Observed and Projected Climatic Changes, Their Impacts and Adaptation Options for Sri Lanka: A Review

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Abstract

Climate is changing world-wide, and the science community in Sri Lanka has come up with ample evidence to suggest that the country's climate has already changed. During 1961-1990 the country's mean air temperature increased by 0.016 ^{0}C per year, and the mean annual rainfall decreased by 144 mm (7 %) compared to the period 1931-1960. In addition, mean annual daytime maximum and mean annual night-time minimum air temperatures increased. However, the bigger question of national importance is what Sri Lanka's climate will look like in 50 or 100 years and how prepared is the country to face it. Apart from the Intergovernmental Panel on Climate Change (IPCC) projections at the coarse global scale, few studies have attempted to project future climate scenarios for Sri Lanka and to identify climate change impacts on agriculture, water resources, the sea level, the plantation sector, the economy and health. Vulnerability and adaptation to climate change are the least studied areas. This paper reviews the status of climate change research and activities in Sri Lanka with respect to future climate projections, impacts, climate change mitigation and the country's ability to adapt, and identifies existing knowledge gaps. Messages emerging from this review suggest that Sri Lanka's mean temperature during the North-East (December-February) and South-West (May-September) monsoon seasons will increase by about 2.9 ^{0}C and 2.5 ^{0}C, respectively, over the baseline (1961-1990), by the year 2100 with accompanying changes in the quantity and spatial distribution of rainfall. Extreme climate events are expected to increase in frequency. These changes will bring about widespread impacts on the country's agriculture and economy. For example, an increase of 0.5 ^{0}C in temperature can reduce rice yield by approximately 6 %; extended dry spells and excessive cloudiness during the wet season can reduce coconut yield resulting in annual losses between $32 and $73 million to the economy. Pilot studies in the Galle District suggest that sea level rise could inundate about 20 % of the land area of Galle's coastal District Secretariat Divisions. Adaptation measures already undertaken in the agriculture sector include the development of low water consuming rice varieties and the use of micro-irrigation technologies. Tools have been developed for predicting seasonal water availability within the Mahaweli Scheme and annual national coconut production. However, Sri Lanka is yet to undertake a comprehensive national study on the vulnerability of her water resources and agriculture to climate change. The formulation of detailed and reliable future climate scenarios for the country is therefore, urgently required.

Introduction

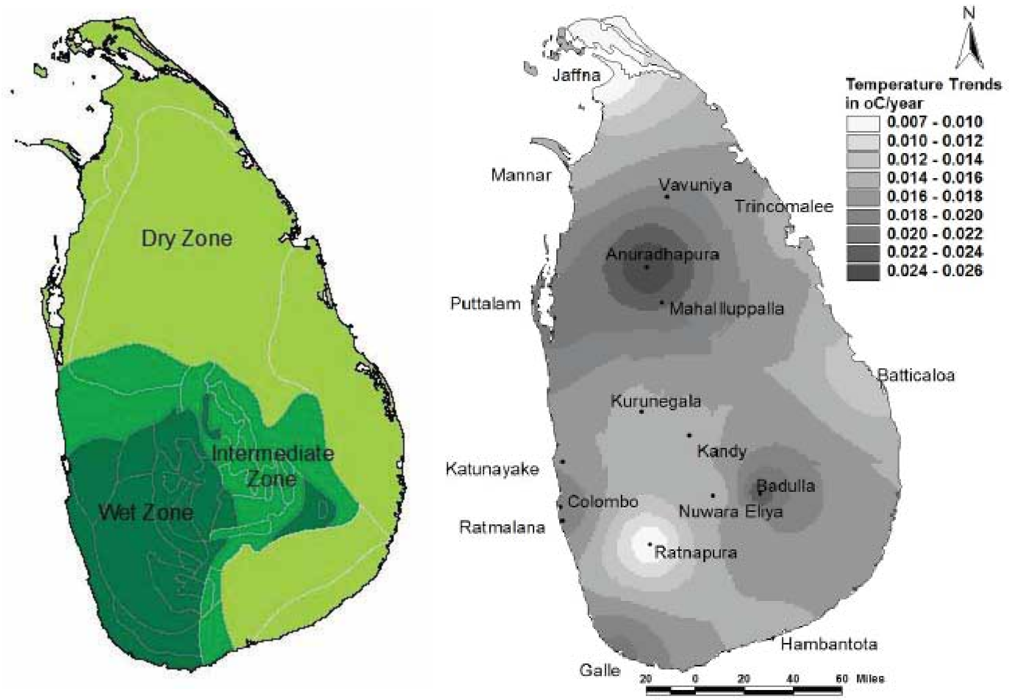
The Intergovernmental Panel on Climate Change (IPCC 2007) defines climate change as "a change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer." The IPCC definition refers to changes in climate over time due to both natural variability as well as anthropogenic activities, as opposed to the use of the United Nations Framework Convention on Climate Change (UNFCC), where climate change refers to "a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability, observed over comparable time periods." (IPCC 2007). For the purpose of this review the IPCC definition is adopted since generally climate change research and activities that have been carried out in Sri Lanka do not differentiate between natural and human induced variability. However, be it due to natural variability or human activity, a pronounced change in the country's climate is observed, as evidenced by a number of recent studies, which are presented in the section on present climate, observed changes and future projections. Many of these studies were fed into the IPCC's Third and Fourth Assessment Reports. After the IPCC's Fourth Assessment Report (AR4) in 2007, which projected an alarming increase in global average temperature, being in the range 0.3-6.4 ^{0}C, at the end of the twenty-first century (IPCC 2007), researchers have divulged even more disconcerting information on greenhouse gases (GHG) in the atmosphere (the build-up of which is the primary cause of global warming and associated changes in climate). The global carbon dioxide (CO_2) concentration in 2008 was 387 ppm and was the highest on record in human history (NOAA 2009; Adam 2008). The present GHG emissions are 'far higher than even the worst case scenario' envisaged by the AR4 (Irwin 2009). In this context, limiting the rise in global temperature to 2^{0}C above pre-industrial levels (the EU long-term climate goal popularly regarded by many as 'the' climate target to achieve) is unlikely to be realized unless stringent GHG emission reduction targets are agreed and adhered to. Such global changes will surely alter Sri Lanka's climate even further. Sri Lanka, being an island state, is especially vulnerable to all identified impacts of climate change including rise in land and sea surface temperature, changes in precipitation amount and pattern, increase in extreme climate events and rise in sea level. These 'direct' impacts, in turn trigger a wide variety of secondary effects on water resources, agriculture, livelihoods, health and well-being, the economy and nature. It is critically important that these impacts are identified, quantified, and suitable action is initiated to adapt to them. This paper attempts to review the progress already made in this direction, especially with regard to water resources and agriculture, and to identify key knowledge gaps and future research needs.

Present Climate, Observed Changes and Future Projections

Present Climate

Sri Lanka is an island in the Indian Ocean situated just north of the equator. Its topography consists of a central highland (altitudes of 300 m amsl) that is surrounded by an extensive lowland area. The long-term mean annual temperature is 27 ^{0}C in the lowlands and 15 ^{0}C in the highlands (Nuwara Eliya at an altitude of 1,895 m amsl; Chandrapala 1996). Mean annual rainfall ranges from under 1,000 mm in the north-western and south-western coastal areas to over 5,000 mm in the western slopes of the central highlands. The spatial pattern of precipitation is strongly influenced by topography and two seasonal wind regimes (Chandrapala 1996). The South-West Monsoon (SWM) is from May to September and the North-East Monsoon (NEM) from December to February. There are two inter-monsoonal periods from March to April (first inter-monsoon – IM1) and from October to November (second inter-monsoon – IM2). Sri Lanka consists mainly of three climatic zones: The Wet Zone, Dry Zone and the Intermediate Zone (Figure 1). The El Nino-Southern Oscillation (ENSO) is a primary mode of climate variability in the South Asian region as a whole (Zubair et al. 2008).

Figure 1. Climatic zones of Sri Lanka (left) and observed warming trends in mean annual temperature (right).



Source: Zubair et al. 2005

Observed Changes in Climate

Time series data of annual mean temperature anomalies from1871-1990 show a significant warming trend throughout the country during the latter half of this period (Chandrapala 1996; Fernando and Chandrapala 1992). The rate of increase in temperature from 1961 to 1990 is 0.016 ^{0}C per year (Chandrapala 1996), which is higher than the global average rate of 0.013 ^{0}C per year for the period 1956 to 2005 (IPCC 2007). Sri Lanka's 100 year warming trend from 1896 to 1996 is 0.003 ^{0}C per year, while it is 0.025 ^{0}C per year for the 10-year period of 1987-1996 (Fernando 1997), indicating faster warming in more recent years. Seasonal mean temperatures for the agricultural seasons yala (April - September) and maha (October – March) also display similar warming (Basnayake et al. 2002). Mean (annual and seasonal) daytime maximum and mean (annual and seasonal) night-time minimum air temperatures have both increased during 1960-2001 with trends of 2.6 ^{0}C/100 years and 1.7 ^{0}C/100 years, respectively (Basnayake et al. 2002; Zubair et al. 2005). The highest warming trends in the country have been observed in Anuradhapura and Badulla (Figure 1; Zubair et al. 2005). Scientists attribute this warming trend, seen throughout the country, to both the enhanced greenhouse effect as well as the 'local heat island effect' caused by rapid urbanization (Basnayake 2008; Basnayake et al. 2003; Fernando and Basnayake 2002; Emmanuel 2001).

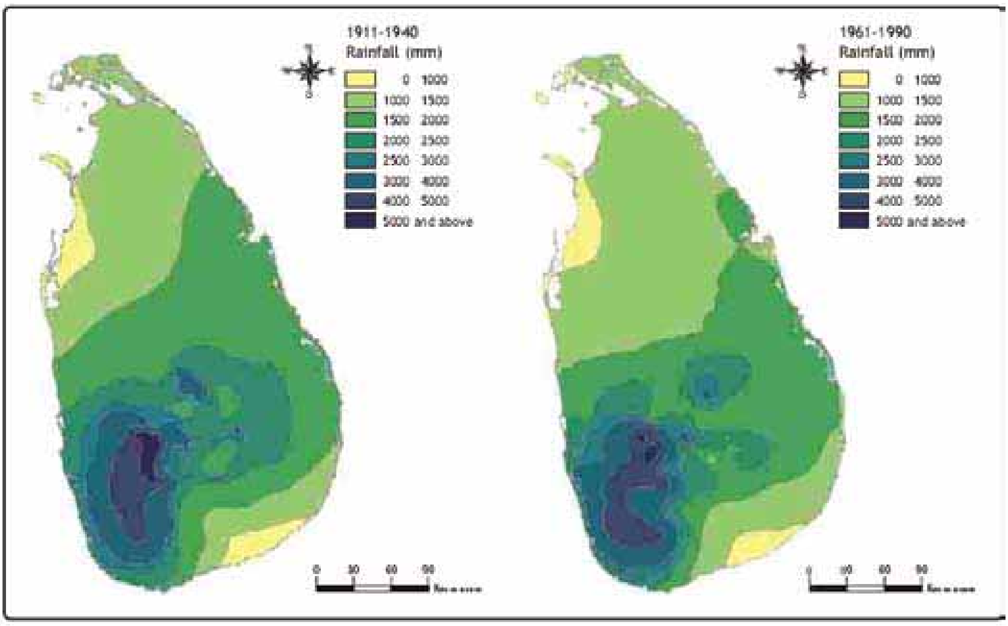
There has not been a significant trend in Sri Lanka's mean annual rainfall (MAR) during the past century, nevertheless, a higher variability is evident (Jayatillake et al. 2005; L. Chandrapala NDMC, pers. comm.). However, more recent data records reveal a decreasing trend: MAR during 1961-1990 has decreased by 144 mm (7 %) compared to that during 1931-1960 (Chandrapala 1996a; Jayatillake et al. 2005); and rainfall data for the period 1949-1980 at 13 stations reveal decreasing trends with steeper downward trends in recent decades. However, there is a wide disparity in the magnitude of changes that have taken place in different rainfall seasons and different spatial locations. Although no significant changes in rainfall amount have been observed in the SWM and the IM2, rainfall in the NEM (the maha season when the majority of agricultural areas in the country receives rainfall) and the IM1 has reduced with the NEM showing increased variability (Jayatillake et al. 2005; Basnayake et al. 2002; L. Chandrapala NDMC, pers. comm.).

A few authors have made observations on rainfall in the central region: for example, an analysis of inter-annual as well as intra-annual rainfall trends of the central region from 1964-1993, suggests that there is a decrease in MAR, with the IM1 showing the highest decrease (Herath and Ratnayake 2004); Shantha and Jayasundara (2005) also observe a 39.12 % decrease in MAR in the Mahaweli upper watershed from 1880 to 1974. Bandara and Wickramagamage (2004) reveal that rainfall on the western slopes of the central highlands has declined significantly from 1900 to 2002 due to reduced SWM rainfall (this region has the highest MAR in the country, often exceeding 5,000 mm). The reduction in observed rainfall in the central region is attributed to the interaction of both local and global factors (Wickramagamage 1998). In the country as a whole, the number of consecutive dry days has increased while the number of consecutive wet days has reduced (Ratnayake and Herath, 2005; Premalal 2009). Recent analysis of the spatial pattern of rainfall also indicates an expansion of the dry zone (MAR<1,750 mm) (Figure 2; Imbulana et al. 2006).

The intensity and frequency of extreme climate events (floods and droughts) have increased in recent times, triggering an increase in natural disasters (Imbulana et al. 2006;

Herath and Ratnayake 2004; L. Chandrapala NDMC, pers. comm.). The country has already experienced 2 years of serious drought and one major flood event within the first 5 years of the twenty-first century (Imbulana et al. 2006) and the districts of Ratnapura and Kalutara, which are generally flooded once or twice a year, experienced floods four times in 2008 including one severe event (L. Chandrapala, NDMC, pers. comm.). According to Ratnayake and Herath (2005), the daily rainfall intensity (amount of rainfall per rainy day) and the average rainfall per event, have both increased, triggering an increase in landslides. Upward trends in the occurrence of thunder activity as well as increased lightening hazards have also been observed (Fernando and Chandrapala 1994; Jayaratne 1997).

Figure 2. A comparison of average rainfall 1911-1940 and 1961-1990 indicating expansion of the dry zone (MAR < 1,750 mm).



Source: Imbulana et al. 2006 (original image prepared by U. R. Ratnayake)

The current rate at which the sea level is rising in the coastal areas of Asia is reported to be 1-3 mm/year, which is marginally greater than the global average (Cruz et al. 2007). Evidence also suggests that there has been an accelerated rate of sea level rise over the past decade (3.1 mm/year) compared to that over the twentieth century as a whole (1.7 to 2.4 mm/year) in Asia (Cruz et al. 2007).

Future Climate Projections

Studies that spell out future climate scenarios for Sri Lanka are scarce and even the ones that exist appear to project contradictory results, especially with respect to future rainfall. However, there is a general consensus within them that Sri Lanka will become increasingly warmer during the twenty-first century, although the projected magnitude of temperature increase differs from study to study. IPCC regional projections based on AR4 Atmospheric Ocean General Circulation Models (AOGCMs or simply - GCMs) suggest a significant acceleration of warming in Asia over that observed in the twentieth century; warming will be stronger than the global mean in South Asia while higher warming is projected during the NEM than during the SWM (Cruz et al. 2007). Temperature increases of 5.44 ^{0}C and 2.93 ^{0}C are projected over South Asia in the summer of 2070-2099 (compared to 1961-1990) for the two IPCC emission scenarios: A1F1 (highest future emissions) and B1 (lowest future emissions - Cruz et al. 2007; IPCC 2002). Other regional climate models for South Asia also project widespread warming in the region, including in Sri Lanka (rise in annual mean temperature in the range 2.5–4 ^{0}C for IPCC scenario A2 and 2–3 ^{0}C for B2), towards the end of the twenty-first century (see Kumar et al. 2006: Islam and Rehman 2004). Both, Kumar et al. 2006 and Islam and Rehman (2004) confirm IPCC's projections of higher warming during the NEM and lower warming during the SWM.

A few studies have attempted to statistically downscale projections of GCMs over Sri Lanka and project mean temperature increments of varying magnitudes by 2100, for example, Basnayake et al. (2004) predicts 2-3 ^{0}C under scenario A1F1, 0.9-1.4 ^{0}C under B1 and 1.7-2.5 ^{0}C under B2; Basnayake (2008) predicts 2.9 ^{0}C in NEM season and 2.5 ^{0}C in SWM season. De Silva (2006b) predicts increases of 1.6 ^{0}C under A2 and 1.2 ^{0}C under B2 by 2050 and that increases will be mainly in the north, north-eastern and north-western regions (all within the dry zone). Meanwhile, Jayatillake and Droogers (2004) suggest a 0.5 ^{0}C increase in 2010-2039 and a 2-3 ^{0}C increase in 2070-2099 within the Walawe Basin in southern Sri Lanka. Zubair et al. (2005) constructed 1 km resolution present climatology fields (i.e., minimum, mean and maximum temperatures, rainfall and solar radiation) and projected future temperature climatology fields for 2025 and 2050 by assuming that present trends (1960-2001) will continue.

Rainfall projections for Sri Lanka within this century appear to be confusing and sometimes contradictory. While the majority of them project higher MAR, a few project lower MAR. Out of those models which project higher MAR, some, such as the AR4 models (Cruz et al. 2007), regional climate models by Kumar et al. (2006) and Islam and Rehman (2004), and statistically downscaled projections from the HadCM3 model by De Silva (2006b), all show increases in MAR under a range of IPCC scenarios (A1F1, B1, A2, B2). De Silva (2006b) further elaborates that these increases will be 14 % for A2 and 5 % for B2 by 2050 with reference to 1961-1990. While statistically downscaled projections from the HadCM3 and CSIRO models by Basnayake et al. (2004) show an increase in MAR, the CGCM model shows a decrease in MAR for scenarios A1F1, A2 and B1. Seasonally, AR4 models (Cruz et al. 2007), De Silva (2006b) and Basnayake and Vithanage (2004a) project an increase in SWM rainfall (the season when rainfall is confined mainly to the wet zone) and a decrease in NEM rainfall (the season when the majority of the dry zone receives rainfall). De Silva (2006b) envisages a 26-34 % decrease in the NEM rainfall and a 16-38 % increase in the SWM rainfall compared to 1961-1990 for scenarios B2-A2; this will result in enhanced rainfall in the wet zone, northern, north-western and south-western dry zones and reduced rainfall in other dry zone areas such as Anuradhapura, Batticaloa and Trincomalee (Figure 1). A 2 % increase in rainfall is projected in the intermediate zone by 2050 (De Silva 2006b).

The two regional climate models (Kumar et al. 2006; and Islam and Rehman, 2004), and downscaled projections by Basnayake and Vithanage (2004b) suggest increases in both SWM and NEM rainfall (for a range of IPCC scenarios from A1 to B2), with Basnayake and

Vithanage (2004b) suggesting higher increases in SWM than in NEM. They also envisage much higher increments of rainfall on the windward side of the central hills in each monsoon season and lesser increments on the leeward side by 2100. In contrast, downscaled CGCM model projections (Basnayake et al. 2004) indicate decreases in both SWM and NEM. A recent study by the Purdue University, especially on the South Asian summer monsoon also projects a weakened and delayed (by 5-15 days by the end of the twenty-first century) SWM over the majority of South Asia. However, image results of future projections suggest increased SWM rainfall in western Sri Lanka (which is generally wetter than the east) and decreased rainfall in the eastern part. This spatial trend has also been noted by De Silva (2006b) and Basnayake and Vithanage (2004b). Meanwhile, Jayatillake and Droogers (2004) project a somewhat wetter situation with simultaneously more variation in annual precipitation in the Walawe Basin. Shantha and Jayasundeara (2005) envisage a 16.6 % reduction in rainfall in the upper Mahaweli watershed by 2025.

The IPCC envisages an increase in the occurrence of extreme weather events including heat-waves and intense precipitation events in South Asia within this century; inter-annual variability of daily precipitation in the SWM is also projected to increase (Cruz et al. 2007). An increase of 10-20 % in tropical cyclone intensities (for a rise in sea surface temperature of 2-4 ^{0}C relative to current threshold temperature), amplification of storm surge heights (due to stronger winds), with increase in sea surface temperatures and low pressures associated with tropical storms could contribute to an enhanced risk of coastal disasters (Cruz et al. 2007).

This review suggests that considerably more work is needed to verify and refine the available climate projections for Sri Lanka. Scientist are of the view that since South Asia, in general, is unique from the rest of the world, with very complex topography, global models like the ones featured in the IPCC reports have difficulty capturing some of the more subtle atmospheric processes. Therefore, understanding the potential impacts of future climate change in this region requires an improved understanding of a host of climate processes. Consequently, it is of utmost importance that projections from detailed high-resolution regional climate models (RCM) are employed to obtain reliable climate scenarios for Sri Lanka. Accurate quantification of impacts and identification of adaptation strategies both depend on it. Climate simulations by the Purdue University, using model RegCM3, which accurately recreate the monsoon season of past years, are believed to be the most detailed to date for the South Asian Region.

Impacts of Climate Change

Impacts on Water Resources

There are 103 distinct radial draining river basins in Sri Lanka with considerable variations in hydrological characteristics. Sixteen (16) of these are classified as wet zone rivers and carry approximately half the annual runoff (Arumugam 1969). One half of all rivers have zero or negligible flow during the yala (dry) season (Amarasinghe et al. 1999). Sri Lanka depends primarily on its surface water resources for agricultural, domestic and industrial uses. Agriculture is largely sustained by direct rainfall and irrigation water extractions from rivers, while 42 % of electricity is generated from hydro sources. However, groundwater use is also rapidly increasing in the country (IWMI 2005). In this context, accurate quantification of climate change impacts on water resources will be the key to successful adaptation, as Sri Lanka transforms gradually from an agriculture-oriented society to a more industrialized one. The country will face the dual challenge of adapting to climate change while meeting rising demands on water resources due to the growing population and increased allocations to sectors other than agriculture. One school of thought is that while Sri Lanka will actually gain in terms of mean annual water availability due to climate change, its increased variability and inequitable spatial distribution (wet areas getting wetter and dry areas getting drier: Basnayake, 2008; Basnayake et al. 2004; Basnayake and Vithanage, 2004b; De Silva, 2006b) will negatively impact agriculture and food security. The brunt of the impact of climate change on water resources is expected to be borne by the north-eastern and eastern dry zone of the country. The changes in rainfall and temperature, together with other climatic factors, would increase the potential maximum annual soil moisture deficit (MASD) significantly in the dry zone, where some of the agriculturally intensive areas are located and the availability and reliability of water resources are already under severe pressure (De Silva 2006b, De Silva et. al. 2007). The areas with the highest MASD (1961-1990) are located in the north and the east, notably in Jaffna, Mannar, Vavuniya, Trincomalee, Anuradhapura and Batticaloa, while Colombo, Galle, Ratnapura and Nuwara Eliya have the lowest (De Silva 2006a). By 2050, Jaffna will experience a 12 % increase (from 1,162 mm to 1,305 mm) in MASD and in general, the northern, eastern and south-eastern areas (covering the whole of the dry and intermediate zones) will see substantial increases in MASD (De Silva 2006b). However, among the dry zone areas, Hambantota, in the southern tip of the island, is expected to see a decrease in MASD, while also gaining in MAR (De Silva 2006a; Jayatillake and Droogers 2004).

As stated earlier, reduction in rainfall in the central highlands have been observed and projected by several authors. Since the central highlands contribute the largest volume of water for hydro-power generation and subsequently for irrigation (through multipurpose reservoirs in the Mahaweli System), negative climatic changes in this region will very likely result in significant negative ecological and economic impacts. The Kotmale, Victoria, Randenigala and Rantembe reservoirs, constructed in the heart of the upper Mahaweli watershed, supply nearly one-third (29.11 %) of the national power generation and 23 % of the irrigation water supplied by major irrigation schemes (Shantha and Jayasundara 2005). Since the Mahaweli is a multi-purpose water supply scheme, hydro-electricity generation by associated power stations is governed by downstream irrigation requirements. In the event of low runoff, water allocation between the two sectors (hydropower and irrigation) will be problematic. This emphasizes even more the need for reliable climate projections for the country so that appropriate adaptation strategies for the two sectors are formulated based on those projections.

Research on climate change impacts on groundwater resources in Sri Lanka, both in terms of quantity and quality, is notably absent, except perhaps in the Walawe Basin (see Ranjan et al. 2007). For example, the country’s dry zone area suffers from excess fluoride (Seneviratne and Gunatilaka 2005), while sea level rise due to climate change is expected to increase salinity in coastal aquifers. A global scale evaluation of fresh groundwater resources has found that groundwater resources in South Asia are highly vulnerable to salt water intrusion due to global warming (Ranjan et al. 2007). Some other unanswered questions are whether Sri Lanka will be able to satisfy its national water needs (agricultural, industrial and domestic) and how its surface water quality will vary in the twenty-first century amid increased warming.

Impacts on Agriculture

The impact of climate change on agriculture may be broadly categorized into three areas: impact of temperature on crop growth; impact of CO_2 on crop growth and impact of precipitation on crop growth. As regards the impact of temperature, there are two possible effects that could arise, and which have been distinguished as physiological effects, at the level of plants and plant organs; and the crop ecosystem effects, at the field or regional level (Jayatillake and Droogers 2004). Efforts have been made to quantify the impact on crop growth due to the combined effects of enhanced atmospheric CO_2 and increased temperatures, both globally as well as within Sri Lanka. According to the results of world-wide experiments, combined and collected by the Centre for the Study of Carbon Dioxide and Global Change, in Tempe, Arizona (www.co2science.org), increases in potential crop growth due to enhanced CO_2 levels (Table 1) are indicated for rice, Sri Lanka's staple food, and other vegetables (Jayatillake and Droogers 2004). Meanwhile other studies show that a 0.1-0.5 ^{0}C increase in temperature can reduce rice yield by approximately 1-6 % (Vidanage and Abeygunawardena 1994). However, more recent experiments carried out in Sri Lanka suggest that rice yields respond positively to elevated CO_2 (increases of 24 % and 39 % in the two seasons) even at higher growing temperatures (>30 ^{0}C) in sub-humid tropical environments (De Costa et al. 2006).

Table 1. Increases of potential crop growth as a result of enhanced CO_2 levels.

Crop	Period	IPCC Scenario A2 (%)	IPCC Scenario B2 (%)
Rice	2010-2030	20	10
	2070-2100	40	20
Beet	2010-2030	10	5
	2070-2100	20	10
Tomato	2010-2030	15	8
	2070-2100	30	15

Source: Jayatillake and Droogers 2004

The real threats to rice cultivation might be the third factor impacting crop growth, namely, changes in precipitation amount and temporal distribution. Nearly 72 % of paddy production is grown during the wet (*maha*) season in dry areas, where water resources are already stressed (De Silva et al. 2007). De Silva et al. (2007) suggest that by 2050, the average paddy irrigation water requirement during the *maha* season will increase by 23 % and 13 %, respectively, in A2 and B2 scenarios due to reductions in average rainfall, increase in potential evapotranspiration and early ending of rainfall. Irrigation water requirements for other field crops cultivated in the dry and intermediate zones during the dry (*yala*) season will also significantly increase (De Silva 2006a). However, positive impacts are shown in the extreme south (De Silva et al. 2007; Jayatilleke and Droogers 2004). According to Jayatilleke and Droogers (2004), rice yields in the Walawe Basin will increase as a result of enhanced CO_2 levels and higher precipitation, although a substantial variation in yield is expected. Overall, the impact on food production will be positive in the Walawe Basin.

Plantation crops, tea, rubber and coconut, are the next most important crops to Sri Lanka's economy, being some of the main foreign exchange earners and generating income for the majority of unskilled laborers in the country. Several studies have been undertaken to assess the impact of climate change on plantation crops. Wijeratne et al. (2007) have found that tea cultivations at low- and mid-elevations are more vulnerable to the adverse impacts of climate change, than those at high elevations. They also found that reduction of monthly rainfall by 100 mm could reduce productivity by 30-80 kg of 'made' tea/ha while an increase in ambient CO_2 concentration from the present level (around 370 ppm) to 600 ppm may increase tea yield by 33-37 % depending on elevation. Yield projections also show that rising temperatures and diminishing rainfall reduce tea yield in many tea growing regions except in the up-country wet zone (Wijeratne et al. 2007).

Coconut is almost exclusively grown as a rain-fed crop in Sri Lanka, hence rainfall and temperature are the important climatic factors influencing coconut yield (Peiris et al. 1995; Mathes et al. 1996). Future yields in coconut production under six different climate scenarios, using integrated crop models suggest that the projected coconut production after 2040 in all climate scenarios, when other external factors are non-limiting, will not be sufficient to cater to local consumption (Peiris et al. 2004). Extended dry spells and excessive cloudiness during the wet season can reduce coconut yield so that annual losses can range between $32 and $73 million (Fernando et al. 2007). However, on the other hand, during a high rainfall year, the economy could gain by $42-$87 million due to high coconut yields (Fernando et al. 2007). Among the different stakeholders in the coconut industry, the coconut oil industry will be most vulnerable to climate change: increasing air temperatures will increase pest and disease problems in the future and, therefore, increased investment in pest control will be required (Peiris et al. 2004).

Climate change is expected to affect Sri Lanka's forest distribution as well, with increases in tropical very dry forest areas (5 %) and tropical dry forest areas (7 %), and a decrease in tropical wet forest areas (11 %) (Somaratne and Dhanapala 1996). Sea level rise caused by global warming poses another threat to coastal agricultural areas due to inundation and salinity intrusion of coastal wetlands and aquifers. Weerakkody (1996) states that inundation will be in the range 41 km^2 for a rise of 0.3 m and 91.25 km^2 for a rise of 1 m for lowlands along the south-west coast. The Galle District (one of Sri Lanka's 25 administrative districts), situated along the south-west coast is further subdivided into 18 District Secretariat (DS) Divisions. Pilot studies suggest that sea level rise could inundate about 20 % of the land area of Galle's five coastal DS divisions (Wickramarachchi, undated). The damage caused could be of higher magnitude if the combined effects of beach erosion, storm surges and coastal flooding are considered along with inundation due to sea level rise. However, on a positive note, a recent study by the WorldFish Centre, Malaysia, which compared the vulnerability of 132 national economies to potential climate change impacts on fisheries under IPCC scenario B2, finds that Sri Lanka's vulnerability is low in this respect (Allison et al. 2009).

Climate change impacts on agriculture invariably impact the country's economy. Seo et al. (2005) find that nationally, the impact on agriculture (rice, tea, rubber and coconut) will result in economic impacts in the range of a decrease of 11 billion rupees ($96.4 million, minus 20 %) to an increase of 39 billion rupees ($342 million: plus 72 %) depending on the climate scenario on which the calculations are based. They confirm that climate change damage could be large in tropical developing countries but is highly dependent on the actual climate scenario.

Mitigation and Adaptation to Climate Change

Climate Change Mitigation

Sri Lanka is a signatory to UNFCC and has ratified the Kyoto Protocol on climate change. Therefore, under its obligation to contribute to efforts to mitigate climate change, Sri Lanka made its Initial National Communication on Climate Change in October 2000. Its Second National Communication is under preparation (C. Panditharatne, Ministry of Environment, pers. comm.). According to Sri Lanka's latest GHG inventory (1994), annual emissions stand at 33,630.22 Gg CO_2, 1,098.38 Gg Methane (CH_4) and 162.8657 Gg of Nitrous Oxide (N_2O) (Ministry of Forestry and Environment 2000). The largest contributors to GHG emissions in Sri Lanka are changes in forest and woody biomass stocks; forest and grassland conversion; and liming and organically amended soils. The largest source of CH_4 is the treatment and handling of waste, while the energy sector also contributes in a small scale through incomplete burning of fossil fuel (Ministry of Forestry and Environment 2000). Biomass (47 %), petroleum (45 %) and hydropower (8 %) are the main primary energy resources used in the country (ADB 2006).

Sri Lanka has initiated a host of activities aimed at reducing its GHG emissions including afforestation, reforestation, and development of sustainable energy and incorporation of emission reduction strategies to the transport sector. Studies have been conducted to assess the carbon sequestration potential of Eucalyptus plantations in the up-country region and in-situ Gliricidia plantations, providing innovative thermal energy to desiccated coconut mills in Sri Lanka (Nissanka and Ariyaratne 2003; Fernando and Jayalath 2003). Efforts have also been made to introduce renewable energy such as small hydropower plants, solar and wind energy (Weerakoon and De Silva 2006; Prasad 2006) and biofuels (Ambawatte and Kumara 2007; Ambawatte et al. 2007) to the energy sector. Some innovative projects aimed at mitigating climate change impacts, have also been implemented including the planting of 73,000 trees to offset carbon emissions generated by the tourism industry as part of a 'carbon clean Sri Lanka' campaign, and the installation of ten trial base stations using solar and wind power by Dialog Telekom, a mobile telecommunications provider (Anderson 2009). A number of non-governmental organizations are also active in the country in implementing community-based projects aimed at reducing GHG emissions to the atmosphere, such as through the Small Grants Program of the Global Environmental Facility (GEF).

Apart from the Initial National Communication, Sri Lanka has also developed a Clean Development Mechanism (CDM) policy and strategy and a few CDM projects in the form of small hydropower are already underway. Introduction of Vehicle Emission Standards and the 'Green Lanka' program are other initiatives taken in this direction. The country is also contemplating the introduction of new strategies into the transport sector (heavily dependent on fossil fuels at present) such as promoting public transport instead of private transport within major cities.

Climate Change Adaptation

Adaptation to climate change is defined as any 'adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities' (IPCC 2007). Although there are a number of environmental policies, legal enactments and plans that contain provisions that could contribute to reducing or mitigating the effects of climate change, the subject of climate change has not been directly addressed in them (Ministry of Forestry and Environment 2000). Therefore, the Initial National Communication recommends the incorporation of climate change considerations into existing policies. Munasinghe (2008) proposes the adoption of the 'sustainomics' framework (developed by the World Bank) and its tools to integrate climate change policies into Sri Lanka's development strategy, to help make the transition from the risky, 'business-as-usual' scenario to a safer and more sustainable future. Sustainomics seeks to provide a comprehensive, practical framework for making present and future development efforts more sustainable. Using one of its tools called the 'Action Impact matrix,' he identifies that, vulnerability of Sri Lanka's water resources and agricultural output, will be the key challenge to national food security in the wake of CC. Hence, the island's successful adaptation depends on accurate projections of climate change impacts on its water resources and agriculture, and finding ways to manage and adapt to such projections. Some examples of initiatives already undertaken in this regard are explained in the next paragraph. However, a more comprehensive national study, on river basin or district scale, on vulnerability of Sri Lanka's water resources and agriculture to climate change, is an urgent need for the country.

Understanding the present climate is imperative in projecting future climate conditions and impacts. Hence, a significant number of attempts have been made to understand and quantify the effect of climate parameters such as ENSO and Sea Surface Temperature (SST) on Sri Lanka's present climate (see Zubair et al. 2008; Pathirana et al. 2007; Zubair and Ropelewski 2006; Suppiah 1996). Some, such as Zubair et al. (2008), propose short- and medium-term rainfall predictions based on ENSO and SST. Tools for predicting annual national coconut production (Peiris et al. 2008) and seasonal water availability within the Mahaweli scheme (Zubair 2003) make use of such short- and medium-term rainfall predictions. Studies on crop adaptation are performed mainly by six research institutes in the country conducting research on rice, field crops, horticultural crops, tea, rubber and coconut. The Rice Research and Development Institute (RRDI) is involved in developing technologies and appropriate rice varieties that respond positively to increased air temperature and humidity, increased atmospheric CO_2, moisture stress conditions, increased salinity and submergence (W. M. W. Weerakoon, RRDI, pers.com.; Piyadasa et al. 1993). Short-term (low water consuming) rice varieties, suitable for shorter growing seasons, have already been developed and tested (Harris and Satheeswaran 2005). Other adaptation options recommended for rice (especially in the dry zone) include partial shift of present locations to areas projected to receive more beneficial rainfall and changing planting time to suit altered rainfall onset times (De Silva et. al 2007). Introduction of micro-irrigation technologies (Peiris et al. 2006; Aheeyar et al. 2005), shifting from rice to field crops (Chandrika et al. 2004), crop diversification (Nanthakumaran 2004), and investigating the impact of increased temperatures, humidity and moisture stress on crops (Inpadevy and Mahendran 2003; Weerasinghe et al. 2001, Peiris et al. 1993) are other adaptation strategies under consideration. Adaptation measures proposed in the tea sector are: the use of hardy tea clones resistant to drought, pests and diseases; improvement and implementation of soil conservation measures; proper shade management; and expansion of multi-cropping systems (Wijeratne 1996). Coconut farmers have already adopted moisture conservation methods such as cover crops, organic manure, burying coconut husks and contour drains to minimize the effects of less rainfall. Adaptation strategies focused on two alternative development approaches of sustaining food security versus enhancing environmental quality, have been proposed for rice farmers in the Walawe Basin by Jayatillake and Droogers (2004).

Rainwater harvesting and storage during higher rainfall seasons, especially in the dry and intermediate zones, is a viable solution for utilizing available water resources throughout the year. De Silva (2006b) suggests the provision of a rainwater harvesting system to all households in drought-prone areas, making it a prerequisite to receive drought relief. Renovating the existing tanks in the dry and intermediate zones to store excess rainfall during the SWM season, and devising methods to store and transfer excess rainfall in the wet zone to the dry zone are other available alternatives for water resources adaptation when considering the country as a whole (De Silva 2006b). A greater shift towards alternative energy sources, from hydropower and fossil fuels, is advocated in the energy sector (Shantha and Jayasundera 2005), while the Coast Conservation Department (CCD) is in the process of formulating a Climate Change Action Plan for adapting to sea level rise (B. Wickramarachchi, CCD, Pers. Comm.). However, equally important is creating awareness among different stakeholders on vulnerabilities, impacts and adaptation options.

Research Priorities

First and foremost among research priorities is the need for reliable and detailed climate scenarios for the country, without which no country can even begin to understand what its vulnerabilities are. A comprehensive national study on river basin or district scale on the vulnerability of Sri Lanka's water resources and agriculture sectors to climate change should follow. This study should include not only surface water but also groundwater, covering both water quality as well as water quantity issues. Only if the combined impact on agriculture of increased temperature, increased CO_2 in atmosphere and increased or decreased rainfall is quantified, can a true picture of the benefits or costs of climate change on agriculture, food security and the economy be projected. Appropriate adaptation measures may be implemented based on such a study. Central to any research on climate change is the need for data sharing and cooperation among different stakeholder agencies. The Water Resources Board, which already has the mandate to act as the leading coordinating authority in Sri Lanka's water sector, could play a pivotal role as the central agency facilitating such research, including the maintenance of a data depository.

Conclusion

It is evident that Sri Lanka's climate has already changed. This review suggests that although a few attempts have been made to project Sri Lanka's climate in the twenty-first century, such studies lack consensus and their results and projections are even contradictory. However, many available projections indicate that climate change impacts will be large in the dry zone, especially in the north-east and the east. A decline in rainfall in the dry zone, combined with an increase in temperature, evapotranspiration and soil moisture deficit, will have serious impacts on the country's food production, livelihoods and the economy. A recent study finds Sri Lanka to be one of the 'hot-spots' of food insecurity in the Asia Pacific Region, while another suggests yet further decreases (0-15 %) in agricultural productivity by 2080 (Nellemann et al. 2009). Apart from food insecurity, the predicted adverse impacts on the dry and intermediate zones will worsen the existing economic and social inequities and widen the gap between the developed core (Colombo Metropolitan Region) and less developed areas. Therefore, reliable and detailed climate scenarios and a comprehensive national study on the vulnerability of Sri Lanka's water resources and agriculture to climate change are urgently needed so that timely action is initiated towards adapting to such adverse impacts.

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