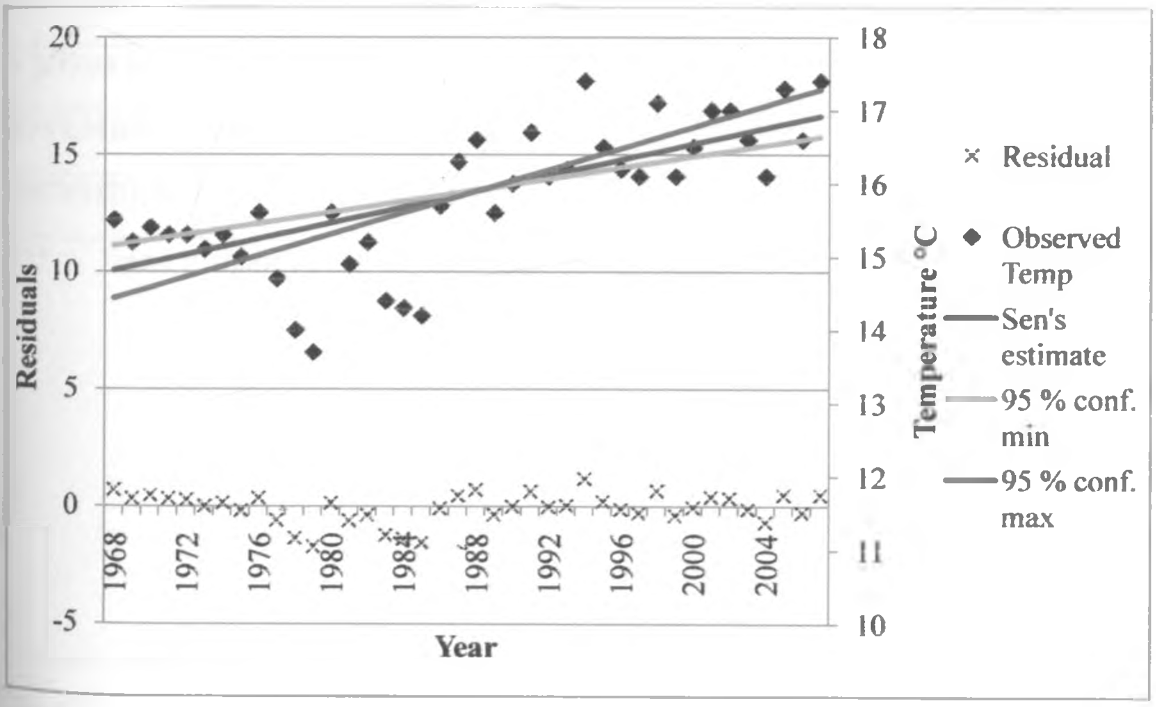

Figure 8: Sen's slope for minimum temperature in May

Table (2) and (3) show the results from Mann Kendall and Sen's analysis of minimum temperatures in Mumias during the study period respectively.

Table 2: Mann Kendal results for minimum temperature during study period

Period	**Kendall sum**	**Test Z**	**z-probability**	**Significance**	**Trend**
JANUARY	331	4.26	0	***	Increasing
FEBRUARY	295	3.43	0	***	Increasing
MARCH	424	4.93	0	***	Increasing
APRIL	422	4.91	0	***	Increasing
MAY	408	4.75	0	***	Increasing
JUNE	400	4.66	0	***	Increasing
JULY	304	3.53	0	***	Increasing
AUGUST	405	4.71	0	***	Increasing
SEPTEMBER	404	4.70	0	***	Increasing
OCTOBER	366	4.26	0	***	Increasing
NOVEMBER	376	4.38	0	***	Increasing
DECEMBER	405	4.71	0	***	Increasing

*** Trend is significant at $\alpha = 0.05$ level of significance

Table 3: Sen's estimated results for minimum temperatures during study period

	Sen's slope estimate									
Period	**Q**	**Qmin99**	**Qmax99**	**Qmin95**	**Qmax95**	**B**	**Bmin99**	**Bmax99**	**Bmin95**	**Bmax95**
January	0.08	0.04	0.12	0.05	0.11	12.60	13.55	11.85	13.30	12.01
February	0.06	0.02	0.10	0.03	0.09	13.74	14.57	12.80	14.34	12.90
March	0.07	0.05	0.11	0.05	0.10	14.12	14.67	13.06	14.56	13.40
April	0.06	0.04	0.08	0.05	0.08	14.78	15.18	14.33	15.01	14.52
May	0.05	0.03	0.08	0.04	0.07	14.82	15.23	14.26	15.16	14.44
June	0.06	0.04	0.09	0.05	0.08	13.84	14.38	13.39	14.28	13.50
July	0.05	0.02	0.08	0.03	0.07	13.63	14.32	13.03	14.08	13.16
August	0.06	0.04	0.09	0.05	0.08	13.50	13.98	12.96	13.80	13.07
September	0.07	0.04	0.10	0.05	0.09	13.35	13.79	12.50	13.63	12.69
October	0.08	0.04	0.10	0.05	0.10	13.65	14.26	13.30	14.15	13.36
November	0.08	0.05	0.11	0.05	0.10	13.70	14.16	12.73	14.12	13.05
December	0.07	0.05	0.10	0.06	0.10	13.08	13.38	12.40	13.24	12.48

Although the minimum temperature is generally on the increase, the variability is generally decreasing. Table (4) shows the analysis of the variance during the study period. The results show that the variability of minimum temperature in Mumias is only increasing in the months of October and December although this increase is insignificant at the $\alpha=0.05$ significance level. For the rest of the year this variability is generally decreasing but only significant during the months of July and February at the $\alpha=0.05$ significance level.

Table 4: Results of analysis of variability in minimum temperature

MONTH	**Mean 1**	**Mean 2**	**Variance 1**	**Variance 2**	**F-calc**	**F-prob**	**Significance**	**Trend**
JANUARY	13.19	15.29	1.23	0.59	2.07	0.06	Ns	Decreasing
FEBRUARY	13.82	15.48	1.29	0.52	2.45	0.03	Significant	Decreasing
MARCH	14.30	16.25	0.99	0.46	2.16	0.05	Ns	Decreasing
APRIL	15.12	16.70	0.50	0.35	1.42	0.23	Ns	Decreasing
MAY	15.04	16.56	0.42	0.26	1.58	0.16	Ns	Decreasing
JUNE	14.24	15.89	0.42	0.32	1.32	0.27	Ns	Decreasing
JULY	13.70	15.51	0.65	0.27	2.39	0.03	Significant	Decreasing
AUGUST	13.71	15.39	0.34	0.39	1.15	0.38	Ns	Increasing
SEPTEMBER	13.49	15.44	0.58	0.29	1.96	0.07	Ns	Decreasing
OCTOBER	14.02	15.79	0.66	0.97	1.47	0.20	Ns	Increasing
NOVEMBER	13.90	15.83	0.80	0.62	1.30	0.28	Ns	Decreasing
DECEMBER	13.35	15.12	0.79	1.16	1.46	0.21	Ns	Increasing

Ns Trend not significant

The possible reasons for this observed increasing trend in mean monthly minimum temperature could be due to global warming or changes in atmospheric circulation patterns and thus further analysis on the synoptic and mesoscale is necessary.

Figures 9 to 16 are graphical illustrations of this trend in minimum temperatures using the Sen's method for the months of April. June. July. August. September. October. November and December and are presented here for completeness.

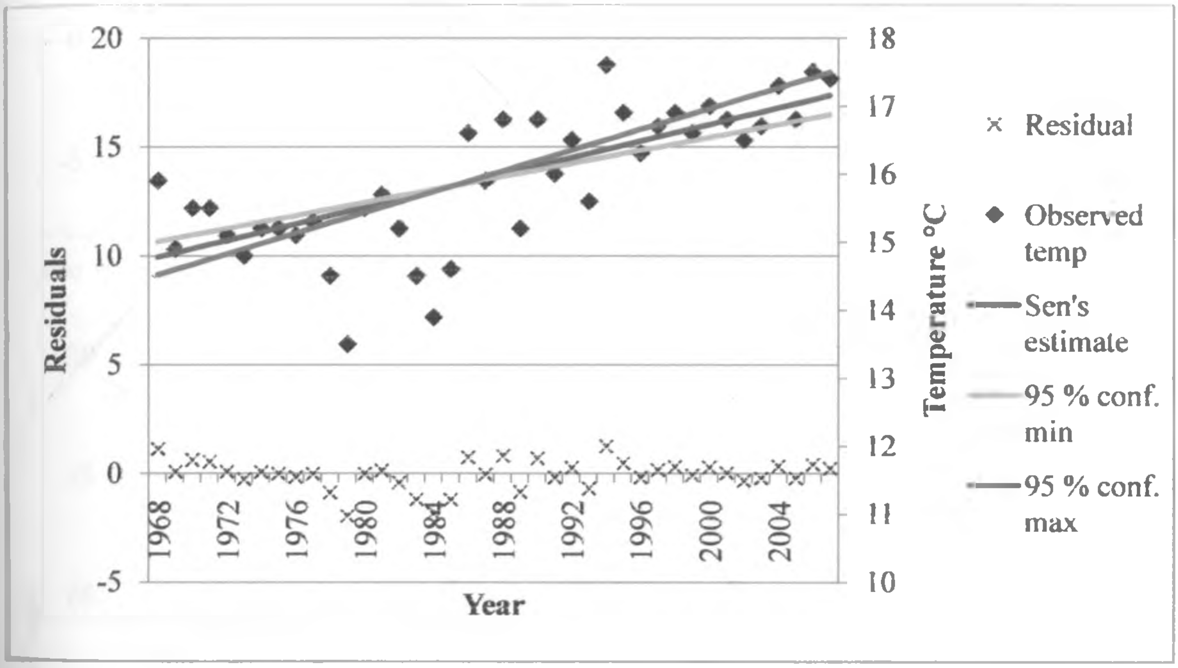

Figure 9: Sen's slope for minimum temperature in April

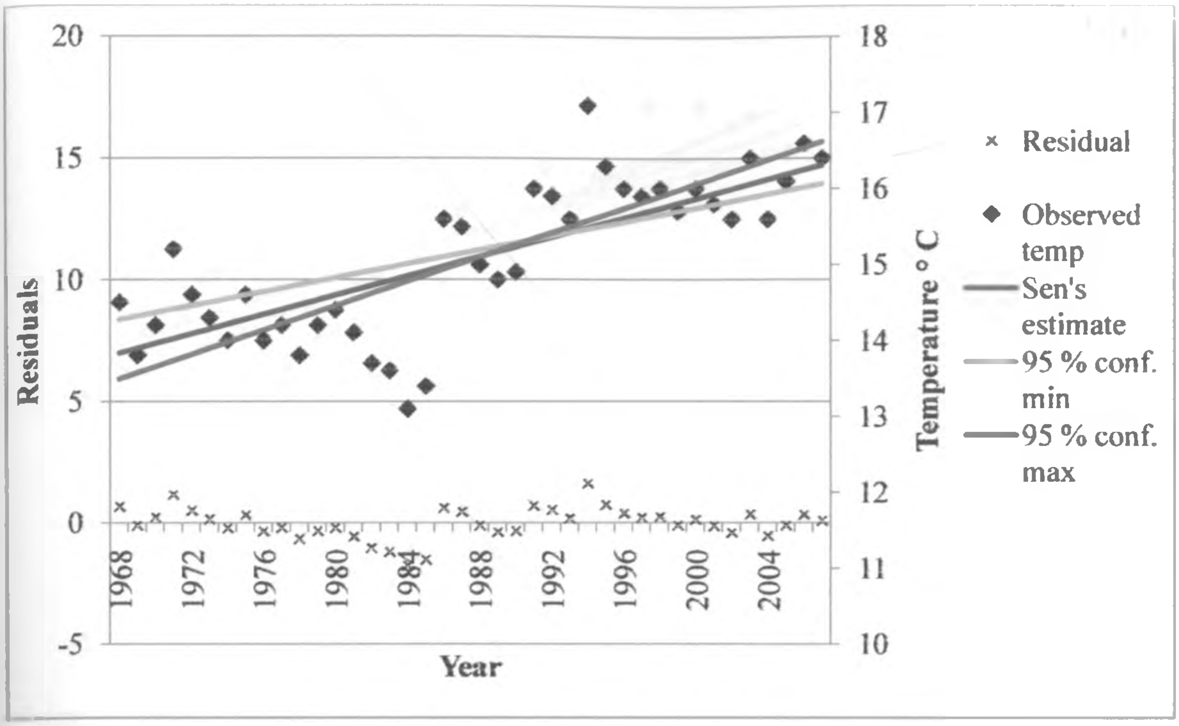

Figure 10: Sen's slope for minimum temperature in June

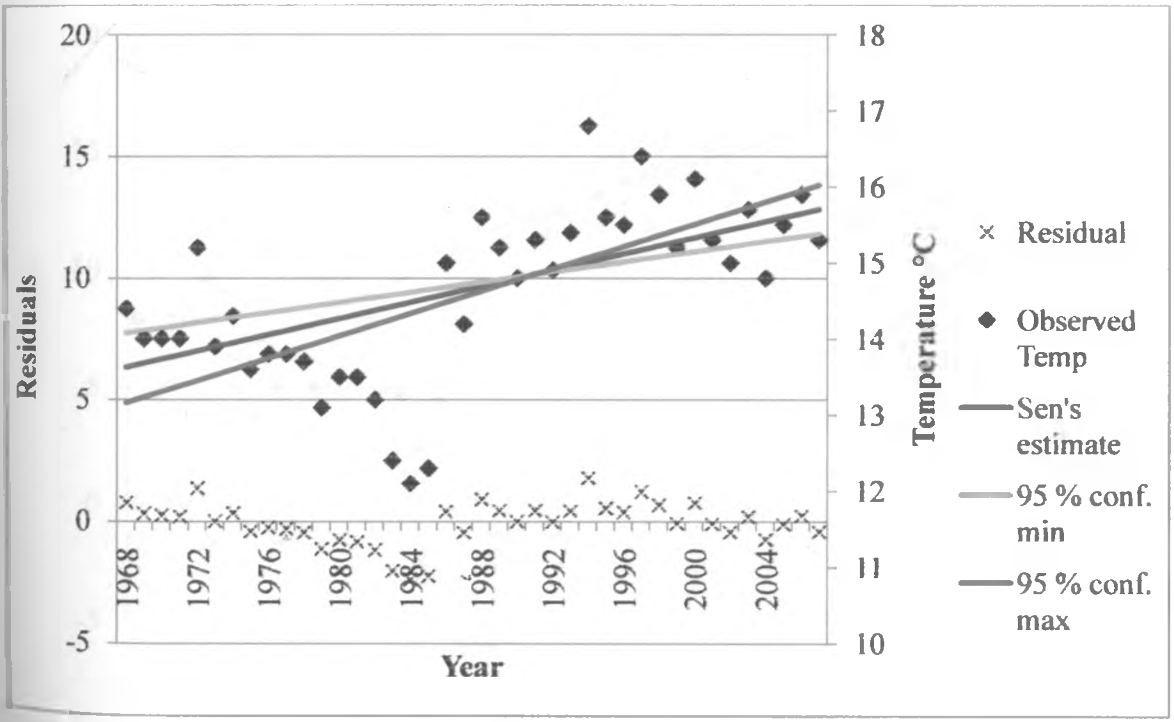

Figure 11: Sen's slope for minimum temperature in July

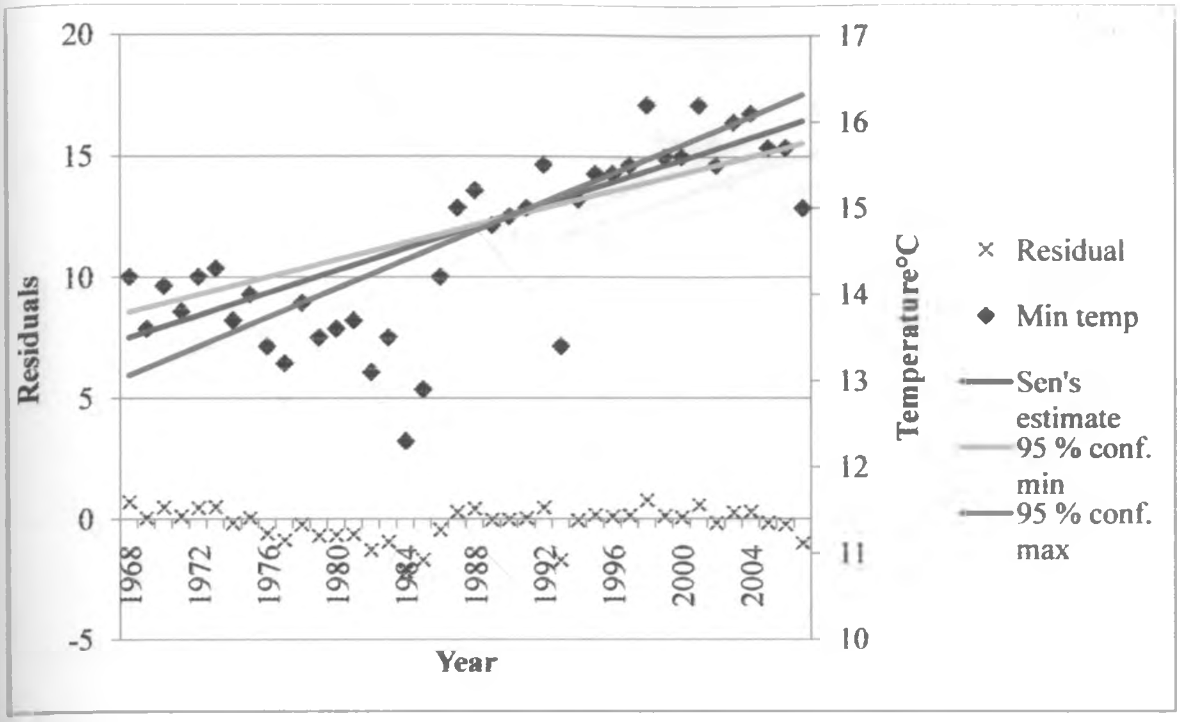

Figure 12: Sen's slope for minimum temperature in August

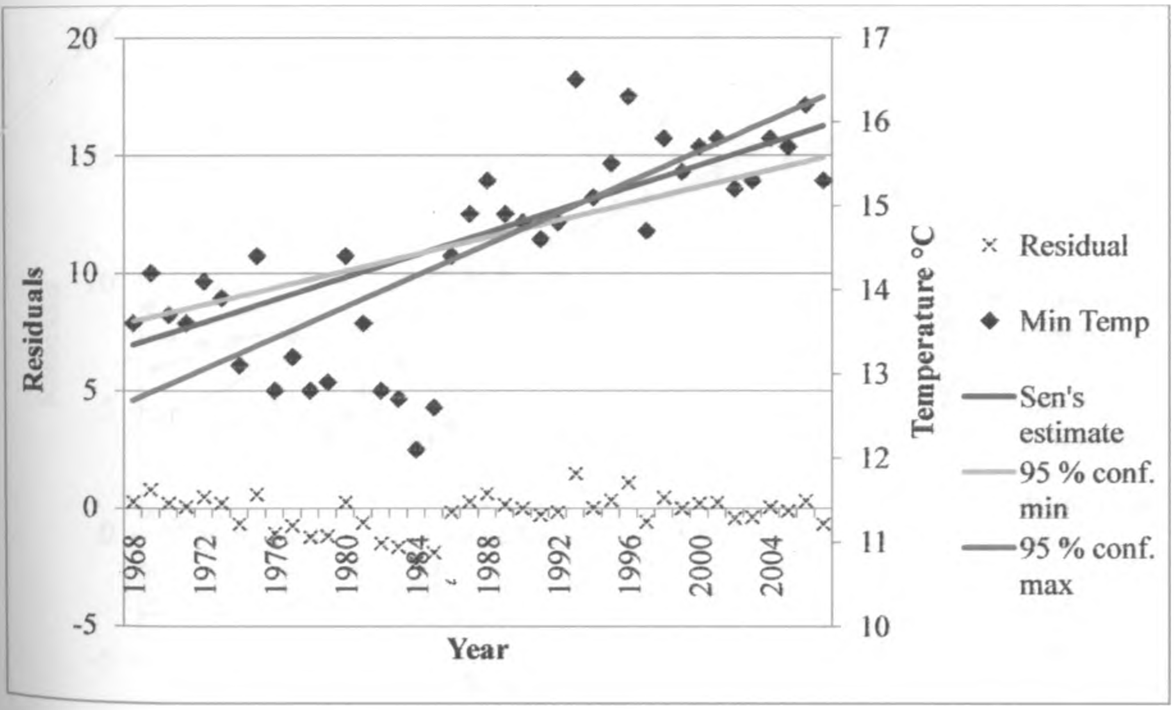

Figure 13: Sen's slope for minimum temperature in September

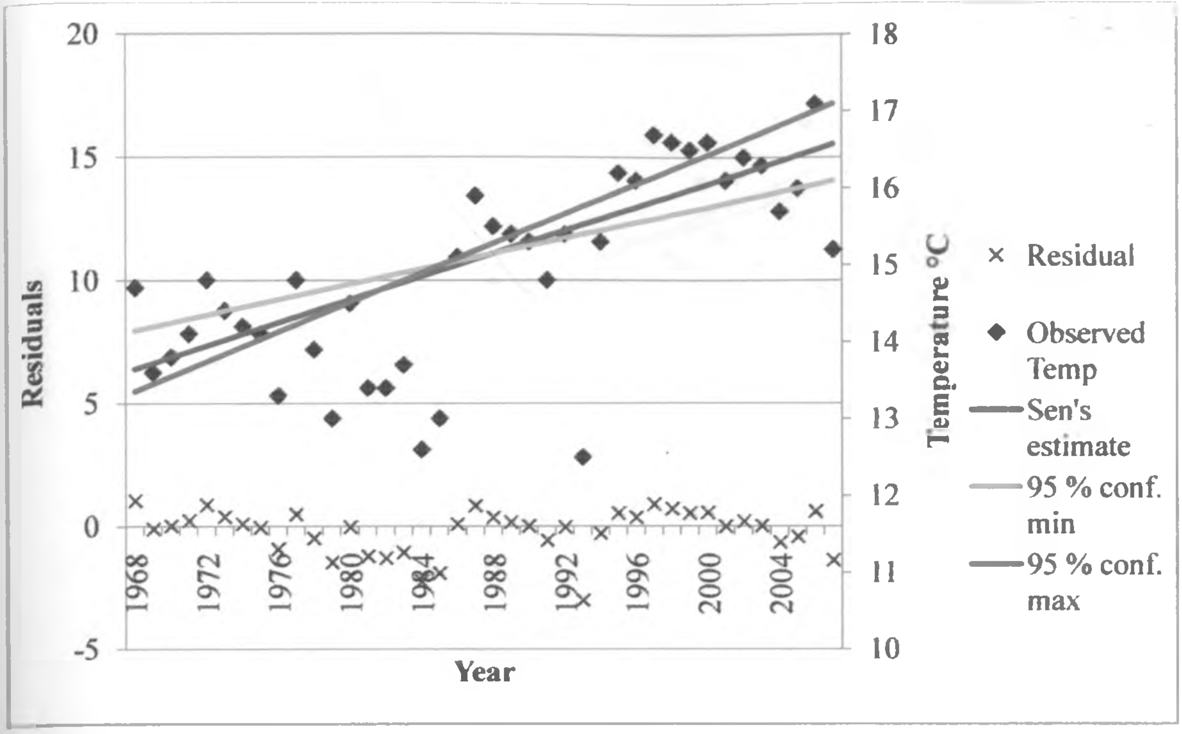

Figure 14: Sen's slope for minimum temperature in October

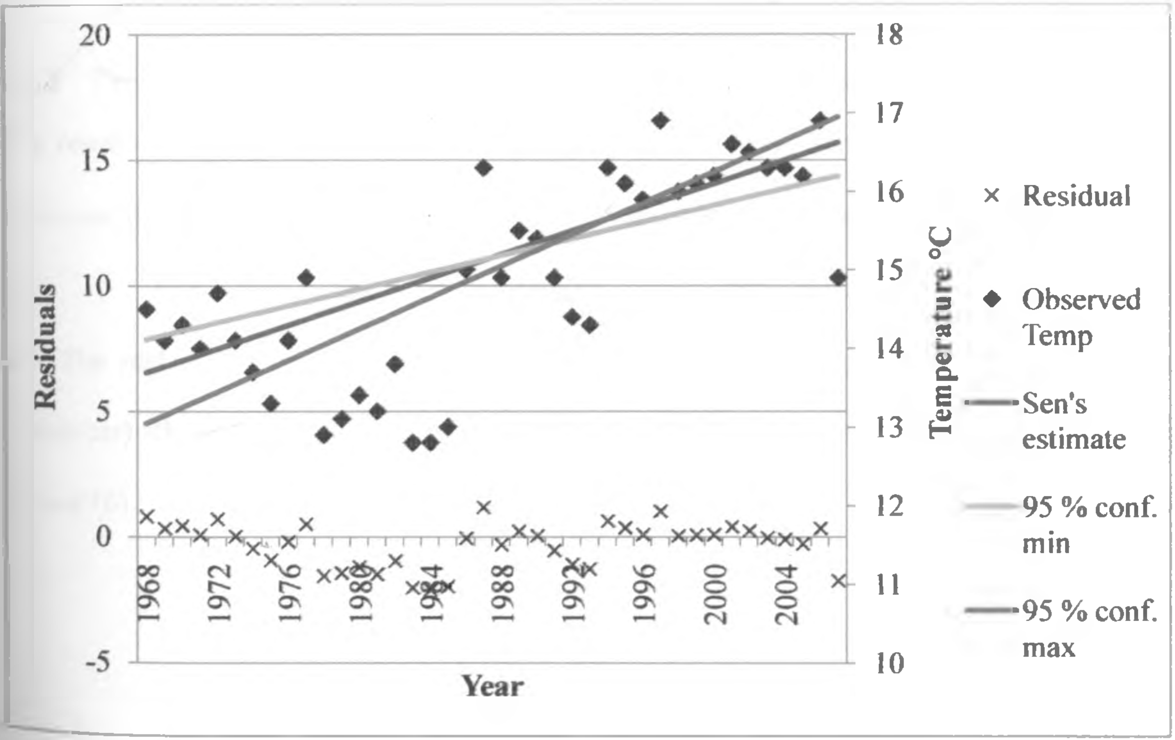

Figure 15: Sen's slope for minimum temperature in November

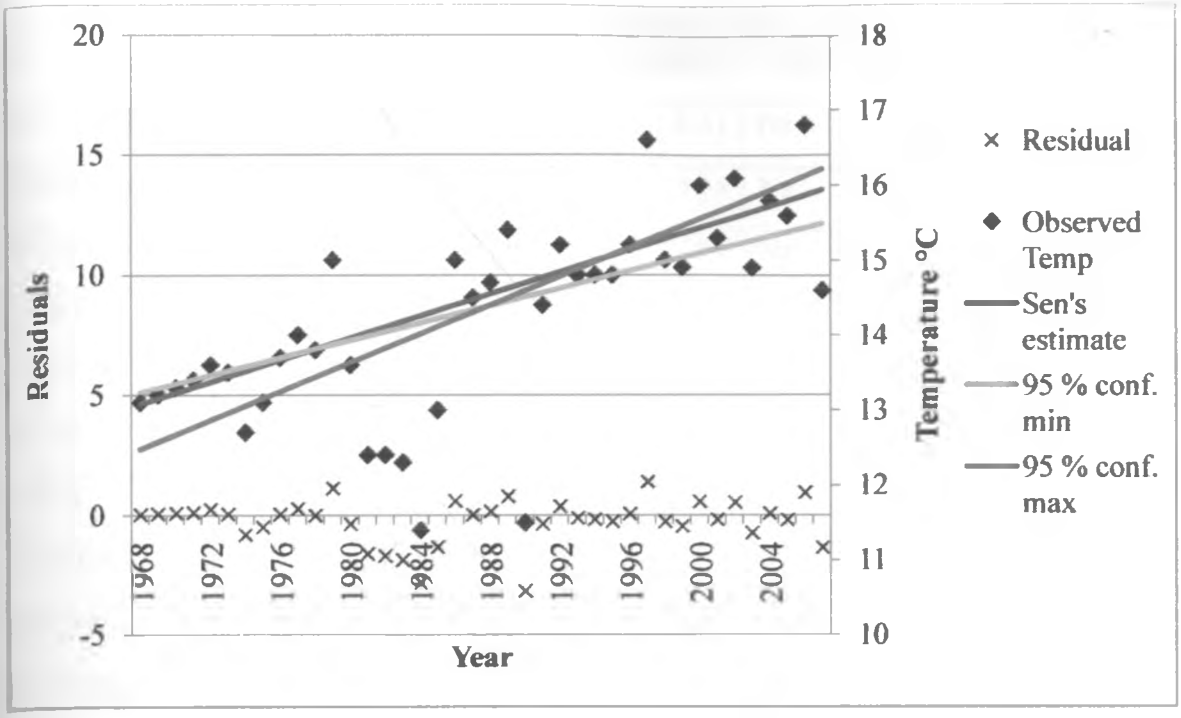

Figure 16: Sen's slope for minimum temperature in December

4.2.2 Trend analysis of mean monthly maximum temperatures

The results show a positive trend during the months of May, September, July and August. However, the trend was significant at the α= 0.05 level of significance only during the months of July and August, (Figures 17 and 18). The rest of the year (January, February, March, April, June, October, November and December) showed no significant trend at all the tested significance levels as shown in Tables (5) and (6).

Table 5: Mann Kendall results for maximum temperature during study period

Period	Kendall Sum	Test Z	Z-probability	Significance	Trend
JANUARY	88	1.02	0.31	Ns	Insignificant
FEBRUARY	124	1.56	0.14	Ns	Insignificant
MARCH	20	0.19	0.82	Ns	Insignificant
APRIL	95	1.10	0.27	Ns	Insignificant
MAY	179	2.08	0.04	***	Increasing
JUNE	125	1.54	0.13	Ns	Insignificant
JULY	131	1.69	0.12	+	Increasing
AUGUST	182	2.38	0.03	***	Increasing
SEPTEMBER	160	1.86	0.06	+	Increasing
OCTOBER	50	0.57	0.57	Ns	Insignificant
NOVEMBER	136	1.58	0.12	Ns	Increasing
DECEMBER	65	0.75	0.46	Ns	Insignificant

*** Trend is present at $\alpha = 0.05$ level of significance

+ Trend is present at $\alpha = 0.1$ level of significance

Ns not significant at all the tested significance levels

The results show that the variability of maximum temperature in Mumias. Table (7) is decreasing in the months of January and March although this decrease is insignificant at the α=0.05 significance level. For the rest of the year this variability is generally increasing and significant during the months of June, July, September, November and December but insignificant in February, April, May, August and October at the α=0.05 significance level.

Table 6: Results of analysis of variability in maximum temperatures

MONTH	Mean 1	Mean 2	Variance 1	Variance 2	F calc.	F-prob	Significance	Trend
JANUARY	31.20	31.06	1.93	1.43	1.35	0.26	Insignificant	Decreasing
FEBRUARY	31.74	32.15	2.25	3.86	1.72	0.13	Insignificant	Increasing
MARCH	31.69	31.43	3.14	2.65	1.19	0.36	Insignificant	Decreasing
APRIL	29.58	29.63	1.84	2.64	1.44	0.22	Insignificant	Increasing
MAY	28.81	29.10	0.54	1.01	1.86	0.09	Insignificant	Increasing
JUNE	28.30	28.67	0.48	1.13	2.35	0.04	Significant	Increasing
JULY	28.05	28.24	0.58	1.35	2.32	0.04	Significant	Increasing
AUGUST	28.51	28.81	0.69	0.84	1.22	0.34	Insignificant	Increasing
SEPTEMBER	29.45	29.80	0.66	1.44	2.19	0.05	Significant	Increasing
OCTOBER	29.88	29.69	0.83	0.88	1.06	0.45	Insignificant	Increasing
NOVEMBER	29.50	29.73	0.65	1.70	2.61	0.02	Significant	Increasing
DECEMBER	30.38	30.36	0.99	2.72	2.73	0.02	Significant	Increasing

Table 7: Sen's estimate results for maximum temperatures during study period

	Sen's slope estimates									
Period	**Q**	**Qmin99**	**Qmax99**	**Qmin95**	**Qmax95**	**B**	**Bmin99**	**Bmax99**	**Bmin95**	**Bmax95**
JANUARY	0.019	-0.029	0.072	-0.017	0.054	30.954	31.578	29.897	31.461	30.212
FEBRUARY	0.043	-0.033	0.117	-0.011	0.100	31.114	32.600	29.312	32.200	29.700
MARCH	0.004	-0.064	0.070	-0.044	0.055	31.085	32.711	29.780	32.397	30.145
APRIL	0.024	-0.040	0.079	-0.021	0.062	29.209	30.290	28.110	30.007	28.544
MAY	0.027	-0.005	0.060	0.000	0.051	28.429	28.874	27.585	28.750	27.772
JUNE	0.020	-0.019	0.059	-0.008	0.050	28.140	28.671	27.397	28.563	27.600
JULY	0.027	-0.015	0.066	-0.001	0.055	27.720	28.159	27.039	27.908	27.258
AUGUST	0.026	0.000	0.055	0.004	0.048	28.268	28.700	27.736	28.646	27.800
SEPTEMBER	0.029	-0.011	0.067	0.000	0.058	28.893	29.717	28.417	29.600	28.582
OCTOBER	0.007	-0.027	0.044	-0.020	0.034	29.528	30.277	28.975	30.070	29.037
NOVEMBER	0.025	-0.018	0.069	-0.007	0.057	29.128	29.787	28.390	29.610	28.529
DECEMBER	0.013	-0.029	0.061	-0.017	0.048	29.894	30.700	29.162	30.467	29.328

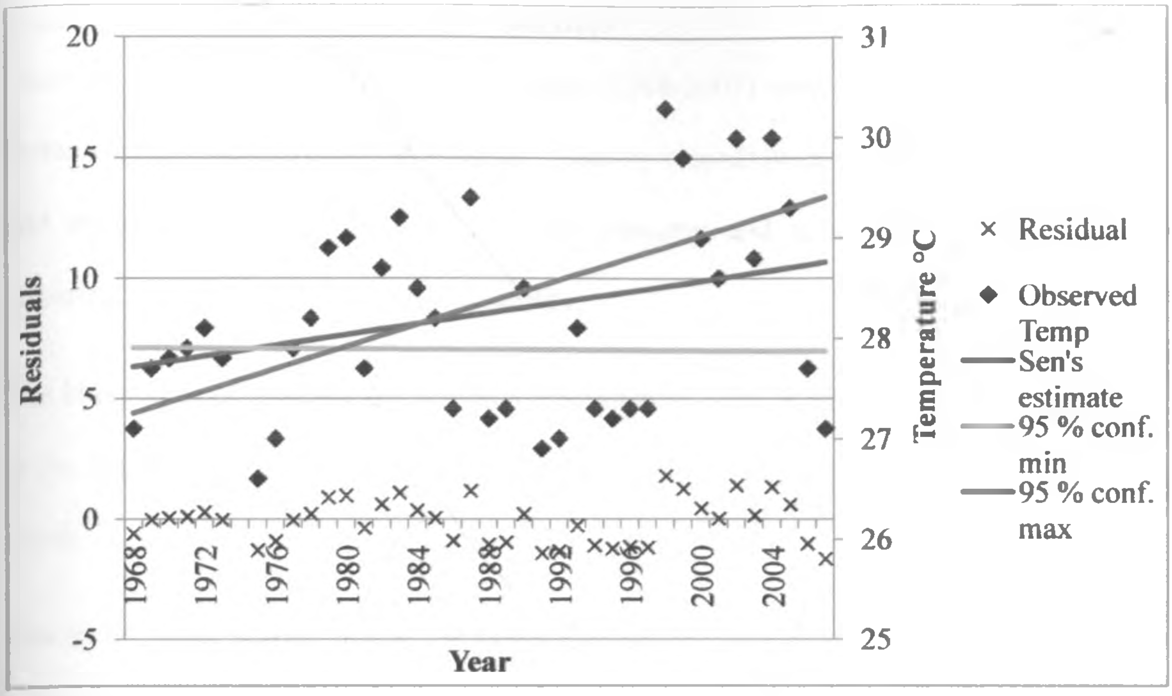

Figure 17: Sen's slope for maximum temperature in July

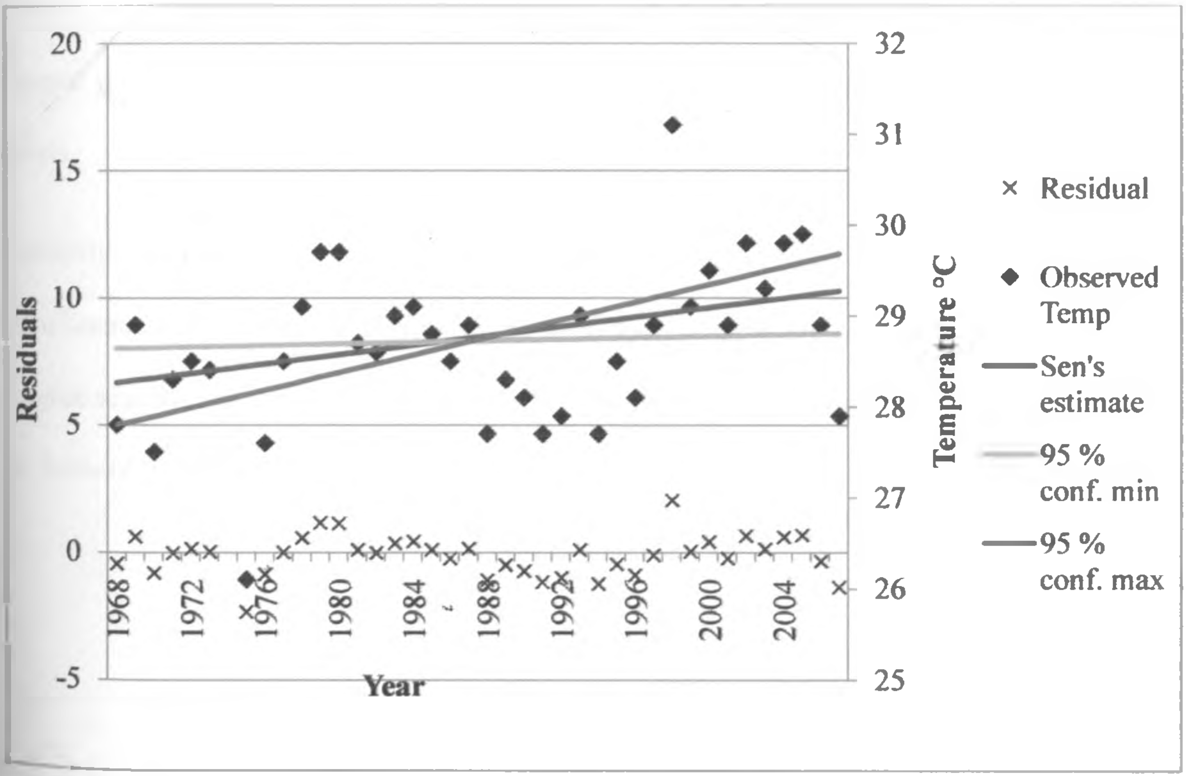

Figure 18: Sen's slope for maximum temperature in August

4.2.3 Trend Analysis of Precipitation

Monthly precipitation records for 40 years (1968-2007) were obtained from the central meteorological station (CMS) at Mumias. Monthly records were summed to provide seasonal and annual totals for each year. Monthly, seasonal and annual time series were then statistically analyzed for trend and variability.

The importance of monthly and seasonal precipitation totals is emphasized as opposite trends in the seasonal signals may weaken each other, resulting in little or no change in the annual trends.

Results on trend analysis using the Mann Kendall and Sen methods in Tables (8) and (9), show that although the rainfall totals tend to be increasing during the months of January, March, April, May, September and December, and decreasing during February, June, July, August and October, there is no significant trend in these totals at all the tested significance levels.

Similarly, there is no significant trend in the annual and seasonal rainfall totals at all tested significance levels although the totals tend to be decreasing in the January-February and June-August seasons and increasing in the March-May and September-December seasons as shown on Tables (10) and (11).

Table 8: Mann Kendall results for monthly rainfall totals

MONTH	Kendall sum	Test Z	z-prob	Significance.	Tendency
JANUARY	105	1.212	0.226	Ns	Increasing
FEBRUARY	-99	-1.142	0.254	Ns	Decreasing
MARCH	62	0.711	0.477	Ns	Increasing
APRIL	70	0.804	0.421	Ns	Increasing
MAY	-9	-0.093	0.926	Ns	Decreasing
JUNE	-22	-0.245	0.807	Ns	Decreasing
JULY	-16	-0.175	0.861	Ns	Decreasing
AUGUST	-98	-1.13	0.258	Ns	Decreasing
SEPTEMBER	8	0.082	0.935	Ns	Increasing
OCTOBER	-72	-0.827	0.408	Ns	Decreasing
NOVEMBER	44	0.501	0.616	Ns	Increasing
DECEMBER	28	0.315	0.753	Ns	Increasing

Ns = not significant all tested levels of significance

Table 9: Sen's slopes estimates for monthly rainfall totals

Sen's slope estimate										
MONTH	**Q**	**Qmin 99**	**Qmax 99**	**Qmin 95**	**Qmax 95**	**B**	**Bmin 99**	**Bmax 99**	**Bmin 95**	**Bmax 95**
JANUARY	0.82	-1.33	2.90	-0.73	2.35	49.22	95.19	10.12	81.50	19.61
FEBRUARY	-0.90	-3.50	1.41	-2.81	0.70	91.01	148.31	47.18	130.73	63.81
MARCH	1.19	-2.69	4.87	-1.70	3.87	135.95	221.74	67.61	197.19	87.01
APRIL	0.98	-2.37	4.23	-1.69	3.51	265.59	331.35	196.77	322.33	209.84
MAY	-0.11	-2.60	2.61	-2.03	2.00	287.86	321.75	244.90	311.00	251.93
JUNE	-0.16	-2.36	2.06	-1.80	1.53	185.91	219.03	142.97	212.28	156.29
JULY	-0.15	-2.30	1.88	-1.68	1.40	115.69	162.19	74.90	156.32	84.04
AUGUST	-0.89	-2.54	0.91	-2.05	0.50	187.02	218.65	151.68	206.41	158.28
SEPTEMBER	0.11	-2.06	2.42	-1.69	1.91	166.45	209.11	96.62	201.97	110.65
OCTOBER	-0.87	-3.18	1.61	-2.45	1.07	197.39	247.65	141.62	230.26	154.04
NOVEMBER	0.31	-1.99	3.69	-1.31	2.62	137.99	173.78	86.67	155.96	98.27
DECEMBER	0.31	-1.92	3.04	-1.32	2.25	70.18	119.28	31.25	104.64	38.56

Table 10: Results of Mann Kendall analysis of seasonal and annual rainfall totals

PERIOD	**First year**	**Last Year**	**n**	**Test Z**	**Significance**	**tendency**
Jan-Feb	1968	2007	40	-0.59	Ns	Decreasing
Mar-May	1968	2007	40	0.64	Ns	Increasing
Jun-Aug	1968	2007	40	-1.13	Ns	Decreasing
Sep-Dec	1968	2007	40	0.62	Ns	Increasing
ANNUAL	1968	2007	40	0.08	Ns	Increasing

Ns not significant all tested significance levels

Table 11: Results of Sen's analysis of seasonal and annual totals

Sen's slope estimate										
PERIOD	**Q**	**Qmin 99**	**Qmax 99**	**Qmin 95**	**Qmax 95**	**B**	**Bmin 99**	**Bmax 99**	**Bmin 95**	**Bmax 95**
Jan-Feb	-0.71	-4.88	2.41	-3.73	1.62	157.66	266.78	104.98	240.38	113.37
Mar-May	1.54	-4.59	8.17	-3.13	6.78	736.27	852.74	601.55	829.71	633.58
Jun-Aug	-1.53	-5.77	2.43	-4.83	1.35	516.68	566.39	434.43	547.86	445.24
Sep-Dec	1.50	-5.48	6.87	-4.18	5.29	559.70	678.60	474.24	646.68	516.38
ANNUAL	0.36	-10.26	11.40	-7.65	7.48	1978.02	2154.17	1813.95	2125.88	1867.13

Table 12: Results of analysis of variability in rainfall totals

PERIOD	Mean 1	Mean 2	variance 1	variance 2	F calc.	F-prob	Significance	Trend
JANUARY	70.36	84.86	3731.52	2508.53	1.49	0.20	Insignificant	Increasing
FEBRUARY	106.97	79.70	6800.97	3845.55	1.77	0.11	Insignificant	Decreasing
MARCH	160.78	182.23	8546.06	7308.01	1.17	0.37	Insignificant	Increasing
APRIL	282.07	304.67	7071.27	7086.62	1.00	0.50	Insignificant	Increasing
MAY	297.13	277.91	2254.60	8621.36	3.82	0.00	Significant	Decreasing
JUNE	188.64	184.41	3614.03	3098.41	1.17	0.37	Insignificant	Decreasing
JULY	135.38	118.67	3907.47	2151.91	1.82	0.10	Insignificant	Decreasing
AUGUST	184.45	168.47	2793.36	2810.22	1.01	0.49	Insignificant	Decreasing
SEPTEMBER	160.51	160.22	3378.80	3170.72	1.07	0.45	Insignificant	Decreasing
OCTOBER	176.80	178.24	4351.91	2137.25	2.04	0.07	Insignificant	Increasing
NOVEMBER	152.66	178.04	4585.10	10127.58	2.21	0.05	Significant	Increasing
DECEMBER	85.43	105.35	3275.53	7505.36	2.29	0.04	Significant	Increasing
ANNUAL	2001.14	2022.75	61961.52	83353.23	1.35	0.26	Insignificant	Increasing
JAN-FEB	177.32	164.56	8697.12	7417.73	1.17	0.37	Insignificant	Increasing
MAR-MAY	739.97	764.80	22746.87	20991.46	1.08	0.43	Insignificant	Increasing
JUN-AUG	508.46	471.54	10305.72	13441.29	1.30	0.28	Insignificant	Decreasing
SEP-DEC	575.38	621.83	17820.43	28144.42	1.58	0.16	Insignificant	Increasing

The results for variability of monthly totals (Table 12), show that the variability of rainfall totals in Mumias is decreasing in the months of February, May, June, July, August, and September although this decrease is only significant in May at the $\alpha=0.05$ significance level. For the rest of the year rainfall variability is generally increasing and significant during the months of November and December but insignificant in January, March, April, and October at the $\alpha=0.05$ significance level.

The variability of annual totals is generally increasing although this increase was insignificant during the study period. The January-February, March-May, September-December seasonal totals show an increase in variability whereas the June-August season, a decrease in variability, however, these tendencies are insignificant at the $\alpha=0.05$ significance level. Further analysis of this variability in both the short and long rain seasons needs to be further investigated.

4.2.4 Possible impacts of the observed weather trends to sugarcane production

During the study period, minimum temperature rise is more evident than is the change in maximum temperature. This is as is expected from greenhouse warming projections (Hulme et.al 2001). As a result, heat stress during the day may be less probable but increased nighttime respiration may increase due to the increasing minimum temperatures and thus reduce potential yields. Significant negative yield responses to higher nighttime temperatures with a much smaller and statistically insignificant effect of daytime temperature and solar radiation has been demonstrated by Peng et al. (2004), who showed a negative response of rice yields to increased minimum but not maximum temperature. The physiological mechanisms associated with this response more likely involve greater rates of plant respiration during warmer nights.

Another important effect of high temperature is accelerated physiological development, due to faster accumulation of GDD resulting in hastened maturation and reduced yield. These consistent increases in minimum temperatures and in some months the maximum temperature may lead to increased flowering in sugarcane varieties. Flowering in sugarcane is a complex physiological process consisting of multiple stages of development, each stage having specific environmental and physiological requirements. Thus, if the specific day length, temperature and moisture requirements are not satisfied, flowering is inhibited or the intensity is reduced. Under natural conditions, day length being fixed at any given latitude and date, (Moore and Nuss, 1987) is essential. The location (altitude), temperature, (Coleman, 1963), moisture stress and the nutrition level (Gosnell, 1973; and Nuss, 1987) are other factors that affect the timing and intensity of flowering. High daytime temperatures could also reduce flowering intensity or delay emergence due to a direct temperature effect or indirectly through the resulting water stress. Cane yield (TCH), sugar yield (TSH), are significantly reduced by flowering, (Berding and Hurney, 2005).

Temperature influences the pest, disease outbreak and their spread as well as their control. Rust incidence is high when the minimum temperatures are drastically reduced, (Strand, 2000). Therefore the increasing trend in minimum temperature may reduce the incidences of rust in Mumias.

4.3 Trend analysis of sugarcane yield data

4.3.1 Trends on yield data

The analysis shows that between 1984 and 2008 there is a significant decrease in sugarcane yields at Mumias in both varieties. CO 945 showing twice greater yield decline than CO421.

The yield data was then split into two periods; Period 1, between 1984 and 1997 when filter mud was routinely added into the fields and period 2, between 1997 and 2007 after the diffuser technology was installed in the factory and hence no filter mud produced or applied to the cane fields.

Analysis based on these two periods showed that in period 1, both varieties showed insignificant trends with CO 421 showing a positive trend or increase in yield and CO 945 showing a negative trend or decrease in yields. In the second period, both varieties showed a decreasing trend in yields although this trend was only significant in CO 421. The magnitude of change in the yields of CO 421 was 3.4 times that of CO 945.

Tables (13) and (14) show the Mann Kendall and Sen's estimates for these 2 varieties during the 1984-2007 study period, while, Figures (19) and (20) illustrate the same.

It can therefore be concluded that CO 421 is more sensitive to management practices than CO 945.

Table 13: Mann Kendall Statistic for sugarcane yields during the study period

Variety	Period	Mann-Kendall trend	
		Test Z	**Significance**
CO 945	1984-2008	-4.37	***
	1984-1997	-1.31	Ns
	1997-2008	-1.71	Ns
CO 421	1984-2008	-2.75	***
	1984-1997	0.99	Ns
	1997-2008	-2.50	***

*** Trend significant at α = 0.05

Ns no significant trend observed

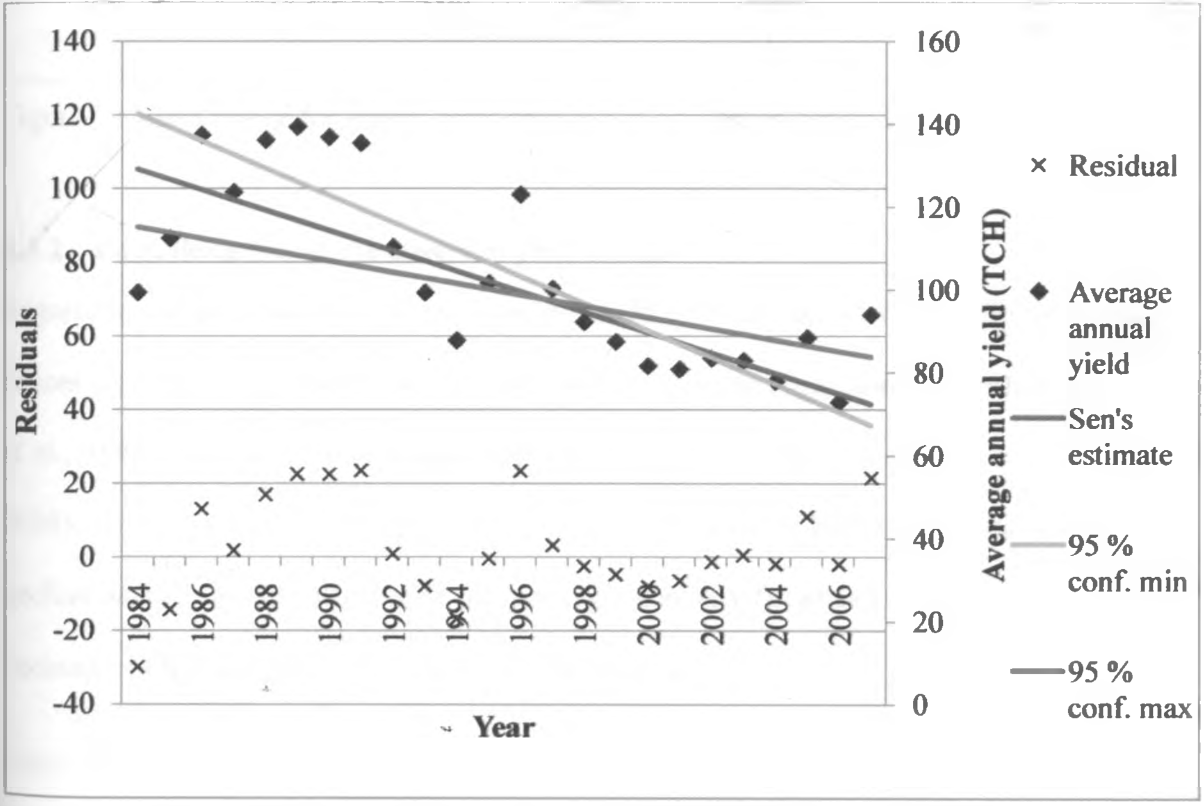

Figure 19: Sen's results for annual plant crop in CO 945 yields during 1984-2007 period

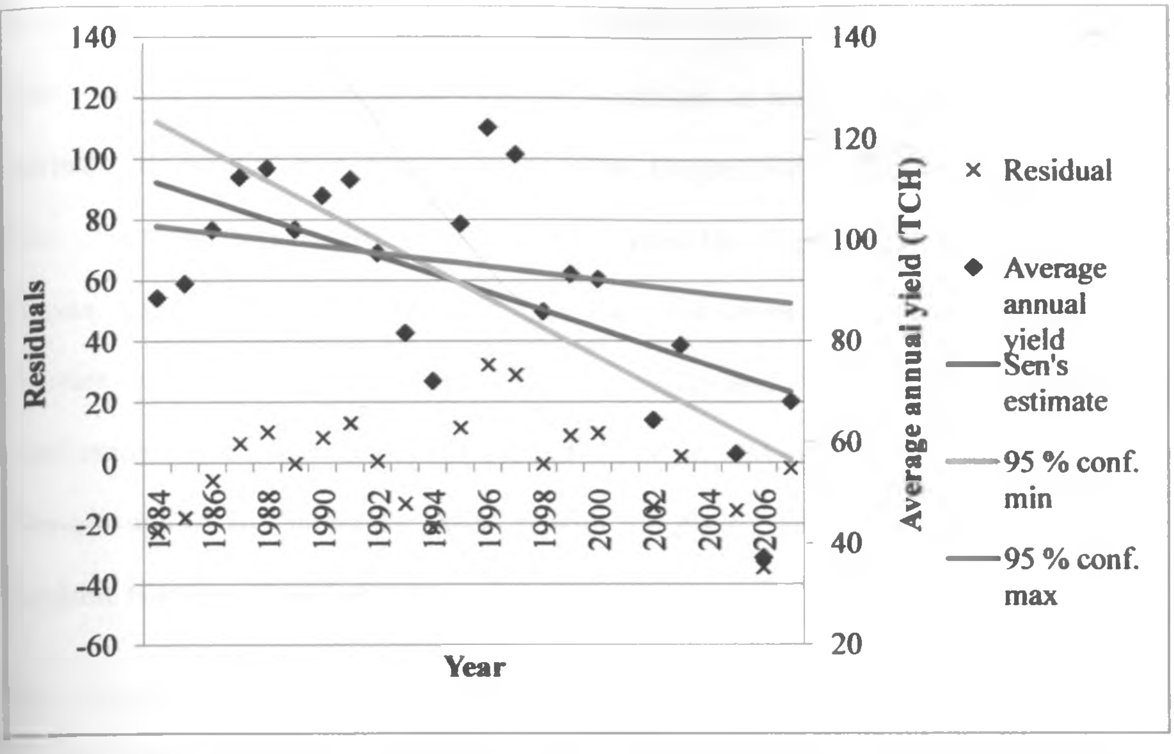

Figure 20: Sen's results for annual plant crop in CO 421 yields during 1984-2007 period

4.3.2 Possible causes of the observed yield trends

Sugarcane yield decline is a complex issue caused by a number of factors. Some attributed causes are (1) soil degradation as the result of the long-term sugarcane monoculture (Garside, et al., 1995; Pankhurst, et al., 1999); (2) poor nutrition (Singh, et al., 2007; Elsayed, et al., 2008); (3) or weather (Brüggemann, et al., 2001; Greenland, 2005). Other causes of yield decline include uncontrolled traffic from heavy machinery (Braunack et. al., 2006), diseases, excessive tillage and burning of cane before harvesting.

From 1997, Mumias Sugar Company stopped applying filter mud (FM) to their fields. Although the analysis does not show this as an abrupt period when yields began declining it is a probable contributor to this decline as shown by the analysis. FM is an agro-industrial waste of sugarcane mills obtained through the clarification of sugarcane juice. It is a source of major plant nutrients like nitrogen, phosphorus and potassium, as well as notable amounts of other nutrients like Sodium, Iron, Manganese, Calcium, Copper, Silicon, Magnesium, Sulphur and Zinc. It is thus used as a fertilizer in several countries like Argentina, Brazil, India, Pakistan, Taiwan, South Africa, Swaziland and Australia. FM varies in composition, quantity and moisture content depending upon the sugarcane quality and the process used for cane juice clarification in the sugar factory (Elsayed et al., 2008). FM application also increases plant Nitrogen uptake and increases yields in both the plant crop and ratoon as compared to inorganic Nitrogen-Phosphorus-Potassium (NPK) fertilizers, (Singh et al., 2007).

This change in management of crops could have significantly affected the yield and also possibly mask the effect of weather on sugarcane yields in the nucleus estate in Mumias.

Table 14: Sen estimates for the trend analysis of yields in Mumias during the study period

Variety	**Period**	**Sen's slope estimate**									
		Q	**Qmin 99**	**Qmax 99**	**Qmin 95**	**Qmax 95**	**B**	**Bmin 99**	**Bmax 99**	**Bmin 95**	**Bmax 95**
CO 945	**1984-2008**	-2.341	-3.379	-1.084	-3.218	-1.407	127.34	144.16	111.13	142.06	113.79
	1984-1997	-1.456	-5.863	3.207	-4.652	1.050	124.87	158.35	104.23	150.12	110.85
	1997-2008	-1.265	-3.297	1.274	-2.817	0.252	90.16	100.61	77.43	97.94	81.74
CO 421	**1984-2008**	-1.916	-3.300	-0.293	-2.891	-0.839	112.62	127.30	96.94	125.67	103.55
	1984-1997	1.103	-2.892	3.428	-1.557	2.795	98.07	120.71	86.35	113.37	88.49
	1997-2008	-4.336	-9.547	0.454	-8.356	-1.668	103.54	122.00	70.03	117.04	86.13

4.4 Statistical relationships between weather parameters and sugarcane yield.

4.4.1 Results on the correlation analysis

4.4.1.1 Analysis of variance of variety and crop class effects on the yield

Before the correlation was done, an ANOVA analysis was performed to determine whether there was significant difference between the two varieties and also if there was any significant difference in yields due to the crop class. The ANOVA results showed that there was significant difference between the varieties and the crop classes. Hence, two correlations were done. Variety and crop class were thus held as factors in the first and second correlations respectively. For simplicity the ratoon crops were treated as one entity. Tables (15) and (16) show the results of the ANOVA analysis and the Student Neumann Kohl's test respectively.

Table 15: The results of the ANOVA on the varietal and crop class differences

Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F**	**p>F**
Variety	1	56677.8	56677.8	58.89	<.001***
Crop class	3	247666.3	82555.4	92.37	<.001***

*** significant at p=0.05 significance level

Table 16: Least Significant differences between the varieties and crop classes

Parameter	Least significant difference (LSD)	t-grouping	Mean	Class level
Variety	2.47	A	107.95	CO 421
		B	98.28	CO 945
Crop class	3.17	A	116.97	Plant crop
		B	112.29	Ratoon 1
		C	99.47	Ratoon 2
		D	93.32	Ratoon 3 and above

4.4.1.2 Effects of the correlated weather variables and yield of variety CO 421 in the plant crop and in combined ratoon crops

Mean maximum temperature

In the plant crop mean maximum temperature had strong, positive effects during the germination, tillering and grand growth phases these effects were significant during the germination and tillering phases. It had weak and insignificant negative effects during the grand maturation phase.

In the ratoon crops the mean maximum temperature had weak positive and insignificant effects on yield during the germination and tillering phases and negative effects on the yield during the grand growth and maturation phase although this effect was only significant during the grand growth phase.

Mean minimum temperature

In the plant crop mean minimum temperature had positive effects during all growth phases. This effect was strong and significant during the germination and tillering phases

In the ratoon crops the mean minimum temperature had weak positive effects on the yield that were only significant during the maturation phase.

Total number of degree days

In the plant crop total number of accumulated degree days had weak, negative insignificant effects during the germination, tillering and grand growth phases. It had weak and insignificant positive effects during the maturation phase.

In the ratoon crops the total number of accumulated degree days had weak positive effects the yield during all phases although this effect was only significant during the maturation phase.

Total amount of photosynthetic radiation intercepted

In the plant crop the total amount of intercepted photosynthetic radiation had weak, negative and insignificant effects during germination, tillering and grand growth phases; it had weak positive effects on yield during the maturation phase.

In the ratoon crops the total amount of intercepted photosynthetic radiation had weak, positive but insignificant effects on the yield during all phases.

Total amount of rainfall received

In the plant crop total amount of rainfall received had strong negative and significant effects during the germination and grand growth phases. Its effects during the tillering and maturation phases were weak, negative and insignificant.

In the ratoon crops the total amount of rainfall received had weak, negative and insignificant effects on the yield during the germination and grand growth phases; Its effects were weak and positive during the tillering and maturation phases although only significant during the maturation phase.

Table (17) presents a summary of the effects of the weather variables on cane yield in CO 421 plant and ratoon crops.

Table 17: Effects of the correlated weather variables and yield of variety CO 421 in the plant crop and in combined ratoon crops

Variable	CO 421 plant crop		CO 421 Ratoons	
	Pearson Correlation	Significance	Pearson Correlation	Significance
Mmaxgerm	-0.69	0.00	0.03	0.71
Mmingerm	0.74	0.00	0.00	0.95
Pargerm	-0.44	0.06	0.13	0.07
Raingerm	-0.12	0.61	-0.05	.0.51
Sddgerm	-0.38	0.10	0.01	0.87
Mmaxtill	-0.57	0.01	0.01	0.88
Mmintill	0.62	0.00	0.10	0.19
PARtil	-0.36	0.11	0.09	0.23
Raintill	0.12	0.63	0.04	0.61
Sddtill	-0.22	0.34	0.07	0.33
Mmaxg	-0.42	0.06	-0.21	0.00
Mming	0.37	0.10	0.05	0.51
PARg	-0.44	0.05	0.05	0.54
Raing	-0.35	0.13	-0.09	0.22
Sddg	-0.03	0.90	0.13	0.09
Mmaxmat	-0.05	0.83	-0.12	0.11
Mminmat	0.14	0.56	0.17	0.03
PARmat	0.40	0.08	0.13	0.08
Rainmat	0.11	0.63	0.32	0.00
Sddmat	0.43	0.06	0.18	0.02

4.4.1.3 Effects of the correlated weather variables and yield of Variety CO 945 in the plant crop and in combined ratoon crops

Mean maximum temperature

In the plant crop mean maximum temperature had weak positive effects during the germination, tillering and grand growth phase although the effects were only significant during the germination phase and tillering phase. It had weak and insignificant negative effects during the maturation phase.

In the ratoon crops the mean maximum temperature had weak negative effects on the yield although this effect was significant during the germination and grand growth phases.

Mean minimum temperature

In the plant crop mean minimum temperature had weak negative and significant effects during the germination and tillering phase and grand growth and a weak positive and insignificant effect on yield during the maturation phase of the crop development.

In the ratoon crops the mean minimum temperature had weak negative effects on the yield that was significant during the all growth phases

Total number of degree days

In the plant crop total number of accumulated degree days had weak negative effects during the germination and grand growth and maturation phases although the effects were insignificant during the germination phase. It had weak and significant positive effects during the tillering phase.

In the ratoon crops the accumulated degree days had weak significant negative effects on the yield throughout the growth phases.

Total amount of photosynthetic radiation intercepted

In the plant crop the total amount of intercepted photosynthetic radiation had weak positive but significant effects during the germination, tillering and grand growth phases; it had weak negative and insignificant during the maturation phase.

In the ratoon crops the total amount of intercepted photosynthetic radiation had weak, positive effects on the yield during the germination, tillering and maturation phases, these effects were significant during maturation phase; it had negative insignificant effects during the grand growth phase

Total amount of rainfall received

In the plant crop total amount of rainfall received had weak negative and significant effects during the germination and grand growth phases. It had weak positive insignificant effects during the tillering phase and weak positive significant effects during the maturation phase.

In the ratoon crops the total amount of rainfall received had weak negative effects on the yield during the germination, tillering and maturation phases although these effects were only significant during the tillering phase. The effects were weak positive and significant effects during the grand growth and maturation phase.

Table (18) presents a summary of the effects of the weather variables on cane yield in CO 945 plant and ratoon crops.

Table 18: Effects of the correlated weather variables and yield of Variety CO 945 in the plant crop and in combined ratoon crops

	CO 945 plant crop		**CO 945 ratoons**	
Variable	**Pearson Correlation**	**Significance**	**Pearson Correlation**	**Significance**
Mmaxgerm	0.44	0.00	-0.16	0.04
Mmingerm	-0.40	0.00	-0.31	0.00
Pargerm	0.52	0.00	0.27	0.00
Raingerm	-0.60	0.00	-0.07	0.34
Sddgerm	-0.16	0.16	-0.28	0.00
Mmaxtill	0.37	0.00	-0.11	0.15
Mmintill	-0.27	0.01	-0.34	0.00
PARtil	0.48	0.00	0.34	0.00
Raintill	0.01	0.92	-0.24	0.00
Sddtill	0.25	0.02	-0.23	0.00
Mmaxg	0.03	0.82	-0.24	0.00
Mming	-0.29	0.01	-0.19	0.01
PARg	0.43	0.00	-0.10	0.20
Raing	-0.28	0.01	0.16	0.04
Sddg	-0.35	0.00	-0.29	0.00
Mmaxmat	-0.19	0.09	-0.14	0.06
Mminmat	0.07	0.53	-0.19	0.01
PARmat	-0.07	0.53	0.25	0.00
Rainmat	0.45	0.00	-0.03	0.66
Sddmat	-0.06	0.58	0.09	0.25

4.4.1.4 Effects of the correlated parameters on yields in combined plant crop and combined ratoon crops across varieties

Mean maximum temperature

In the plant crop mean maximum temperature had weak positive effects during the germination and tillering phase although the effects were only significant during the germination phase. It had weak and insignificant negative effects during the grand growth and maturation phases.

In the ratoon crops the mean maximum temperature had weak negative effects on the yield although this effect was significant during the grand growth and maturation stages.

Mean minimum temperature

In the plant crop mean minimum temperature had weak negative effects during the germination and tillering phase and grand growth phases although the effects were only significant during the germination phase and a weak positive but insignificant effect on yield during the maturation phase of the crop development.

In the ratoon crops the mean minimum temperature had weak positive effects on the yield that was significant during the grand growth and maturation stages.

Total number of degree days

In the plant crop total number of accumulated degree days had weak negative effects during the germination and grand growth phase although the effects were only significant during the germination phase. It had weak and insignificant positive effects during the tillering and maturation phases.

In the ratoon crops the accumulated degree days had weak negative effects on the yield although this effect was only significant during the maturation phase.

Total amount of photosynthetic radiation intercepted

In the plant crop the total amount of intercepted photosynthetic radiation had weak positive effects during all the growth phases; these effects were significant during the germination, tillering and grand growth phases but insignificant during the maturation phase.

In the ratoon crops the total amount of intercepted photosynthetic radiation had weak, positive and significant effects on the yield during the germination, tillering and maturation phases but had negative insignificant effects during the grand growth phase

Total amount of rainfall received

In the plant crop total amount of rainfall received had strong negative and significant effects during the germination phase. Its effects during the tillering phase were weak, negative and insignificant. It had weak negative but significant negative effects during the grand growth and weak positive significant effects during the maturation phase. In the ratoon crops the total amount of rainfall received had weak negative effects on the yield during the germination and tillering phases although these effects were only significant during the tillering phase. The effects were weak and positive during the grand growth and maturation phase but the effect were only significant during the maturation phase.

Table (19) presents a summary of the effects of the weather variables on cane yield in the combined plant and ratoon crops.

Table 19: Correlation coefficients and their significance on yields in combined plant crop and ratoon crops

Parameter	Plant crop		Ratoon crops	
	correlation coefficient (R)	Significance	correlation coefficient (R)	Significance
Mmaxgerm	0.2156	0.0296	-0.0862	0.106
Mmingerm	-0.2533	0.0102	0.0254	0.635
Sddgerm	-0.1885	0.0577	-0.0313	0.559
Pargerm	0.381	<0.001	0.1712	0.001
Raingerm	-0.5252	<0.001	-0.082	0.126
Mmaxtill	0.1882	0.0582	-0.0943	0.077
Mmintill	-0.1583	0.1121	0.0901	0.092
Sddtill	0.1625	0.1026	0.0423	0.428
PAR till	0.3547	<0.001	0.1731	0.001
Raintill	0.0275	0.7841	-0.1474	0.006
Mmaxg	-0.0633	0.5277	-0.2609	<0.001
Mming	-0.1927	0.0523	0.1302	0.015
Sddg	-0.2929	0.0028	0.0639	0.232
PARg	0.3371	<0.001	-0.0863	0.106
Raing	-0.2797	0.0044	0.0694	0.194
Mmaxmat	-0.1628	0.1021	-0.1466	0.006
Mminmat	0.0831	0.4063	0.1769	<0.001
Sddmat	0.0313	0.7546	0.1896	<0.001
PARmat	0.0055	0.9561	0.1857	<0.001
Rainmat	0.3961	<0.001	0.1731	0.001

4.4.1.5 Effects of the parameters on yields in the combined crop classes in the different varieties

When the varieties were separated during the correlation majority of the variables showed significant effects on cane yield except mean minimum temperature during germination phase; mean maximum temperature during germination phase and mean maximum temperature during tillering phase

Mean maximum temperature

In both varieties the mean maximum temperature had weak negative effects during the germination, grand growth and maturation phases although the effects were insignificant during the germination phase. It had weak and insignificant positive effects during the tillering phase.

Mean minimum temperature

In the CO 421 the mean minimum temperature had weak positive effects during all the phases although these were only significant during the germination, grand growth and maturation phases and insignificant during the tillering phase.

In CO 945 the mean minimum temperature had weak negative effects on the yield that was significant throughout the crop phases.

Total number of degree days

In both varieties the total number of accumulated degree days had weak positive and significant effects during the germination, grand growth and maturation phases but had weak and significant negative effects during the tillering phase.

Total amount of photosynthetic active radiation intercepted

In both varieties the total amount of photosynthetic active radiation intercepted had weak positive and significant effects during the germination, grand growth and maturation phases but had weak and significant negative effects during the tillering phase.

Total amount of rainfall received

In both varieties the total amount of photosynthetic active radiation intercepted had weak positive and significant effects during the germination, grand growth and maturation phases but had weak and significant negative effects during the tillering phase.

Table (20) presents a summary of the effects of the weather variables on cane yield in combined classes in the different varieties

The correlation coefficients of the individual variables are generally small, because a single variable only describes a small amount of the yield variability in crop yields. The negative effect of rainfall received during the grand growth phase is contrary to the findings of Robertson et al., (1999), who reported that the period where rainfall was critical during the grand growth phase and that water stress during this phase significantly reduced biomass formation. The reasons for this contradiction could be that correlation is not causation and that this relationship is purely statistical and not a physiological one.

Table 20: Correlation coefficients and the significance of the parameters on yields in the two varieties

Parameter	**CO 421**		**CO 945**	
	correlation coefficient (R)	**Significance**	**correlation coefficient (R)**	**Significance**
Mmaxgerm	-0.0329	0.6417	-0.0067	0.9155
Mmingerm	0.0851	0.2275	-0.4025	<0.001
Sddgerm	0.5221	<0.001	0.4714	<0.001
Pargerm	0.5361	<0.001	0.5334	<0.001
Raingerm	0.3574	<0.001	0.196	0.0018
Mmaxtill	0.0081	0.9082	0.0997	0.1152
Mmintill	0.2094	0.0027	-0.4121	<0.001
Sddtill	-0.3749	<0.001	-0.4817	<0.001
Partill	-0.4627	<0.001	-0.3372	<0.001
Raintill	-0.1711	0.0146	-0.2713	<0.001
Mmaxg	-0.394	<0.001	-0.2522	<0.001
Mming	0.2052	0.0033	-0.3671	<0.001
Sddg	0.5421	<0.001	0.4268	<0.001
Parg	0.529	<0.001	0.5077	<0.001
Raing	0.3058	<0.001	0.3855	<0.001
Mmaxmat	-0.1902	0.0066	-0.2738	<0.001
Mminmat	0.312	<0.001	-0.2397	<0.001
Sddmat	0.3989	<0.001	0.2617	<0.001
Parmat	0.3848	<0.001	0.3819	<0.001
Rainmat	0.4322	<0.001	0.2988	<0.001

4.4.2 Results of the regression analysis

This section presents the results from the both the linear multiple regression analyses performed using the Proc Reg and the mixed linear regression analysis performed using the Proc Mixed.

4.4.2.1 Proc Reg results

The following are the resultant equations obtained from the Proc Reg analyses of the varieties and crop classes;

1. **C0 421 Plant crop**

$Y = 344 - 13.53a + 13.95b$

Where;

Y = Yield in TCH

a = the mean maximum temperature during the germination phase

b = the mean minimum temperature during tillering phase

2. **CO 421 ratoon crops**

$Y = 223.49 - 5.08a + 0.02b$

Where;

Y = Yield in TCH

a = the mean maximum temperature during the grand growth phase

b = the total rainfall received during the maturation phase

3. CO 945 plant crop

$$Y = 6.86a + 0.28b - 0.10c - 16.07d + 0.38e - 0.13f + 13.65g - 0.04h - 0.03i$$

Where;

Y = yield in TCH

a = the mean maximum temperature during the germination phase

b = the total amount of PAR received during the germination phase

c = the total amount of rainfall received during the germination phase

d = the mean maximum temperature during the tillering phase

e = the total amount of PAR received during the tillering phase

f = the total number GDD accumulated during the tillering phase

g = the mean minimum temperature during the grand growth phase

h = the total amount of rainfall received during the grand growth phase

i = the total amount of rainfall received during the maturation phase

4. CO 945 ratoon crops

$$\text{Yield} = -4.73a + 0.37b + 0.09c - 0.02d - 0.05e + 2.02f - 9.89g + 0.03h + 7.85i + 0.02j$$

Where;

Y = Yield in TCH

a = the mean maximum temperature during germination phase

b = is the total amount of PAR received during the germination phase

c = the total PAR received during the tillering phase

d = the total amount of rainfall received during tillering phase

e = the total number of GDD accumulated during the tillering phase.

f = the mean maximum temperature during the grand growth phase

g = the mean minimum temperature during the grand growth phase

h = the total amount of rainfall received during the grand growth phase

i = the mean minimum temperature during the maturation phase

j = the total amount of PAR received during the maturation phase

The models for variety CO 421 indicate that in the plant crop, high mean maximum temperature during germination reduced the yields while an increase in mean minimum temperatures during tillering increased the yields. The higher maximum temperatures could be associated with dry conditions. In the ratoon crop, mean maximum temperature during the grand growth phase reduced the yields (possibly due to drought or dry conditions) while an increase in rainfall during the maturation phase resulted in higher yields (possibly due to rehydrating of canes).

In CO 945 (plant crop and ratoon crops), the models with lowest AIC had no intercept, this is due to the higher number of variables. In the plant crop, higher mean maximum temperatures and total amount of photosynthetically active radiation at germination increased the yield, while as the total rainfall received during this phase increased, the yields decreased possibly due to the rotting of setts resulting in poor germination. A summary of the statistical parameters is shown on Table 21.

Table 21: Results of the regression analysis showing the best model selected on the basis of AIC

	CO 421 Plant Crop		**CO 421 Ratoon crops**		**CO 945 Plant crops**		**CO 945 Ratoon crops**	
	Variable	**Estimate**	**Variable**	**Estimate**	**Variable**	**Estimate**	**Variable**	**Estimate**
Significant weather variables	Mmaxgerm	-13.53	Mmaxg	-5.08	Mmaxgerm	6.86	Mmaxgerm	-4.73
	Mmintill	13.95	Rainmat	0.02	Pargerm	0.28	Pargerm	0.37
					Raingerm	-0.10	Partill	0.09
					Mmaxtill	-16.07	Raintill	-0.02
					Mmintill	-10.65	Sddtill	-0.05
					Partill	0.38	Mmaxg	2.02
					Sddtill	-0.13	Mming	-9.89
					Mming	13.65	Raing	0.03
					Raing	-0.04	Mminmat	7.85
					Rainmat	-0.03	Parmat	0.02
Intercept	344.19		223.49		nil		Nil	
RMSE	16.45		19.23		19.64		21.80	
SSE	4600.87		66535.52		27772.30		75548.38	
R^2	0.70		0.13		0.98		0.96	
Adjusted R^2	0.66		0.12		0.98		0.95	
AIC	114.77		1084.97		497.66		1051.34	

4.4.2.2 Proc Mixed Results

Linear mixed regression analysis in SAS Proc Mixed was used to establish a statistical relation among the variables and eliminate the non-significant variables while factoring in the effects of the categorical variables. Sugarcane yield (TCH) was defined as the dependent variable. The predictor variable set comprised 4 qualitative parameters, defined as categorical variables, and 15 quantitative parameters defined as continuous variables.

Only 4 weather variables were found to significantly account for observed yields in Mumias nucleus estate from the Proc Mixed analysis. These were;

(i).	Number GDD during the germination phase	Negative effects
(ii).	Total PAR during grand growth phase	Positive effects
(iii).	Total rainfall received during the grand growth phase	Positive effects
(iv).	Number GDD during the maturation phase	Negative effects

The number of GDD during germination had negative effects on yields. GDD is a temperature derivative and thus more GDD simply implies high temperatures and as a result possible dehydration of planted cane setts. Positive effects of total PAR and rainfall received during the grand growth are consistent with the work of Robertson, et al., (1999) and Koonjah, et al., (2000). The total number of GDD accumulated during the maturation phase had a negative effect on yield. This can be attributed to desiccation of canes in the field before harvest as yields are based on fresh weight. Further work on the quality of cane in terms of sugar content in the stalks could help refine this work.

Using Proc GLM in the SAS software these variables were regressed against cane yield to obtain parameter estimates that can be used in the regression equation. Table (22) shows the results of this analysis.

Specimen calculation:

Y = Constant + Season - Management - Variety + Plant / Ratoon crop + $0.375a - 0.033b + 0.11c + 0.01d - 0.028e$

Where;

Y = Yield in TCH

a = the age of cane at harvest

b = the total number of GDD accumulated during the germination phase

c = the total amount of PAR received during the grand growth phase

d = the total amount of rainfall received during the grand growth phase

e = the total number of GDD accumulated during the maturation phase

This model accounted for 36.8% of yield variation and had a RMSE of 24.94

Two important considerations should be borne in mind when interpreting this model. Firstly, the predictor variables are not necessarily the cause of sugarcane yield variations, but are related only in a strictly statistical sense. Secondly, variables in a multiple regression are seldom independent of one another thus complicating the interpretation.

Phased weather effects predicted by a regression model are not easily interpreted from a physiological background because the model can only be an approximation of the underlying processes, and may fail to include some of them. Because of their empirical nature of this regression model, application is restricted to the range of weather data from which it was developed and for the particular area studied, therefore extrapolation to other areas or periods cannot be made without testing.

Table 22: Regression coefficients for the Proc Mixed yield model

CATEGORICAL VARIABLES	Levels	Regression coefficients differences	Standard error	t-value	Probability Pr >! t!
Intercept		-114.198	29.212	-3.91	<0.0001
Crop class	A#	50.739	11.223	4.52	<0.0001
	B#	39.748	11.287	3.52	0.0004
	C#	35.164	11.246	3.15	0.0018
	E#	Reference	-	-	-
Variety	CO 421	-14.366	1.169	-12.29	<0.0001
	CO 945	0	-		
Management	0*	-23.320	1.764	-13.22	<0.0001
	1*	Reference	-	-	-
Season	1	5.884	1.510	3.90	<0.0001
	2	16.623	1.534	10.84	<0.0001
	3	10.037	1.168	8.59	<0.0001
	4	Reference	-	-	-
CONTINUOUS VARIABLES		Regression coefficient	Standard error	t-value	Probability Pr >!t !
Age		0.375	0.043	8.51	<0.0001
Sddgerm		-0.033	0.012	-2.71	0.0069
Sparg		0.011	0.004	2.35	0.0188
Sprg		0.006	0.002	3.14	0.0017
Sddmat		-0.028	0.004	-6.92	<0.0001

E# Plant crop

A# =ratoon 1

B# ratoon 2

C# >ratoon 2

0* =yields after 1997

1*= yields before 1997

Season 1= January to February

Season 2 = March to May

Season 3= June to August

Season 4 September to December

CHAPTER 5

5.0 CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the conclusions that can be drawn from the results and discussions in chapter 4 and proposes several recommendations for future work

5.1 Conclusions

Based on the analysis of monthly minimum and maximum temperature and both monthly and seasonal precipitation over the 40-year period (1968–2007), several general conclusions can be made. First, precipitation in Mumias seems not to have significantly increased during the study period. Second, minimum temperatures have significantly increased over the period, throughout the year. Third, maximum temperatures have changed little over the last 40 years of the study period. This suggests that the prevailing synoptic weather systems responsible for the observed trends may be undergoing significant shifts. This requires further analysis. The results from analysis of rainfall and temperature trends in Mumias are consistent with the findings of Sabiiti, (2008), who observed increasing trends in both the minimum and maximum temperatures over the Lake Victoria Basin. These observed and projected changes may impact on sugarcane production in Mumias.

Yields have significantly reduced. With a steady decline since 1997 which is attributable change in crop management. Yields before 1997, which marks the period when filter mud was applied to the fields were significantly higher than after 1997 by 18.88 tonnes per hectare. CO 421 although less sensitive to weather variables than on CO 945 was seemingly more sensitive to management practices. Data on agronomic management could have increased the ability of the model.

The above findings show that the yield variability at Mumias depends on variations in weather only to a certain extent and that this weather-yield relationship also depends on the variety cultivated.

This preliminary work on sugarcane-weather yield relationships is not exhaustive. Further studies will be required to establish the effect of planting and harvesting dates and management practices on sugarcane productivity.

5.2 Recommendations and suggestions for further work

Based on these findings, the increasing minimum and maximum temperatures may result in increased flowering in the study site then sugarcane yields will be further affected. Therefore, further research needs to be conducted on this. Given the complex system involving many interactions under which sugarcane is cultivated in Kenya, I recommend that crop simulation models be calibrated and made available as this will expedite future studies. Crop simulation modeling requires very detailed crop and climatological data, as such, the availability of long period, high quality weather and agricultural records is crucial for maximum application of weather and climate information in agricultural planning and operations.

Metadata associated with weather and crop data needs also be collected and well archived. These include considerable changes in the locations, exposure and types of instruments, changes that may have occurred in observation routines, types of sensors, and any changes due to fast development in science and technology. Such changes can make observations taken before and after such changes not too strictly comparable. These can mask the typical linkages between weather and agricultural systems. The length and quality of the weather and agricultural records are key issues that must be addressed as they provide the information base in any efforts to optimize applications of climate and weather prediction products in agricultural planning and management. This requires user specific computerized databases, and improved agrometeorological networks.

Optimum utilization of any weather and climate prediction products in the industry will require basic and applied agrometeorological research, including understanding of the local climate/agricultural systems and the associated linkages, especially with respect to extreme events, climate and pests/diseases linkages, and adaptation of agricultural systems to the local climate variability. Enhanced agrometeorological research is required to meet the agrometeorological challenges facing the industry. Improved and integrated data sources and interpolation methods, locally validated crop models, and the use of downscaled forecasts are realistic and attainable goals.

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