CLIMATE CHANGE ASSESSMENT IN SRI LANKA USING QUALITY EVALUATED SURFACE TEMPERATURE DATA

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Abstract

We assessed trends in the annual and monthly means of averaged daily surface temperature observations at 15 stations in Sri Lanka, after subjecting the data to quality control procedures. The quality assessment was based on station histories, comparison with neighbors and inter-station consistency. The time series, probability distribution functions, outliers, and "cumulative sums" were inspected. The data for each station were compared with a reference time series constructed from observations at neighboring sites that were well correlated with it. Most stations have consistent data after the first decade of island-wide observations starting in 1869. Approximately 425 of the nearly 2000 station-years of data were suspect. The reasons for poor quality included relocations of stations and poor calibration. We estimated that adjustments of means and variance can be used to salvage at least 190 of the 425 suspect station-years of data. The quality of the data has improved particularly in the 20th Century save for three stations in the Northern conflict region since 1983.

There are significant differences in the trend estimates with and without quality control. The warming trend varies spatially from 0.09 to 3.0 ºC/100 years. The stations that had errors were in the North (Jaffna, Mannar, Trincomalee) and in the hills (Nuwara Eliya and Ratnapura). If the estimates of the trend from reconstructions of these stations are used then the warming trends are consistent with that for the other stations. These trends proved to be statistically significant at confidence levels exceeding 99%. The North-Western and South-

Eastern region have a higher trend. On a seasonal time scale, the trend is highest from January to April and lowest from June to September.

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1. Introduction

The global trend in surface temperature measurements are of the order of 0.56 to 0.92 ºC for the century from 1906 to 2005 (IPCC, 2007). Minor errors in temperature data can throw off estimates of climate change of such low magnitudes and therefore it is important to undertake careful assessments of data quality. A review of quality control procedures is provided by Peterson *et al.* (1998).

Exploratory data analysis through examination of time series of probability distribution functions, and detailed examination of outliers are simple but important procedures that can quickly identify egregious errors. As temperature fields over limited regions are likely to have high spatial consistency (Legates and Willmott, 1990), examination of cross-correlations among different stations is a quick way to identify particular stations that have poor quality.

Objective measures for establishing data homogeneity and discontinuities are available (Peterson and Easterling, 1994, Easterling and Peterson, 1995, Eischeid *et al.*, 1995, Easterling *et al*., 1996) along with methods for adjusting temperature records for site changes (Rhoades and Salinger, 1993). A review of the techniques that have been developed for homogeneity adjustment is provided in Peterson *et al.* (1998). A recent review of data homogenization techniques can be found on the website of the WMO/CLIVAR/CCl Expert Team on Climate Change Detection and Indices (http://cccma.seos.uvic.ca/ETCCDI/) and its application globally was reported in Alexander *et al.*, 2006.

Analyses of historical variations of instrumental temperature records are important for the investigation of regional effects of global warming (IPCC, 2001). The South Asian and Indian Ocean regions are of importance on account of the monsoon system and the economic impacts that climate has on a significant fraction of humanity. There have been several studies of the climate change trends so far focused on India (Shrestra *et al*., 1999, Kothyari and Singh, 1996). Assessments of rainfall and temperature trends for Sri Lanka have been provided previously (Rupa Kumar and Patil, 1996, Chandrapala, 1996). While there have been a few such attempts to estimate trends, no attempts at systematic quality control work on this data has been reported.

Regional quality control exercises have been reported in many temperature regions and a few in the tropics such as the work in Asia (Klein Tank et al., 2006) and in the Carribbean (Peterson et al. 200. Sri Lanka provides a good test case for detailed investigations in the tropics because of its unique high density of records that extend to the nineteenth century (Peterson and Vose, 1997). The annual temperature ranges between 22 and 29 ^{o}C in stations other than in the hills. The inter-annual variation at all stations is within 2 ^{o}C.

Data from eleven Sri Lankan stations have been incorporated into the Global Historical Climate Network (GHCN) database (Peterson and Vose, 1997, Vose *et al.*, 1992) and subjected to globally applicable procedures of quality control. This analysis was based on the volumes of Colonial archives in England and reports from the Sri Lanka Department of Meteorology until 1990. A more complete data record (but not exhaustive) is available through the Sri Lanka Department of Meteorology and publications of this Department and its predecessors.

Here, we assess the quality of a more complete set of monthly and annual mean temperature data for Sri Lanka bringing to bear records of station histories. We then use these data sets to identify the influence on estimates of climate change trends. We report only on the quality control of work using the mean annual temperature but in our assessments of temperature trends we report on both the trends in annual data and also the trends in the monthly data.

2. Data

Monthly means of averaged daily temperature observations for 15 stations (figure 1 and table 1) were obtained through the Sri Lanka Department of Meteorology and through publications of its predecessors (Trigonometrical Survey of Sri Lanka, the Colombo Observatory and the Ceylon Department of Meteorology). The observations are taken at a height of approximately 1.25 to 2 meters (World Meteorological Organization, 1983) at 3 hourly intervals and then averaged to obtain the daily average for each day. Details regarding the instrumentation are provided by the Superintendent of the Colombo Observatory (Bamford, 1926, Jameson, 1936). Data were also recorded in reports submitted to the Colonial Office in London. Towards the end of the colonial period the data were published in journals (Zubair, 2004).

According to Bamford, in the early period, the thermometers were exposed in the verandahs of various Government offices and only around 1880 where the instruments maintained in open sheds. After 1904, the materials used in the contstruction of these sheds were improved but these variations in construction did not produce serious differences in observations (Bamford, 1926).

Although the Stevenson screen type enclosure was used in many countries by 1910, there was a deliberate delay in the adoption of the Stevenson screen until 1920. Bamford argues that white ants making them unviable in Ceylon and they needed adaptation before adoption. Bamford (1926) showed using parallel measurements that the departures observed with the Stevenson screen and the existing enclosures departed only minimally.

Station histories were obtained from the Ceylon Administrative Reports (1884-1896), Ceylon Blue Books (1901-1938), Colombo Observatory Reports (1946-1974), Tropical Agriculturalist (1920-1975), and Ceylon Journal of Meteorology (1972-1976) and through personal communication with officers of the Department of Meteorology. The availability of multiple sources ensured that we could cross-check for transcription errors.

3. Methodology

The work in quality control involved cross checking of data from the primary and secondary sources (for transcription errors, consistency and completeness), the application of exploratory data analysis techniques (to identify immediate problems), the construction of a reference time series for each station, and the detection of in-homogeneities and the identification of suspect data. Thereafter the trend in temperature at each station was estimated along with the significance of these trends. These are detailed below.

3.1 Preliminary Quality Assessment

The following analyses were carried out:

Exploratory data analysis of the time series helped identify errors in transcription and data entry. The statistics of mean, median and standard deviation along with the range in observations provide a quick indication of potential errors. Data which exceeded the median by 3 times the inter-quartile range (IQR) were checked. The inter-quartile range is defined as the difference between the 25^{th} and 75^{th} percentile values. If there was no transcription error, then the neighbouring stations were checked for similar anomalies. In cases, where the anomalies were not replicated, further checks were carried out at a monthly level to narrow down the suspect data. Suspect data were replaced with the mean values.

An average "All Sri Lanka Temperature" (ASLT) time series was constructed from the observations at the 15 stations. The average anomaly was estimated by summing the anomalies of the individual stations and then dividing by the number of stations. The anomalies were estimated with respect to the long-term mean for values up to 1960 (constant) and with respect to a mean that took account of a warming trend at each station in subsequent years. Such averaging shall provide an adequate approximation since the stations are well distributed in Sri Lanka both spatially and in terms of elevation. Such a reference time series is useful as in comparing it with the observations, shifts in locations of the station, calibration errors and decline in quality can be identified.

A cross-correlation table of the mean temperature records of the 15 stations and the ASLT was constructed.

3.2 Construction of Reference Time Series

A "reference time series" for each station can be constructed based on the data of the other stations to facilitate comparison with the observations. Five techniques (Normal Ration, Inverse Distance, Optimal Interpolation, Multiple regression, Single Best Estimator) to construct such reference time series has been reviewed by Eischeid et al (1995). The multivariate "optimal interpolation" algorithm that proved to be among the better algorithms and it was implemented here. A reference time series for a given station is constructed based on the temperature anomalies in other stations that exhibit the strongest relationship with the chosen station for a reference period. The contributions of the respective predictand stations are weighted to reflect the degree of correlation with the predictor station. This technique is more appropriate for regions with hills and strong wind regimes rather than an inverse-distance based method. Data from five other stations that had the highest correlation with the target stations during the years from 1900-2000 were used in constructing the reference time series. The reference time series were estimated following Eischeid *et al.*, (1995) as

$$Z_{ref} = \sum (W_i * Zj) / \sum (W_i) \rightarrow (1)$$

where

Z_j - Standardized anomaly for jth year

where the weight for the i^{th} station, W_i, is given by

$$W_i = (r_i^2(n_i - 2))/(1 - r_i^2) \rightarrow (2)$$

Here ,

r_i - Correlation between the station and the i^{th} surrounding station

n_i - Number of data used to derive the correlation coefficient for i^{th} station.

Where there were significant discrepancies between the observed and reference, the data was identified as suspect.

3.3 Detection of Inhomogeneities and Adjusting for Change Points

While there are several methods to detect inhomogenities in meteorological time series (e.g. Rhoades and Salinger), the state of the art has been implemented and made available by the WMO/CLIVAR/CCl Expert Team on Climate Change Detection at (http://cccma.seos.uvic.ca/ETCCDMI/software.shtml referred to as RHtest). The methodology can be used to detect, and adjust for, multiple change points (mean-shifts) that could exist in a data series that may have first order autoregressive errors. It is based on the penalized maximal t test (Wang et al. 2007) and the penalized maximal F test (Wang 2008a), which are embedded in a recursive testing algorithm (Wang 2008b), with the lag-1 autocorrelation (if any) of the time series being empirically accounted for. The time series being tested may have zero-trend or a linear trend throughout the whole period of record.

3.4 Trend Estimation and Significance Testing

Trend estimation of temperature data is most often undertaken by fitting least squares linear trend to the data (Santer *et al.,* 2000). Denoting the time series of annual average mean temperature anomalies as *x(t)* and number of time samples as $n_{t,,}$ the least squares linear regression estimates of the trend, *b,* is estimated from minimization of the squared differences between *x(t)* and the regression line, *x`(t),*

$$\hat{x}(t) = a + bt; \qquad t = 1, \cdots, n_t.$$

The estimation of statistical significance of the trends has to consider the strong autocorrelation within the data. A simple method to account of the autocorrelation is to adjust the sample size used in the computation of degrees of freedom(Wigley and Jones, 1981).

In this paper, the significance of the trends is estimated using a technique described in Santer *et al*. (2000) and described as follows.

The regression residuals *e(t)* are estimated as

$$e(t) = x(t) - \hat{x}(t); \qquad t = 1, \cdots, n_t.$$

For statistically independent values of *e(t)*, the standard error of *b* can be calculated as

$$s_b = \frac{s_e}{\left[\sum_{t=1}^{n_t} (t - \bar{t})^2\right]^{1/2}},$$

where the variance of residual about the regression line, s_e^2, is estimated as:

$$s_e^2 = \frac{1}{n_t - 2} \sum_{t=1}^{n_t} e(t)^2$$

Whether a trend in *x(t)* is significantly different from zero is tested by computing the ratio between the estimated trend and its standard error ($t_b = b/S_b$). The calculated t_b is then compared with a critical *t* value for a stipulated significance level and n_{t-2} degrees of freedom. As the values of *e(t)* for temperature are not statistically independent, the simplest means of adjusting for it is to use an effective sample size n_e instead of n_t based on r_1 which is the lag-1 autocorrelation coefficient of *e(t)*.

$$n_e \approx n_t \frac{1 - r_1}{1 + r_1}.$$

4. Results

4.1 Data Exploration

Time Series Plots: The annual temperature data of all but 4 of the 15 stations (figure 2) have annual temperature which lies between 27.5 ±1.5 ^{o}C. There have been some excursions outside these bounds from 1885 and 1918 and from 1975 to 1985. The four stations with colder temperatures (Nuwara Eliya, Diyatalawa, Badulla, Kandy) are at high elevations and also have a range of ±1.5 ^{o}C. Their respective means were 15.5 ^{o}C for Nuwara Eliya, 20.22 ^{o}C for Diyatalawa, 23.42 ^{o}C for Badulla and 24.43 ^{o}C for Kandy.

Statistics: The mean and median differ by less than 0.1 ºC for all the stations (table 2). The standard deviation is a measure of both natural variability and measurement error. The standard deviations for the different stations are largely consistent ranging from 0.3 to 0.5 (table 2). Of these, the stations that have deviations above 0.4 (Nuwara Eliya, Puttalam, Diyatalawa, Anuradhapura, Badulla, Ratnapura and Trincomalee) deserve further scrutiny.

Probability Distribution Functions: The probability distribution functions (*pdf*) of the temperature values for the stations were estimated (figures not shown). The *pdf*s which showed more than one peak were Jaffna, Trincomalee, Kandy, Kurunegala, Nuwara Eliya and Colombo. Such departures could indicate shifts in location or of defective calibration. Of the five stations that showed the most discrepancy, three are coastal stations (Jaffna, Colombo, Trincomalee) and two are in the hills (Kandy and Nuwara Eliya). While the *pdf's* provide a quick summary of data quality, the particular portions of the time series that may be suspect can only be identified with other methods.

Outliers: The outliers in the time series and histograms which were larger than a threshold of thrice the Inter-Quartile-Range of the distribution were identified. Such data was cross-checked from multiple sources (identified in section 2). In addition, anomalies in neighbouring stations during that period were also checked. In most cases, the data from the different stations were consistent but there were exceptions. The suspect data were identified as Jaffna and Ratnapura (1896), Galle and Hambantota (1901), Nuwara Eliya (1997) and Anuradhapura, Batticaloa, Badulla, Galle, Hambantota and Diyatalawa (1998). These stations were treated as missing values for further analysis.

4.2 Average Sri Lanka Temperature Estimates and its Internal Consistency

The salient features of the ASLT (figure 4a) include a period of warming around 1900 followed by cooler periods until 1960 after which there is consistent warming. The consistency of the data as measured by the standard error of temperature anomalies (Figure 4b) shows consistent improvement after 1895 until 1974. Thereafter, the consistency has been impaired particularly by poor quality of the three stations in the conflict zone (Jaffna, Trincomalee and Mannar).

Inconsistencies in observations from one station to another could be either natural or due to poor quality of observations in some stations. Given that there is high correlation between stations in the last fifty years; one can assume that spatial consistency of temperature anomaly patterns is to be expected. Hence, the standard error computed from the temperature anomalies for each year (Figure 4b) can be taken as a reflection of the quality of data. This measure shows that the data quality has improved very much in the last century.

4.3 Cross-Correlation Analysis

The correlations between each time series and the ASLT for the entire record length from 1869-2000 ranged between 0.71 and 0.94 (table 3). The stations that had the lowest correlations below 0.4 were Jaffna, Puttalam and Nuwara Eliya. The correlations for Kandy, Ratnapura and Hambantota were between 0.4 and 0.5.

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It is possible that only part of these time series are of poor quality. A quick way to identify the deterioration is to inspect cross-correlations for shorter durations. Since the quality of the data improves over time, we broke up the periods so that older records have shorter durations. Thus cross-correlations undertaken were estimated for 1869-1894, 1895-1919, 1920-1949 and 1950-2000 (not included).

In summary, the data whose correlations with ASLT were below 0.3 are listed were:

Jaffna	1869-1894 (-0.1), 1981-2000
Puttalam	1894-1905 (-0.23)
Batticaloa	1869-1880 (0.10), 1895-1905 (-0.16)
Hambantota	1869-1880 (0.28), 1895-1905 (-0.15)
Ratnapura	1869-1880 (-0.30)

In addition, the data listed below were flagged on account of their correlation lying between 0.3 and 0.5 with the ASLT.

Puttalam	1869-1894 (0.31)
Batticaloa	1881-1894 (0.43)
Hambantota	1881-1894 (0.43)
Nuwara Eliya	1869-1894 (0.44), 1895-1919 (0.43)
Ratnapura	1881-1894 (0.47)

All other data had a correlation greater than 0.5.

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4.4 Comparison of Observations with Reference Time Series

Reference time series for individual stations are shown along with the observations in figure 2. The five stations that were used in the construction of the reference series of individual station temperature are highlighted in table 3 and were the stations whose observations had the highest correlation with that of the individual station for 1900-2000.

The method for the construction of reference time series has potential flaws if the same type of error is found in two stations. An examination of the stations used in the reconstruction (table 3) shows that that there were a few instances. Kurunegala and Kandy has the highest correlation (r=0.85). Jaffna and Ratnapura have the highest correlation between each other (r=0.59) which is counter-intuitive as Jaffna is to the far north and Ratnapura is in the South-West. The high correlations among these stations may be attributed to the fact that both have unexpected drops in temperature starting in 1986 and 1991 respectively. The reference time series for these stations shall be suspect after 1986.

Although in many cases, the site changes did not affect the homogeneity of the data, our analysis did bring out shifts in mean of observations in Mannar (1900-1935), Kandy (1921-1954), Ratnapura (1911-1920), Colombo (1930-1968) and Nuwara Eliya (1950-1975) and shifts in variance at Galle (1902-1913). In these cases, data adjustment techniques can be used to build a homogeneous time series (e.g.: Rhoades and Salinger, 1993).

4.5 Inhomogeneity Detection and Reconstruction of Data

Inhomogeneity detection was undertaken as described in section 3.4 based on comparison of the observations with a reference time series which has been constructed (figure 2). The change points were identified using the RHtest Version 2 (see table 4). The station histories were not used in the initial identification. The majority of change points that were identified had levels of statistical significance exceeding 95%. The occasions when the significance level associated with the change point was within the 95% uncertainty range, were cross-checked against station histories for evidence of stations having been moved. In the instances, in which the stations were moved or were otherwise impaired, we retained these as change points.

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Badulla, Diyatalawa, Kurunegala, Trincomalee, Anuradhapura and ALST were identified as homogeneous throughout their record. The change points that were identified are listed in table 4. Based on these change points and an examination of figure 2, the data that were suspect were identified are also listed in table 10.

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Note, that a few of these change points were perhaps due to the construction of the reference time series as it included stations that had errors in them. For instance, Galle has major anomalies between observations and reference in the few years prior to 1912. Galle was used in the construction of the reference time series for Kandy and Colombo. This led to an identification of a spurious change point in 1911 for Kandy and Colombo. This change point was neglected. Similarly, errors in Colombo (1953-1963) may have led to a spurious change point in Mannar in 1964 and errors in Batticaloa data upto 1928 may have led to a spurious identification of errors in Puttalam in 1930. All such change points that were disregarded are italicized in table 10.

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The list of suspect data that was established as suspect based on this analysis is tabulated in Table 10. The total number of station-years during which the data was identified as suspect was 435 out of nearly 2000 station years. Out of these 435 station years, a further 200 station years (identified in the last column of table 10) may be salvage with an adjustment of means.

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Using the RHtest version 2, we reconstructed Ratnapura, Nuwara Eliya, Mannar, Puttlam and Kandy. Jaffna was reconstructed manually as it is known that the latter part of the data set is less accurate when compared to the initial part. These reconstructed data was then used to calculate the "Reference Series" for each station.

4.5 Comparison of Results with GHCN

This analysis presents quality assessments for more stations and longer records (2000 station-years) when compared with the GHCN (1150 station-years). The findings are summarized in table 11. In general, this quality assessment is in agreement with the GHCN assessment with the following modest exceptions. Under the GHCN scheme, the following data failed quality tests – Trincomalee (1865-1949), Colombo (1853-1949) and Batticaloa (1869-1980). In the work that we carried out, we identified the data for Trincomalee from 1865-1894 alone as suspect; the data in Batticaloa as good after 1928, and the data in Colombo as adequate apart from 1953-1963. Apart from these, there were few other segments of data that we identified as suspect - for example the observations in Kandy were admitted by GHCN. Knowing the history of relocations of station along with identification of change points enabled us to identify the need to adjust for site changes in Kandy in 1919 and 1953.

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4.6 Estimated Trends for Observed and Reference Time Series

The estimated linear trend of the surface temperature varies with the period considered. The trend estimates for recent periods is considerably greater than for the full record. We have undertaken trend estimation for both, the 1870-1900, 1901-2000 and the 1960-2000 periods but shall report here in detail only on the latter period.

The trends and their statistical significance were estimated for the 15 stations from 1960-2000 (table 5). There are significant differences in the trend estimates based on the observed and quality controlled data for Jaffna, Mannar, Nuwara Eliya, Ratnapura, and Trincomalee. The result of poor data quality is to lead to underestimates for the warming trend. For example, the trend estimated for the period from 1870 to 2000 for Kandy increases from near-zero (for observations) to a value of 0.55 ºC/100 years (after adjustment) (Figure 5) consistent with that for other stations during that duration. The trend estimates for Jaffna and Ratnapura which are not significant for the observations are raised to 99.95% confidence levels if the reference time series is considered. The trend estimates for the Batticaloa and Kurunegala stations are raised from 99.5% significance levels for the observations to 99.9% for the reference time series. Poor data quality explains the discrepancies in these 8 stations as opposed to the other 7 stations where there is already a 99.9% level of significance. For exercise in mapping the trends, we use the estimates from the reference time series.

Mapping these trend estimates (Figure 6) brings out some distinctive features. The trend values range from -0.3 to 3.3 ^{o}C/100 years. Note, that in the mapping, we have used three additional stations from the Department of Meteorology that have data from 1960-2000 (Vavuniya, Ratmalana and Maha Illuppalama) as these help fill gaps. Anuradhapura, Badulla, Galle, Puttalam and Colombo stations show the highest warming trends after 1960. The trend in the South-Western mountain region is lower than in the surrounding coastal areas. There is enhanced warming towards the North-Central region.

We have also undertaken quality assessment of monthly mean temperature data (not reported here) similar to that for the annual data. These estimates (figure 7) show that there is significant seasonal variation in the warming trends. For example, the average warming trend in February is twice as great as that during July.

4.7 Uncertainity due to Land Use/ Land Cover Changes and Civil Conflict

Land use, land cover changes (LULC) can lead to observations of temperature (Pielke et al., 2007). The errors in estimates can arise from poor initial site selection, changes in the environment in the vicinity of the observation sites and relocation of stations in response to various changes. In Sri Lanka, the initial site selection in the early years was based on convenience of the administrative and military personnel but they have been generally well selected as these were generally in the administrative rather than the commercial parts of the city. By 1880, the observation sites were significantly improved (Bamford, 1936). The sites that were close to the military cantonments were relocated (e.g: Kandy in 1924 and Diyatalawa in 1990) so as to limit access to these sites. In regions of conflict, observations have not always been made regularly and there have been less frequent contemporaneous quality checks and infrequent calibration.

In Sri Lanka, there has been an increase in population from 2.5 million in 1881 to 20 million in 2006 (Department of Census and Statistics, 2007) and associated urbanization. Major urban centers have been concentrated around Colombo (includes the Katunayake, Ratmalana and Colombo stations). Other urban centers include the towns of Kandy, Mannar, Galle, Batticaloa, Ampara (close to the Pottuvil station) and Trincomalee. There has also been reduction in forest cover (for example from 80% in 1820 to 44% in 1956 to 24% by 1993 (Somasekeram et al., 1988, Zubair, 2005). There have also been several transbasin irrigation schemes where there is transfer of water from the wetter South-Western region to the dry regions (Zubair, 2005).

There are no simple means of identifying precisely the impacts of land use and land cover changes (LULC) (Pielke et al., 2007) absent parallel measurements in neigbhouring sites over an extended period. There are some parallel measurements on the impact of observation in 6 different sites within Colombo (Emmanuel and Johannson, 2006) but this is only from April 30 to May 17, 2003. The conclusion that may be taken from this work is that the immediate vicinity of the observation site is important. In this context, Colombo observatory has been generally in an undisturbed area until 2007 (see background in Zubair, 2003). Thus we are left with trying to provide the best assessment we can of the influence of LULC through indirect means.

Note that major change in observations (which are not replicated in other sites) is likely to be captured by the inhomegeniety tests that were undertaken (Peterson, 2006). In addition, a study (Lim et al., 2005) comparing the temperature changes from observations and from reanalyses (taken to represent the difference between temperature change driver by climatic process and that which includes LULC shows no significant difference for Sri Lanka).

We can compare the temperature changes in regions where there has been greater urbanization (Colombo, Kandy, Anurhadhapura, Batticaloa, Puttalam, Mannar, Galle, Trincomalee) against the observations for other stations (Badulla, Diyatalawa, Hambantota, Jaffna, Kurunegala, Nuwara Eliya, Ratnapura). The stations with greater urbanization shows an average warming of 0.019 ^{o}C/ year and the stations with less urbanization shows an average warming of 0.0183. This difference is not significant. Thus the evidence points to rather modest influences of LULC on climate change estimates. Further work shall be carried out to study the warming trends of minimum and maximum temperature data as that shall help sharpen the assessment of the influence of LULC.

5. Conclusions

Overall, most stations have useable and consistent data particularly after the first decade of island-wide observations starting in 1869. The internal consistency of the data as estimated through cross-correlations and standard-error estimates show that the data quality was poor until the last decade of the 19th Century. This is supported by reports of the meteorologists in charge. The quality of the data has improved thereafter in the 20th Century. However, there is a decline in data quality in the stations in the conflict areas in the North after 1983. This is still a short period spanning (~435 station-years) compared with the nearly 2000 station-years of data that was used in the analysis. With adjustments in mean at least 200 of these station-years can be recovered.

There are significant differences in the trend estimates with and without quality control. The stations that had errors since 1960 were in the Northern region (Jaffna, Mannar, Trincomalee) which has been conflict-ridden since 1983 and two of the stations surrounded by hilly terrain (Nuwara Eliya and Ratnapura). If the estimates of the trend from reconstruction of the station are used, then the warming trends in these stations are consistent with that for the other stations. The warming trends were statistically significant at above 99% for all stations.

The results indicate a significant warming trend in the mean annual Sri Lankan temperature. There is a warming trend of 0.54 and 0.68 ^{o}C/100 years for mean annual temperature for the period of 1901-2000 and 1906-2005 respectively (not shown in the paper) and it shows a steeper trend of 1.43 ^{o}C/100 years for the period from 1960-2000. These trends proved to be statistically significant at high confidence levels (exceeding 99%) where the data quality had not been identified as suspect. These trends are significantly steeper than the globally averaged warming trend of 0.6 and 0.74 ^{o}C/100 years for 1901-2000 and 1906-2005 (IPCC, 2007).

Sri Lanka has been subject to nearly a 10-fold rise in population from 1870 to 2005, a decline in forest cover by more than half and several large scale transbasin irrigation schemes. All of these changes shall affect the estimates of climate change particularly if the localities of the observatories are directly affected. The evidence suggests that the impact of all of this on climate change estimates for the period from 1960-2000 was modest. Stations that were in the more rapidly urbanizing regions had climate change trends that were within 5% of the stations that were least rapidly urbanizing.

The regional variation of mean temperature for Sri Lanka from 1960 to 2000 shows that the warming trend ranges from 1.5 to 2.6 ºC/100 years. The warming in the South-West is the least and the warming in the North-West and South-East is the greatest. There are important seasonal variations in the warming trends with the warming in the boreal winter months up to twice as high as that during the summer months. There are some “bulls eyes” in this map in Anurhadhupura and Badulla (showing high values). These could be due to undetected in-homogeneities. Some caution is due in interpreting the detailed regional variations.

6. Discussion

The work here has provided a case study of the utility of quality assessment procedures in a tropical setting. The majority of data for these 15 stations for the 136 year record are of high quality save for the first decades. This work has led to the identification of transcription errors, site changes and calibration errors.

These errors are particularly important in the case of climate change assessments. For example, in the case of Jaffna and Mannar, the underestimates in measurements since 1984 led to erroneous estimates of climate change prior to the quality control procedures. In the case of Kandy, with stations being moved in 1920 and 1953, a century long estimate of trend shall be erroneous (near zero instead of +0.0055 ºC/year).

The quality control procedures that were implemented combining objective methods with detailed station records were quite time consuming. Nonetheless, this work shows that it must be undertaken for reliable assessments of climate change particularly at the fine spatial and temporal scales that are needed for adaptation policy and risk management.

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References

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahim F, Tagipour A, Kumar Kolli R, Revadekar JV, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez Aguirre JL. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research-Atmospheres* 111: D05109, DOI:10.1029/2005JD006290.

Bamford, A. J., 1936. On the Exposure of Thermometers in Ceylon. *Ceylon Journal of Science E*, I : 153-168

Chandrapala, L, 1996, Long-term trends of rainfall and temperature in Sri Lanka, In Ed. YP. Abrol, S. Gadgil, GB. Pant, Climate Variability and Agriculture, Narosa Publishing House, New Delhi, p153-162.

Domroes, M., 1996, Rainfall variability over Sri Lanka, In Ed. YP. Abrol, S. Gadgil, GB. Pant, Climate Variability and Agriculture, Narosa Publishing House, New Delhi, p163-179.

Department of Census and Statistics, 2007, Statistical Abstract of Sri Lanka, Department of Census and Statistics, Colombo.

Easterling, DR. and TC. Peterson. 1995. A new method for detecting undocumented discontinuities in climatological time series. *International Journal of Climatology*. 15: 369-377

Easterling, DR., TC. Peterson and TR. Karl. 1996. On the Development and Use of Homogenized Climate Datasets. *Journal of Climate*, 9 : 1429-1434

Eischeid, JK., CB Baker and TR. Karl, HF. Diaz. 1995. The Quality Control of Long-Term Climatological data Using Objective data analysis. *Journal of Applied Meteorology*, 34 : 2787-2795.

Emmanuel R, Johansson E (2006) Influence of urban morphology and sea breeze on hot humid microclimate: the case of Colombo, Sri Lanka. Clim Res 30:189–200

Jameson, H., 1936. Note on the Exposure of Thermometers in Ceylon. *Ceylon Journal of Science E*, II : 61-67

IPCC, 2007: *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, eds.: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Johansson EJ, Emmanuel R, (2006) The influence of urban design on the outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka. Int J Biometeorol 51(2): 119–133, doi: 10.3354/cr00694

Legates, DR. and CJ. Willmott. 1990. Mean Seasonal and Spatial Variability in Global Surface Air Temperature, *Theoretical and Applied Climatology*, 41: 11-21.

Lim, Y.-K., M. Cai, E. Kalnay, and L. Zhou, 2005: Observational evidence of sensitivity of surface climate changes to land types and urbanization. Geophys. Res. Lett., 32, L22712, doi:10.1029/2005GL024267.

Peterson, TC. and RS. Vose, 1997: An overview of the Global Historical Climatology Network temperature data base, *Bulletin of the American Meteorological Society*, 78, 2837-2849.

Peterson TC, Vose R, Schmoyer R, Razuvaev V. 1998. Global Historical Climatology Network (GHCN) quality control of monthly temperature data. International Journal of Climatology 18: 1169-1179. Links

Peterson, TC. and DR. Easterling. 1994. Creation of homogeneous composite climatological reference series. *International Journal of Climatology*. 14 : 671-679

Peterson, TC., DR. Easterling, TR. Karl, P. Groisman, N. Nicholls, N. Plummer, S. Torok, I. Auer, R. Boehm, D. Gullett, L. Vincent, R. Heino, H. Tuomenvirta, O. Mestre, T. Szentimrey, J. Salinger, E. J. Førland, I. Hanssen-Bauer, H. Alexandersson, P. Jones, D. Parker, 1998, Homogeneity adjustments of in-situ atmospheric climate data: a review, *International Journal of Climatology*, 18 (13), 1493-1517

Peterson, T. C., Taylor, M.A., Demeritte, R., Duncombe, D.L., Burton, S., Thompson, F., Porter, A., Mercedes, M., Villegas, E., Fils, R.S., Tank, A.K., Martis, A., Warner, R., Joyette, A., Mills, W., Alexander, L., and Gleason, B., 2002: 'Recent Changes in Climate Extremes in the Caribbean Region'. *Journal of Geophysical Research,* 107(D21): 4601.

Rhoades, DA. and MJ. Salinger. 1993. Adjustment of temperature and rainfall records for site changes. *International Journal of Climatology*. 13: 899-913

Rupa Kumar, K and Patil, SD., Long-term variations of rainfall and surface air temperature over Sri Lanka, In Ed. YP. Abrol, S. Gadgil, and GB. Pant, Climate Variability and Agriculture, Narosa Publishing House, New Delhi, p. 135-152.

Wigley, TML. and Jones, PD. 1981, 'Detecting CO2 induced climate change', *Nature*, 292, 205.

Santer, BD., TML. Wigley, JS. Boyle, DJ. Gaffen, JJ. Hnilo, D. Nychka, DE. Parker and KE. Taylor, March 2000, Statistical Significance of trends and trend differences in layer-average atmospheric temperature time series, *Journal of Geophysical Research*, 105 (D6): 7337-7356.

Vose RS, Schmoyer RL, Steurer PM, Peterson TC, Heim R, Karl TR, Eischeid J. 1992. The Global Historical Climatology Network: long-term monthly temperature, precipitation, sea level pressure, and station pressure data. ORNL/CDIAC-53, NDP-041. (Available from CDIAC, Oak Ridge National Laboratory).

Wang, X. L., Q. H. Wen, and Y. Wu, 2007: Penalized maximal t test for detecting undocumented mean change in climate data series. J. Appl. Meteor. Climatol., 46 (No. 6), 916-931. DOI:10.1175/JAM2504.1

Wang, X. L., 2008: Accounting for autocorrelation in detecting mean-shifts in climate data series using the penalized maximal t or F test. J. Appl. Meteor. Climatol., 47 (9): 2423-2444. DOI: 10.1175/2008JAMC1741.1.

World Meteorological Organization, 1983, Guide to Meteorological Instruments and Methods of Observation, Fifth Edition, Publication Number 8, Geneva: Secretariat of the World Meteorological Organization.

Zubair, L. 2002, Development of Meteorology in Sri Lanka, *Journal of the Institution of Engineers*, Sri Lanka. 15(2):14-18.

Zubair, L. 2003, Saving Weather Data, *TIEMPO*, University of East Anglia, 49:16-22..

Zubair, L. 2004, *Weather and Climate of Sri Lanka and Impacts and Adaptation: A Reference Guide*, Natural Resources Management Services, Kandy, Sri Lanka ISBN 955-8968-00-5, 117 pages.