Impact and implications of climate variability and change on glacier mass balance in Kenya

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Declaration

I con rm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

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Abstract

Kenya's economy relies heavily on the agricultural indsutry as its main source of economy. Glaciers provide a large store of freshwater and modelling of the meltwater associated with this is of great interest to water management. with growing concern over the impact of glacier retreat on runo and stream ow, this study aims to simulate runo from the tropical Lewis Glacier in Central Kenya and its impacts on runo due to climate variability.

Acknowledgments

The writing of this dissertation has been one of the most signi cant academic challenges I have ever had to face. Without the support, patience and guidance of the following people, this study would not have been completed. It is to them I owe everlasting gratitude.

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To Jasdeep Giddie, thank you for all your love and patience, for believing in me and most of all, for all the compromises you have had to make this year so I could undertake this task.

`Asante Sana' to all friends and family who have taken this journey with me.

Contents

Chapter 1

Introduction

1.1 Background

Kenya relies heavily on its natural resources to generate income. High altitude, fertile soils and abundance of precipitation (1000mm) in Central and Western Kenya make it the ideal place for growing tea and co ee, two of Kenya's highest GDP earners. Other agricultural goods such as horticulture and sugar cane also rely heavily on water availability. The impacts on water resources in Kenya due to climate variability are thus of great importance.

Mount Kenya is located on the equator in East Africa with the two highest peaks, Batian and Nelion, reaching about 5,200 m. It lies at the apex of three water sheds, Uasin Nyiro, Tana and Rift Valley catchments as per the map below. According to Young & Hastenrath (1991), there are total of 11 glaciers on Mount Kenya, of which the Lewis and Tyndall glaciers are the two largest and most studied. In this study, the focus will be on the modelling of the mass balance of the Lewis Glacier as it covers the largest area of 0.31 km^2.

In high mountainous catchments, glaciers represent the most important

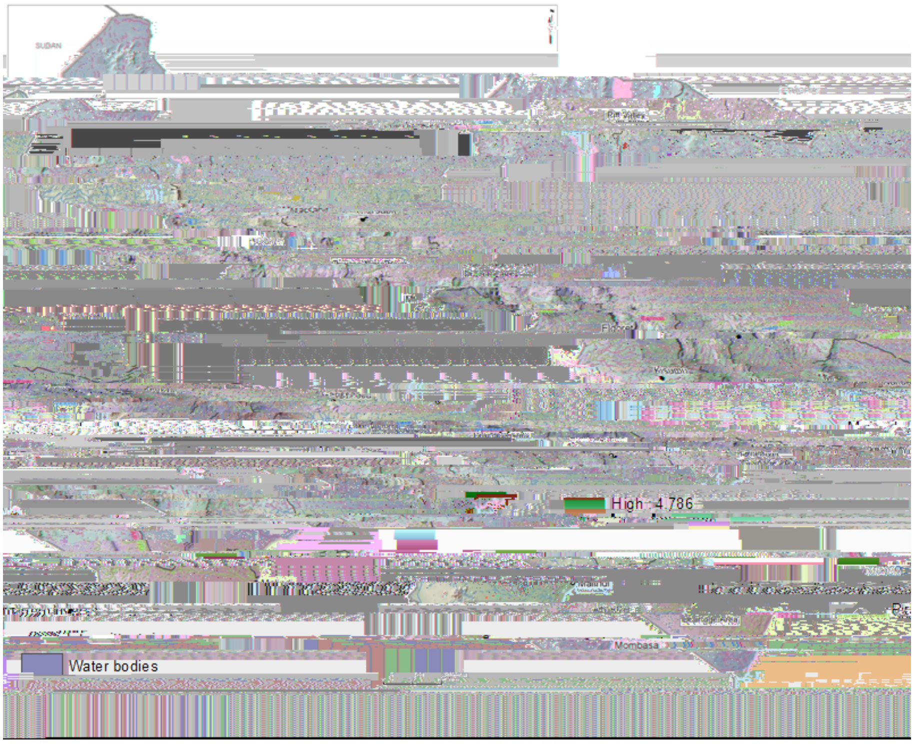

Figure 1.1: Kenya and major catchments (World Resources Institute)

balance can be predicted for catchments containing advancing or retreating glaciers (Bienn and Evans (1998)).

1.2 Goals

The aims of this study are:

1. To model the mass balance profile of the Lewis Glacier using baseline and climate change data; and
2. To assess the effects of the change in glacier mass balance on downstream water resources

1.3 Outline

The outline of the dissertation is as follows:

In the second chapter the study approach, an introduction to the glacier model, the hydrological model and data sets used are discussed.

In Chapter 3, the glacier model based on Kaser (2001) and Kaser and Osmaston (2002) is developed.

Results of the study are presented in Chapter 4.

Finally, Chapter 5 summarises the findings of the study along with caveats and further work is proposed.

Chapter 2

Experimental Design

This is the chapter where I describe the models and data sets used.

1. Glacier model

2. Mac-PDM model

3. Data Basis

2.1 The Study Approach

tion and ablation gradients. The mass balance pro le is proportional to the size of the glacier and hence we can estimate the volume of water stored in the glacier may be estimated. Converting the glacier into the water equivalent, the meltwater runo can be added to average runo in each grid cell that the glacier occurs in.

2.3 The Hydrological Model - Mac-PDM

Background

A macro-scale model is one which can be applied repeatedly over a large geographic domain and does not need to be calibrated at the catchment scale. According to Arnell (1999a), the model was rst developed to be used by hydrologists to simulate the e ects of climate change in East Africa (Arnell (1999b)), where observed data is scarce, and later extended to cover the whole world.

The hydrological model was used to simulate runo in Kenya using Climatic Research Unit (CRU) dataset for present day data from 1961 - 1990, while climate change projections came from 5 di erent models, CCMA-CGCM31, IPSL-CM4, MPI-ECHAM5, NCAR-CCSM30 and UKMO-HADCM3 using the A1B emission scenario from the International Panel on Climate Change (IPCC) 1997 reports.

Mac-PDM Hydrological Model

The Mac-PDM Model as explained by Arnell (1999a, 2003) is described below.

The hydrological model used is a conceptual water balance model working on a time step of one day, with the following basic structure:

$$\frac{dS}{dt} = P \quad E \quad D \quad Q$$

where P, E, D and Q are precipitation, evaporation, delayed run o and direct runo during the time interval t, respectively. dS is the change in storage of water in soil, lakes and wetlands over the time t.

Stream ow is simulated at a spatial resolution of $0.5 \times 0.5^\circ$ (or 2000 km^2), treating each grid cell as an independent catchment. Input parameters are assumed to be constant across the entire grid cell while soil mositure storachieved by statistically varying the soil moisture storage capacity in each grid cell.

Actual evaporation (AE) is a linear function of potential evaporation (PE) and average cell soil moisture content. When eld capacity (FC)is reached, actual evaporation is less than the potential evaporation and can be summarised as

Parameter	Description	Source
T_{crit}	Temperature threshold for snowfall and snowmelt	0° C - Fixed
Melt	Melt rate	4 mm $°C^{-1}$ $d^{-1)}$ Fixed
b	Parameter describing distribution of soil moisture capacity	0.25 Fixed
Sat	Saturation capacity in %	Function of soil texture and vegetation
FC	Field capacity in %	Function of soil texture and vegetation
RFF	fraction of cell that is not "not grass"	Function of vegetation type
	Interception capacity	Function of vegetation type
	Parameters of interception model	Fixed
Root depth	Depth of vegetation used to de ne saturation and eld capacity in absolute terms	Function of vegetation type
LAI	Leaf area index used in Penman-Monteith	Function of vegetation type
r_s	Stomatal conductance used in Penman-Monteith	Function of vegetation type
H_c	Vegetational roughness height used in Penman-Monteith	Function of vegetation type
S_{rout}	Routing parameter for direct runo	Fixed
G_{rout}	Routing parameter for delayed runo	Fixed

Each grid cell is classi ed according to a soil type based on United Nations Food and Agriculture (FOA) data. Soil type is important as soil moisture storage is a function of texture.

To account for variations in seasons, a sine curve is tted to maximum and minimum monthly temperatures with an additional random deviation of 2° around the sine curve to simulate uctuations in daily temperature.

2.4 Emission Scenarios Data Sets

The climate change data is based upon the pattern scaling technique. The scenarios have been developed using ClimGen. The data for 5 GCMs, for the A1B emissions scenario, for 2040-2069. The scenarios used are for the patterns of climate change associated with 5 different General Circulation Models (GCM). The 5 models are (modelling institution and model version):

IPSL CM4

CCCMA CGCM31

UKMO HadCM3

MPI ECHAM5

NCAR CCSM30

The A1B scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies) (UNEP, 2001)

Chapter 3

The Lewis Glacier Model

3.1 Background

Modelling of glaciers (prediction of meltwater driven stream ow)has been regarded as a valuable tool for e cient water resource management. As a result, several models have been developed. According to Hock (2005), the range of models used to forecast meltwater production from glaciers ranges from energy-balance models to temperature-index models and several mixtures of the two.

Glaciers can be classed into three broad categories, each with unique characteristics: polar glaciers, midlatitude glaciers and tropical glaciers.

2. the region experiences net heating: incoming solar radiation is greater than outgoing terrestrial radiation;

3. sea surface temperatures exceed 24° C; and

4. the diurnal cycle of temperature exceeds the annual cycle (no seasonal variation except for oscillating `wet' and `dry' periods de ned by precipitation).

Mount Kenya thus clearly falls within the tropics and the glacier modelled accordingly.

Mass Balance can be measured in one of four ways:

The amount of annual ablation and accumulation varies systematically with altitude. The rate at which annual ablation and accumulation change with altitude are termed ablation gradient and accumulation gradient, respectively. Together they de ne the mass balance gradient.

Mass balance gradients link climatic conditions on ablation and accumulation with glacier behaviour and is therefore an important measure of glacier activity (Bienn and Evans, 1998). Ablation gradients vary approximately linearly with altitude, being highest at the snout and decreasing with altitude because temperature declines with higher altitude at a lapse rate of 0.0065 K m^{-1}. Conversely, accumulation generally increases with altitude, rising from zero at the equilibrium line (ELA). ELA is the altitude at which ablation is equal to accumulation and hence net mass balance is zero. According to Kaser (2001) and Kaser and Osmaston (2002), the ELA is more or less equal to the altitide at which the air temperature is 0° C at the inner tropics.

3.3 The Model

The model described below is based on the vertical mass balance gradient compiled by Kuhn (1980) and further developed by Kaser (2001) and Kaser and Osmaston (2002).

The speci c mass budget b at any altitude z on a glacier over a speci c period, usually one year, is made up of the sum of speci c accumulation $c(z)$ and speci c ablation $a(z)$

$$b(z) = c(z) + a(z). \tag{3.1}$$

This is also true for the vertical mass balance gradient

$$\frac{db}{dz} = \frac{\partial c}{\partial z} + \frac{\partial a}{\partial z} \tag{3.2}$$

with $c(z)$ positive, $a(z)$ negative and z positive vertically upward.

Ablation is made up of meltwater runo $m(z)$ and the sublimation process $s(z)$ into the atmosphere, Both are goverened by latent heat uxes $Q_M(z)$ for melting and $Q_L(z)$ for sublimation. Thus speci c ablation is

$$a(z) = m(z) + s(z) = \quad (z) \quad \frac{1}{L_M} Q_M(z)) + \frac{1}{L_S} Q_L(z) \tag{3.3}$$

with the heat of fusion $L_M = 0{:}334$ in [MJ kg^{-1}], the heat of sublimation $L_S = 2{:}835$ in [MJ kg^{-1}], and the duration of the ablation season , counted in days [d].

The heat balance on the surface of the glacier is given by

$$Q_M(z)+Q_L(z)+Q_R(z)+Q_S(z) = 0 \qquad [\text{MJ m}^{-2} d^{-1}][\text{MJ m}^{-2} d^{-1}][\text{MJ m}\ ^2 d\ ^1][\text{MJ m}\ ^2 d\ ^1] \tag{3.4}$$

where $Q_R(z)$ is the heat ux resulting from the radiation balance and $Q_S(z)$ is the sensible heat ux. If $Q_M(z)$ is replaced with the help of (3.4), then speci c ablation becomes

$$a(z) = \quad (z) \quad \frac{1}{L_M}(Q_R(z) + Q_S(z)) + \quad \frac{1}{L_S} \quad \frac{1}{L_M} \quad Q_L(z) \tag{3.5}$$

The sensible heat ux $Q_S(z)$ is derived from the heat transfer coef- cient for turbulent exchange $_s$ in [MJ m^{-2} d^{-1} °C^{-1}] and the di er- ence in temperature between the atmosphere and the surface of the glacier $(T_a(z) \quad T_s(z))$ in [K]

$$Q_S(z) = \ _s(T_a(z) \quad T_s(z)): \tag{3.6}$$

The radiation balance is composed of the absorbed portion of the global (shortwave) radiation $G(z)(1 \quad r(z))$, the atmospheric incoming longwave radiation $A(z)$ **r**

Taking a reference level z_{ref} where $T_a = 273.15$ K $= 0°$C, which is equal to the 0°C level during the ablation period and taking into account the following assumptions:

- the surface temperature $T_s = 273.15$ K $= 0°$C over the entire glacier,
- the vertical gradient of the effective global radiation is $\partial G(1-r)/\partial z = 0$, and
- the vertical gradient of the latent heat flux is $\partial Q_L/\partial z = 0$,
- $4\varepsilon_a \; 273.15^3 = \; _R$

then the vertical ablation gradient at z_{ref} is

∂a

and air temperature, and the duration of the ablation period. The possible in uences of the remaining heat balance key variables and their dependency on the vertical variations of the length of the ablation period are ignored here.

Note: This equation describes the variation of the speci c mass balance with altitude (and thus the mass balance pro le) under the assumption that it depends entirely on the vertical gradients of the accumulation, ablation and air temperature, and the duration of the ablation period. The possible in uences of the remaining heat balance key variables and their dependency on the vertical variations of the length of the ablation period are ignored here.

The vertical mass balance pro le in the tropics

The above model was rst used on Hintereisferner in Switzerland from climatic data under the assumptions of equilibrium conditions and then compared with a measured pro le to form a model for the midlatitudes, with the aim of developing a simple formulation that could be transferred to the postulated climatic di erences in the tropical regions.

One of the foremost patterns to note is that the ablation period in tropical regions is assumed = 365 days per year everywhere on the glacier and below the z_{ref} (due to the absence of distinct seasons as per the mid to high latitudes (since the uctuation in seasonal temperature does not exceed the diurnal temperature)). This implies that @ =@z = 0,which in turn makes

The average values for the parameters used in the model calculation are cient since all the terms in equation 3.13 are linear. A Runge Kutta scheme could be used to discretize the di erential if the vertical accumulation gradient is assumed to be non linear or if the scheme is applied to midlatitude glaciers where the ablation term becomes non linear since $/ \ z = 0.1$.

m^{-2} and 1200 kg m^{-2} when compared with the baseline pro le (top line).

4.2 Mass Balance and Volume of Glacier

Having determined the optimum parameter values for the model, the volume of the glacier was determined by mulitplying the speci c mass balance at each elevation band with the corresponding area that the glacier occupied at that level. However, the area occupied by the glacier can only be inferred from observation. At present, there is no way of predicting the area occupied by a glacier in the future apart from statistical inference of present data.

The observed area covered by the glacier was used to project when the glacier would cease to exist using linear regression. It was assumed that the area of the glacier would continue to decrease since the model predicts negative mass balance trends. As suggested by Figure 4.3, the Lewis Glacier will cease to exist in 2039 if the linear regression line is used to predict future changes in area of the glacier.

The relationship between speci c mass balance, meltwater and area of the Lewis Glacier is summarised in Figure 4.4. The volume of the glacier is directly proportional to the potential runo from the glacier. Negative mass balance coupled with decreasing area of the glacier implies that meltwater from the glacier also decreases.

4.3 Implications of Surface Runo and Glacier Melt

To analyse the implications of glacier meltwater downstream from the glacier, average annual runo from the hydrological model for the grid cell was added to the meltwater and then divided by 2000 km^2 to get the runo per square km. The Lewis Glacier has a south east aspect and average annual runo from 8 grid cells adjacent to the east, south and south east of Mount Kenya grid cell were used to analyse the e ect of the glacier downstream.

It is clear from the gures above, that as the size of the catchment is increased, the impact of the glacier on runo generation decreases. Infact, it has little e ect on the runo from baseline 1961 - 1990 data and no e ect on runo for projected climate change scenario using 2010 - 2039 IPSL data (Figure 4.6).

The glacier presently occupies 0.31 km^2, which accounts for 0.0155% of the grid cell. As per the analyses above, this area is projected to decrease even further and hence runo generated from the meltwater of the glacier has little e ect on the catchment area. As per Figures 4.5 and 4.6 below, it can be seen that as the size of the catchment is increased, the meltwater from the glacier has no impact on the runo generated in adjacent grid cells.

4.4 Climate variability and Runo

From the above analyses, it was noted that the Lewis Glacier has little or no e ect on average annual runo . The following gures show changes to runo in Kenya due to climate variability using the 5 models, CCMA CGCM31, IPSL CM4, MPI ECHAM5, UKMO HADCM3, and NCAR CCM30 which are based on IPCC SRES emssion scenario A1B for the years 2040 - 2069.

Figure 4.7 shows the average annual runo between 1961 and 1990. It shows higher runo in the Rift Valley, Central Kenya, West Kenya and the Coast. Average runo in the North and North East of the country is less than half of that in other parts. The model shows that there is highest runo in the Mount Kenya region.

The CCMA CGCM31 model shows the highest increase in average runo by 105% for most parts of Kenya and in particular the Rift Valley Region. In contrast, the MPI ECHAM5 model simulates decrease in runo in Western Kenya by 15% and an increase in runo in Eastern Kenya. All the models show a decrease in runo at the coast between 5 and 15% excpet NCAR CCM30.

This bodes well for agricultural sector since tea and co ee farms are locared in the highlands (Central Kenya) and horticultural farms are located in the Rift Valley.

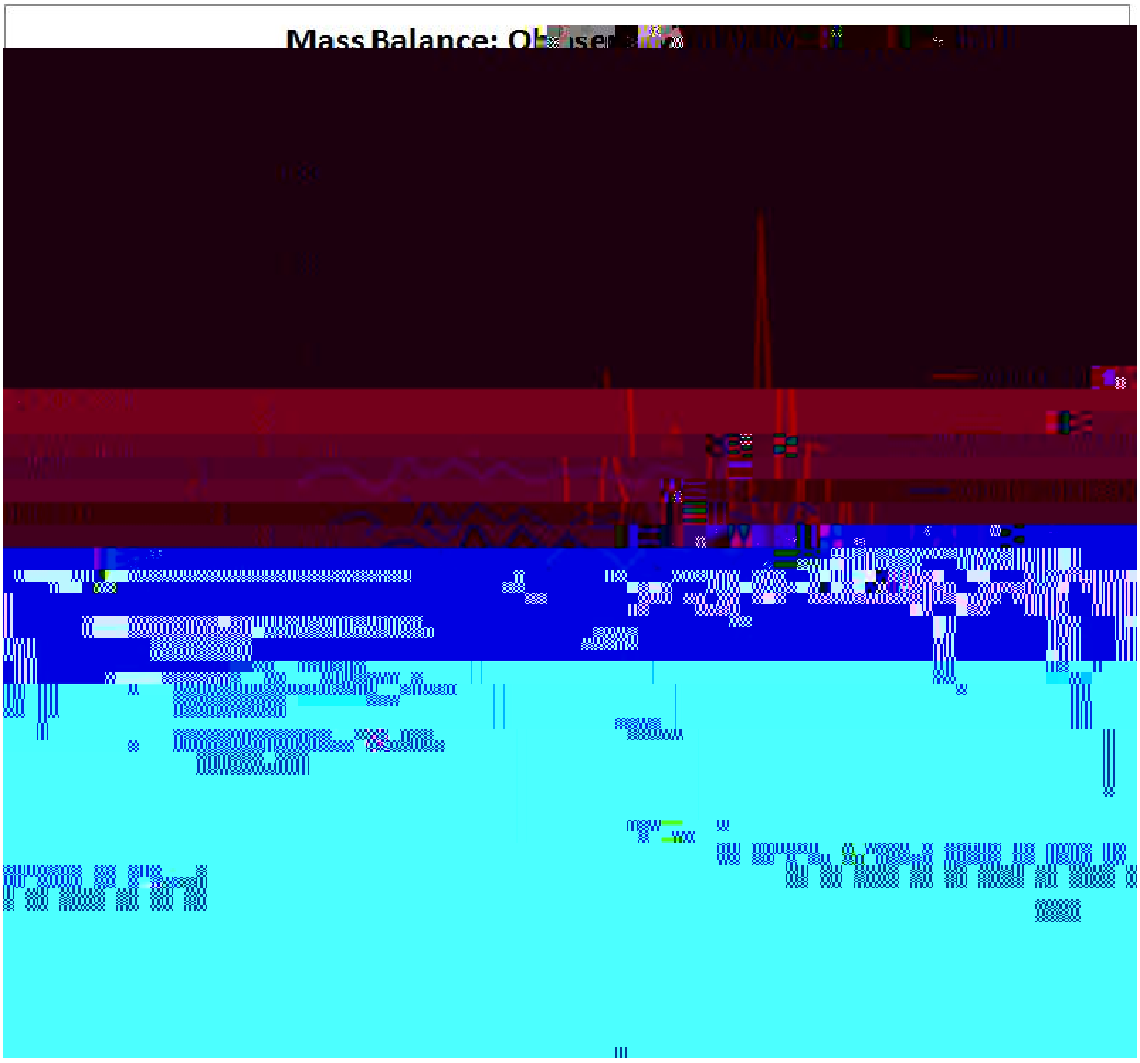

Figure 4.1: Observed and simulated mass balance profiles.

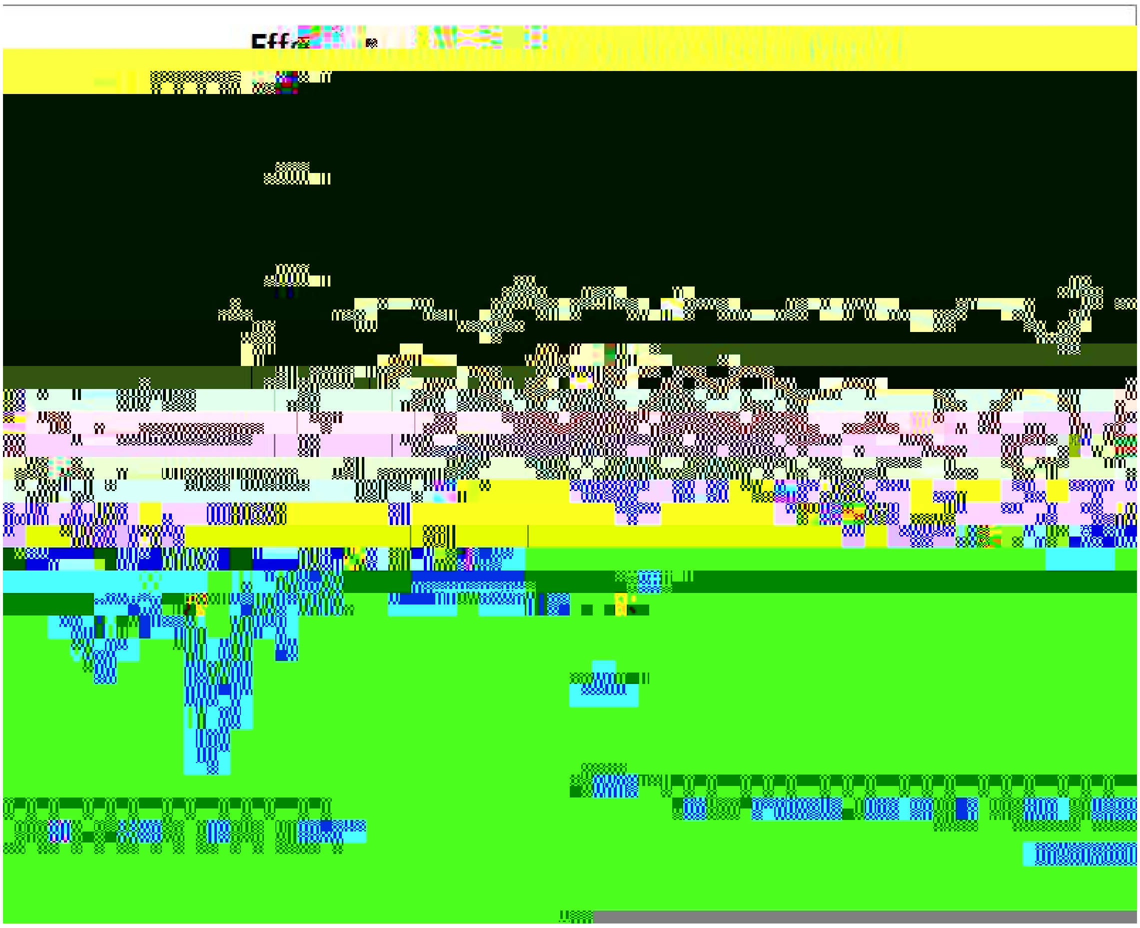

Figure 4.2: Specific mass balance profile simulations with different climate change projections.

Figure 4.3: Projected area of Lewis Glacier over time.

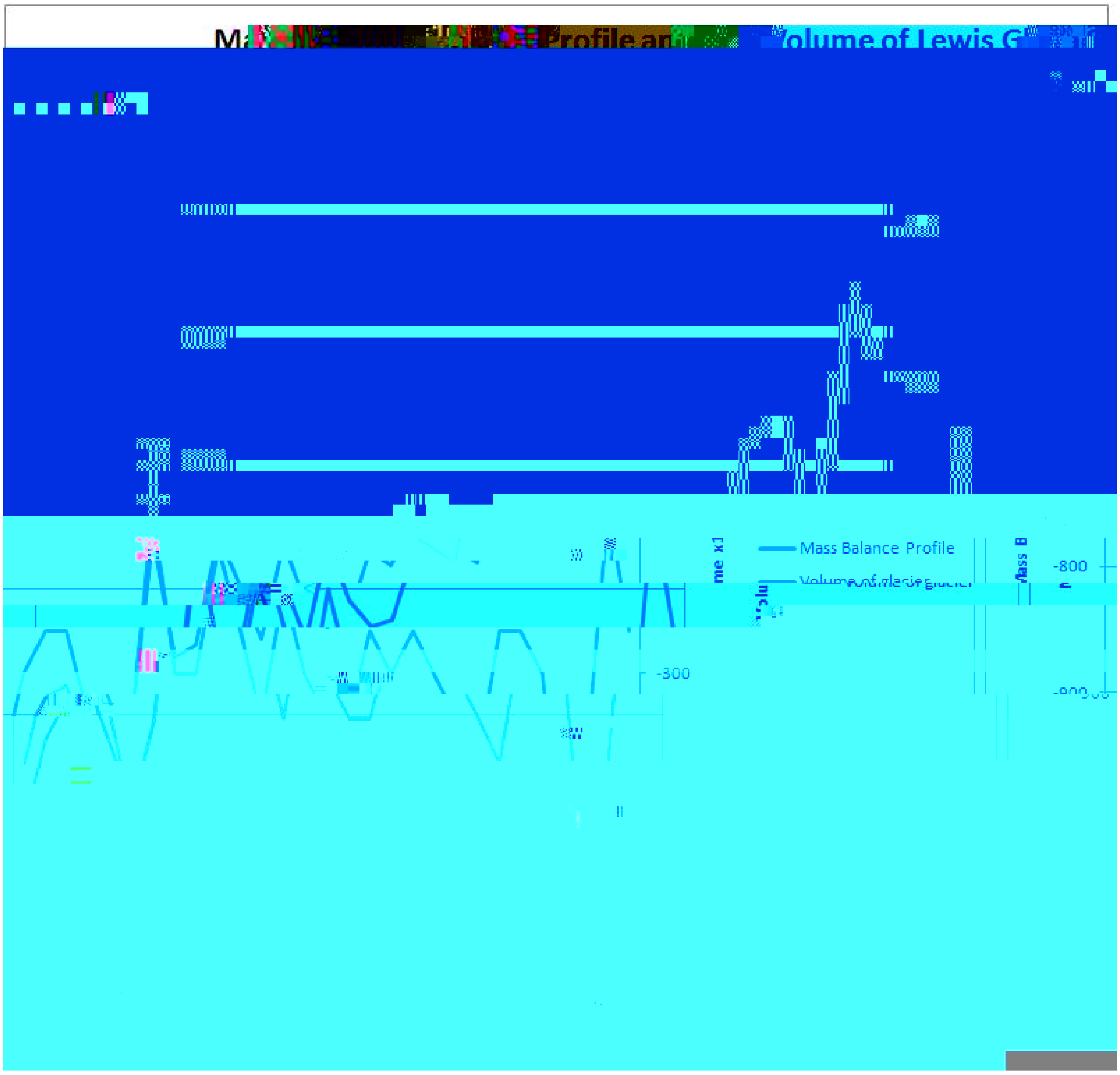

Figure 4.4: Change in volume of glacier.

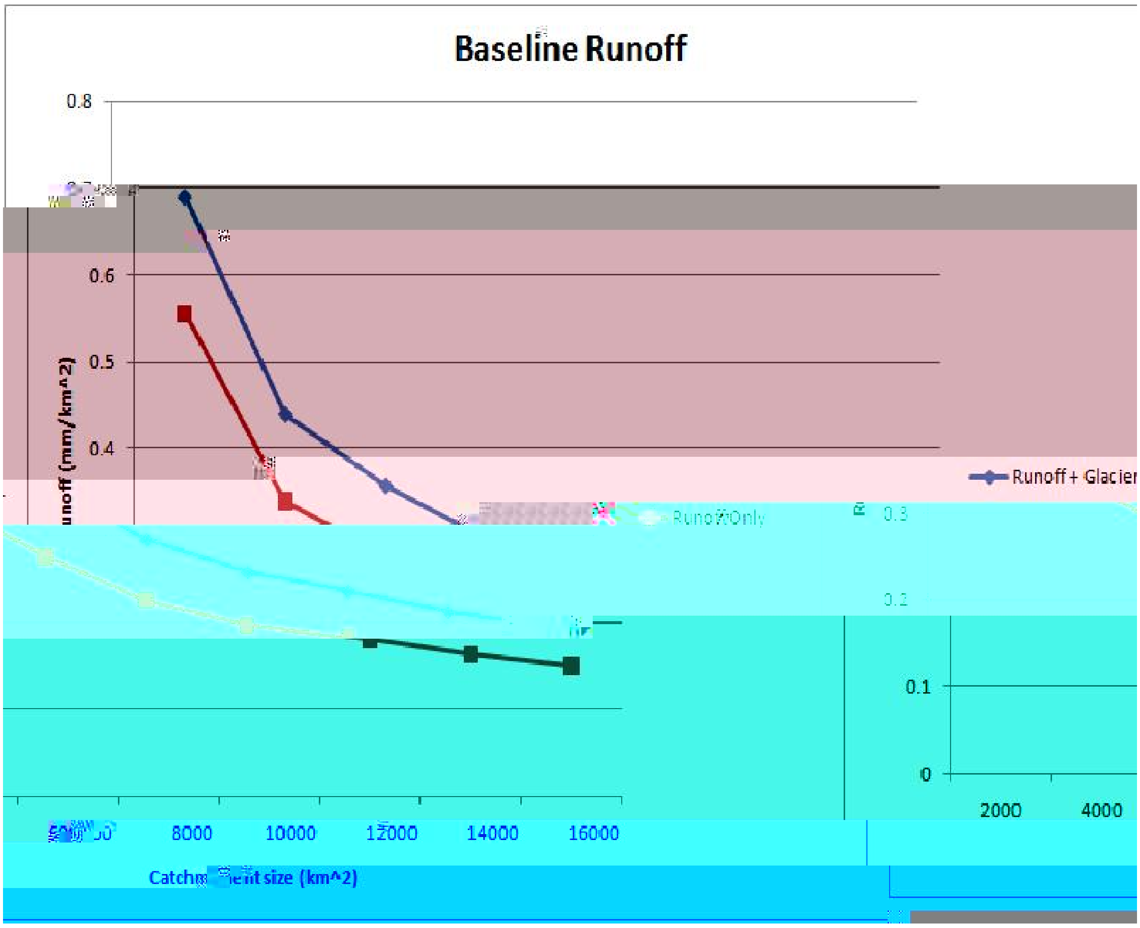

Figure 4.5: E ect of glacier on runo and surrounding catchment for current climate.

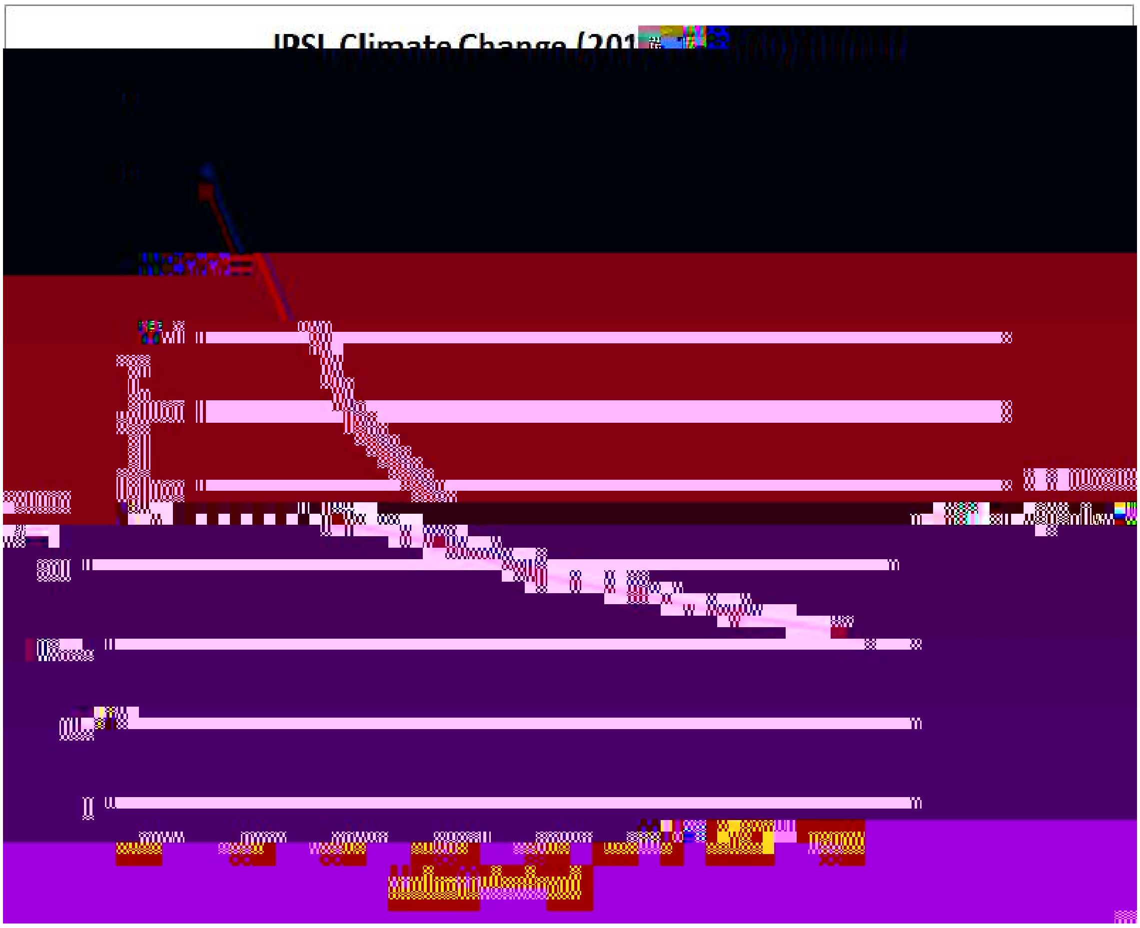

Figure 4.6: Effect of glacier on runoff and surrounding catchment for future climate.

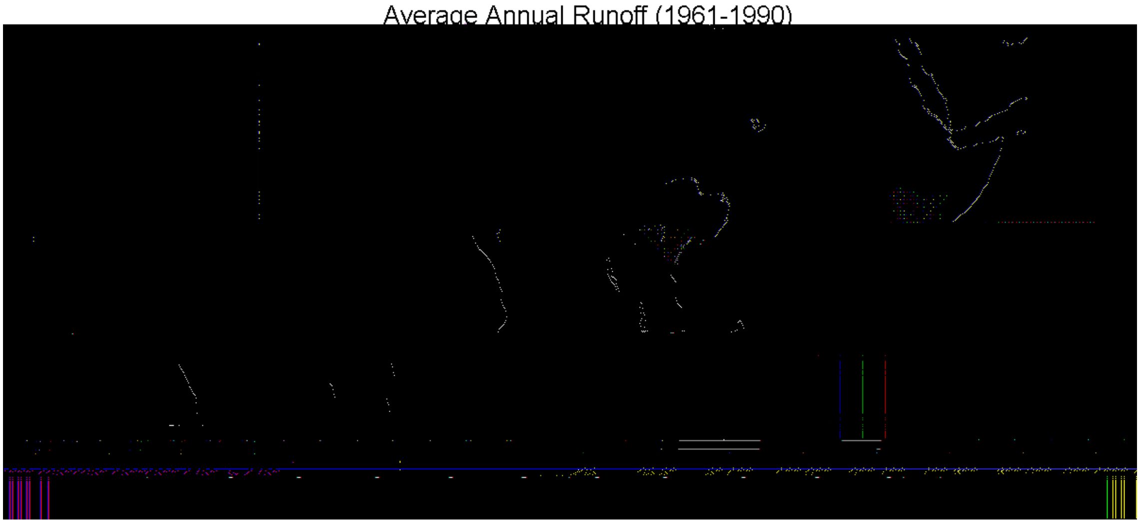

Figure 4.7: Average annual runo simulation for baseline data (1961 - 1990).

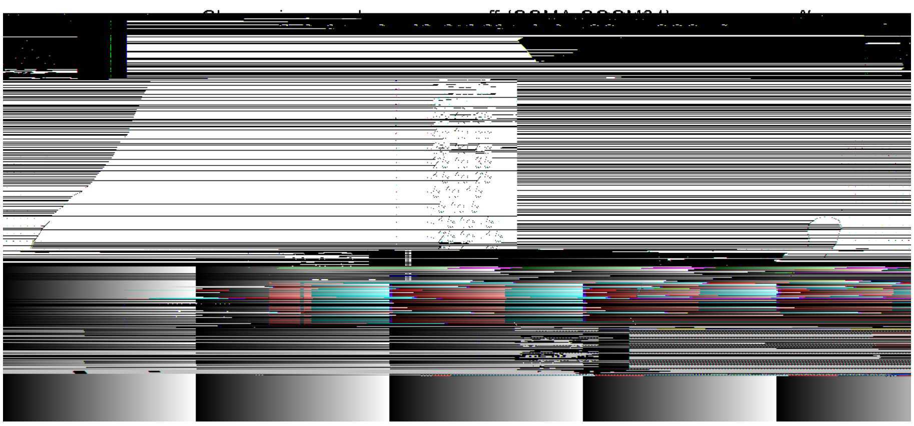

Figure 4.8: Percentage change in annual average runo for CCMA CGCM31 model.

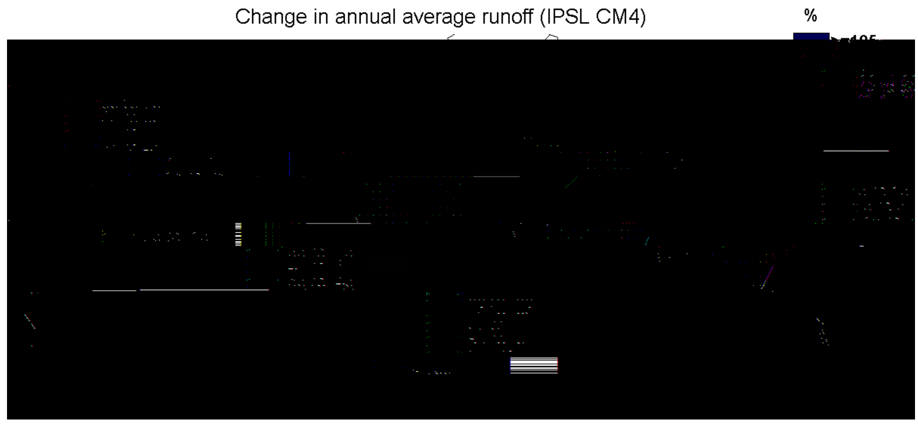

Figure 4.9: Percentage change in annual average runo for IPSL CM4 model.

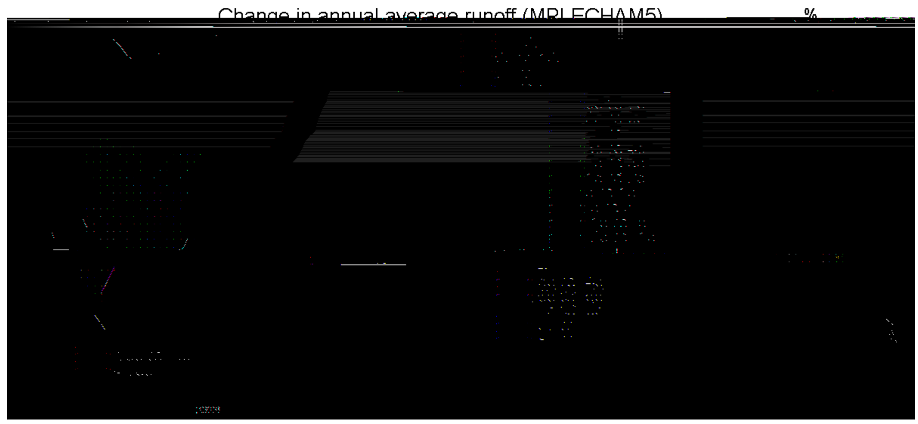

Figure 4.10: Percentage change in annual average runo for MPI ECHAM5 model.

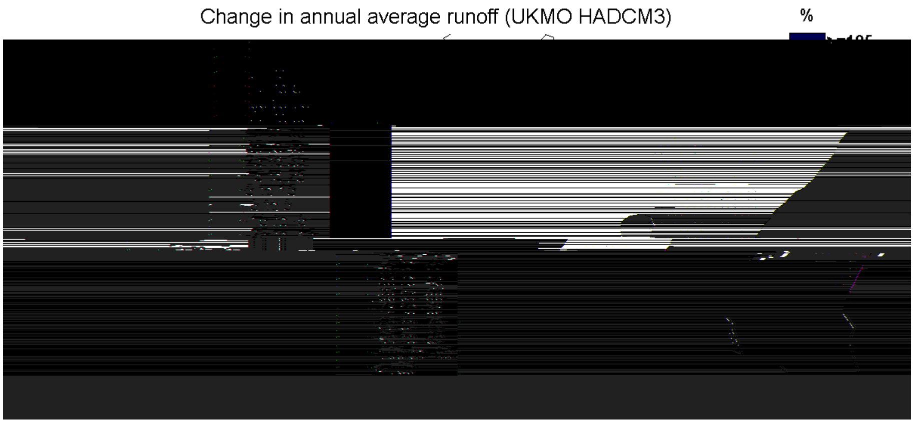

Figure 4.11: Percentage change in annual average runoff for UKMO HADCM3 model.

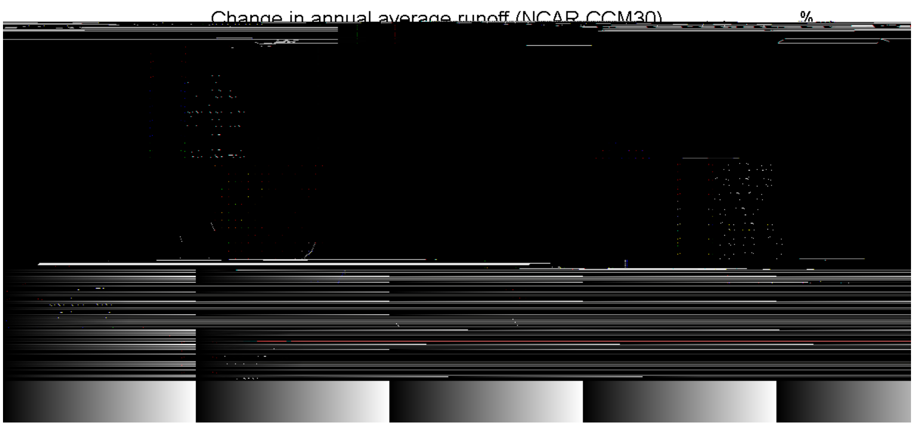

Figure 4.12: Percentage change in annual average runoff for NCAR CCM30 model.

Chapter 5

Discussion and Summary

5.1 Caveats

Caveats are associated with all components of the study - the glacier model, the hydrological model, and in climate variability projections.

One of the key limitations of all the models is that estimation of current and future mass balance profiles and runoff is based on simulated data and not on observations. Therefore, any bias in the simulation model will be lead to a bias in the projected changes (Arnell, 2004).

The glacier model does not simulate the specific mass balance to the cor-

may also see an increase in runo which may relieve stress on the people living in this semi-arid region at present.

5.3 Further Work

Due to time constraints and problems encountered during the study, the following work could not be investigated but would add avlue to the study::

{ Extend the simulations to other tropical glaciers and the e ect of climate variability on runo from glacier melt;

{ Develop a method to predict the change in the area covered by the glacier based on physical concpets; and

{ Incorporate the glacier model into the hydrological model to account for glacier meltwater contributions to stream ow at the global level;

Other investigations could be based on the socio-economic impacts of melting of tropical and other glaciers, including changes in sea level.

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