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GLOBAL WARMING INDUCED CLIMATIC SHIFTS – A CASE STUDY OF ADDIS ABABA CITY, ETHIOPIA

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Abstract

Keeping global warming in view, an attempt has been made in this paper to predict future change in the climate of Addis Ababa from the present. Based on earlier studies and IPCC reports rise of temperatures assumed as 2 °C to 6 °C and thermal and moisture regime climates of Addis Ababa were analyzed by using Thornthwaite's water balance technique (1955) for the present situation of temperatures as well as for the predicted rise of temperatures. The analysis revealed that with the temperature increase by 2 °C there will be no much change in the thermal regime. Hence, the city will experience the same mesothermal (B'_2) type of climate which is experiencing at present. However, with the temperature rise by 6 °C, the analysis indicates that the present mild Mesothermal (B'_2) climate may become intensified into Mesothermal (B'_4) climate. In terms of moisture regime, with 2°C rise in temperature, Addis Ababa will shift to drier side of humid climate (from B'_2 to B'_1). And with 6 °C rise, Addis Ababa will become more drier than the present and may experience dry sub humid (C_2) climate. The study reveals that with global warming the region may experience enormous thermal potential at the same time decline in the moisture potential. Water balance technique which was initiated by Thornthwaite has been employed as a major tool in the study to estimate hydrological elements and climates based on temperature and precipitation of the region. For that purpose, temperature and rainfall data for 41 years (1970-2010) were collected from the weather records of two weather stations located in the city.

Introduction

Climate of a region may be defined as the synthesis of weather elements prevailed over a long period of time, at least 30 years (Ayoade, 1983). The climate, in general is represented through the weather elements such as temperature, atmospheric humidity, pressure, wind and precipitation (Rao et al. 2007). Climate is never static phenomena. It is very dynamic and fluctuates in all time scales; monthly, yearly, decadal, centennial and millennial (Hema Malini, 2002). The change in weather parameters leads to fluctuations in the climate of a region.

Several research findings had also confirmed that the increase in global surface temperatures have been attributed to two important phenomena namely urbanization and industrialization (Rao, 1983; Charlson, 1993; Kumar et al., 2007; Reibeek, 2010). The human activities such as land use/land cover changes, deforestation, draining of wet lands etc, tend to alter the albedo of the earth surface which in turn influences the variations in the microclimatic elements such as rainfall, temperature, humidities etc (Landsberg, 1984). Further, the process of urbanization creates concrete jungles which trap heat by multiple reflections, and the process of industrialization causes increase in greenhouse gasses (Hema Malini, 1984). In addition, burning of fuel by vehicular traffic and domestic activities trap the heat at the lower levels and raises the temperature near the ground (Rao et al., 2007; Katam et al., 2007).

Streutker (1999) in his study mentioned that several researchers have confirmed in their investigations that temperature rise has been observed in the cities such as, Tokyo and other Japanese cities (Fukui, 1970; Fumiaki (2009), Paris (Detwiller, 1970), Athens (Katsoulis and Theoharatos, 1985, and Katsoulis, 1987), Washington D.C., (Kim, 1992) and Singapore and Kuala Lumpur (Tso, 1996). Further, Kawamura (1977) indicated that the rapid rise in temperatures was observed since 1950 in number of cities of Japan apart from Tokyo as result of urbanization and industrialization. Hema Malini (1995) witnessed rise in temperature at Visakhapatnam city, due to human induced activities. Of late, Addis Ababa, the capital city of Ethiopia experiences urban heat island phenomena due to rapid urban growth, increase in the industrial establishments and consequential air pollution (Bisrat, 2007).

Analysis of the past 140 years of temperature data of the world revealed that the global temperatures are rising at a rapid rate. It was also found that the 20th century was the warmest period in the last millennium with 1990s being the warmest decade, and the 1998 is the warmest year of the century (Michael et al., 1994). The global climatic data shows that average surface temperatures increased over the past century by about 0.4 ^{0}C to 0.8 ^{0}C (Oliver and Hidore, 2002). Recent studies show that the average surface temperature of the earth is likely to increase by 1.1 ^{0}C to 6.4 ^{0}C by the end of 21st century, relative to 1980-1990, with the best estimate of 1.8 ^{0}C to 4.0 ^{0}C (IPCC, 2007).

To understand whether any fluctuations are going with the present climate of a particular area due to global warming, knowledge of temperature and rainfall is essential. Based on these two parameters it is possible to evaluate water balance and related indices to assess the climate of a particular area. Water balance refers to the balance between the water supply in the form of precipitation and the outflow of water by Potential Evapotranspiration (Thornthwaite and Mather, 1955). Potential Evapotranspiration is a derivative of temperature and it is defined as a combined loss of water to the atmosphere by evaporation and transpiration if there is sufficient water available in the soil at all times for full use (Thornthwaite, 1948). Water balance analysis in the climatic evaluation was initiated by Thornthwaite and his associates since 1940's. Such studies gained popularity in the analysis of climates, assessment of crop suitability, assessment of droughts, planning of irrigation scheduling and in the preparation of crop weather calendars. Water balance technique is helpful in land use planning in any set of climatic conditions, since the water need and water availability of a region can be accurately estimated from these techniques (Hema Malini, 1984).

This paper tries to examine how an increase in the atmospheric temperature will actually bring about changes in the climatic conditions of a particular region. Considering an overall increase of temperature by 2°C and 6°C as envisaged by Riebeek, (2010) and US Environmental Protection Agency (2010) for the beginning of the 21 century, predictive models for Addis Ababa have been worked out based on Thornthwaite technique. These models would indicate the possible changes that the city is likely to experience if, and when, such a temperature increase really occurred.

Study Area

Addis Ababa, the capital of Ethiopia, is an elevated city (2440 m above mean sea level) in the world and is situated in the central highlands of Ethiopia. Geographically, the city is located between 8º55' and 9º05' North Latitudes and 38º40' and 38º50' East Longitudes (Fig.1). The area of Addis Ababa city is 540 km^2 and administratively the city is divided into 10 Sub-Cities *(Kifle-Ketemas)* and further subdivided into 99 *kebelles* (Addis Ababa City Administration Reports, 2008).

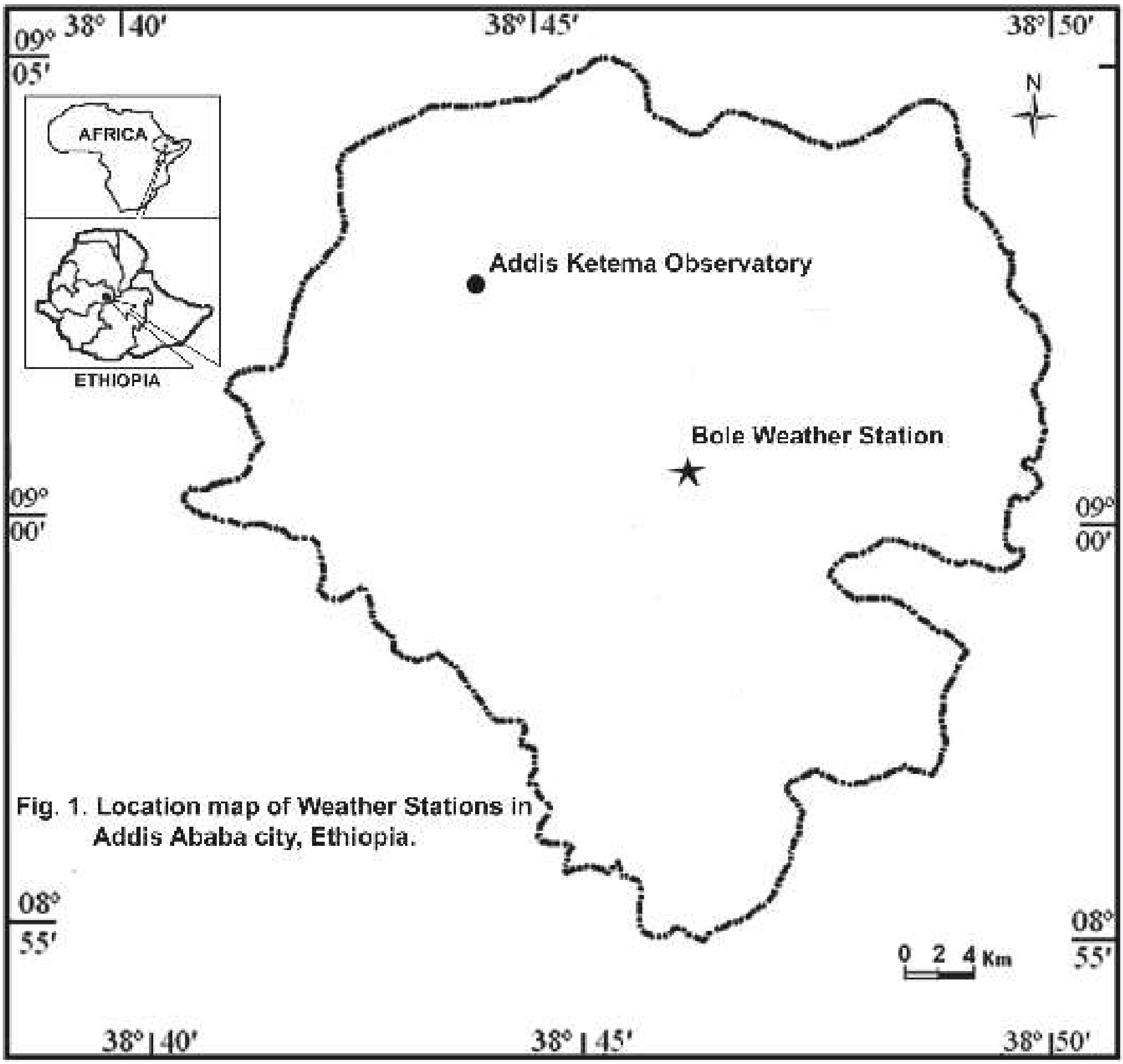

Fig. 1. Location map of Weather Stations in Addis Ababa city, Ethiopia.

According to 2007 census the population of the city is 3 million (Central Statistical Agency of Ethiopia, 2008).

Data and Methodology

Data on rainfall and temperature on monthly basis were collected for the city pertaining to 41 years (1970-2010). Thornthwaite and Mather (1955) water balance method has been applied to find out the hydrological conditions and climatic regimes of the study area. Average monthly water balances of the city for two existing meteorological stations were computed. This method of computing water balance has multiple applications through which one can assess the hydrological conditions, climatic regime, climatic shifts and drought situation of any region. PE (Potential Evapotranspiration) and P (Water supply) are the two fundamental elements of water balance and the parameters, namely, Actual Evapotranspiration (AE) and water surplus (P) are derivative elements. Further indices namely Index of aridity (Ia), Index of humidity (Ih) and Index of moisture (Im) are computed from the derived annual water balance elements.

Earlier studies indicated that, the average surface temperatures could rise between 2 ºC and 6 ºC by the end of the 21st century (Riebeek, 2010; US Environmental Protection Agency, 2010). In order to see how the predicated increase in temperature would affect the nature of climate of Addis Ababa, the average water balances of the study area are recomputed by uniformly adding 2°C and 6°C to all the months of the present day normal temperatures. Thus, water balances of Addis Ababa were computed for 2°C rise of temperatures as well as 6 °C rise temperatures and climatic types of these two situations were reassessed. The existing water balance conditions and climatic regimes of Addis Ababa are compared with those of the predicted regimes.

Techniques and Methodologies of Water Balance

Thornthwaite (1948) has developed a simple book-keeping procedure by making a comparison between the precipitation and potential evapotranspiration on a monthly basis taking into consideration the role of soil as storage of rainwater which can be used in times of inadequate rainfall. Later he modified his scheme in 1955.

To begin with, data on precipitation and temperature of the region under study should be acquired for a period of not less than 30 years. Though the climatic characteristics of a place can be assessed to some extent by using Precipitation (P) along with evaporation and transpiration, the measurement of evaporation is rather a difficult task. The concept of Potential Evapotranspiration (PE) was introduced by Thornthwaite. Monthly or daily PE values will be derived from daily or monthly temperatures. PE is the combined loss of water to atmosphere by evaporation and transpiration and plays a significant role in the water balance studies. Thornthwaite (1948) defined PE as the maximum amount of water which would be lost to the atmosphere from a surface completely covered with vegetation if there is sufficient water in the soil at all times for full use. Rate of PE primarily depends on climatic conditions (energy from the Sun), and therefore its determination is easier than the actual evapotranspiration.

In the water balance procedure, P is treated as income, PE as expenditure and the amount of moisture stored in the soil as a sort of reserve available for use to a limited extent for purposes of evapotranspiration during rainless periods. While water supply (i.e., Precipitation) and the water need (i.e., PE) are the basic elements of the water balance, Actual Evapotranspiration (AE), Water Deficiency (WD) and the Water Surplus (WS) are the derivatives which in turn enable to compute water balance indices such as Aridity (Ia), Humidity (Ih) Moisture (Im) and moisture adequacy (Ima). These indices play a key role in the assessment of climate of a particular region.

Estimation of PE

Potential evapotranspiration (PE) which is also called as Thermal Efficiency (TE) of any region can be determined by field measurements with the help of an instrument called Evapotranspirometer. However, in the absence of such an instrument, PE can be estimated empirically, since there is a relation between PE and mean temperature of the region. In India, estimation of PE for different regions was first attempted by Subrahmanyam (1956) who was the student of Prof.C.W.Thornthwaite. Prof. Subrahmanyam trained several scientists and research in this direction is still continuing. Thornthwaite and Mather published a volume (10) entitled 'Instructions of Tables for Computing Potential Evapotranspiration and Water Balance' in 1957, from their Laboratory of Climatology. For computing PE and water balances for the study area, same volume has been used and procedure is discussed in detail as under:

PE can be estimated through two procedures. In the first method, PE can be estimated using a formula and in the other method it is estimated using series of tables and nomograms.

Formula to estimate PE is given below:

$e = 1.6 (10 t / I)^a$

Where,

e = mean monthly thermal efficiency

t = mean monthly temperature in ºC

I = annual heat Index being equal to

$$\sum_{n=1}^{n=12} i_n$$

Where i_n = mean heat index of the n^{th} month given as

$$= (t^n / 5)\ 1.514$$

Where $\mathbf{t_n}$ = mean temperature of the n^{th} month and a = $0.0000006751\ (I)^3 - 0.0000771\ (I)^2$ $\delta + 0.01792\ (I) + 0.49239$

The formula gives unadjusted values of thermal efficiency, for a standard month of 30 days, each day having 12 hours of sunshine. Since the number of days in a month ranges from 28 to 31 (nearly by 11 %) and the number of hours of sunshine during the day between sunrise and sunset (when maximum evaporation takes place) varies with the latitude and season of the year it becomes necessary to reduce or increase the unadjusted values of the thermal efficiency by a correction factor that varies with latitude of that place and month under investigation.

In the second method, monthly or daily potential evapotranspiration can be estimated directly by using series of Conversion Tables and Nomograms prepared by Thornthwaite and Mather (1955) provided the mean air temperature and the latitudinal location of the station are known.

To estimate monthly potential evapotranspiration values of a particular station, mean monthly values of temperature are essential. In addition, latitude of the station is required. Three steps are involved to estimate PE values by using this method.

The first step is derivation of annual heat Index (I). It is the sum of the monthly values of (i) corresponding to mean monthly temperature. The second step is to find out unadjusted daily potential evapotranspiration for different mean temperatures and I values. The third step is to adjust these unadjusted daily values of potential evapotranspiration for month and day length by multiplying by proper correction factor (Correction factor is derived based on the latitude of the study area). Apart from the values of PE and P, knowledge of moisture holding capacity (field capacity) of a particular area is essential to carry out water balance computations. Field capacity of a soil depends on the depth of the soil layer considered and the type and structure of soil medium. It can vary from 50 mm to over 400 mm.

Thornthwaite and Mather (1955 and 1957) have tabulated the field capacities for different combinations of soil and vegetation types. With the knowledge of soil and vegetation, field capacity of a particular region can be determined. By referring Standard Water Retention Tables prepared by Thornthwaite and Mather, water balance may be assessed.

Once monthly PE is calculated and precipitation already known, the next step to compute water balance is to calculate monthly P – PE. A series of monthly positive as well as negative values will be derived when PE of each month is deducted from its respective Precipitation. Positive values indicate the amount of excess precipitation which is available for soil storage and run off, whereas negative values represent a potential deficiency of precipitation.

The next step is to compute the accumulated potential water loss. At dry stations where the annual total P – PE is negative, it is essential to find out a value of potential water deficiency with which accumulation process starts. This is possible by performing a series of successive approximation process. Next step is to enter accumulated potential water loss for all the months. By referring tables prepared by Thornthwaite and Mather (1955) soil moisture storage values can be entered corresponding to the accumulated potential water loss of each month. This is followed by the computation of change in the soil moisture storage (ΔSt) from one month to the next.

Next step is to estimate Actual Evapotranspiration (AE). PE and AE are equal during the months when precipitation is more than the potential evapotranspiration. On the other hand, in the months when precipitation is less than PE, the AE becomes low. In these months summing of precipitation and water drawn from the storage ($P+ \Delta St$) gives the value of actual evapotranspiration. The difference between potential evapotranspiration and actual evapotranspiration (PE – AE) in each month is the water deficit of that particular month. Water surplus in any month results when soil moisture storage reaches its field capacity.

Water runoff is another component of water balance. According to this concept, in the large watersheds 50 per cent of the surplus water is available for runoff in any month as actual runoff while the remainder of surplus water is detained within the watershed and available for runoff in the following month. The delay factor depends on the size of the watershed basin, vegetation, soil cover and its degree of slope. In the urban areas the runoff is faster due to concretization and less scope for infiltration.

To illustrate procedure of water balance analysis, Addis Ababa station is taken into consideration and normal water balance of Addis Ababa has been computed for 1970-2010 period. The Actual Evapotranspiration (AE), water surplus, water deficit, soil moisture storage and other elements of water balance of Addis Ababa were derived and presented in the Table 1. Monthly variations of water elements are graphically represented in Fig. 2A.

Table 1
Addis Ababa City: Average Water Balance Conditions during 1970-2010
(All values are in mm)

Elements	MONTHS												Annual
	J	F	M	A	M	J	J	A	S	O	N	D	
PE	57	58	74	74	78	66	65	64	61	61	53	54	765
P	18	36	67	87	82	126	255	262	154	35	6	7	1135
P-PE	-39	-22	-7	+13	+4	+60	+190	+198	+93	-26	-47	-47	+ 558 -188
Acc.Pot.Wl	-159	-181	-188						(0)	-26	-173	-120	
Storage	176	163	159	172	176	236	300	300	300	275	235	200	
ΔSt	-24	-13	-4	+13	+4	+60	+69	0	0	-25	-40	-35	
AE (P+ΔSt)	42	49	71	74	78	66	65	64	61	60	46	42	718
WD (PE-AE)	15	9	3	0	0	0	0	0	0	1	7	12	47
WS	0	0	0	0	0	0	126	198	93	0	0	0	417
Runoff	7	4	1	1	0	0	63	130	111	55	28	14	

Source: Computed by the authors

The monthly distribution of Potential Evapotranspiration of Addis Ababa indicates that PE is maximum during March - May (74-78 mm), moderate during June – October (61-66 mm) and low during November - February (53-58 mm, Table 1). The annual PE is about 765 mm. Addis Ababa receives 1135 mm of rainfall in an average year, of which 70.2 per cent occurs during the Kiremt season (rainy season of Ethiopia which prevails from May to August).

As a first step P-PE values were derived for all the months. The values show that P-PE is positive by 558 mm and negative by 188 mm. Based on the soil and vegetation cover field capacity of Addis Ababa was taken as 300 mm (Thornthwaite and Mather, 1957). It may be noted that the estimated value of accumulated potential water loss of Addis Ababa is entered as '0' since the water storage capacity at the end of rainy season is more than its field capacity (300 mm). Hence, accumulated potential loss is '0' and it is the starting point of the computation. Accumulated potential water loss for all the months were worked out by adding P-PE value of the present month to the previous month. After entering accumulated potential water loss for all the months, the next step is to enter the monthly storage values of each month by referring 300 mm water retention Table 31 prepared by Thornthwaite and Mather (1957). In the case of Addis Ababa, it can be noted that the station experiences excess of field capacity (300 mm) during July, August and September. Hence, the excess amount appears as water surplus in these three months. In the remaining months of the year the storage never exceeds its field capacity. As a result, water surplus is zero.

The next step is to estimate variation in the soil storage (ΔST) in all the months. It can be derived by deducting the present month's storage value from the previous month's storage. Monthly Actual evaporation can be derived by adding precipitation and soil moisture variation of each month. However, during the months of excess precipitation AE and PE will be the same. Further monthly water deficit can be assessed by deducting AE from PE in each month.

As already mentioned the city receives 1135 mm of rainfall out of which 765 mm is moisture lost to the atmosphere in the form of

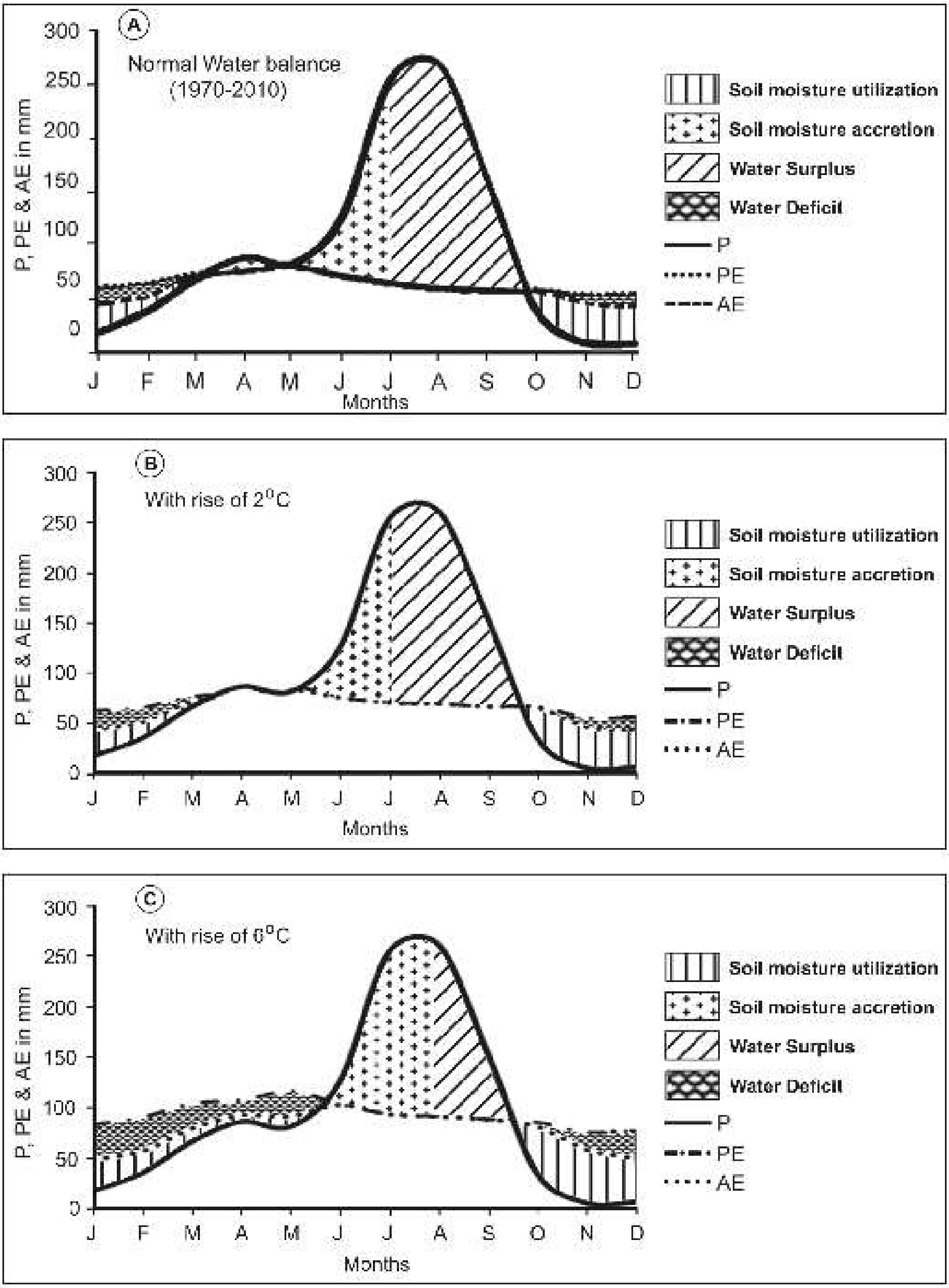

Fig. 2 (A-C). Present and predictive models of water balance conditions - Addis Ababa

PE. During three months namely July, August and September, the rainfall exceeds the atmospheric water demand (PE). The excess rainfall during *Kiremt* season, after fulfilling the demand of PE, replenishes the soil moisture up to its field capacity (300 mm). As a consequence, the city experiences three months of water surplus during July, August and September (417 mm). Water deficit conditions are significant during *Bega* season (long dry season of Ethiopia which prevails from September to February). In the *Belg* season (short rainy season in Ethiopia which prevails between March and May) water deficit conditions are nil except in March. The annual water deficit of Addis Ababa is 47 mm. Thus, it is revealed that the study area experiences more or less humid conditions with a minimum water deficit conditions in most part of a normal year. However, the distribution of the water deficit and water surplus periods exactly matches to the seasons designated by NMSA (2004).

Global warming Vs Trends in Climate

An attempt has been made to predict the impact of climate change in hydrological conditions of Addis Ababa from the present, if there will be rise in temperature of about 2 ^{0}C and 6 ^{0}C in all the months over the present averages (1970-2010). After adding 2^{0}C and 6^{0}C for each month water balances were recomputed and compared with the present day water balance conditions. Fig.2 (A- C) reveals changes in water balance elements.

With the assumption of 2°C temperature rise in the coming decades as a consequence of global warming, recomputed water balance elements namely PE, AE,WD and WS indicate very slight variations with the present day water balance elements in terms of monthly quantity and distribution (Table 2). The annual PE may increase by 72 mm when compared with present day annual PE. Due to increase in atmospheric demand quantity of annual water surplus may decrease by 54 mm. On the other hand, annual water deficit may increase slightly. Fig.2 B shows the monthly distribution of water balance elements with 2 °C rise in

Table 2
Addis Ababa City: Average Water Balance Conditions/Elements with Predicted 2 ^{0}C Temperature Rise (All values are in mm)

Elements	MONTHS												Annual Total
	J	F	M	A	M	J	A	S	O	N	D		
PE	63	66	77	80	87	76	71	70	67	67	56	57	837
P	18	36	67	87	82	126	255	262	154	35	6	7	1135
P-PE	-45	-30	-10	+7	-5	+50	+184	+192	+87	-32	-50	-50	+520 -222
Acc.Pot.wl	-177	-207	-217	(-202)	-207				(0)	-32	-82	-132	
Storage	166	150	145	152	150	200	300	300	300	269	228	192	
ΔSt	-26	-16	-5	+7	-2	+50	+100	0	0	-31	-41	-36	
AE (P+ΔSt)	44	52	72	80	84	76	71	70	67	66	47	43	776
WD (PE-AE)	19	14	5	0	3	0	0	0	0	1	9	14	61
WS	0	0	0	0	0	0	84	192	87	0	0	0	363
Runoff	6	3	1	1	0	0	42	117	102	51	25	13	

Source: Computed by the authors

Table 3
Addis Ababa City: The Average Water Balance Conditions/elements with Predicted 6^0C Temperature Rise (All values are in mm)

Water balance elements	MONTHS												Annual Total
	J	F	M	A	M	J	J	A	S	O	N	D	
PE	84	91	105	108	117	104	94	92	89	86	76	78	1124
P	18	36	67	87	82	126	255	262	154	35	6	7	1135
P-PE	-66	-55	-38	-21	-35	+22	+161	+170	+65	-51	-70	-71	+391 -782
Acc.Pot.Wl	-258	-313	-351	-372	-407				(0)	-51	-121	-192	
Storage	125	105	92	86	76	98	259	300	300	253	200	157	
ΔSt	-31	-21	-13	-6	-10	+22	+161	+41	0	-47	-53	-43	
AE (P+ΔSt)	49	57	80	93	92	104	94	92	89	82	59	50	953
WD (PE-AE)	35	34	25	15	25	0	0	0	0	4	17	28	171
WS	0	0	0	0	0	0	0	129	65	0	0	0	194
Ruoff	4	2	1	0	0	0	0	64	64	32	16	8	

Source: Computed by the authors

monthly temperature from the present.

The monthly Water Balance conditions/elements with 6^0C rise in temperature are presented in Table 3 and Fig 2 C. Table 3 reveals increase in the annual PE, AE and WD and decrease in water surplus when compared to present situation.

On the whole, if the temperature of the study area increases by 2^0C and 6^0C as predicted, the precipitation may fail to meet the demands of atmosphere during the months from January to May and October to December, thereby leading to water deficit conditions in those months (Table 2 and 3). Moreover, the water surplus which exists in the remaining months of the year will be reduced. It is predicted that the present water surplus will be reduced to half as a result 6 ^{0}C temperature increase. Hence, it is clear that if global warming continues and if a temperature rise of 2 ^{0}C and 6 ^{0}C as predicted becomes a reality, there will be a considerable change in water balance conditions of Addis Ababa and thereby change in the climate.

Climatic Types of Addis Ababa

Based on the water balance conditions, normal climatic conditions of a particular region can be assessed. Thornthwaite classified the climates of a region based on thermal and moisture regimes.

1. Climatic Classification based on Thermal Regime

By thermal regime approach, climate of a region can be assessed on the basis of Thermal Efficiency (TE) of the region. Thermal Efficiency indicates thermal potentiality of a region and is nothing but Potential Evapotranspiration. It is a fact that luxuriant growth of vegetation is dependent on the thermal potential of the region. Since, PE is derivative of temperature and length of the day, Thornthwaite considered PE as an index of thermal efficiency. Thornthwaite proposed a scheme to classify the climates based on TE (PE) in 1948. It is retained as it is in the modified 1955 classification also. Table 4. shows the Thornthwaite's scheme of thermal regime.

Near the equator seasonal variation of thermal efficiency is small because the length of the day remains the same throughout the year with more or less uniform high temperatures. While in the Polar Regions the conditions are different. Thornthwaite introduced another parameter namely Summer Concentration of Thermal efficiency (SCTE) in order to study complicated variations from place to place located in the same latitude. It is the ratio of the sum of the thermal efficiencies for the three highest summer months to the annual TE total. The scheme of this sub-classification is presented in the Table 5.

Based on thermal regime, main

Table 4
Climatic Classification Scheme Based on Thermal Regime

Thermal Efficiency (mm)	Climatic type	Symbol
Above 1140	Megathermal	A′
998 to 1140	Mesothermal	B'_4
856 to 997		B'_3
713 to 855		B'_2
57 to 712		B'_1
428 to 570	Microthermal	C′
286 to 427		C′
143 to 285	Tundra	D′
Below 142	Frost	E′

Source: Thornthwaite (1948 and 1955)

Table 5
Sub-climates Based on Seasonal Variation of Thermal Efficiencies

SCTE %	Climatic Type	Symbol
Below 48.0	Megathermal	a′
48.0 to 51.9	Mesothermal	b'_4
51.9 to 56.3		b'_3
56.3 to 61.6		b'_2
61.6 to 68.0		b'_1
68.0 to 76.3	Microthermal	c'_2
76.3 to 88.0		c'_1
Above 88.0		d′

Source: Thornthwaite (1948 and 1955)

categories and sub categories of climates of Addis Ababa are assessed for present temperature situation as well as for 2 ºC and 6 ºC rise of temperature. Table 6 shows the climate types of Addis Ababa in different situations of temperature rise.

Based on Thermal Efficiency, Addis Ababa city comes under the climatic category namely Mesothermal (B'_2) as its mean annual value of PE is 765 mm. With the rise of 2 °C of temperature, Addis Ababa will experience same Mesothermal (B'_2) climate but with little more intensity. However, with rise of 6 °C temperature there will be increase in thermal potential and the city may experience intensified Mesothermal (B'_4) climate.

Table 6
Addis Ababa City: Climatic Classification based on Thermal Regime

Addis Ababa	Thermal Regime			
	Annual TE/PE (mm)	Climatic Type	SCTE %	Climatic Type
Present temperature situation	765	B'_2	29.54	a′
With 2 ºC rise of temperature	837	B'_2	29.15	a′
With 6 ºC rise of temperature	1124	B'_4	29.35	a′

Source: Computed by the authors

Analysis of Summer Concentration of Thermal Efficiency (SCTE) reveals that Addis Ababa with its SCTE values below 48.0 per cent in all the situations of temperature comes under a′ type climate. Thus, both annual and seasonal distribution of thermal efficiency (TE/PE) suggests that Addis Ababa is experiencing abundant thermal potential which can support luxuriant vegetation if moisture is not a constraint.

2. Climatic Classification – Moisture Regime

Further, Thornthwaite classified the climates based on the moisture status of the region which is otherwise known as moisture regime classification. In the moisture regime approach, Index of aridity (Ia) and Index of humidity (Ih) are the basic indices for the classification. Index of aridity is the percentage ratio between water deficit and Potential Evapotranspiration (Annual water deficit/ Annual PE x100) and Index of humidity is the percentage ratio between water surplus and Potential Evapotranspiration (Annual water surplus/ Annual PE x100). When Index of humidity is subtracted from Index of Aridity the resultant index is moisture index (Im=Ih-Ia). Moisture index is the key index to determine moisture regime climate of a region. Carter and Mather modified the 1948 climatic classification of Thornthwaite. For the present purpose, in determining climate type of Addis Ababa, the revised expression of moisture index and the revised climate limits of Carter and Mather (1966) were adopted. Table 7 provides the climatic classification based on the values of moisture index according to Carter and Mather.

Based on the moisture regime, the general climate of a region can be recognized as moist or dry climate on annual basis. However, a moist climate may not be wet throughout the year. Similarly, a dry climate may not experience dryness throughout the year. However, in agricultural studies, it is also essential to know the periodicity of moist and dry conditions of a region. In moist climates if

Table 7
Scheme of Moisture Regime Classification

Moisture Index Range (Im)	Moisture Regime Type	Symbol	General Association of Vegetation
Moist Climates (Im > 0)			
100 and above	Prehumid	A	Rainforest
Humid			
80 to 99.9	Humid category 4	B_4	Forest
60 to 79.9	Humid category 3	B_3	Forest
40 to 59.9	Humid category 2	B_2	Forest
20 to 39.9	Humid category 1	B_1	Forest
0 to 19.9	Moist Subhumid	C_2	Tall Grass
Dry Climates (Im < 0)			
-33.3 to 0	Dry subhumid	C_1	Short Grass
-66.7 to -33.3	Semiarid	D	Steppe
-100 to -66.7	Arid	E	Desert

Source: Carter and Mather (1966)

there is a water deficit it may be extensive, moderate, very little or non-existent. The same is true with dry climates regarding water surplus. A sub classification based on Seasonal Variation of Effective Moisture (SVEM) has been formulated using seasonal Index of aridity (Ia) and Index of humidity (Ih). For moist climates Seasonal Variation of Effective Moisture (SVEM) is the ratio of seasonal aridity index to the seasonal total Potential Evapotranspiration. Similarly, for dry climates Seasonal Variation of Effective Moisture (SVEM) is the ratio of seasonal water surplus to the total seasonal Potential Evapotranspiration. Table 8a and 8b provide scheme of sub-classification of moisture regime based on Seasonal Variation of Effective Moisture (SVEM) for both moist and dry climates.

For the present purpose, climates of Addis Ababa delineated based on moisture regime for both annual and seasonal variations of the water balance elements and presented in Table 9.

Table 9, reveals that at present the Addis Ababa experiences humid (B_2) climate with moderate winter water deficit (w) conditions. It is predicted that with rise of 2°C (due to global warming), the climate may shift to B_1 type of climate with moderate winter deficiency (w). Though the station remains in the same humid climate, its shifting from B_2 towards B_1 indicates that the station may become little dry than the present climate (B_2). Further, with a rise of 6°C temperature, Addis Ababa may become more drier and experience moist sub-humid climate (C_2) with large winter dryness (w_2). On the whole, moisture regime analysis indicated that the present climate of Addis Ababa city may become drier and drier especially during winter season with the rise of temperatures in future.

Conclusions

In this study, the water balance of Addis Ababa

Table 8 a
Moisture Regime Sub-classification based on Seasonal Variation of Effective Moisture (SVEM) for Moist Climates (A, B, C_2)

Aridity Index (%)	SVEM	Symbol
0 – 16.6	Little or no water deficit	r
16.7 – 33.3	Moderate summer water deficit	s
16.7 – 33.3	Moderate winter water deficit	w
Above 33.4+	Large summer water deficit	s_2
Above 33.$+	Large winter water deficit	w_2

Source: Carter and Mather (1966)

Table 8 b
Moisture Regime Sub-classification based on Seasonal Variation of Effective Moisture (SVEM) for Dry Climates (C_1, D, E,).

Humidity Index (%)	SVEM	Symbol
0 - 9.9	Little or no water deficit	d
10 – 19.9	Moderate summer water deficit	s
10 – 19.9	Moderate winter water deficit	w
20+	Large summer deficit	s_2
20+	Large winter deficit	w_2

Source: Carter and Mather (1966)

Table 9
Addis Ababa City: Climatic Types based on Moisture Regime with the Present and Rising Temperature Conditions.

Addis Ababa Region	Annual				SVEM	
	Ia (%)	Ih (%)	Im (%)	Climatic type	Ia (%)	Type
Existing Average	6.14	54.50	+48.4	Humid (B_2)	21.3	w (Moderate winter water deficit)
With 2 ºC rise of temperature	7.76	43.3	+35.5	Humid (B_1)	25.2	w (Moderate winter deficit)
With 6 ºC rise of temperature	16.28	17.35	+ 0.97	Moist Sub humid (C_2)	38.0	w_2 (Large winter deficit)

Source: Computed by the authors

city has been worked out using the Thornthwaite and Mather (1955) method. Based on thermal efficiency (TE), Addis Ababa experiences Mesothermal (B'_2). With assumed increase of 2°C the city may experience same intensity Mesothermal (B'_2) climate. However, with the rise of 6°C the study region may experience intensified Mesothermal (B'_4) climate. This means that the thermal potential of the region will be increased with rising temperatures. Further, Addis Ababa experiencing humid type (B_2) of climate at present may experience Humid (B'_1) and Moist Sub-humid (C_2) climate with the rise of 2 °C and 6 °C temperatures respectively. This indicates that the region will become more drier than the present with rise of temperatures.

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