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COMMITTEE ON COMMODITY PROBLEMS

INTERGOVERNMENTAL GROUP ON TEA

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REPORT OF THE WORKING GROUP ON CLIMATE CHANGE

FAO-IGG Working group on climate change

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Introduction

There are many countries in Asia and Africa, where agriculture shape regional economies, besides acting as a main source of livelihood for the local population. Under the larger ambit of Agriculture, tea plantations in some of the countries of these two continents (inhabiting some of the poorest countries of the world), are the major livelihood option for millions of people. During recent years, some of these tea growing countries indicate disturbing trends of decline in tea yield at many places and its productivity primarily due to the stresses (biotic and abiotic) brought about by climate abrasions. The possible fallouts of the climate change impacts are already being witnessed and have increased management costs. Most of the tea growing regions are typified by a kind of monsoonal climate or an alternate wet or dry season interspersed by temperature changes from mild to severe. As these changes are taking place in space and time, hence the concept of climate change is a spatio-temporal phenomenon. Statistical methods coupled with earth observation technologies can thus be used as efficient tools for quantifying and monitoring tea plantation and to study tea yield and quality.
Different tea clones/cultivars may respond differently to changing climate parameters. In these studies, we have used downscaled General Circulation Models (GCM) data to Regional Climate Models (RCM) data wherever available. Some data have been used directly from the General Circulation Models also where the resolution is coarse, while we developed future climatic scenarios. The effect of some of the chosen future climate scenarios obtained from the modelled data on performance of currently grown clones/ cultivars is being observed in open top chambers (OTCs).

1. India

Action area 1: Database development

A fair amount of historical data on meteorology, soil, crop and management has been collected and quality checks have/are being done. The spatial and temporal data are having fairly good resolution depending upon the availability. More data are being collected and the current database is being refined and updated. The socio –economic data collection is in process and the database is being prepared.

Action area 2: Impact analysis- climate trends, frequency of extreme events, area & production

A. Trends and extremities

Ninety years of annual total rainfall data indicates that the rainfall in Northeast India has declined by more than 200 mm (Fig. 1a). Long term trends have been developed for seven tea growing regions in North Eastern India. Detailed studies show that there was a sudden drop in annual rainfall after 1979 and thereafter it had never risen beyond 2299.7mm (2011) and has even gone down to 1184.4 mm (2009).Some of the upper limits of the rainfall before 1979 were 2614.8 mm(1950), 2664.0 mm(1966) and 2706.7 (1977)and lower limit never went below1540.0 mm(1960). The data are presented here for only one location, but such trends have been observed at other locations also in North Eastern India. Looking at the recent extreme events, the years 2009 and 2010 were highly contrasting with respect to rainfall. At Tocklai, Jorhat, Assam the total rainfall in the year 2009 was 1184.4mm whereas in 2010, it almost doubled to 2299.7mm. This resulted in alternated drought and flood like situation in the tea fields. Since the plants remain in the field for few decades, hence too little and too much water impact the tea production negatively, resulting in the onset of many biotic stresses (pests/diseases etc).

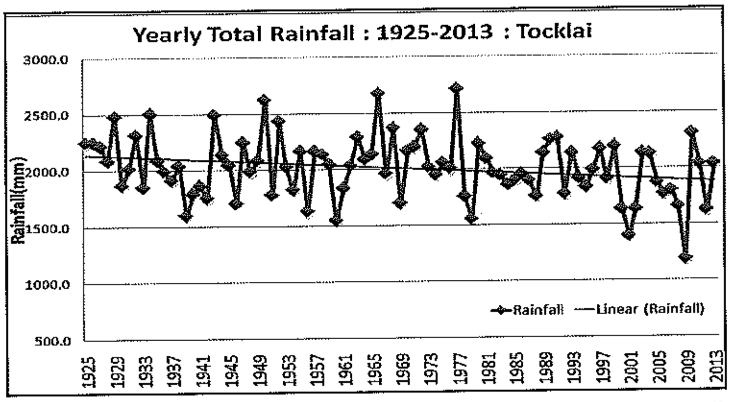

Fig.1a Yearly total rainfall (1925-2013), Tocklai, Jorhat, Assam, India.

The scenario was no different in other parts of Assam and North Bengal provinces of North Eastern India. Dikom (Upper Assam) had 3335.4mm of rainfall in 2010, whereas, it was only 1945.4mm in 2011. Cachar also showed 3022.7mm in 2010 and 1767.0mm in 2011. Same extremes were observed in North Bank in 2004 and 2005 of 3168.0mm and 1848.9mm, respectively. In Darjeeling (North Bengal) the same type of unfavourable conditions were seen in 2011(2447.4mm) and 2012(1761.6mm). A different picture emerged in Nagrakata (North Bengal, India) in terms of long term annual rainfall. While all other regions are facing deficit in rainfall, Nagrakata is showing an increasing trend in last 50 years by a marginal 0.5 mm. Comparing the long term normal rainfall with recent two years (2012 & 2013) for the period April to October (main tea production period), it was found that the year 2012 has a rainfall of 1543.8mm, which is 238.8mm below normal (1934.8mm), whereas, 2013 received 153.8mm more rainfall than the long term normal rainfall. The distribution was also uneven (Fig. 2a). Such trends have been observed at other sites also.

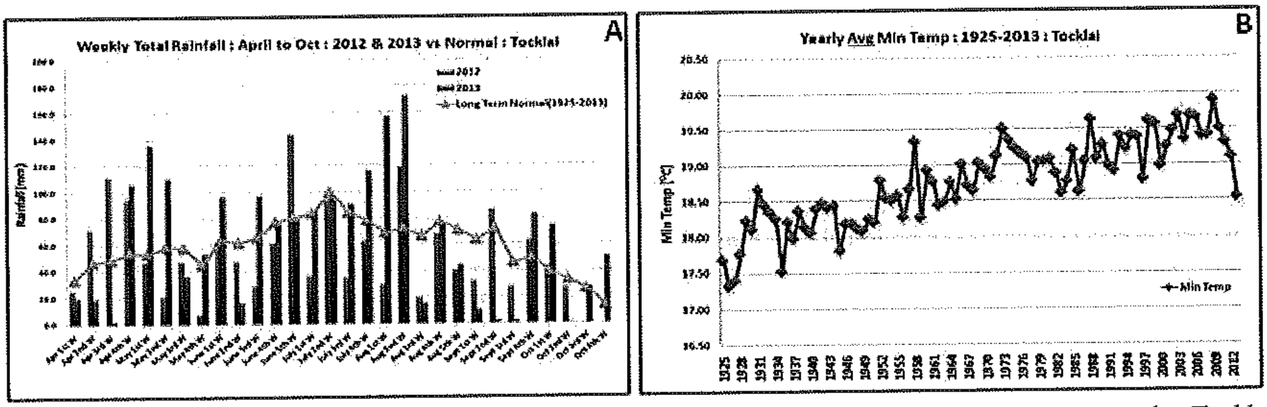

Fig.2 (a) Comparison of weekly total rainfall between April - October (2012 & 2013) with long term normal at Tocklai, Jorhat, Assam (b) yearly average minimum temperature (1925-2013) at Tocklai, Jorhat, Assam

Not only the rainfall decreased over last 90 years but also a significant increase in minimum temperature has been observed in the region. Only in Tocklai, Jorhat there is more than 1.4^{0}C increase in minimum temperature over last 90 years (Fig. 2b). All the other regions are also following the same trend except North Bank where it showed a marginal decline.It is widely believed that tea grows well within a temperature range of 13-30^{0}C. But last about 30 years have witnessed a different trend. It has been observed that the number of days having temperature > 30^{0}C or even>35^{0}C is generally increasing along with the increase in average minimum temperature (Fig. 3a).

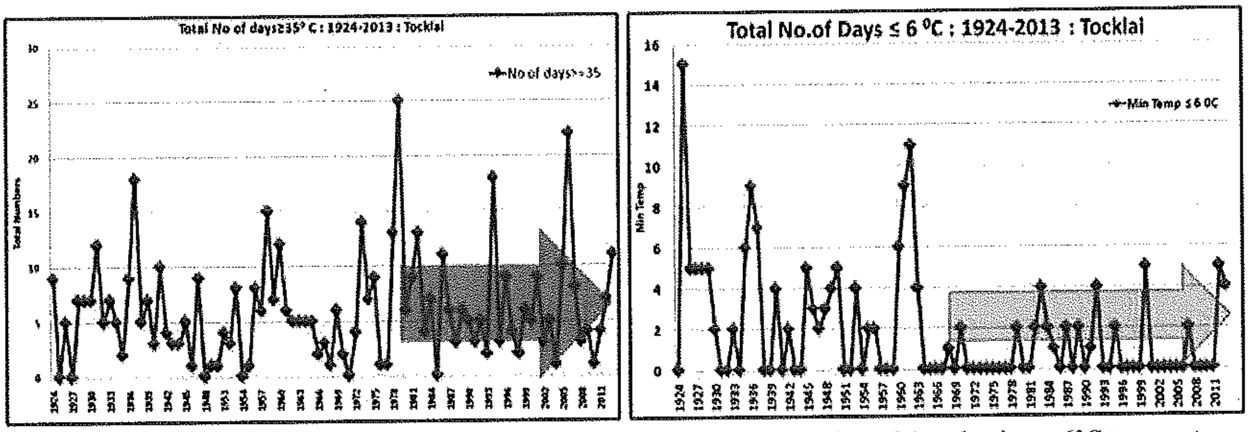

Fig.3 (a) Total number of days having > 35°C temperature and (b) total number of days having ≤6°C temperature at Tocklai, Jorhat, Assam

Further analysis of these extremities shows that the number of days having temperature less than or equal to 6^{0}C and 8^{0}C at different stations have decreased recently (last three decades), which indicates that the minimum temperature is increasing and more number of days are with higher minimum temperature compared to earlier years, indicating a warming trend. The differences are very clear at Tocklai, Jorhat, Assam compared to other regions, because of long term data available at Tocklai (Fig 3b).The short dormant winter season also show cyclic abrasive events of temperature. Segmented analysis is shown in Fig 4a&b for the just over winter season which coincides with pruning time in North Eastern India (October to December 2013), indicates that decision making for pruning tea bushes have to be well thought of and further research is needed in this direction.

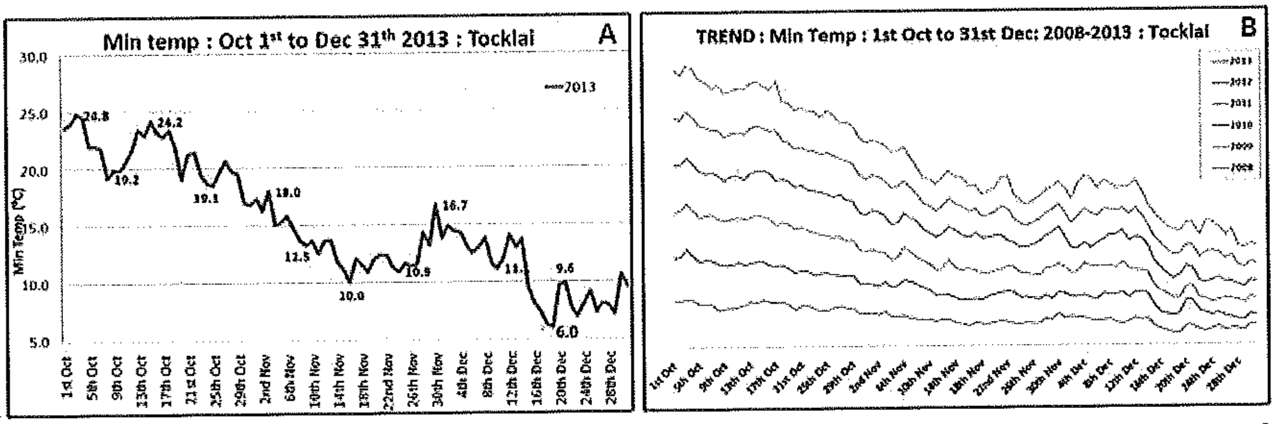

Fig.4 (a) Change in minimum temperature from 1st October - 31st December 2013 (b) trend of minimum temperature for last 5 years from 1st October to 31st December (2008-2013).

Another important parameter that influences tea production is relative humidity. Analysis of long term normal RH compared with the last year i.e. 2013 revealed that RH has gone down both in the morning and afternoon hours (Fig. 5 a, b) almost in every month. This may create a detrimental effect on crop production, which has already been witnessed at many tea growing regions.

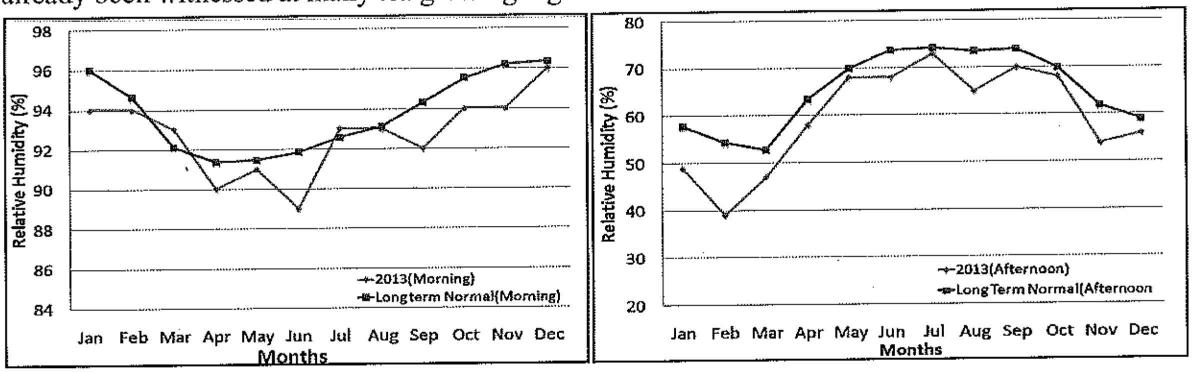

Fig 5: Relative Humidity Long Term Normal vs 2013 (a) Morning (at 0613 hours) and (b) Afternoon(at 1313 hours)

B. Spatial analysis of trends of entire Assam

The spatial analysis of total precipitation (annual as well as production season) in North East India(Assam) shows a wide range of variation during the period 1993-2011 (Fig. 6 a, b). Overall a slow decreasing trend was observed in precipitation. The declining trend of precipitation is more prominent during the recent years (post 2004). In several cases the total precipitation was found to be below normal, especially over the central and eastern Assam. This is a matter of concern as central and eastern Assam hold large areas under tea plantations and produce highest amount of tea in Assam.

Temperature pattern was studied in Assam for the time period of 1993-2012 both annually and for the growing season (April to October) of tea (Fig 7 a, b). It has been observed that both the annual and seasonal maximum temperature remained above ideal in many instances, though no distinct trend in the maximum temperature was found. However, the minimum temperature shows a very clear increasing trend all over Assam. This increase in temperature still needs to be correlated with the production levels.

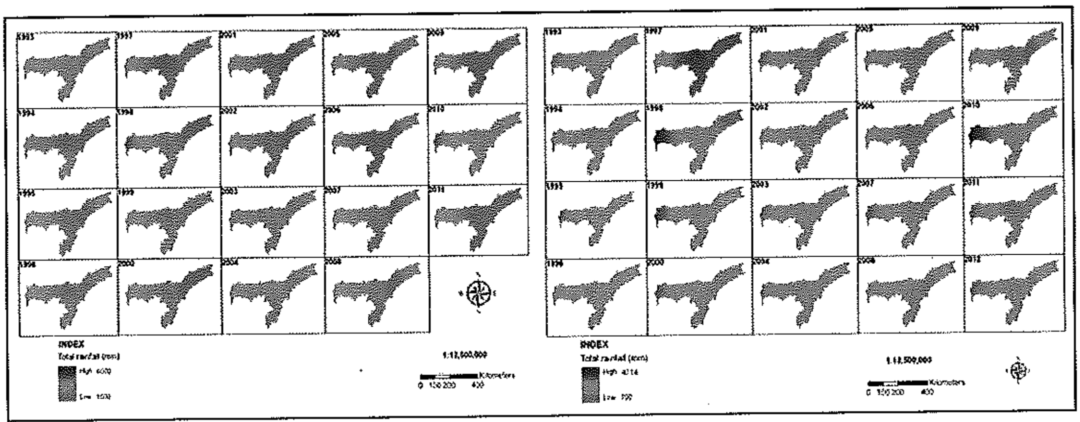

Fig.6(a) Distribution of total annual precipitation (mm) in Assam (1993-2011) and (b) distribution of total precipitation (mm) in production season (April – October) in Assam (1993-2012).

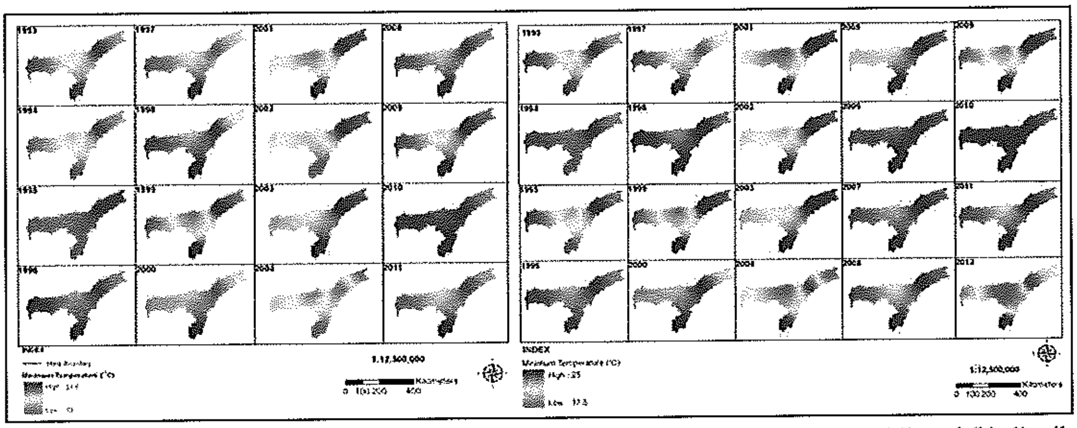

Figure 7 (a) Distribution of average annual minimum temperature (°C) in Assam (1993-2011) and (b) distribution of average minimum temperature (°C) in production season (April – October), Assam (1993-2012).

C. ***Future scenario development***

The future scenario for the climate parameters were developed for two periods namely immediate future and long term future. In both the cases future probabilities of precipitation and temperature scenario were developed using A2 scenario described by IPCC, where the population growth is assumed to converge very slowly resulting in consistent increase in global population. In this scenario the economic growth will be regionally oriented, fragmented and slower than other IPCC scenario.

(a) *Database development: Immediate future* -Immediate future scenario for this region was extracted from the HadCM3 Global Circulation Model (GCM) outputs generated by IPCC (available in http://ipcc-ddc.cru.uea.ac.uk/sres/hadcm3_download.html). The data was downloaded in ASCII format, where mean monthly statistics of precipitation (mm/day) and temperature (maximum and minimum mean daily 1.5m Temperature in Kelvin) was modelled for 12 months for each year of 1980, 2020, 2050 and 2080. The global data was represented in grid format with the size of 3.75 degrees in Long and 2.5 degrees in Lat. The spatial resolution is 150 km. The baseline data was referred as 1980 which represents the mean monthly values of precipitation and temperature for the period of 1961 to 1990. For each of the year 2020, 2050 and 2080 the temperature and precipitation were expressed as mean monthly change in their values from the baseline (1980) data in the respective years. The seasonal precipitation and seasonal mean temperature at 1.5 m for the time slices 2011–2040 and 2041–2070 represent the climatic conditions during 2020s and 2050s, respectively. The absolute values of temperature and precipitation for 2020 and 2050 were then derivedand mapped (Fig. 8), whichindicates precipitation to fall below the current levels and has a decreased rainfall. The real detailed picture will be available when the data are extracted for a high resolution.

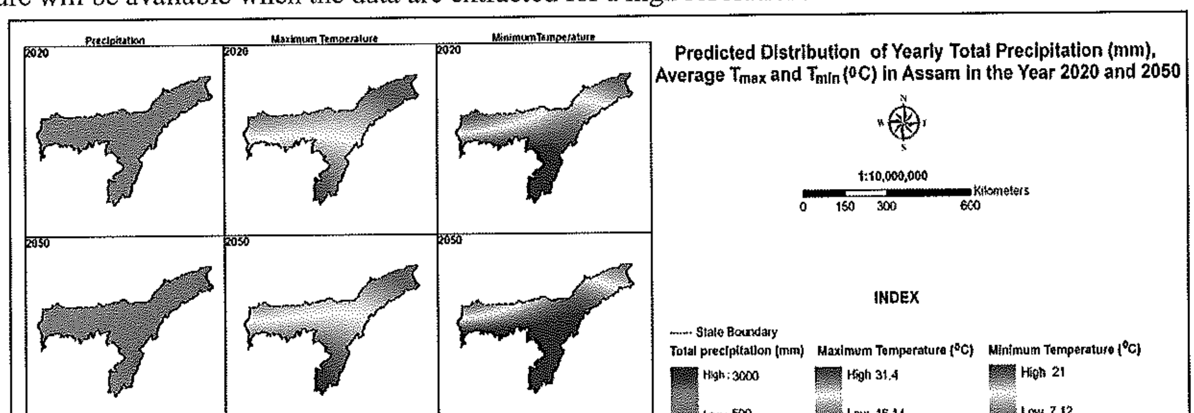

Fig.5 Predicted distribution of yearly total precipitation (mm) and temperature (Tmax and Tmin^{0}C) in Assam for the year 2020 and 2050.

The spatial arrangement of the gridded GCM data depicts that there is no data point in Assam. Therefore to compensate the lack of data in Assam, 16 surrounding data points were considered for interpolation and the data for those points were extracted from the global data. Yearly and seasonal average temperature (max & min) and yearly and seasonal total precipitation were calculated for each location for the year 2020 and 2050. Spatial interpolation was carried out in ArcGIS environment. For maximum and minimum temperature spline algorithm, in-built in Spatial Analyst Toolbox of ArcGIS was used with a smoothing factor of 0.001 for each year (the factor was decided upon several simulation of the interpolation model). The precipitation data were interpolated using Inverse Distance Weighted (IDW) algorithm in Spatial Analyst Toolbox of ArcGIS with the power of 2.

(b) <u>*Database development: Long-term future-*</u>The long-term future scenario was developed from the Hadley Centre Regional Climate Models (HadRM2/HadRM3H/PRECIS). The Regional Climate Model (RCM) simulated for the Indian region on a grid size of 0.44 X 0.44 degrees and a spatial resolution of 50 kms. The baseline data used here was the same as used in the GCM mentioned earlier. And the future climate was developed for each year for the period of 2071 to 2100 under A2 scenario described by IPCC. The data pertains to daily values of temperature and precipitation, which are expressed in degree K and mm units, respectively. It is important to mention here that the PRECIS simulations were carried out in India for only two time slices, viz. 1961–1990 and 2071–2100, as the lower boundary conditions were available only for these periods. Thus simulations for the period 2020 – 2070 are unavailable.

The RCM data was developed for the entire India from which the data for the state of Assam was extracted based on the latitude and longitude of the data points. A total of 36 points were taken for further processing. Although RCM data was available for each year for the period of 2071 to 2100, but to limit the scope of this study the data for 7 individual years namely 2071, 2075, 2080, 2085, 2090, 2095 and 2100 were considered for spatial interpolation. After necessary unit conversion the yearly and seasonal average of temperature and yearly and seasonal total precipitation was calculated for all the 36 data points for above mentioned 7 years. Based on these values same spatial interpolation algorithms were used for temperature and precipitation as used in GCM data to develop the scenario for entire Assam.

The long term scenarios mapped using spatial analysis showed that on long term basis the annual total precipitation is likely to decrease in almost all over Assam except in some areas in the Cachar region where the annual total precipitation may increase (Fig. 9).

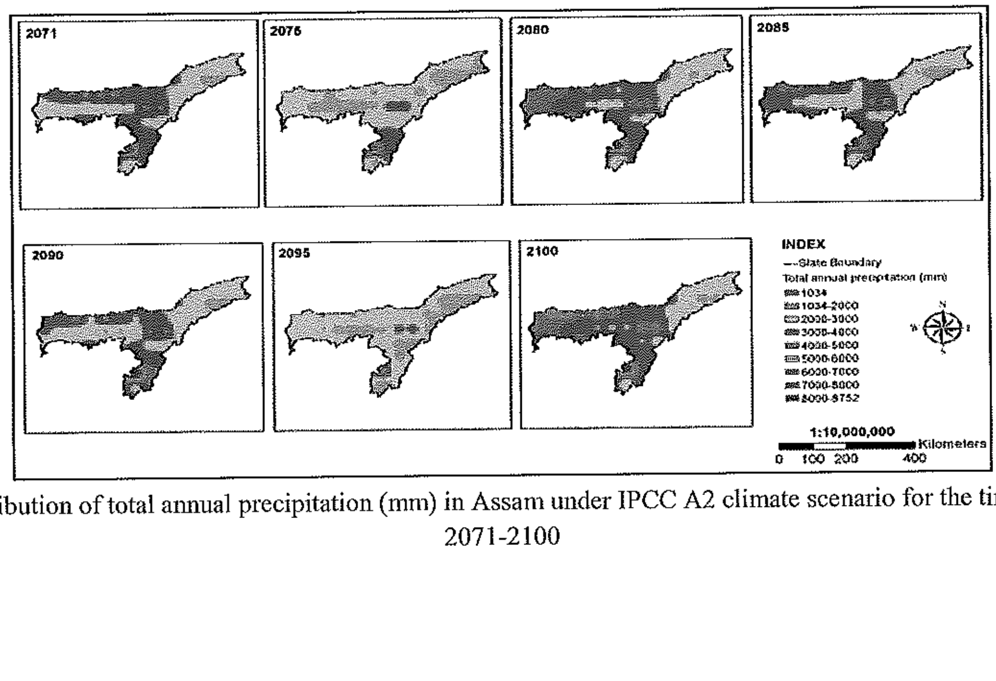

Fig.6. Distribution of total annual precipitation (mm) in Assam under IPCC A2 climate scenario for the time period of 2071-2100

The average annual maximum temperature does not show a specific trend; rather until 2080 it has a decreasing trend considering A2 scenario. However, post 2080 sharp increasing trends are observed, particularly in southern, middle and parts of upper Assam area. The maximum average annual temperature is likely to increase most in the Cachar region, where it may reach up to 36^{0}C. Unlike maximum temperature, the average annual minimum temperature shows a consistent increasing trend (Fig.10). The rate of increase is likely to be faster post 2080.

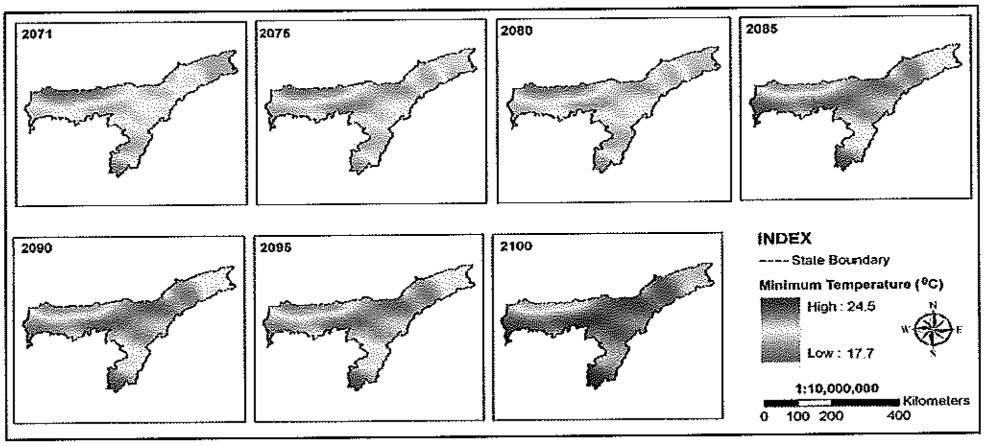

Fig.70.Distribution of average annual minimum temperature (°C) in Assam under IPCC A2 climate scenario for the time period of 2071-2100

Analysis of Crop data (Area and Production):

i. Trends:

From the available data it is understood that the tea plantation area has consistently increased in all the tea plantation regions over the study period, though the rate of increase in not spatially even. The data shows that since 1977 Upper Assam has the largest area under tea plantation followed by South Bank, North Bank and Cachar, respectively. The same trend is followed till the end of the study period. In 1977 the area under tea plantation in Upper Assam was 56781 ha and in 2007 it was 122514 ha, which implies that there has been a whopping 115% (approx.) increase in the plantation area in 40 years and the rate of increase is faster post 1998 (Fig. 11a,b). However, the other regions though show an increasing trend in expansion of plantation area, but the rate of increase (in 40 years) is much slower than Upper Assam. While South Bank and North Bank show around 75% and 32% increase in plantation area, respectively, Cachar falls much behind the rest of region with only 4% increase in plantation area. In fact, it has been found that between 1994 and 1997 the plantation area in Cachar regions decreased. Post 1994, the Tea Board of India data on area of plantation excludes the non-operative tea gardens. Additionally, this data also show that the number of tea gardens in Cachar region has decreased from 121 to 115 which may be non-operative during that period and post 1997 the number of tea estates have again increased. Moreover, the baseline survey by Govt. of Assam published in 2009, it appearsthat while all the other regions have an unprecedented growth of small tea growers, no data on registered small tea grower were found for Cachar region, which also explains the lower growth in the area of plantation in Cachar region.

The production of tea follows the same trend as the plantation area, as it is anticipated to increase the production with the increase in the plantation area. The increase is highest in Upper Assam region followed by South Bank, North Bank and Cachar (Fig.12a,b). Since 1977 Upper Assam shows 106% increase in production till 2007, whereas South Bank, North Bank and Cachar have 66%, 45% and 33% increase in production respectively.

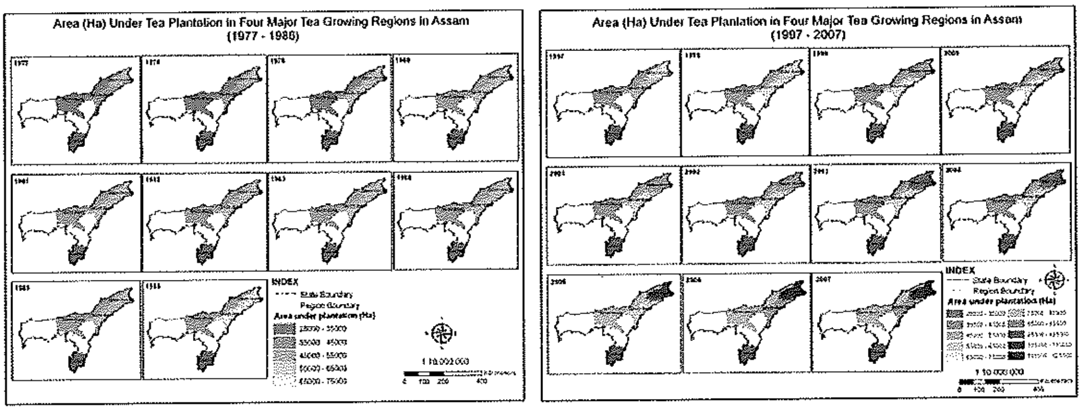

Fig.81 Area (in Ha) under tea plantation in four major tea growing areas of Assam (a) 1977-1986 and (b) 1997-2007.

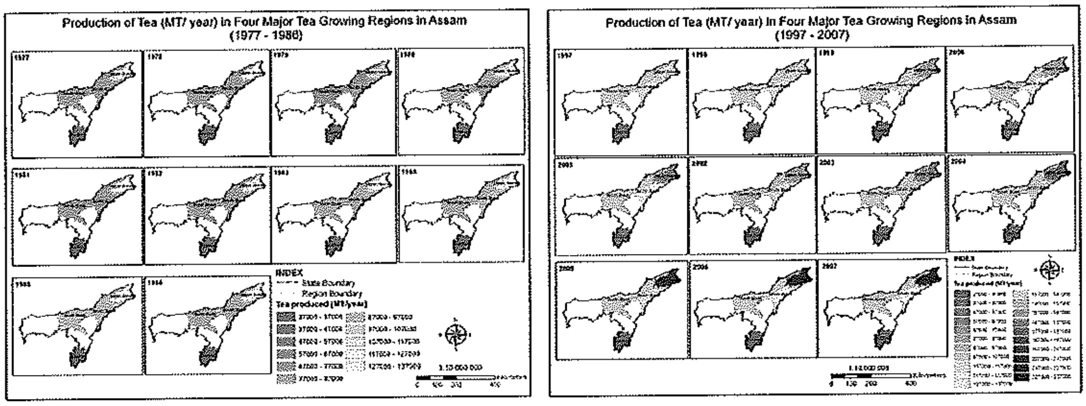

Fig.92. Production of tea (in MT/Year) in four major tea growing areas of Assam (a) 1977-1986 and (b) 1997-2007.

ii. Trend detection and attribution

Simulation experiments:

Process modelling studies in tea production have been rather limited. Simulation models describing tea growth and production are not easily available. The only model described in recent literature is the CUPPA-Tea (Cranfield University Plantation Productivity Analyzer for Tea) model, developed by International Centre for Plantation Studies Silsoe, UK). The first step to use the CUPPA tea model is to generate and tabulate all the input parameters of the model. After providing all the required input parameters the model was run to see the predicted behavior of the tea crop in response to these inputs. It is also possible to view predefined graphs of a number of output variables from the model by selecting the Output. The data for the model was taken from the recently conducted experiments at the Tocklai Tea Research Institute at Jorhat, Assam, India. These data were changed to the required format of the CUPPA Tea model. The harvested yield and the cumulative yield that was simulated by CUPPA tea model were compared with the observed data and the results were in good agreement with each other.

Action area 3: Work out interaction between Genotype (G) x Environment (E) x Management (M) which is the prime driver of productivity

A. ***Test existing and emerging cultivars for future climate scenarios (OTC studies)***

An open top chamber (OTC) facility is capable of providing a means by which the environment (E) around growing plants (G) can be modified to different climatic conditions particularly of temperature and carbon dioxide concentration and management (M) practices. Studies were started by allowing the potted plants to grow inside the OTC with carbon dioxide increments (Fig13 a,b).The observations on morphological, physiological and biochemical characters were recorded.

Fig.103Open Top Chamber facility in TTRI (a) Outside view and (b) inside view.

Fifteen Tocklai recommended clones were selected for the study. Clones were planted in pots and allowed to grow inside the OTC with carbon dioxide increments. The experiments were done in two phase. In the first phase the carbon dioxide level was 400ppm and in the second phase the level was 450ppm.Temperature inside the OTC were 4-5^{0}C more than ambient. The second OTC experiment was started in January, 2014.This year one set of plants were kept in ambient condition also for comparison. In the first phase the carbon dioxide level was 450ppm and enrichment was done for five hours per day up to 400 hours and in the second phase, the level of carbon dioxide was increased to 500ppm and 100hours of enrichment is completed. This phase will be completed after 400 hours of enrichment. Sensor data of daily temperature, humidity, carbon dioxide level of both the OTC and temperature of ambient condition were monitored. Soil samples were also collected. Sensor data recorded during the first phase are presented in the Fig 14.

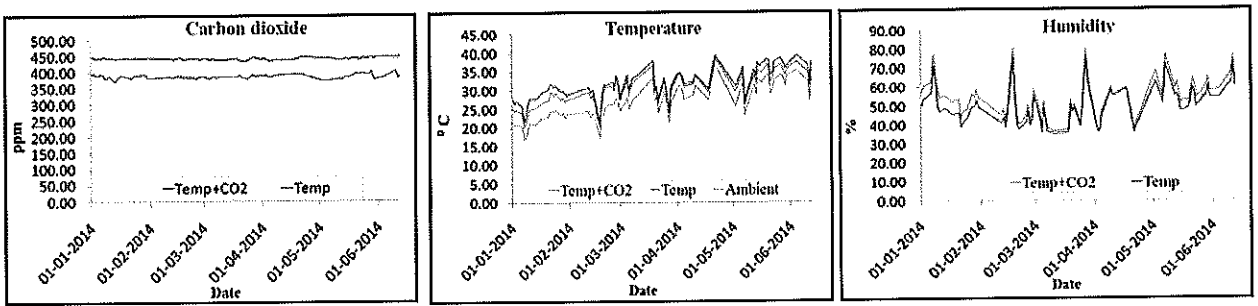

Fig 14: Comparison of sensor data of carbon dioxide, temperature, humidity and after 1st phase.

Impact of different environment on morphological character such as increase of plant height, collar diameter, branch number and leaf number are given in the Fig. 15.Differential response of clones is observed.

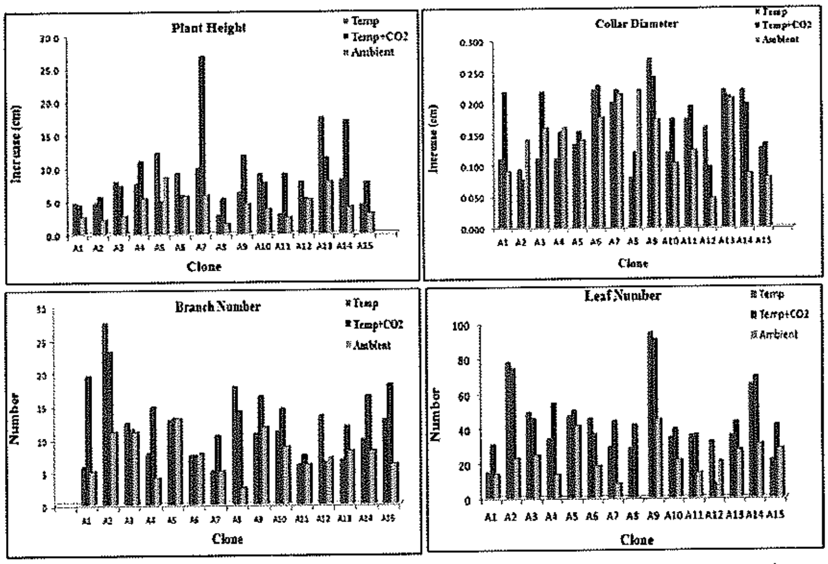

Fig 15.Impact of growing environment on morphological character after 1st phase.

Vulnerable regions

Preliminary analysis on a GIS platform has been done to figure out the climatically suitable and vulnerable regions for tea growth based on the future scenarios for Assam (Fig. 20). For temperature the 13-30^{0}C has been taken as most suitable; 30-35^{0}C suitable; and >35^{0}C vulnerable and for precipitation: <2000mm is vulnerable to drought (drought situations may arise), 2000-4000 suitable: >4000 mm vulnerable to floods (floods may happen). However, it is assumed in the analysis that the precipitation is evenly distributed and there is an efficient drainage system in the garden (which is a very ideal situation). The vulnerability analysis is being refined with more parameters.

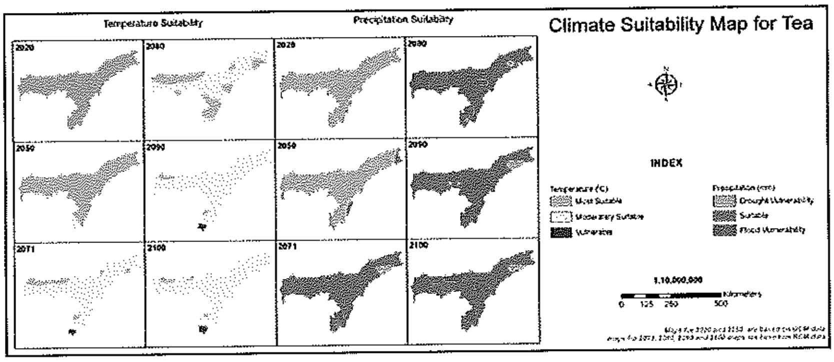

Fig.11 Future climatically vulnerable/suitable regions for growing tea in Assam – GIS outputs.

Action area 4: Identify adaptations trategies/agronomic practices

Agronomic practices to cope with climate change

To combat with the potential hazards and threats from climate change and sustain the tea productivity in North East India following agronomic practices can be applied, which can, not only, increase the resilience of the agro-ecosystem in changing climate condition but also help to adapt to the changes.

- Water Harvesting is an effective measure to store excess water during monsoon in farm ponds and storage tanks and reuse it when necessary. Practice already visible in tea gardens particularly in South Assam.
- Efficient planning on artificial irrigation both sprinkler and drip irrigation can reduce the drought risk in tea plantation areas. Number of gardens under irrigation is increasing in North East India.

- To deal with flooding and waterlogging, it is advisable to build efficient drainage system in the garden to quickly drain out water and eventually remove excess moisture from the root zone.
- Maintaining humid conditions in a tea garden can considerably delay the onslaught of drought. Increasing shade and planting more trees at the periphery of tea gardens can reduce the loss of moisture in the garden microenvironment. The water harvesting structures and farm ditches can also be kept closed at the end of monsoon to minimize water loss and thus enhance humidity in the soil microclimate.
- There are several cultivation practices inherent to tea, which are if followed regularly can be very effective against the impacts of climate change. Pruning is very effective drought management practice. Pruned or deep/ medium skiffed plants are less affected by drought due to less water loss through transpiration. In unpruned bushes maintenance of foliage is mandatory to avoid drought effects. Applying mulches retains soil moisture and thus delays or prevents the wilting of tea bushes.
- To maintain the revenue per unit area multiple cropping is an excellent alternative, which will ensure some earnings from the other crop if the production of tea is hampered due to extreme events.
- Organic cultivation of tea is a sustainable way to combat climate change. Use of naturally available products such as organic manures or composts and biological controlling agents increase climate resilience

2. Sri Lanka

Action area 1: Database development – meteorological, soil, crop and management

Long-term data on rainfall and temperature of different tea growing regions have been recorded in Sri Lanka. The temperature variation in a tropical country like Sri Lanka is largely governed by elevation. Tea Research Institute of Sri Lanka has also recorded various soil properties in tea lands representing major elevations which could be used for assessing the level of productivity under varying climatic conditions. Hence, an attempt was made to develop database on the variation of temperature and rainfall from 1961-2010 and inherited soil conditions to identify tea growing regions vulnerable for climate change in collaboration with the Department of Meteorology, Sri Lanka.

Action area 2: Impact analysis

A. ***Trend analysis***

Tea lands are distributed among 25 Agro Ecological Regions in Sri Lanka. The rainfall data is not recorded on AER basis. In order to get the representative rainfall data for a given AER, rainfall surfaces were developed for the whole country by linear interpolation of all recorded rainfall data for the period of 1961-2010. However, terrain effect of each AER was not considered in this interpolation.

The variation of temperature is largely due to changes in elevation, maximum and minimum temperatures of selected locations representing high, mid and low elevations of wet and intermediate zone were used in this analysis. Four distinct monsoon periods have been identified in Sri Lanka that are widely used in the agriculture sector. Therefore, monthly meteorological data was summarized for the distinct 4 seasons viz. December-February, March & April, May-September and October & November representing north-east Monsoon (NEM), 1st inter monsoon, south-west monsoon (SWM) and 2nd inter monsoon respectively. Mean annual rainfall of tea growing regions for the whole period (1961-2010) has been illustrated in Fig. 1.

Fig. 1 shows that WM3b, IM3a, IU3a, IU3d and IU3e regions receives low rainfall (<2000mm/yr) and hence, are vulnerable to adverse impacts of climate change. The mean temperature of mid (M) and low (L) elevations are found to be higher than the optimum value for tea i.e. 22^{o}C. Therefore, of the above 4 regions, WM3b and IM3a are more vulnerable than other regions to adverse impacts of rising temperatures and rainfall variations under climate change. Analysis of rainfall (1961-2010) of tea growing AERs during 4 distinct seasons (monsoon periods) shows that WM2b and WM3a (wet zone) receive less than 100mm/month (critical rainfall for tea) of rainfall during the NEM period. Mean monthly rainfall of IU3a, IU3c, IU3e, IM1a and IM2b (intermediate zone) during the SWM is also less than 100mm/month.

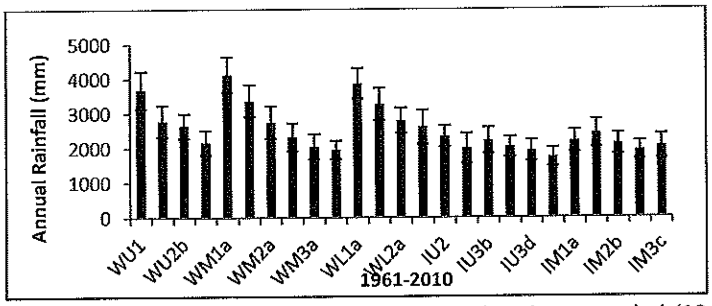

Fig. 1 Mean annual rainfall of tea growing AERs for the 50 year period (1961-2010)

Hence, these regions can also be considered vulnerable to climate change. Of them IM regions are more vulnerable than IU region due to high temperatures of the former. When influence of soil moisture stress on tea yield is considered, period covering NEM and 1st inter monsoon (December-April) in the wet zone (W) regions and 1st inter monsoon and SWM (March-September) in the intermediate zone (I) are critical for growth of tea as they represent distinct dry periods (moisture stress) of those AERs. All the AERs usually receives heavy rainfall during the 2nd inter monsoon. Variability of rainfall (coefficient of variation) over the periods during 1961-1990 and 1991-2010 was estimated for the distinct monsoon periods and results are given in Fig. 2a-d.

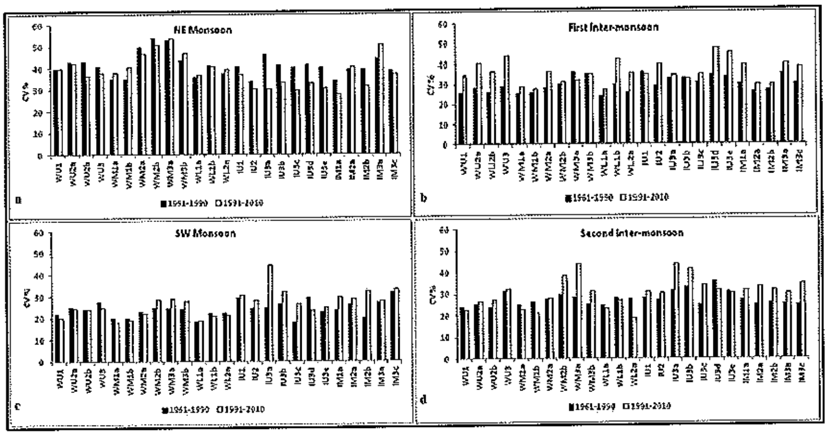

Fig. 2 Comparison of rainfall variability between the base period and the recent two decades of (a) north east monsoon (b) 1st inter-monsoon (c) south west monsoon (d) 2nd inter-monsoon.

The rainfall variability is high during NEM monsoon period while the lowest variability has been found during SWM period. However, variability of NEM rainfall of the majority of the AERs has been reduced during the recent past two decades (1991-2010). Variability of first and second inter-monsoon rainfall has been increased during 1991-2010 period as compared with the base period (1961-1990). The variability of the SWM of the majority of AERs in the wet zone (W) has been found to be low during the recent two decades when compared with the base period. Further, the variability of SWM rainfall seems to be high (CV-23-44%) in the intermediate zone (I) compared to that (CV-17-28%) of wet zone (W) during 1991-2010.

In general, results of the trend analysis of rainfall (1961-1990, 1991-2010 & 1961-2010) for different monsoon periods in tea growing AERs indicates that total annual rainfall has been reduced during the base period (1961-

1990) in almost all tea growing regions. Significant and greater reduction has been recorded in WM1b, WL1a, WL1b, WL2a, IU3a and IM2b regions. The total rainfall of NEM and the 1st inter-monsoon in WU3 (wet zone) and total rainfall of 1st inter-monsoon and SWM in IU1, IM3a and IM3c (intermediate zone) was significantly low during the past two decades as compared with the base period (Fig. 3).

The monthly variation of temperatures is given in the Fig. 4 (a-e). Accordingly, very high temperatures prevailed during the 1st inter-monsoon period at low and mid elevations of wet zone (W) while it is very low during NEM period at high elevations. Mid elevations of intermediate zone (I) recorded high temperatures during SWM period. The ambient temperatures (maximum and minimum) of most of the tea growing regions have shown to have been increased over the last 50 years except maximum temperature in Nuwara Eliya (highest elevation). The highest temperature rise (0.04°C/yr) has been recorded in Talawakelle (WU) and Badulla (IU), followed by minimum temperature of Nuwara Eliya (WU) (0.03°C/yr) during the 1st inter monsoon (March-April) period. Significant positive correlations have shown that the temperature rise in tea growing regions over the 50 year period has been in the range of 0.5-2°C.

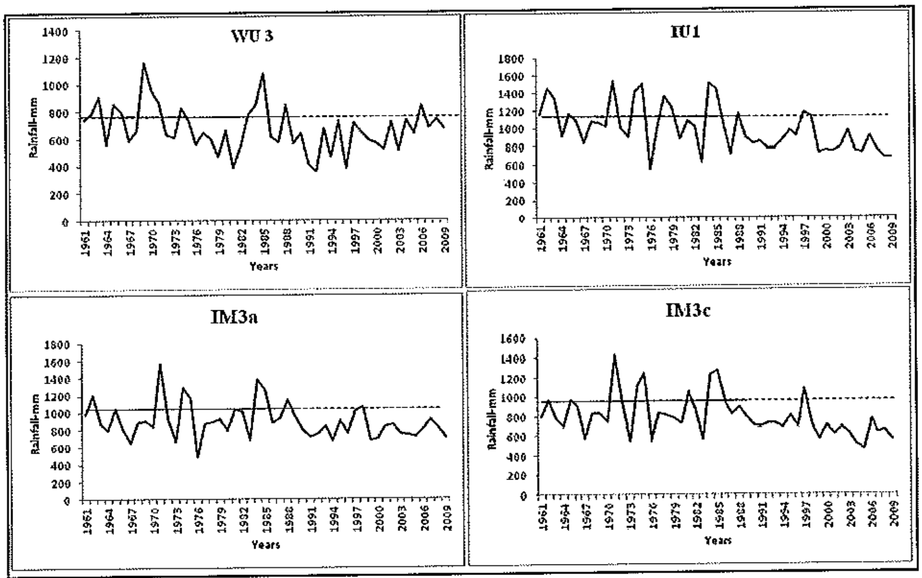

Fig. 3. Rainfall of WU3 during NEM & 1st Inter-monsoon; Rainfall of IU1 during 1st IM3a and IM3c during 1st Inter-monsoon and SWM; straight line indicates the mean rainfall during the base period; 1961-1990.

When the optimum temperatures for tea cultivation (22°C) is considered, increasing temperatures at low (WL) and mid (WM & IM) elevations can adversely affect growth & yield of tea. Rising temperatures above the optimum not only bring direct (adverse) effects on tea but also can make tea vulnerable to moisture stress condition due to high rate of evapo-transpiration. Of these regions, IM and WL are more vulnerable for adverse impacts of rising temperatures due to lack of rainfall of the former and very high temperatures of the latter. Further, high rate of temperature rise during the moisture stress period i.e., the 1st inter-monsoon and SWM of the IM region (March-September) and during NEM and the 1st inter-monsoon (December-April) of some WL regions will be very unfavourable for tea cultivation. Additionally, it is noted in this analysis that the rate (magnitude) of maximum temperature rise at low elevation (Galle, WL) is higher than that of the minimum temperatures. Such temperature variation can adversely affect growth and yield of tea at low elevations. In contrast, high elevation (Nuwara Eliya, WU) have recorded a higher rate for minimum temperatures which could bring in favour of tea production.

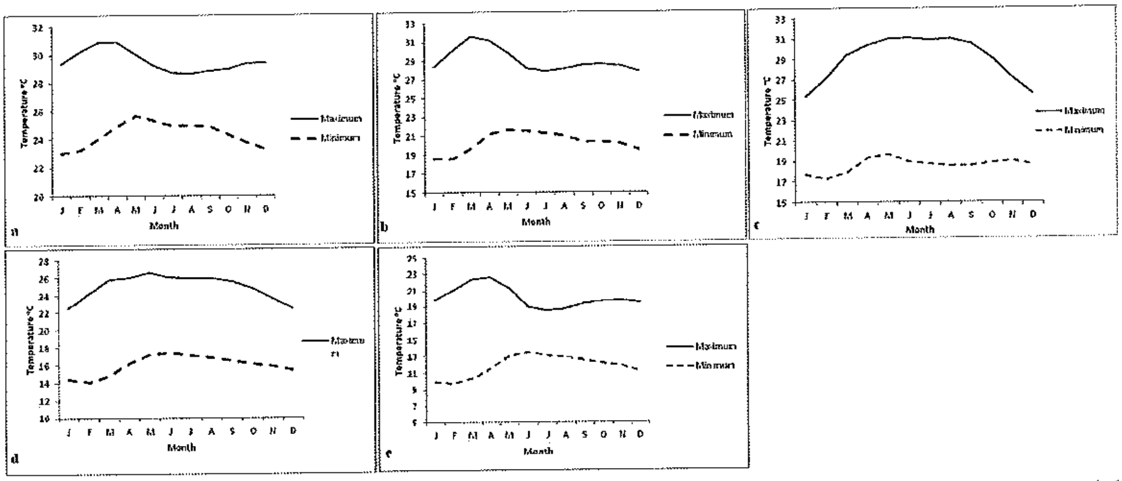

Fig.4Monthly temperaure variation at different AERs (a)WL2a, Galle (b) WM3b, Katugastota (c) IM1a, Badulla (d) IU3c, Bandarawela and (e) WU3, Nuwara Eliya.

B. ***Establishment of indices for identifying tea growing regions vulnerable to climate change***

Degree of vulnerability of tea plantations vary depending on the interaction of impacts of several factors considered. Therefore, vulnerability indices were established for each AER based on rainfall, temperature and soil conditions. In this analysis, AERs with <2000mm of annual rainfall, <100mm of mean monthly rainfall during critical months, significant decline of annual rainfall during 1961-2010, significant change of critical months' rainfall between 1961-1990 and 1991-2010 periods and significant increase in rainfall variability (critical months) in 1991-2010 period as compared with 1961-1990 period were considered vulnerable for climate change impacts. Temperature indices were based on the optimum temperature for growth of tea. Accordingly, low elevation where the present mean temperatures are above 22°C was considered highly vulnerable while mid elevation where the present mean temperatures are around 22°C was considered vulnerable. High elevation was considered not vulnerable to temperature rise as the present mean temperatures were below 22°C. Variation of soil factors was considered only if any of the other two factors (rainfall & temperature) have made significant impact only. Depending on the availability of data and considering soil requirements of the tea plant, soils at high elevation was assumed as ideal for tea and hence was used for comparison. Accordingly, tea soils with a depth of less than 90cm were ranked as vulnerable for climate change while those with a gravel % of 15-30% was considered vulnerable and those with more than 30% as highly vulnerable. The soils with more than 40% sand and those with a bulk density of more than 1.1 g/cm^3 were considered vulnerable. Further, soils with more than 4% carbon content was considered not vulnerable, 2-4% as vulnerable and less than 2% as highly vulnerable.

Tea growing AERs vulnerable to climate change impacts

Based on the individual vulnerability indices developed for rainfall, temperature and soil, an overall vulnerability index for each AER was established. This analysis showed that WL1a, WL1b, WL2a, WM2a, WM2b, WM3a, IM2b, IM3a and IM3c regions are highly vulnerable and WM1a, WM1b, WM3b, IM1a, IM2a, IU3a, IU3d and IU3e regions are vulnerable for climate change. These results provide further evidence to strengthen the findings of the previous study and also more information on the impacts of climate change on the AER basis.

C. ***Future scenarios***

The projected tea yield for 2050 by GCMs developed for Sri Lanka (Table 1) combined with a crop model showed that tea yield likely to increase at high elevation while it showed a declining trend at low elevation. The models have shown mixed results for mid-elevation i.e. increasing as well as decreasing yields of tea under different scenarios. The yield projections by CSIRO model were higher than that of HadCM3. As per the projected yields, the climate change can reduce tea yield up to about 7% at low elevations that contributes to 60% of the total tea production in Sri Lanka. In contrast, tea yield is projected to be increased by around 25-29% at high elevations by 2050. Due to greater production, presence of small tea growers and higher tea prices, the declining trend of tea production projected for low elevation is very vital for the tea industry of Sri Lanka.

Table 1. Projected tea yields for 2050 at different elevations in Sri Lanka

GCM Model& Scenario	Yield (kg/ha/yr)		
	Low elevation Ratnapura (WL1a)	Mid elevation Kandy (WM3b)	High elevation N'Eliya (WU3)
Baseline	2489	2217	2454
HadCM3-A1F1	2348	2174	3130
HadCM3-B1	2419	2189	3115
CISIRO-A1F1	2401	2246	3167
CISIRO-B1	2472	2245	3137
CGCM-A1F1	2314	2217	3108
CGCM-B1	2380	2228	3072

Action area 3: Work out interaction between Genotype (G) x Environment (E) x Management (M) which is the prime driver of productivity

Analysis of the estimated impact of rainfall deficit (optimum-actual) on tea yield and the optimum monthly rainfall requirement for highest productivity of tea in different AERs shows that the optimum (mean monthly) rainfall for tea varies from about 223-417 mm and the loss of yield due to lack of rainfall (rainfall deficit) was estimated to be in the range between 29-81 kg/month/100mm rainfall deficit. The analysis also indicates that the optimum rainfall for tea in WL, WM and IU regions were higher than those of WU and IM. The IM and WU regions are estimated to have greater losses of tea yield due to lack of rainfall. These data shows that optimum rainfall for tea cultivation is in the range between 2675mm and 5000mm/year which is much greater than those previously reported i.e. 2500-3000 mm. The productivity of plantations in all regions seems to be sensitive to lack of rainfall (moisture stress).

Temperature and yield data analysis for different tea growing elevations has shown that tea yield increases with the increase in ambient temperatures from 15 to 22°C (Fig. 5). Moreover, the mean increase in productivity (linear trend) up to 22°C was estimated to be about 15.1kg/°C. It has been found that rising temperatures above 22°C reduces tea yield with a mean rate of 9.6 kg/°C. Therefore, the analysis revealed that the optimum ambient temperature recording the highest productivity of tea in Sri Lanka is about 22°C which agrees with the optimum range reported earlier.

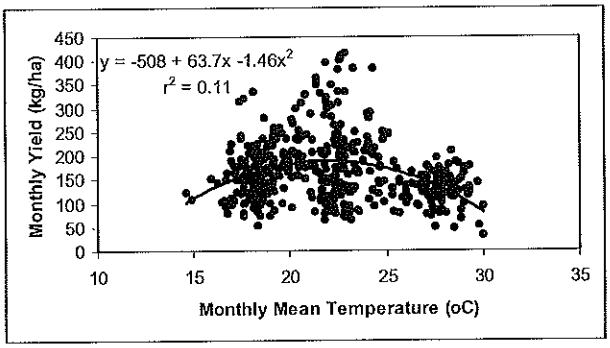

Fig. 5. The effect of ambient temperature on tea yield

This study also showed that the majority of tea plantations can be adversely affected by rising temperatures as the mean temperatures in WL, WM, IM and IU regions are above the optimum temperature for growth of tea (22°C). The beneficial effects of temperature rise can be expected only in the WU regions. Presently, more than 50% of national production comes from the WL and WM regions and the majority of tea smallholders who contributes to around 70% of national production are clustered in these two regions.

Results of field experiments with tea have showed that increase in ambient CO_2 (open-top chamber with 600ppm CO_2 for 18 months) increased average yield of tea by 37% at low elevation (WL1a) and 33% at high elevation (WU2a). The response of tea to enriched CO_2 during dry months was found to be lower than that during wet months. This increase in tea yield with enhanced CO_2 was a result of high shoot density, rate of growth and weight of shoots under enriched CO_2 in comparison with the control. Time taken for bud break was also less under enriched CO_2 which led to produce more shoots. Further, a high rate of assimilation and low rate of transpiration were also recorded in the CO_2 enriched plot. These results revealed that water use efficiency was comparatively high with enriched CO_2. Root analysis showed that starch reserves of tea bushes under enhanced CO_2 were significantly higher than that under ambient CO_2i.e 4.13% and 2.9% respectively (Table 2).

Table 2. The effect of CO_2 concentration on the total shoot density (TSD), harvested shoot density (HSD), shoot weight (SW), shoot growth rate (SGR), time taken for bud break, net photosynthesis rate (NPR), transpiration rate (TR) and water use efficiency (WUE)

CO_2 Concentration	TSD No/m^2	HSD No/bush	SW g/shoot	SGR mm/day	Bud Break days	NPR mol/m^2/s	TR mol/m^2/s	WUE (NPR/TR)
600 ppm	362 ± 11.9	64.1 ± 2.3	0.831 ± 0.017	2.8 ± 0.16	16.8 ± 0.79	12.1 ± 0.58	3.6 ± 0.08	3.36
360 ppm	312 ± 16.3	42.1 ± 3.9	0.698 ± 0.028	2.1 ± 0.23	20.6 ± 0.56	10.2 ± 0.37	6.2 ± 0.52	1.64

Action area 4: Identify adaptation strategies/agronomic practices

__Agronomic adaptation practices__

a) The Tea Research Institute of Sri Lanka has already recommended more than 60 TRI and estate cultivars for tea growers which are adaptable to varying climatic conditions including drought and heat. Additionally, planting of improved seed varieties and grafted plants in the AERs prone to dry weather is helpful for adapting to climate change.

b) A good stand of shade trees in tea reduces ambient temperature around tea bushes, increase RH, and adds organic matter to soil.

c) The loss of organic matter from tea lands could be in the range of 10-20t/ha/yr. Thus, application of compost and green manure will help sustain organic matter status of tea soils and will help combating climate change.

d) To reduce soil erosion during heavy monsoon periods and drying during less rainfall months, establishment and maintenance of drain system and stone terraces, mulching, envelope forking or burying of pruning in tea lands should be carried out in priority.

e) Irrigation prevent moisture stress on tea during dry months can be considered advantageous in minimizing climate change impacts

3. Kenya

Action area 1: Database development – meteorological, soil, crop and management

Some climate change signals already evidenced in Kenya includes; temperature rises, unpredictable rainfall trends and increasing frequency of extreme weather events e.g. hail storms, drought and frost. Some of the above changes are evidence in tea growing areas e.g. Kericho where there is an annual decrease of 2.84mm rainfall for a period of 54 years (153mm decrease) a scenario indicated in Fig. 1 and annual temperature rise of 0.002^{0}C for a period of 54 years (0.1^{0}C increase) as shown in Fig. 2. From a study that was carried out at the Timbilil Tea Estate, Kericho district, Magura Tea Estate in Sotik and Kangaita farm in Kirinyaga district, data showed that all Estates have experienced increasing temperature trends with an annual rise of 0.02^{0}C at Timbilil, 0.22^{0}C in Sotik-Magura and 0.01^{0}C in Kangaita.

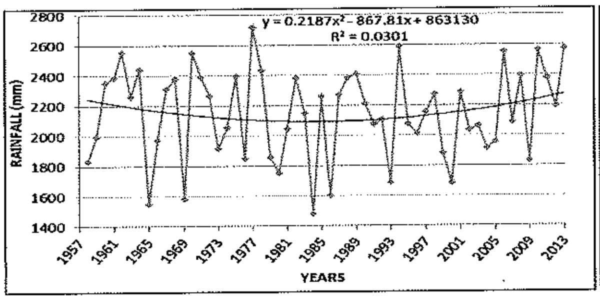

Fig. 1. Longterm annual rainfall

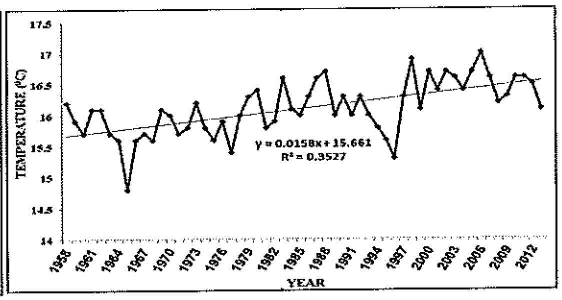

Fig.2. Longterm temperatures

The soil water deficits (SWD) as determined by the Hess (1994) model showed that the deficits are equally on the increase (Fig. 3). Generally, the SWD have been prevalent only in January to March, a period associated with tea plant water stress and low tea crop season. During these periods, some of the tea factories work under capacity. Occasionally, the SWD go as high as 400 mm, but the critical level that can cause extreme water stress characterized by temporary tea growth is about 120 mm. From available data, soil water deficit with a linear decrease of -57mm for every ten-year period average has been observed.

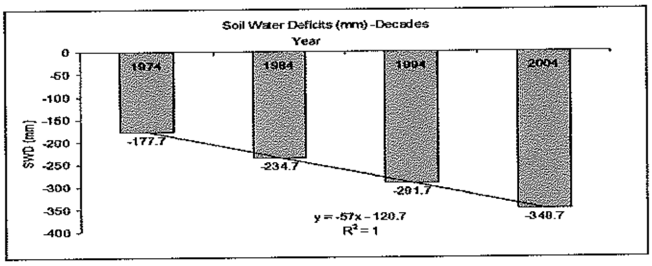

Fig. 3. Soil water deficits

Action area 2: Impact analysis

Impacts of climate change on tea production in Kenya

Tea farmers are vulnerable to climate change mainly due to either unpredictable, inadequate or poorly distributed rainfall or prolonged drought periods. Tea cultivation in Kenya purely depends on rainfall to maintain its soil moisture level and 1200 mm of rainfall annually is considered essential. However, the most important factor is the distribution. Failure of adequate rainfall could results in possible impact of crop decline. The impacts of climate change in tea could be numerous.

i) Long term rainfall decreases and modification resulting to shifts in distribution

Inadequate rain imparts critical soil moisture stress on plants. Research on tea and its water requirements in Kericho concluded that the critical Soil Water Deficit is about 30mm above which there is a linear decrease in yield of about 1.1 kg ha^{-1} $week^{-1}$. Generally, during drought, severity of annual yield losses varies from as low as 12-20% depending on the clonal material planted and the length of the drought period.

Rainfall distribution and patterns have also changed in all the three sites and is unpredictable. Tea does well in warm temperatures only if soil moisture is not limiting. The case of Timbilil Tea Estate showed a significant ($P \leq 0.05$, n=270, r^2=0.928) positive relationship between mean air temperature and tea yields (319 kg ha^{-1} $^oC^{-1}$) when soil moisture is not limiting. Similar observations were made in other sites of Magura in Sotik and Kangaita in Kirinyaga. The results also indicated that temperature and radiation affects tea production. The correlations also showed that rainfall may not be the only important factor that promotes better yields but also mean air temperatures.

The overall climate will become less seasonal in terms of variation throughout the year. The mean air temperature in East Africa is predicted to increase by about 2.5 °C by 2025 and 3.4 °C by 2075, while rainfall is predicted to increase by about 2% by 2025 and 11% by 2075. The implication is that the distribution of suitability of tea growing within the current tea-growing areas in Kenya will decrease. This is attributed to rainfall distribution and not amounts of rain received. The rise in mean air temperatures beyond the threshold of 23.5 °C is likely to occur. The GIS analysis indicated that suitability of tea growing areas is expected to decline by 22.5% by the year 2075 while a suitability increase of 8% is expected by 2025.

ii) Change in patterns of extreme weather events causes harvest losses

In the western tea producing counties of Kenya, for example; Kericho, Bomet (Sotik) and Nandi, net loss of tea green leaf due to hail is estimated at over 2 million kilograms per year depending on severity of hail occurrence in these areas. The reported cases are mainly from the large estates while few of the small scale-farmers report incidences.

Occurrence of Frost on the other hand, is less but when it does strike, there are huge losses incurred. Generally, occurrence is on valley bottoms and low lying areas. Analysis of long-term data suggests that the frost incidences are increasing. Early January, 2012, frost bite hit all the tea growing areas across most tea producing counties causing up to a maximum of 30% yield losses. The crops could not be harvested until after 3 months from the time frost occurred.

A tea producer survey was done to assess vulnerability at the producer level, production techniques and risk coping option. The results indicated that the farmers are more vulnerable to climate change scenarios. To cope with these changes, farmers adopt use of drought tolerant clones and other Good Agricultural Practices. The other aspect is that the farmers have no adequate income from tea during the drought period. This scenario makes farmers to be more food insecure considering the fact that some farmers have planted all their land under tea.

iii) *Expected maximum changes to tea cultivation in 2075*

Fig. 4. Regions that are suitable for tea growing, based on the expected maximum changes in climatic conditions. The maximum expected changes would be a temperature increase of 4.3^{0}C and rainfall increase to 25 percent. Based on this projection, it is noted that the tea areas east and west of the Great Valley Rift will have reduced. In the western part of Kenya, the zones that will largely be affected are the counties of Kisii, Nandi, Kakamega, Tranzoia and Bomet. In the Eastern part of Kenya, counties of the Meru, Kiambu, Thika, Muranga, Kirinyaga, Tharaka and Embu will be the most affected. In both regions, low altitude areas will be considerably influenced.

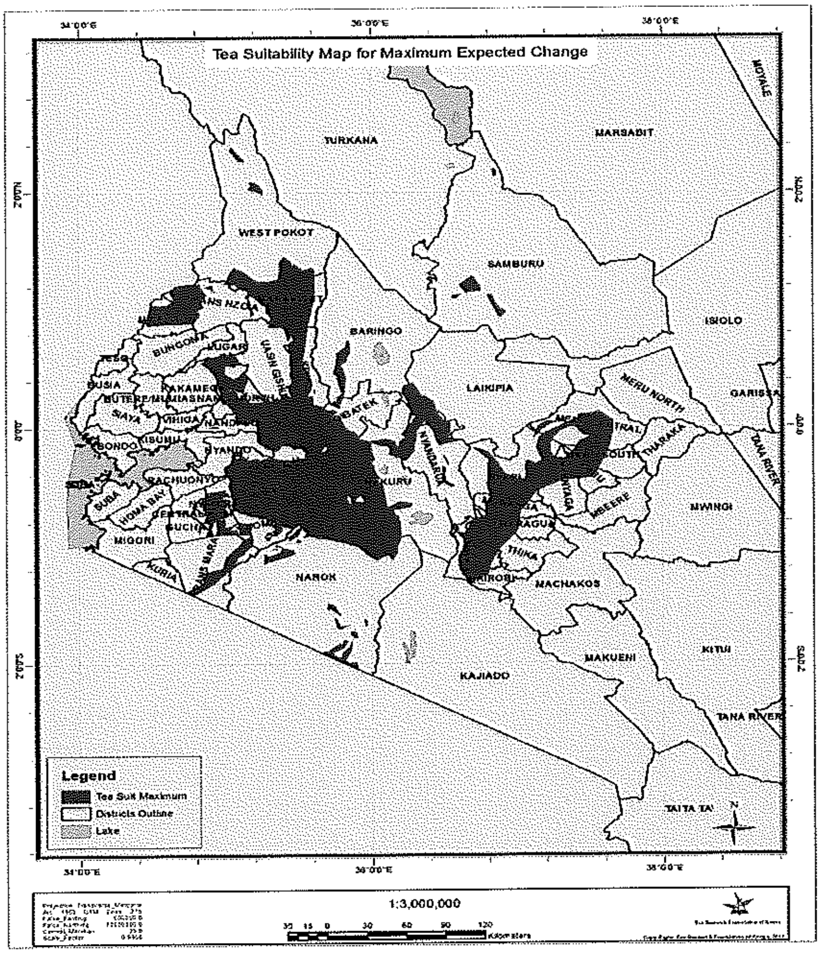

Fig 4: Suitable tea growing areas, based on maximum expected climate change

Action area 4: Identify adaptation strategies/agronomic practices

Climate Change Adaptation Strategies

1. The Tea Research Institute has developed and commercialized over 51 clones which are high yielding and good quality as well as drought, disease and pest tolerant and can be helpful in combating climate change in different scenarios.
2. Tea Research Institute emphasizes on sustainable tea production through promotion of sustainable agricultural farm management practices including; sustainable land use such as agro-forestry in tea production using suitable trees and enhancing water catchment.
3. Due to the fact that most tea farmers have planted their land to tea, and coupled with the low returns from the tea farms, some farmers face food insecurity. Farmers are guided on the land use to assist in enhancing food and nutrition security by introducing other crops with economic benefits to the tea farmers to cushion them from the negative impacts of climate change.
4. Kenya currently relies on few market outlets for her black tea. Kenya mainly produces black tea whose demand has decreased in recent years, while that of green tea has gone up due to its health benefits. In an effort to availing the appropriate materials for product diversification, The TRI has released a number of varieties including the purple tea that has high anthocyanin content, high yields and is tolerant to biotic and abiotic stresses.
5. TRI and other collaborators generate data for use in early warning systems and guide the government in formulation of agricultural insurance policy to cater for livestock and plantation crops. This will reduce sensitivity to the impacts of climate change and increasing the adaptive capacity of tea farmers.

6.The tea industry has three issues to greenhouse gas emissions; (i) use of fuel wood in tea processing resulting from the high cost of electricity (ii) low energy efficiency Estimates show that 1 ha of fuel wood is required for every 3.3 to 4 ha of tea planted. Considering the above situation energy audits of tea factories are mandatory on annual basis to improve on energy efficiency. Feasibility studies have been done to explore alternative sources of energy such as wind, solar and hydro.

7. The tea industry has initiated annual climate change adaptation and mitigations awards. This goes a long way in motivating the stakeholders in taking up the climate change adaptation and mitigation technologies.

4. Malawi

Indicators of climate change

The impacts of climate change in Malawi are being manifested in various ways such as intense rainfall, changing rainfall patterns, floods, droughts and prolonged dry spells.In case of Malawi's tea growing districts, an examination of these parameters revealed changes in climate. Some of the changes that specifically pertain to tea production include prolonged droughts, late start and early cessation of the rainsand, increase in maximum temperatures. The convergence of drought and high temperature stresses will greatly reduce tea production. The mean minimum and maximum temperatures for a number of decades between 1960 and 2001 are presented in fig. 1–4. This has been selectively done to include some months of the year when these factors would have the most impact on tea production. The data has been summarised from the meteorological records for Mimosa weather station.

Action area 1: Database development – meteorological, soil, crop and management

Rainfall

The minimum amount of rain for optimum tea growth and production is about 100mm every month. The trend of rainfall received at Mimosa for the periods 1977-1988 and 1997 – 2008(Fig.1) shows that total precipitation is below this minimum requirement between April and October. Comparison of the data from the two decades, show a drop in monthly rainfall in April, May and June and, in October and November over the period 1997–2008 compared to the period 1977–1988. These changes have significant impacts on bush productivity and survival.

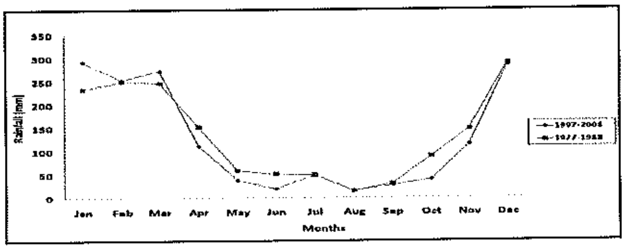

Fig. 1. Monthly rainfall (mm) for Mimosa Research Station, Mulanje for the period 1977-1988 and 1997-2008

While the overall amount of rain received in a season may not change much, it is the change in pattern that might affect tea production. In order to highlight the fact that the rainfall pattern has drastically changed over the years, the monthly rainfall for 1972/73 and 2005/6 seasons, recorded at Mimosa are presented in Fig. 2 for comparison. Whilst during the 1970s, the rains were fairly distributed throughout the season (e.g. 1972/73), the pattern being experienced these days shows very poor rainfall distribution with most of the months in the off-season period receiving very little or no rains at all (e.g. 2005/06, Fig. 2b).

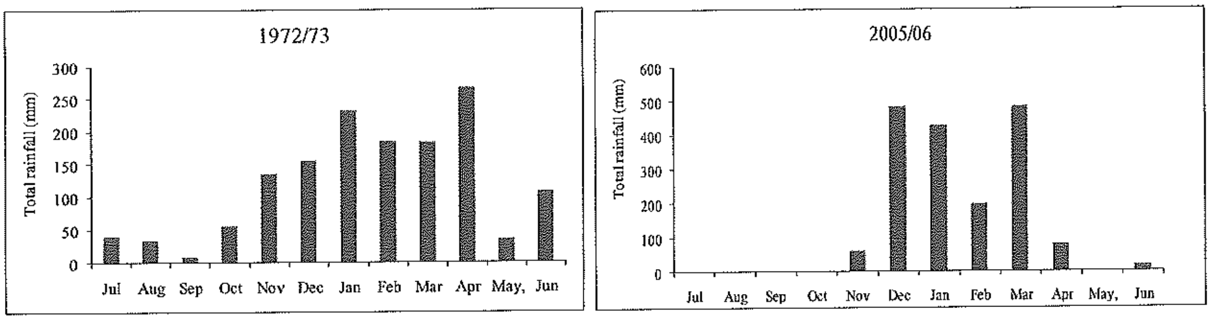

Fig. 2.Total monthly rainfall (mm) for Mimosa Research Station, Mulanje for the 1972/73 (2a) and 2005/06 (2b) seasons

Temperature

Teawill generally exhibit active growth of shoots when mean temperatures are above 12.5°C. This is the generalization for most areas in central and southern Africa. This response varies with different tea cultivars. If the climate could result in increase in minimum temperatures during the winter period, then probably some cultivars might have an extended harvesting period, if moisture is not limiting. Where the tea is irrigated, substantial crop could be harvested during the 'warmer' winter months. The data presented in fig. 2, show that daily minimum temperatures in cool months have been around 12.5°C in the June, July and August over the decade 1992–2001, which is slightly higher than what was experienced over the decades before 1992. This may suggest that winters are getting warmer and this could enhance shoot growth.

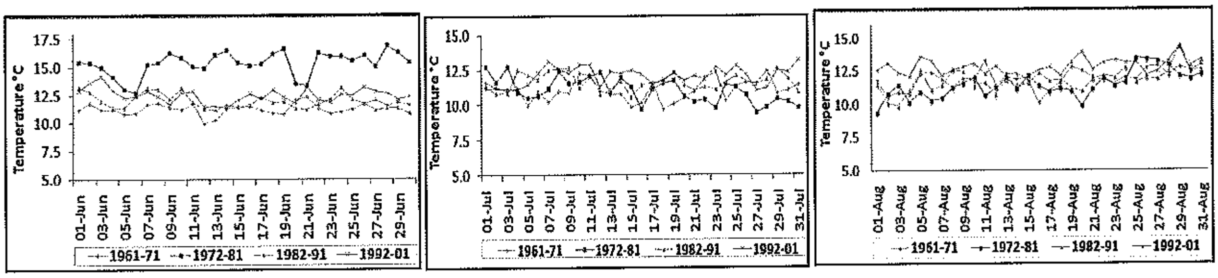

Figure 3.Mean decadal daily minimum temperatures (°C) at Mimosa Research Station, Mulanje for June (3a), July (3b) and August (3c) over the period 1961 to 2001.

Very high maximum temperature reduces shoot extension and development especially during the dry periods when the relative humidity is low and the vapour pressure deficit is also high. In Malawi, increase in temperature of between 0.44°C and 0.83°C has been reported over 50 years. This is a very high increase compared to what has been reported in other tea growing areas, for example, in South India an increase of 0.6°C in temperature was reported. Effects of rising temperature can be confounded by extended severe water stress during the hot dry period.

Average daily maximum temperatures for September, October and November for Mimosa Research Station are presented in Fig. 3. In general, the decade 1992-2001 recorded higher daily maximum temperatures than the other decades. In October and November, the maximum temperatures were about 33°C during the 1992-2001 compared to the other decades when the daily maximum temperatures were hovering around 30°C on most of the days. This had a direct impact on tea growth and productivity.

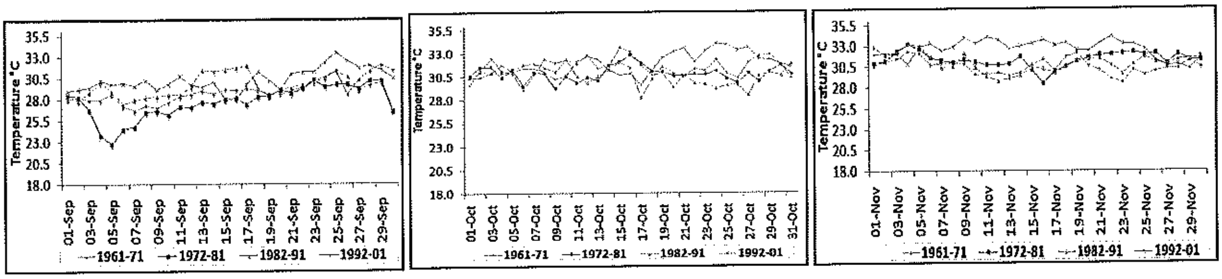

Figure 4.Mean decadal daily minimum temperatures (°C) at Mimosa Research Station, Mulanje for September (a), October (b) and November (c) over the period 1961 to 2001.

Action area 2: Impact analysis

Expected impacts of climate change on tea production in Malawi

Earlier predictions indicated that the region would experience drought every 10 years. However, droughts have now become more recurrent with very short return periods. Frequent drought conditions will affect plant survival and bush productivity. Severe drought conditions will likely result in high bush mortality and consequently reduce yields over time. For some cultivars, drought tolerance comes at the expense of crop production. For example, PC168 that survives drought very well may show yield decrease because it defoliates under severe moisture stress. The recovery period from drought or prolonged dry spell may be long and this might affect crop distribution within the season. A significant proportion of the main harvesting period (December to May) could be lost due to delayed recovery of the bushes.Extreme high temperatures may confound the effects of drought and lead to high bush deaths and result in very low yields per unit area. Malawi's tea production declined by about 33%,9.5% and 7.4% during the 1991/92, 2004/5 and 2007/8 drought years.

Incidence of pests and diseases is expected to increase under high temperature and dry conditions, for example,mitesattacks may become intense under dry and hot conditions. Although mites may not cause economic yield loss, they can weaken bushes and affect rate of recovery from dry conditions. *Helopeltis* attacks and/or their effectshave been reported to be more severe in drought years and this contributes to high bush mortality due to die-back and development of branch cankers. This could result in yield loss. Diseases such as *Phomopsis* (stem / branch canker) may become severe on bushes that are stressed and weakened by the drought.On the socio-economic front, employment for seasonal workers may be at stake as a result of low bush productivity and low production. This could have spin-off effects on the other sectors of the agricultural communities around tea estates. A snap analysis of the size of labour force from 1999 to 2012 shows a general decline in the number of people employed on the estates in Mulanje (Fig. 4). It is common knowledge to many tea growers that the 2004/5 and 2007/8 seasonsexperienced severe droughts. During the 2004/5 season, for example, labour employed on the estates in Mulanje declined from 40,607 to 32,486 (20% decline). From 1999 to 2012, the size of the labour shrunk from 51,325 to 32069 (approximately 38% drop). This could partly be a result of reduced bush productivity due to climate change.

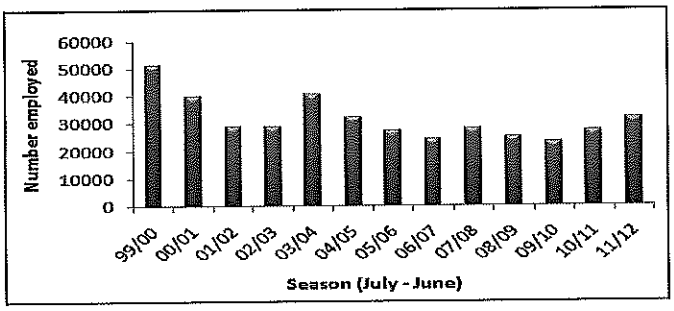

Fig. 5.Total number of labour (male and female) employed on the estates in Mulanje over the period July 1999 to June 2012.

Action area 4: Identify adaptation strategies/agronomic practices

Adaptive/ mitigation strategies for coping with climate change in tea cultivation in Malawi

- Use of hardy plant materials in infilling, replanting and expansion programmes would help in mitigating the effects of climate change.
- Choice of land for expansion (for smallholders) or fields for replanting (estates) should be done carefully to ensure suitability for tea cultivation, especially now that the climate is not so friendly.
- From the viewpoint of field management, timing of some cultural practices might be critical. For instance, time for pruning and fertilizer application may need to be adjusted. Mulching needs to be done at the right time in order to achieve the intended benefits. Organic matter must be replenished, e.g. by keeping pruning material *in-situ* in order to increase the organic matter content of the soils.
- Use of shade trees can help in minimizing the impacts of very high temperatures and increase in radiation that may cause sun-scorch.
- Investment in irrigation facilities should be increased in order to supply water to the stressed plants in times of need.
- Pest attacks such as *Heliopolis* attack on tea that is recovering from pruning can be minimized by executing a properly planned preventive spraying programme that can start at bud break. This will protect the re-growing tender shoots from *Heliopolis* damage and thereby prevent the risks of branch cankers and stem die-back.

5. China

Action area 1 and 2: database development, impact analysis and future scenarios

To understand climate change in the last 60 years, 4 typical cities from south to north in different climate conditions in China were selected. The detailed information is listed in Table 1. Haikou is an island city in Hainan province of south China, producing black tea. Kunming is a plateau, producing Puer and black tea in southwest China. Hangzhou is in subtropical zone, eastern China, producing green tea. And Jinan is in north China, the city is not producing tea as it is too cold in winter, but nearby coastal areas produce green tea.The main climate parameters including monthly mean, lowest, highest, extreme lowest and extreme highest temperatures, monthly precipitation, daily highest precipitation, number of rainy days, mean air relative humidity, sunshine duration and percentage of sunshinein each month were downloaded from China meteorological data sharing service system (http://cdc.cma.gov.cn) with these cities dated from January1951 to December 2010. The climate change trend in the last 60 years was analyzed using linear regression analysis.

Table 1. Selected information in the cities of China for climate change study

City	Location	Altitude (m)	Mean annual temperature (^{O}C)	Extreme lowest temperature (^{O}C)	Mean annual precipitation (mm)
Haikou	110°20′ E 20°02′ N	14	24.1(9.3-36.1)	2.8	1688
Kunming	102°42′ E 25°04′ N	1890	15.0 (2.3-25.6)	-7.8	992
Hangzhou	120°10′ E 30°16′ N	40	16.5 (9.0-33.9)	-9.6	1417
Jinan	117°00′ E 36°40′ N	100	14.5 (-4.8-32.7)	-19.2	689

Temperature change

Annual mean temperature was significantly and steadily increased in the last 60 years (Fig. 1A). Linear regression equations were found according to the temperature change in all 4 cities (Table 2). The temperature increase was different between the cities. Haikou, the tropical city and Jinan, the temperate city increased by

1.0 and 1.1℃, respectively in annual mean temperaturein every 50 years, less than subtropical city of Hangzhou (1.6℃) and plateau city of Kunming (1.6℃)(Table 2). Further analysis showed that the highest temperature including monthly and extreme highest temperature was not much different. They were stable or slightly increase in most of the cities. For Hangzhou, the number of days≥ 35℃ is significantly increased. But for Jinan, the highest temperature was even slightly decreased. However, the lowest temperature including the monthly lowest and extreme lowest was remarkably increased in all the cities studied. The extreme lowest temperature was increased by 2.3, 3.0, 2.1 and 3.8℃ in every 50 years in Haikou, Kunming, Hangzhou and Jinan, respectively (Fig. 1B). The seasonal difference indicates winter is becoming warmer.

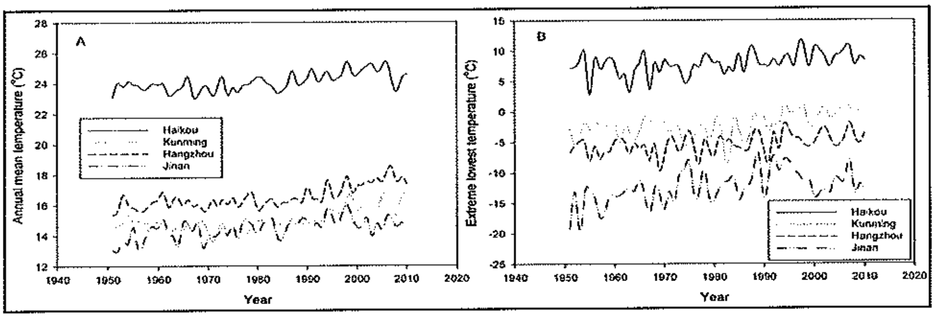

Fig. 1 Changes of annual mean (A) and extreme lowest (B) temperature in 4 cities during the last 60 years

Table 2 Linear regression equations fitted with the change of annual mean temperature in the last 60 years.

City	Linear regression equation (Y: annual mean temperature, X: year).	R^2 (Sig.)	Annual mean temperature increase in every 50 years (℃)
Haikou	Y=0.021X-16.721	0.378 (p<0.001)	1.0
Kunming	Y=0.030X-43.380	0.480 (p<0.001)	1.5
Hangzhou	Y=0.032X-46.149	0.591 (p<0.001)	1.6
Jinan	Y=0.021X-27.401	0.323 (p<0.001)	1.1

Precipitation and relative humidity change

The annual precipitation (Fig. 2A)did not changesignificantly in selected 4 cities in the last 60 years, in spite of the prediction by China NDRC (2007)that mean precipitation tends to increase in China. However, the number of rainy days (≥0.1mm) was reduced (Fig. 2B), though not as significant as the mean temperature. The rainy days were reduced by 13.1, 13.2, 12.0 and 6.7 d in Haikou, Kunming, Hangzhou and Jinan, respectively in every 50 years. Most of tea lands are rainfed and suffer from more seasonal drought or unpredicted highly intensive precipitation.The atmospheric relative humidity was reduced significantly. The annual mean relative humidity was significantly and negatively correlated with the year in all 4 cities (Fig. 3). According to the linear regression equations, the relative humidity decreased by 3.3-9.4% in every 50 years, with the lowest in Jinan and highest in Hangzhou.The annual mean relative humidity in Hangzhou was 83.6% in 1950, but it declined to 72.4% in 2010. If the same trend continues, it will further reduce to 64.8% in 2050, which could seriously affect tea growth and production.

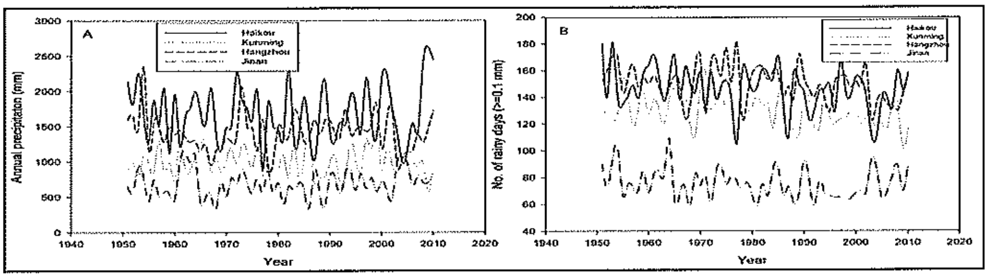

Fig. 2 Changes of annual precipitation (A) and No. of rainy days (≥0.1mm) (B) in 4 cities during the last 60 years.

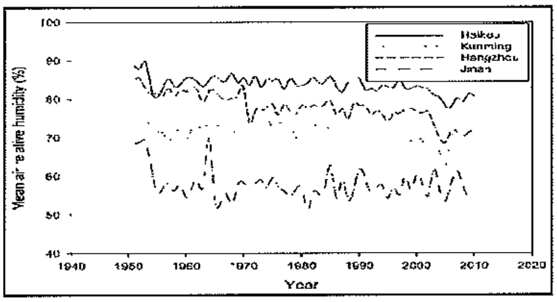

Fig. 3 Change of annual mean relative humidity in 4 cities in the last 60 years.

Sunshine time Change

Annual sunshine time in all the 4 cities had significantly reducedin the last 60 years (Fig. 4). The annual mean sunshine time was reduced from 207.1 h in 1950 to 158.0 h in 2010 in the 4 cities. Accordingly, the percentage of sunshine time was reduced from average of 56.3% in 1950 to 42.9% in 2010. If the same trend continues, the mean sunshine time and percentage of sunshine time will be decreased to 153.0 h and 43% in 2050, which will affect the tea production tremendously.

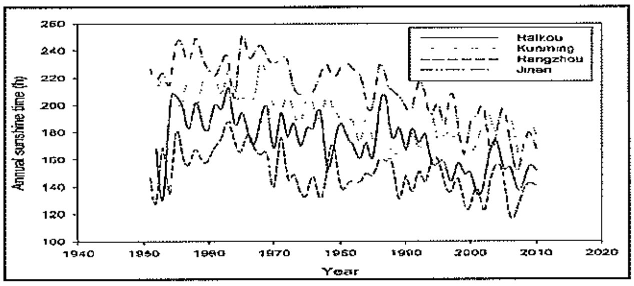

Fig. 4. Annual sunshine time change in 4 cities in the last 60 years

Climate extremes and variations

Compared to the smooth change of annual mean temperature, number of rainy days, relative humidity and annual sunshine timein the last 60 years, the climate extremes and variations have happened more frequently especially in the last few years. In Kunming city, the mean annual precipitation was 992 mm in the last 60 years. However, it was only 565.8 mm in 2009, the most severe drought since the city established meteorological record. It was estimated that tea yield decreased by 20% compared to the year with normal climate. Some tea plants (3300 ha) even totally died off due to the rare drought. In Haikou, same phenomenon was recorded in 2004, when the precipitation was 984 mm accounting for only 58% of the annual mean precipitation. However, the largest daily precipitation was 327.9 mm, accounting for 23.3% of the annual precipitation in Haikou in 1996. In Hangzhou, tea producers suffered late spring coldness almost every year since 2003. About 49% of the tea gardens in Zhejiang province were hit and the direct economic loss reached to ¥988 million Yuan in 2008. Some early sprouting cultivars such as Wuniuzao were plucked nothing in spring tea. And it cost ¥1.69 billion Yuan by the late spring coldness in Zhejiang province in 2010 (Lou, 2010).

Action area 3&4: Work out interaction between plant growth and environment and identify adaptation strategies/agronomic practices

To work out the interaction between plant growth, tea yield and quality, and for the possible environmental change adaptation strategies, the following research has been initiated.

- Study the effect of latitude and altitude on the tea production and quality
- Study the photosynthetic response to elevated CO_2 concentration of "Longjing 43" tea seedlings. It is confirmed for the first time, to our knowledge, that the phenomenon of photosynthetic acclimation occurred in tea seedlings. And we tried to explore the mechanisms of photosynthetic acclimation of tea seedlings. We found that both the tea polyphenol and amino acid content were changed in the elevated CO_2 concentration environment, by contact with the ambient counterparts.
- Study the mechanism of heat stress on the photosynthetic activity, especially on the ability of light harvesting, electron transduction, and the activity of Rubisco and Calvin cycle-related enzymes activities.