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GROUP ON TEA
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**Working Group on
Climate Change¹**

¹Submitted by India, Sri Lanka, Kenya and China.

Introduction

Climate change triggered by global warming is one of the major environmental problems, the world is facing currently. 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).

India

Action area 1: Database development

A fair amount of historical data on meteorology, soil, crop and management have 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 below 1540.0 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 (Fig 1b). 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).

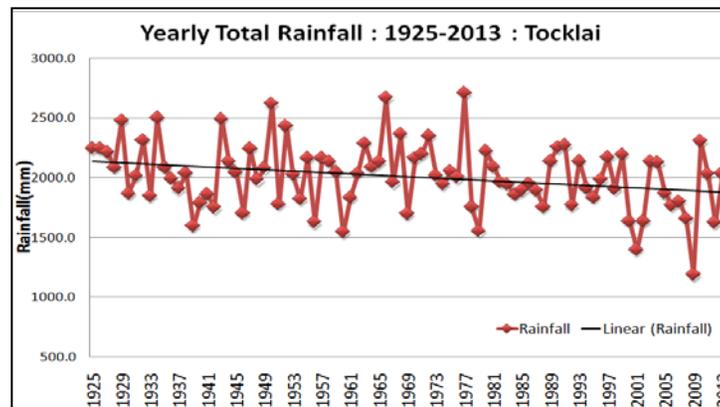


Fig. 1a Yearly total rainfall (1925-2013), Tocklai, Jorhat, Assam, India.

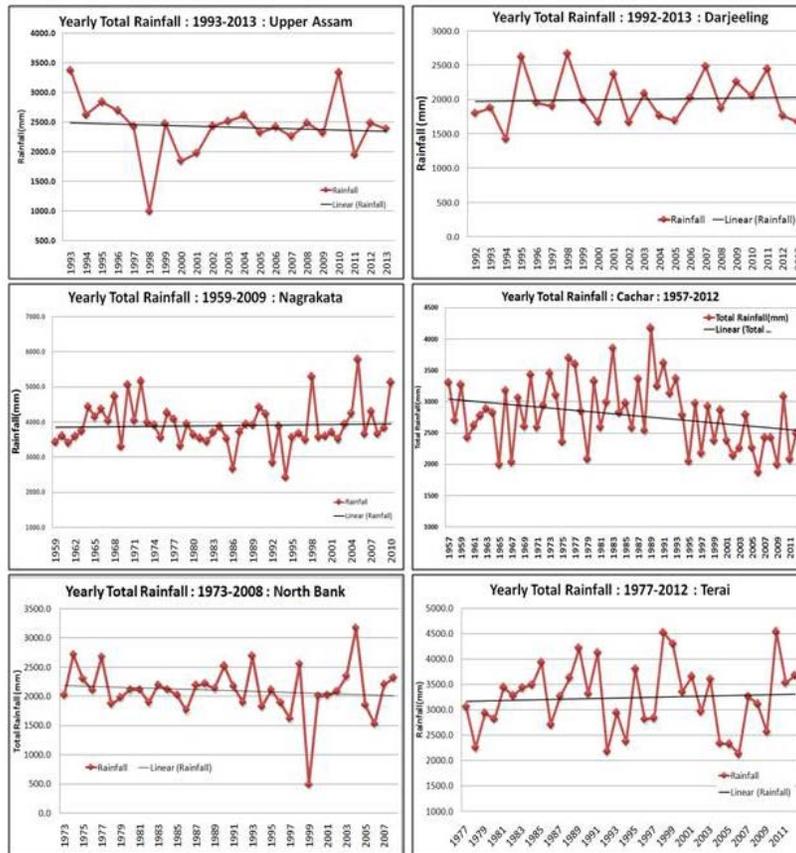


Fig. 1b Yearly total rainfall: Upper Assam, Darjeeling, Nagrakata, Cachar, North Bank and Terai regions, India.

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.

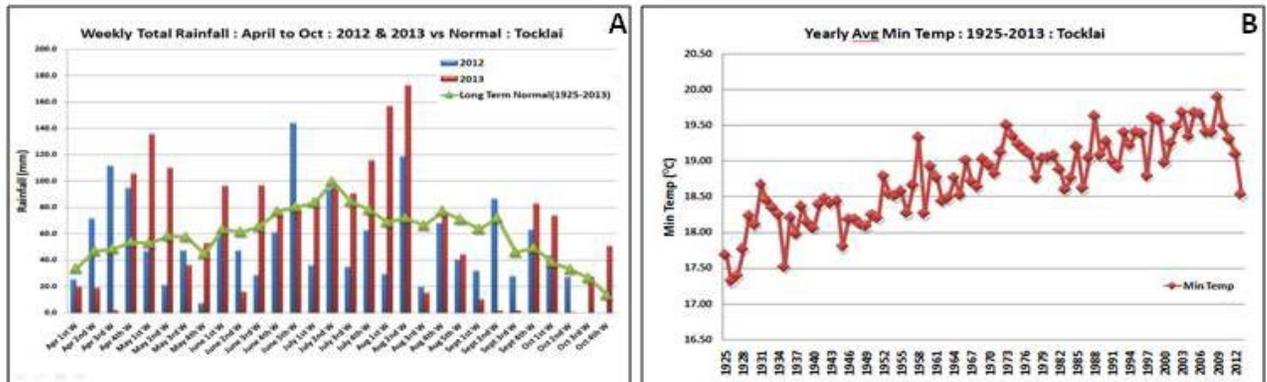


Fig. 2 (a) Comparison of weekly total rainfall between April - October (2012 & 2013) with long term normal at Tocklai, Jorhat, Assam (b) yearly average minimum temperature (1925-2013) at Tocklai, Jorhat, Assam

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^oC 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^oC. But last about 30 years have witnessed a different trend. It has been observed that the number of days having temperature > 30^oC or even >35^oC is generally increasing along with the increase in average minimum temperature (Fig. 3a).

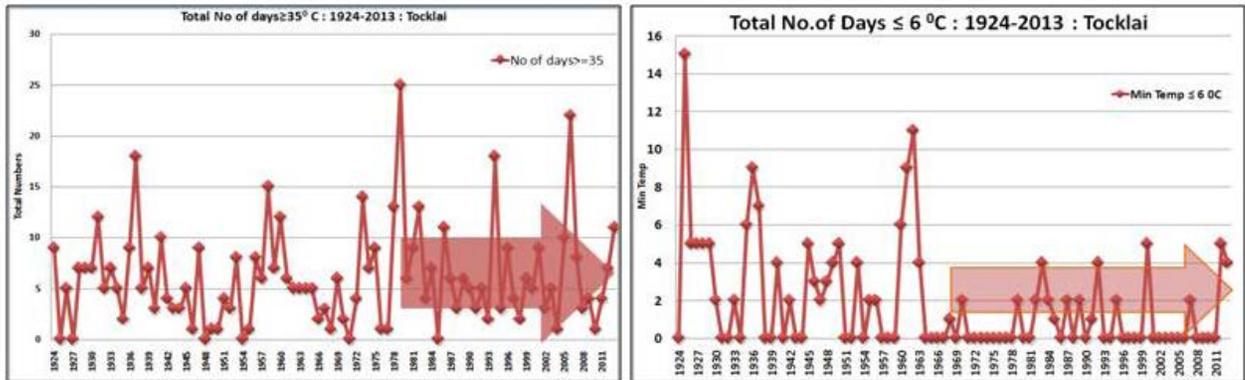


Fig. 3 (a) Total number of days having $> 35^{\circ}\text{C}$ temperature and (b) total number of days having $\leq 6^{\circ}\text{C}$ temperature at Tocklai, Jorhat, Assam

Further analysis of these extremities shows that the number of days having temperature less than or equal to 6°C and 8°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.

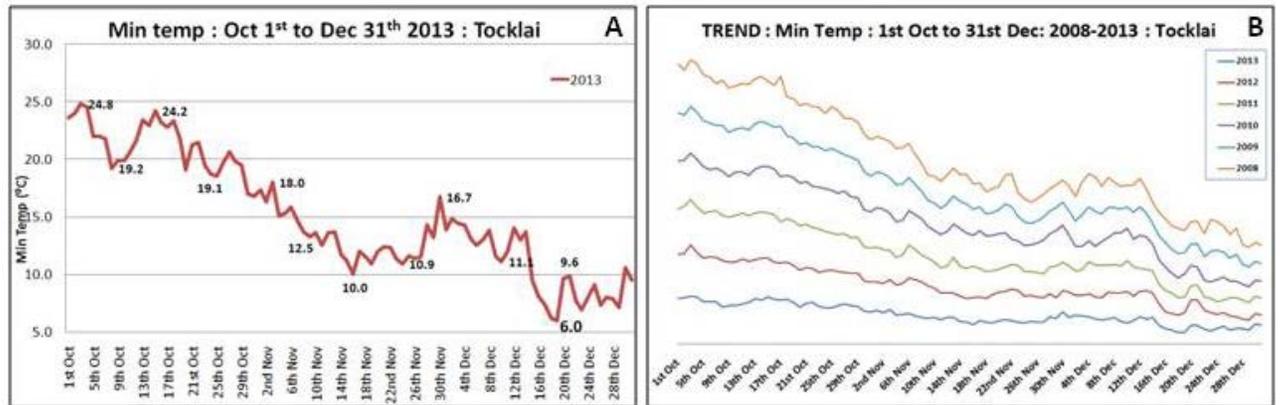


Fig. 4 (a) Change in minimum temperature from 1st October - 31st December 2013 (b) trend of minimum temperature for last 5 years from 1st October to 31st December (2008-2013).

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. 5 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. 6 a, b and 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.

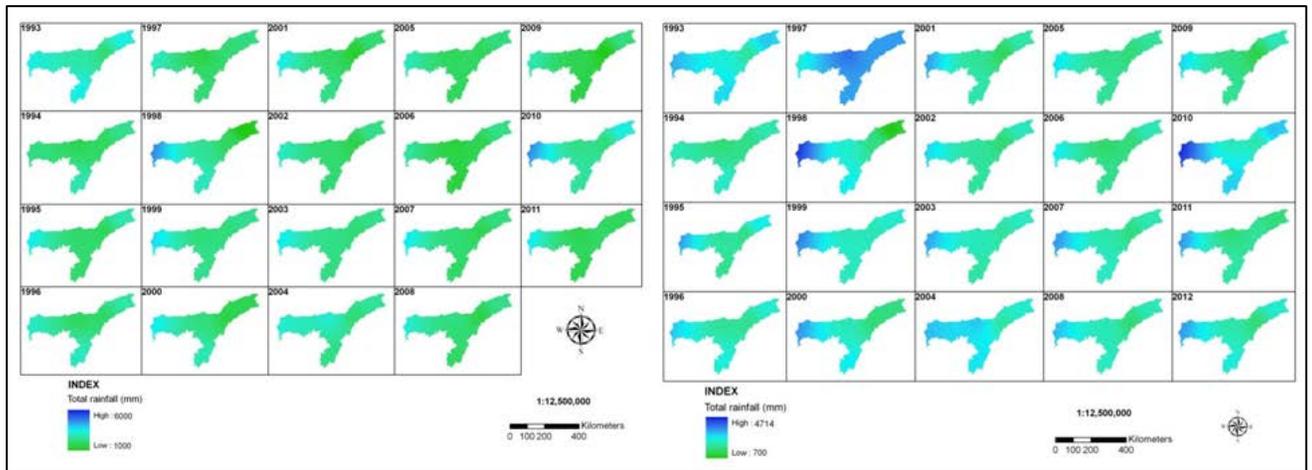


Fig. 5 (a) Distribution of total annual precipitation (mm) in Assam (1993-2011) and (b) distribution of total precipitation (mm) in production season (April – October) in Assam (1993-2012).

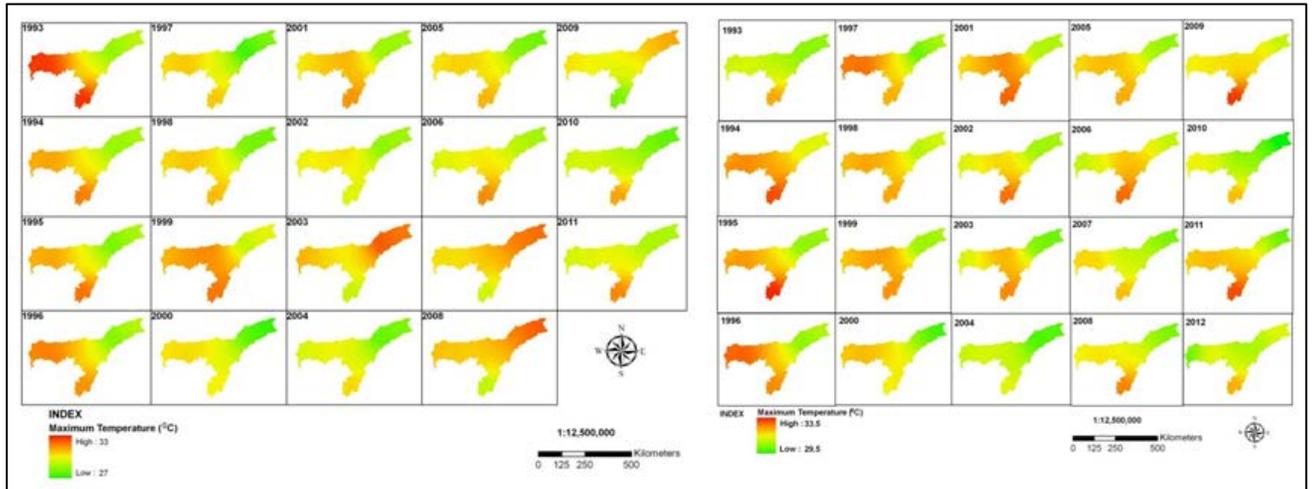


Fig. 6 (a) Distribution of average annual maximum temperature (°C) in Assam (1993-2011) and (b) distribution of average maximum temperature (°C) in production season (April – October), Assam (1993-2012).

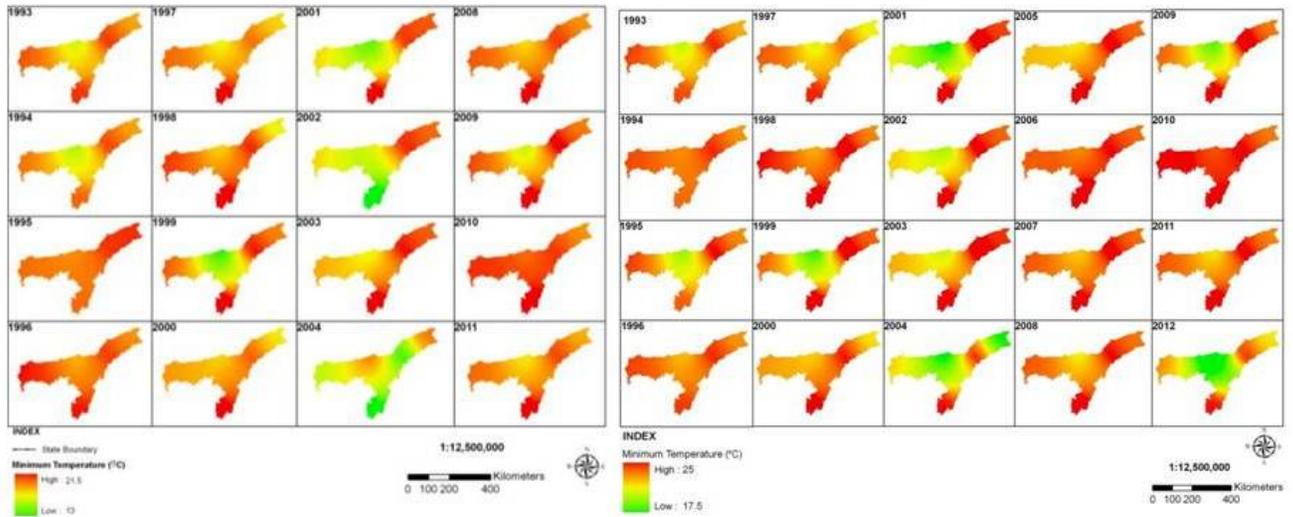


Figure 7 (a) Distribution of average annual minimum temperature ($^{\circ}\text{C}$) in Assam (1993-2011) and (b) distribution of average minimum temperature ($^{\circ}\text{C}$) in production season (April – October), Assam (1993-2012).

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 derived and mapped (Fig. 8), which indicates 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.

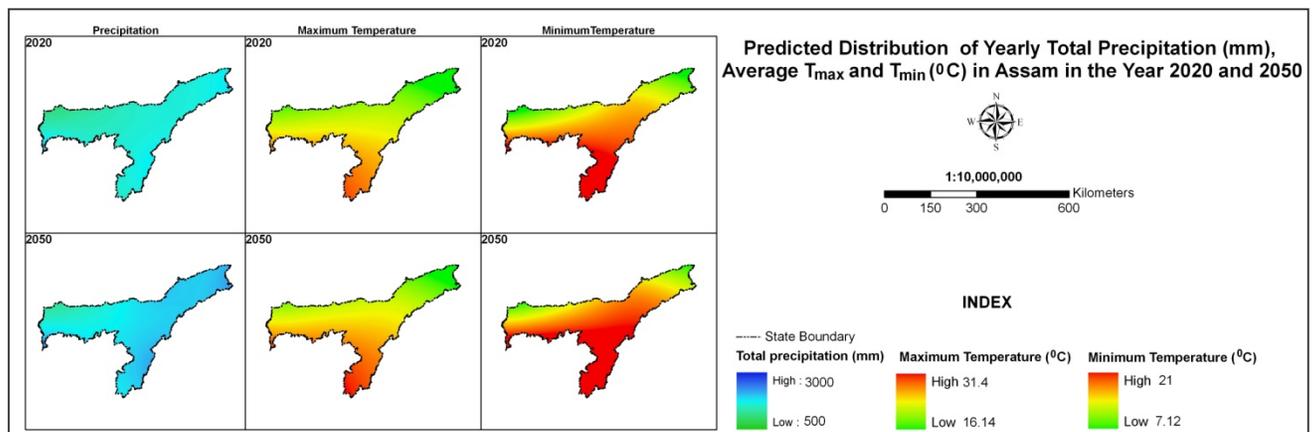


Fig. 8 Predicted distribution of yearly total precipitation (mm) and temperature (Tmax and Tmin °C) in Assam for the year 2020 and 2050.

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) Database development: Long-term future- 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).

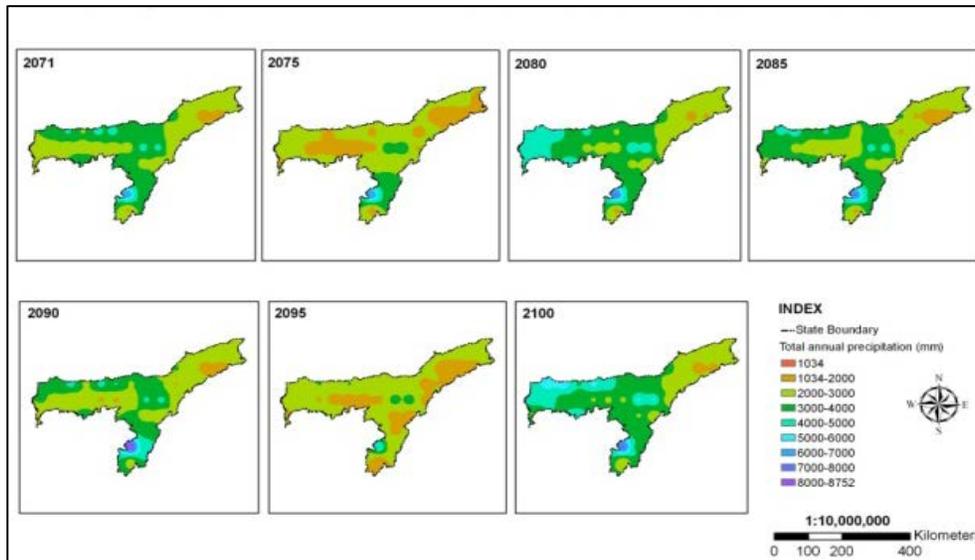


Fig. 9 Distribution of total annual precipitation (mm) in Assam under IPCC A2 climate scenario for the time period of 2071-2100.

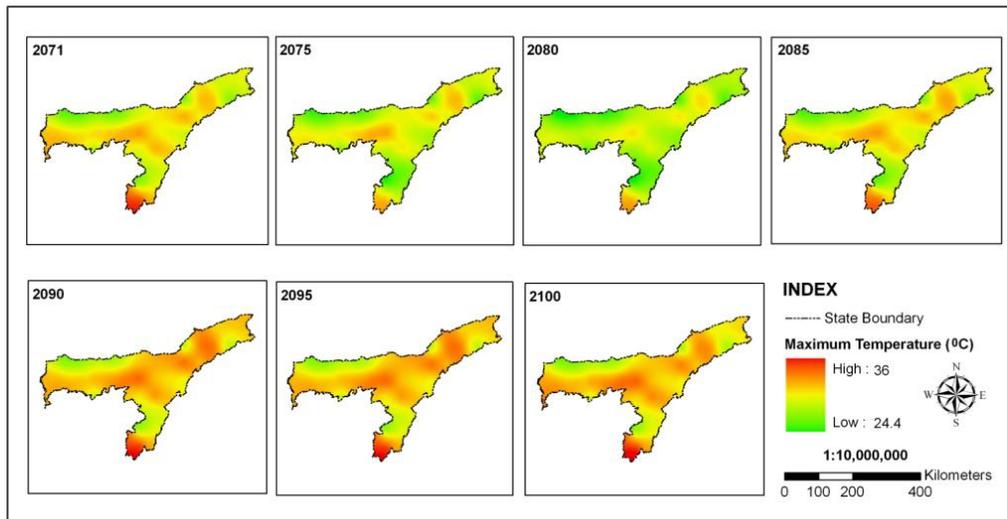


Fig. 10 Distribution of average annual maximum temperature (°C) in Assam under IPCC A2 climate scenario for the time period of 2071-2100.

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 (Fig. 10). The maximum average annual temperature is likely to increase most in the Cachar region, where it may reach up to 36°C. Unlike maximum temperature, the average annual minimum temperature shows a consistent increasing trend (Fig.11). The rate of increase is likely to be faster post 2080.

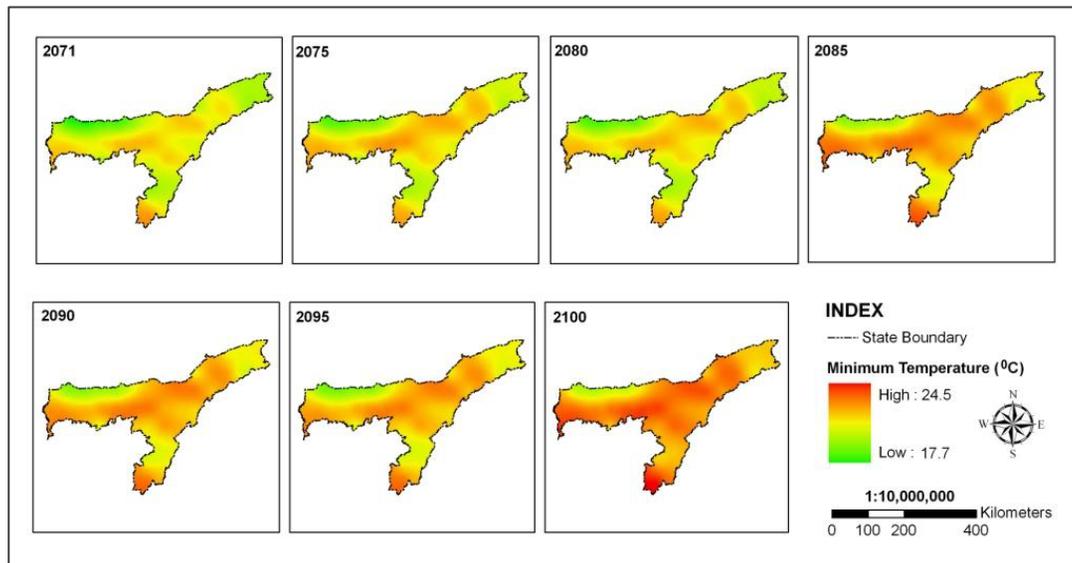


Fig. 11 Distribution of average annual minimum temperature (°C) in Assam under IPCC A2 climate scenario for the time period of 2071-2100.

(b) 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 is 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. 12 a,b,c). 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 appears that 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. 13 a,b,c). 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.

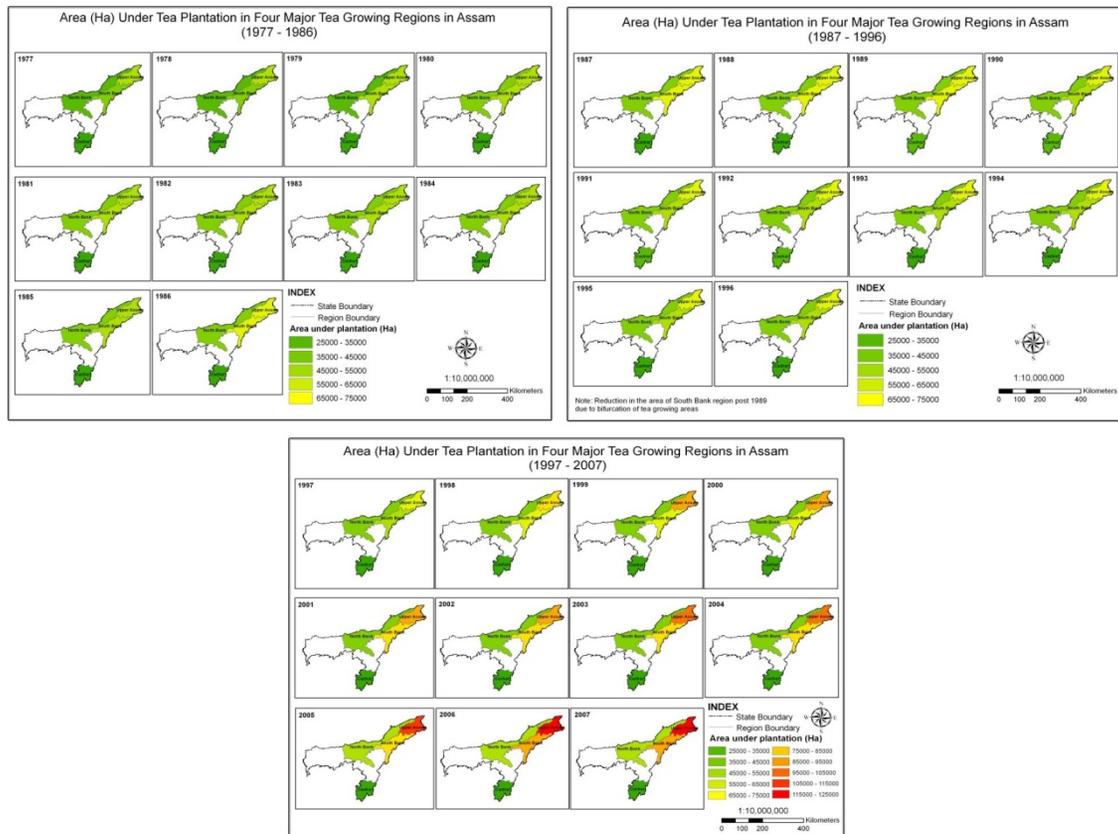


Fig. 12 Area (in Ha) under tea plantation in four major tea growing areas of Assam (a) 1977-1986, (b) 1987-1996 and (c) 1997-2007.

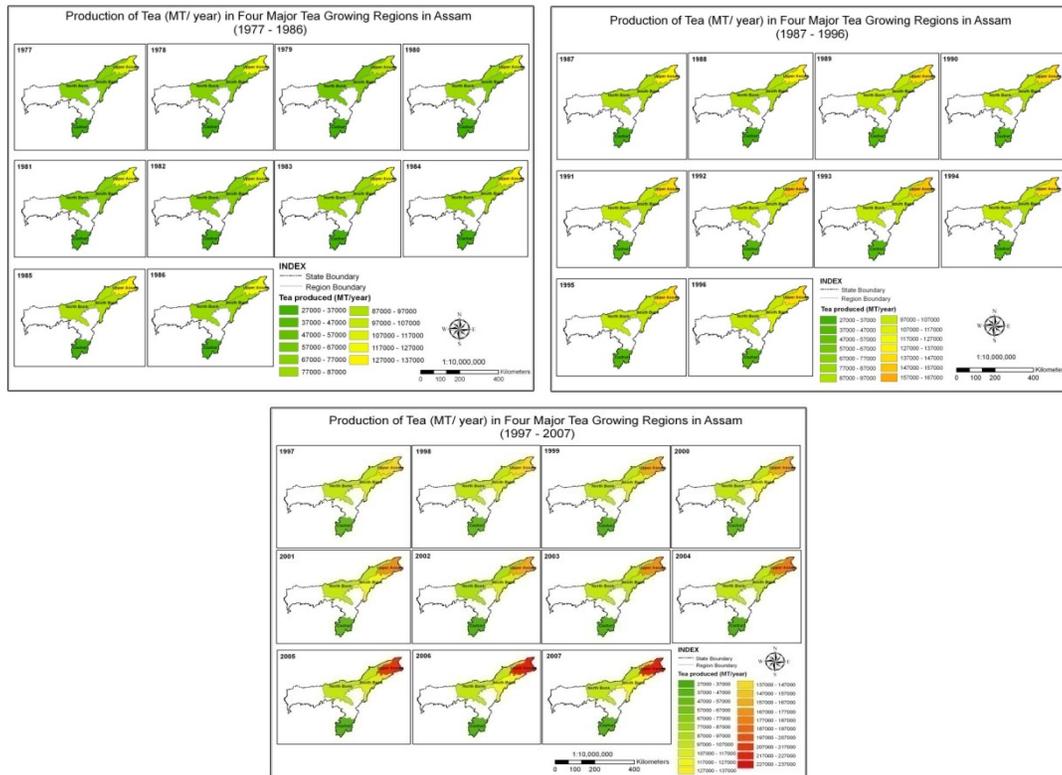


Fig. 13 Production of tea (in MT/Year) in four major tea growing areas of Assam (a) 1977-1986, (b) 1987-1996 and (c) 1997-2007.

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 as seen in Fig. 14.

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 (Fig 15 a, b). The observations on morphological, physiological and biochemical characters were recorded.



Fig. 14 (a) Outside view of OTC and (b) inside view of OTC.

The experiment was done in two phases. All the clones have been coded. In the first phase the carbon dioxide level was 400 ppm and in the second phase the level was 450 ppm. Fifteen Tocklai released/recommended clones were subjected to elevated carbon dioxide inside OTC. Carbon Dioxide enrichment was done for six hours per day upto 240 hours. Daily temperature, humidity and

carbon dioxide level of both the OTC chambers and ambient temperature were monitored. Sensors data were noted (Fig. 16 and Fig. 17).

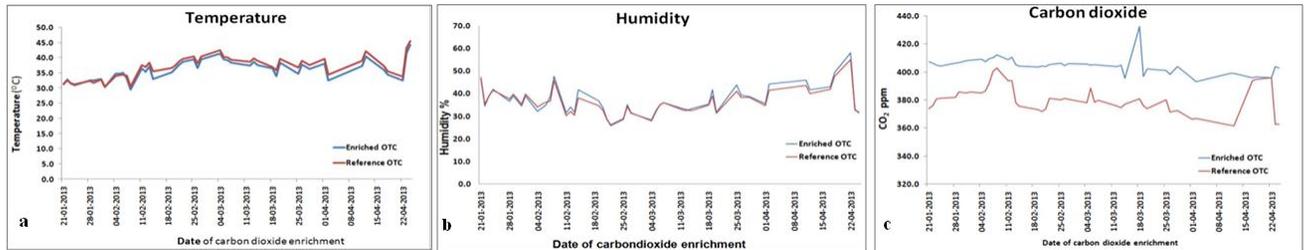


Fig. 15 Sensor data inside OTC - Phase I.

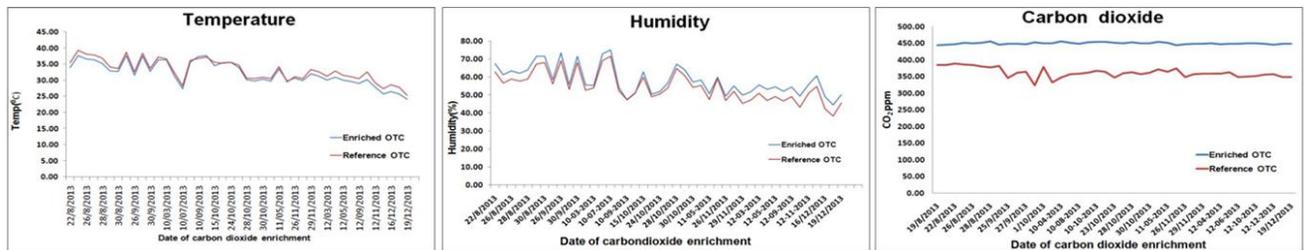


Fig. 16 Sensor data inside OTC - Phase II.

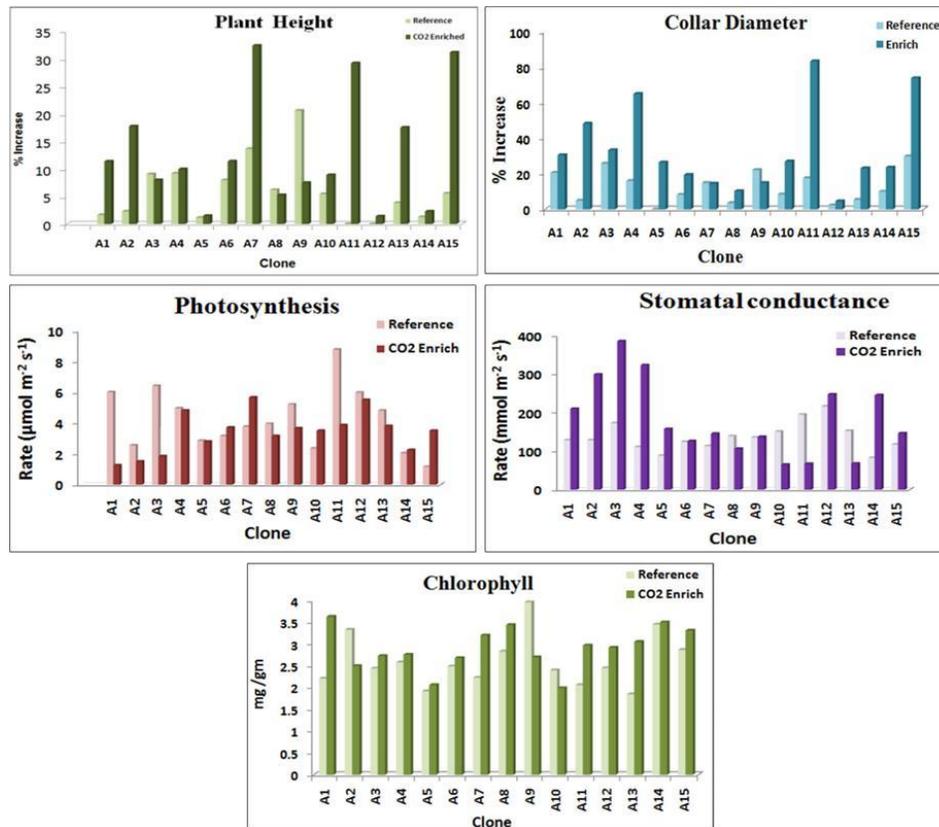


Fig. 17 Plant growth and physiological parameters under OTC - Phase II.

In both the phases of study, plant parameters were observed periodically. The clonal response to elevated carbon dioxide was differential in different clones for different growth parameters as presented in Fig. 18. More detailed studies in the second phase are being continued and the results are highly encouraging. Studies on soil pH and organic carbon are also being carried out and some interesting results have been arrived at (Fig. 19), which need to be carried out for long time period to draw meaningful conclusions. Once the Carbon dioxide enrichment and temperature impact is observed, studies will combine moisture stress also to study the impact of a multitude of factors to develop a decision support system.

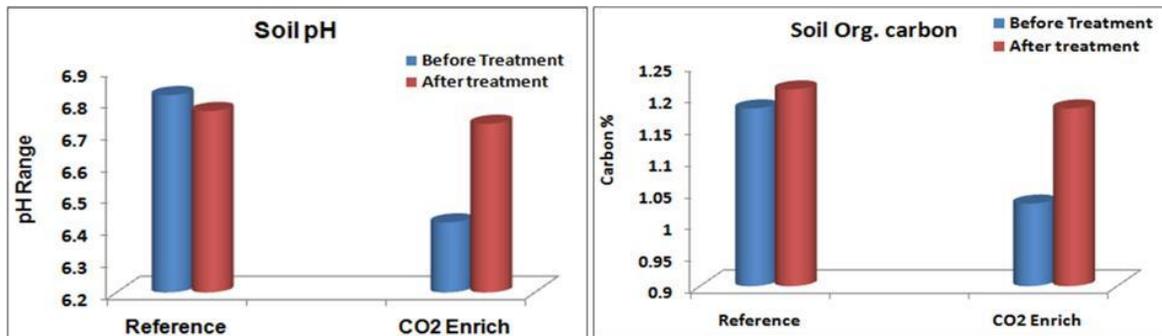


Fig. 18 Soil parameters under OTC- Phase II.

B. 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^oC has been taken as most suitable; 30-35^oC suitable; and >35^oC 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.

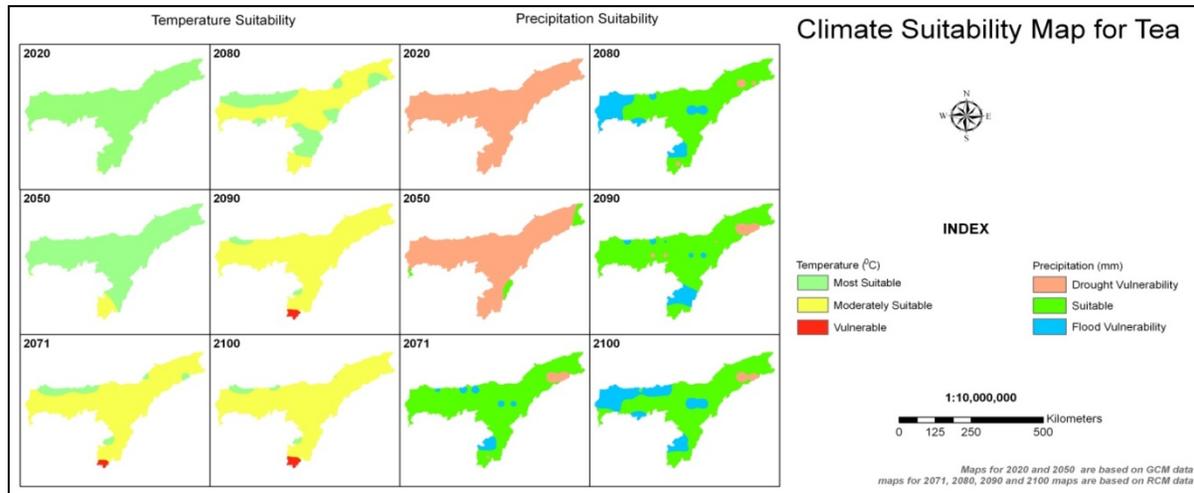


Fig. 19 Future climatically vulnerable/suitable regions for growing tea in Assam – GIS outputs.

Action area 4: Identify adaptation strategies/agronomic practices: Combine surface, satellite and simulation data (model outputs) –nowcasts/forecasts and future climate scenarios

A Decision support system framework has been conceptualized after analysing various factors and considering various available models (Fig. 21)

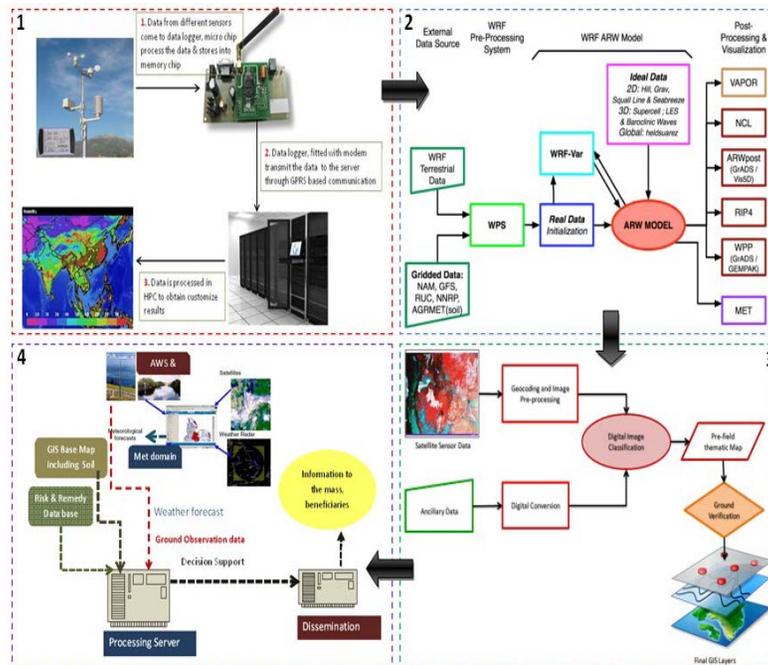


Figure 20 Conceptualized framework for DSS: 1. AWS operation, 2. WRF model, 3. GIS database creation and 4. data acquisition and dissemination.

A. Agronomic practices to cope with climate change

To combat with the potential hazards and threats from climate change and sustain the tea productivity in Assam 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 and reuse it when necessary. Excess water received during monsoon can be stored in farm ponds and storage tanks for irrigation in tea plantation during dry periods. Practice already visible in tea gardens particularly in Cachar.
- Efficient planning on artificial irrigation can reduce the drought risk in tea plantation areas. Both sprinkler and drip irrigation can be used depending on the terrain, nature of plantation, location of plantation and available water during dry seasons. 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 soil transpiration 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. It also helps to conserve the soil from runoff and improves the percolation of rain water during heavy rain condition. Regular weed control and optimum application of nutrients such as Potassium reduces loss of soil moisture and improves water use efficiency of plants.
- 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. Intercropping tea-rubber is very much popular now-a-days. Vegetables, fruits and spices can also be used as intercrops.
- 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.

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°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.

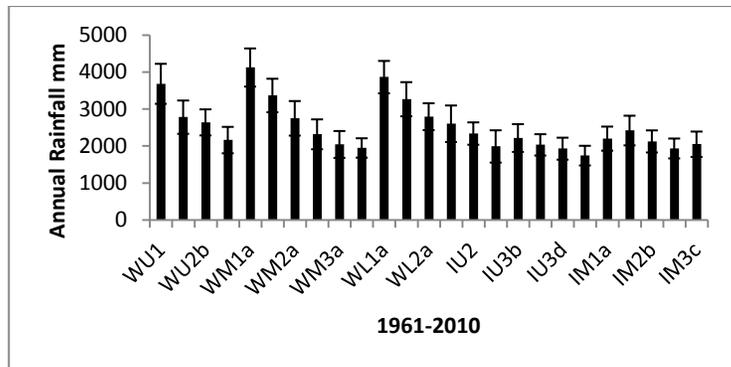


Fig. 1 Mean annual rainfall of tea growing AERs for the 50 year period (1961-2010)

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.

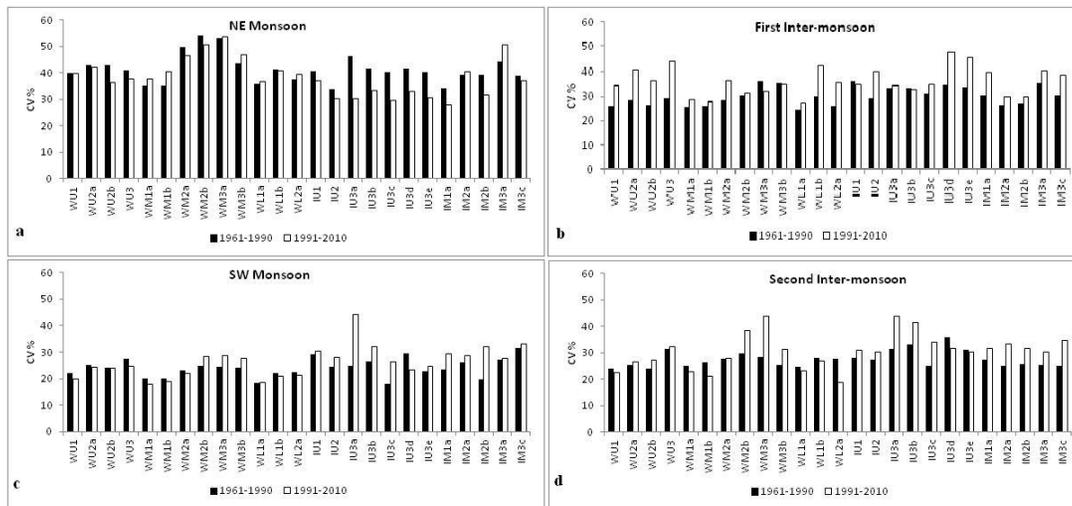


Fig. 2 Comparison of rainfall variability between the base period and the recent two decades of (a) north east monsoon (b) 1st inter-monsoon (c) south west monsoon (d) 2nd inter-monsoon.

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.

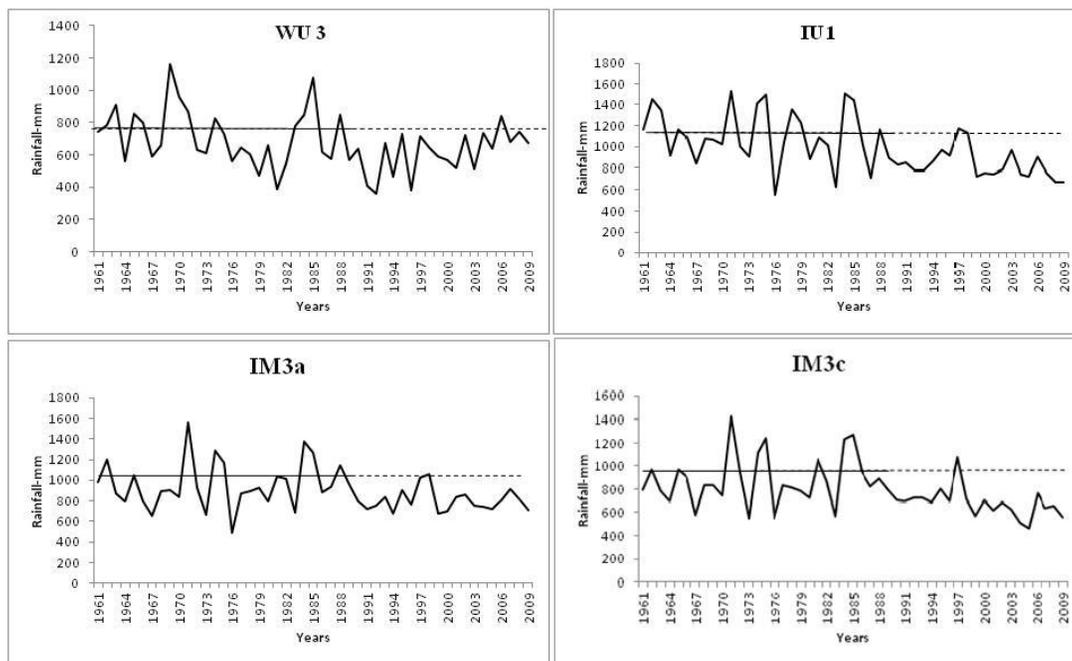


Fig. 3. Rainfall of WU3 during NEM & 1st Inter-monsoon; Rainfall of IU1 during 1st IM3a and IM3c during 1st Inter-monsoon and SWM; straight line indicates the mean rainfall during the base period; 1961-1990.

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.

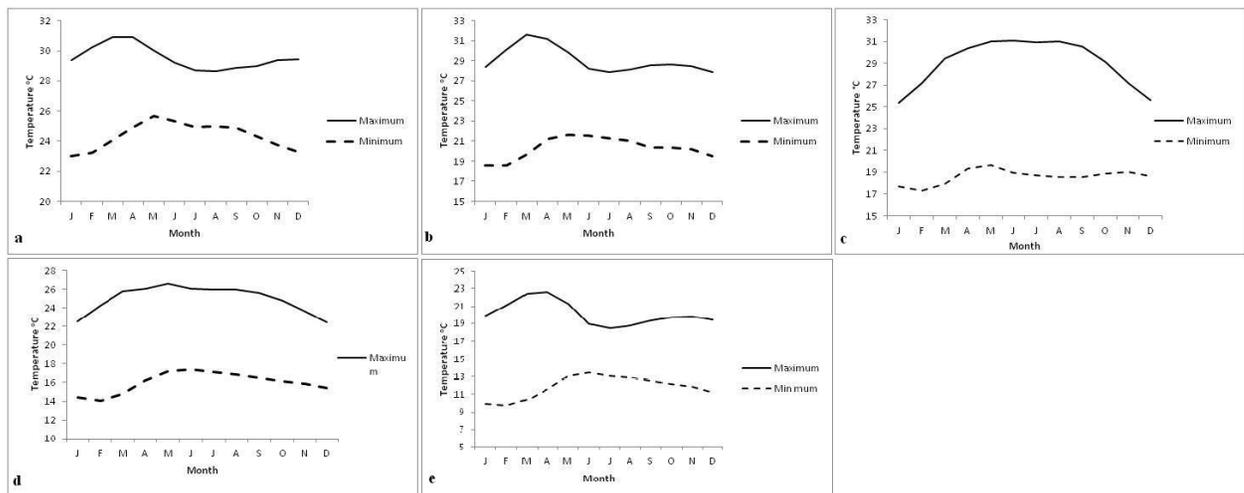


Fig. 4 Monthly temperature variation at different AERs (a)WL2a, Galle (b) WM3b, Katugastota (c) IM1a, Badulla (d) IU3c, Bandarawela and (e) WU3, Nuwara Eliya.

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/cm³ 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.

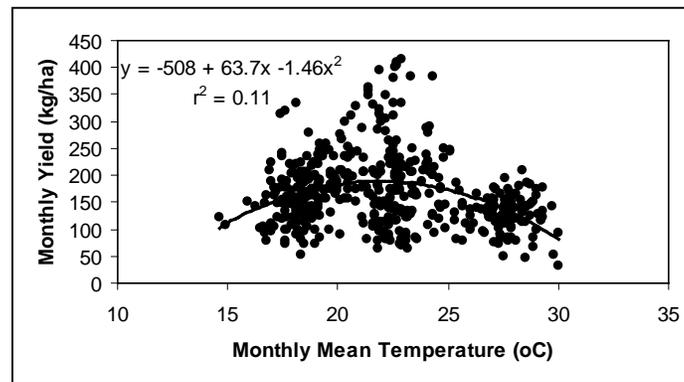


Fig. 5. The effect of ambient temperature on tea yield.

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 CO₂ (open-top chamber with 600ppm CO₂ 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 CO₂ during dry months was found to be lower than that during wet months. This increase in tea yield with enhanced CO₂ was a result of high shoot density, rate of growth and weight of shoots under enriched

CO₂ in comparison with the control. Time taken for bud break was also less under enriched CO₂ which led to produce more shoots. Further, a high rate of assimilation and low rate of transpiration were also recorded in the CO₂ enriched plot. These results revealed that water use efficiency was comparatively high with enriched CO₂. Root analysis showed that starch reserves of tea bushes under enhanced CO₂ were significantly higher than that under ambient CO₂ i.e 4.13% and 2.9% respectively (Table 2).

Table 2. The effect of CO₂ 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: Combine surface, satellite and simulation data (model outputs) –nowcasts/forecasts and future climate scenarios

A. Agronomic adaptation practices

- a) Crop improvement: 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. Development of new varieties with greater drought, heat and pests and disease tolerance is vital in coming years.

- b) Establishment and management of shade trees: A good stand of shade trees in tea reduces ambient temperature around tea bushes, increase RH, and adds organic matter to soil. Observations have shown that shade trees in tea lands can reduce ambient temperature by about 2-3°C thus attenuating the adverse effects of rising temperatures. Field observations have also shown that drought effects are less in tea under a good stand of shade trees which is lacking in tea lands of Sri Lanka are not up to the standards recommended by the TRI.
- c) Application of compost and organic manure: 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. Additionally, such practices will improve fertilizer use efficiency and moisture retention capacity of soils.
- d) Soil and soil moisture conservation measures: 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 during dry months: Irrigation to prevent moisture stress on tea during dry months can be considered advantageous in minimizing climate change impacts. However, this involves a reasonable amount of capital investment. Therefore, presence of a reliable water source with an adequate quantity of water during dry months is vital. This has been a limiting factor in most of the tea growing regions.

Kenya

1. Conducted an assessment of tea vulnerability to climate change:
 - a. Statistical analysis linking climate data trends with tea yields in Kenya based on time series data and GIS suitability mapping.
 - b. A tea producer survey to assess vulnerability at the producer level, production techniques and risk coping option.
2. Developed and tested crop yield model for tea (Aquacrop). The activity was carried out collaboratively between FAO (NRL) and TRFK; the activity included training of TRFK staff; on crop calibration of Aquacrop with long

term data on tea. Validation of the Aquacrop was done on collaboration between the TRFK staff and the FAO technical experts on Aquacrop.

3. Participated in the Life Cycle Assessment of Tea Production and use in Kenya which included environmental assessment, following the standard LCA approach according to ISO standards, including standard assessment tools by providing available data and technical support for data collection required for a life cycle and value chain analysis of the tea sector. Material analysis for carbon and energy was also included.

India

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 produces 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 sunshine in each month were downloaded from China meteorological data sharing service system (<http://cdc.cma.gov.cn>) with these cities dated from January 1951 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 (°C)	Extreme lowest temperature (°C)	Mean annual precipitation (mm)
Haikou	110°20' 20°02' N	E 14	24.1(9.3- 36.1)	2.8	1688
Kunming	102°42' 25°04' N	E 1890	15.0 (2.3- 25.6)	-7.8	992
Hangzhou	120°10' 30°16' N	E 40	16.5 (9.0- 33.9)	-9.6	1417
Jinan	117°00' 36°40' N	E 100	14.5 (-4.8- 32.7)	-19.2	689

A. 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°C, respectively in annual mean temperature in every 50 years, less than subtropical city of Hangzhou (1.6°C) and plateau city of Kunming (1.6°C) (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 $\geq 35^{\circ}\text{C}$ 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°C in every 50 years in Haikou, Kunming, Hangzhou and Jinan, respectively (Fig. 1B). The seasonal difference indicates winter is becoming warmer.

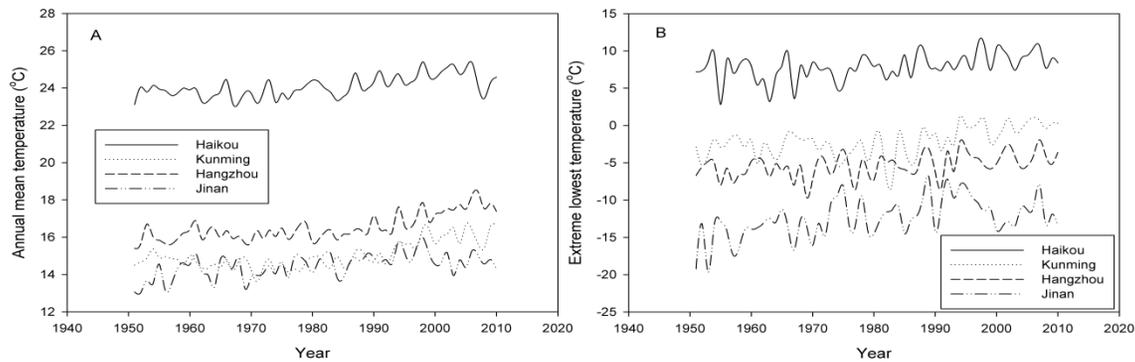


Fig. 1 Changes of annual mean (A) and extreme lowest (B) temperature in 4 cities during the last 60 years

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 (°C)
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

B. Precipitation and relative humidity change

The annual precipitation (Fig. 2A) did not change significantly 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 ($\geq 0.1\text{mm}$) 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 (Table 3). 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.

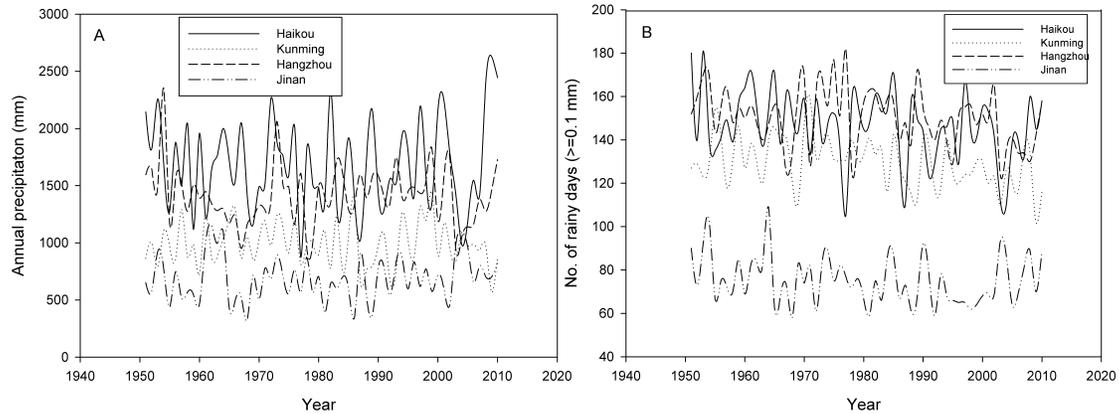


Fig. 2 Changes of annual precipitation (A) and No. of rainy days (≥ 0.1 mm) (B) in 4 cities during the last 60 years.

Table 3 Linear regression equations fitted with the change of annual mean relative humidity in the last 60 years.

City	Linear regression equation (Y: annual mean relative humidity, X: year).	R^2 (Sig.)	Annual mean relative humidity increase in every 50 years (%)
Haikou	$Y = -0.085X + 251.09$	0.432 (p<0.001)	-4.2
Kunming	$Y = -0.095X + 259.52$	0.318 (p<0.001)	-4.7
Hangzhou	$Y = -0.187X + 449.09$	0.728 (p<0.001)	-9.4
Jinan	$Y = -0.066X + 188.59$	0.086 (p<0.05)	-3.3

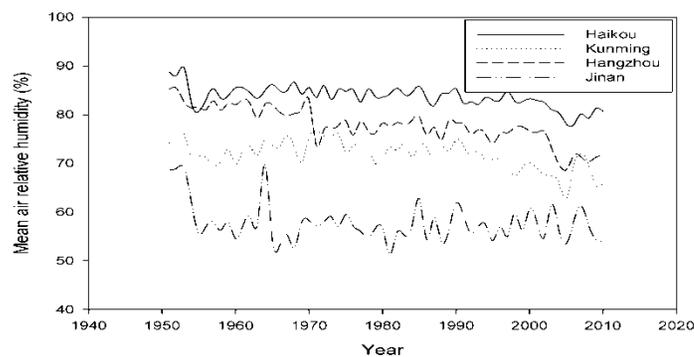


Fig. 3 Change of annual mean relative humidity in 4 cities in the last 60 years.

C. Sunshine time Change

Annual sunshine time in all the 4 cities had significantly reduced in the last 60 years (Fig. 4). Very significant and negative linear regressions were found (Table 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.

Table 4 Linear regression equations fitted with the change of annual sunshine time in the last 60 years.

City	Linear regression equation (Y: annual sunshine time, X: year)	R ² (Sig.)	annual sunshine time increase in every 50 years (h)
Haikou	Y = -0.747X + 1652.98	0.417 (p<0.001)	-37.3
Kunming	Y = -0.854X + 1883.77	0.629 (p<0.001)	-42.7
Hangzhou	Y = -0.538X + 1215.78	0.329 (p<0.001)	-26.9
Jinan	Y = -1.134X + 2457.81	0.681 (p<0.001)	-56.7

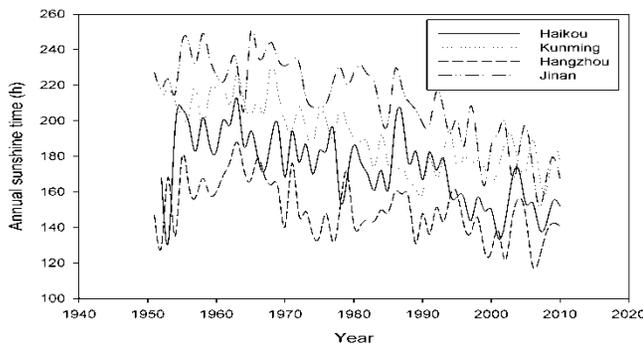


Fig. 4 Annual sunshine time change in 4 cities in the last 60 years.

D. Climate extremes and variations

Compared to the smooth change of annual mean temperature, number of rainy days, relative humidity and annual sunshine time in 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).