Surface Temperature Trends from Homogenised Time Series in South Africa: 1931 – 2015

(Running head: Temperature Trends in South Africa: 1931 – 2015)

Andries C. Kruger[1, 2] and M. Nxumalo[1]

[1]*Climate Service, South African Weather Service, Pretoria, South Africa*

[2]*Dept. Geography, Geoinformatics and Meteorology, Faculty of Natural and Agricultural Sciences, University of Pretoria, South Africa*

Abstract

Previous assessments of historical trends of measured surface temperature in South Africa have all shown a general upward trend, in both mean and extreme values, over recent decades. In addition, some regional differences in trends have been identified. Most of these studies focused on the period from about 1961 up to the last year that could be included before publication, as only climate stations situated in the same position for the entire analysis period were analysed. A data homogenisation procedure enabled the combination of time series of stations from which trend analysis could be applied, extending the common analysis period for this study back to around 1931. The trend results, based on the WMO ETCCDI indices, continue to show the general warming trend shown in previous analyses, with a general increase in extreme warm events, and a general decrease in extreme cold events across South Africa. The analysis of seasonal trends show that, while there are noteworthy differences on a regional basis, austral summer shows on average the strongest warming, followed by autumn, winter and spring. The central interior, which exhibited significant cooling in previous analyses, now shows non-significant or similar trends when compared to the other parts of South Africa. There is no countrywide acceleration in the warming trends, but some regional consistencies in the temporal changes in trends could be determined, i.e. increases in trends in the central interior and decreases in trends along most of the coastal region.

Key words: temperature trends; extreme temperature events; South Africa; homogenised time series

* Corresponding author: Private Bag X097, Pretoria, South Africa 0001, Andries.Kruger@weathersa.co.za, +27 (0)12 367 6074

1. Introduction

Previous studies of historical trends in measured surface temperatures over South Africa (e.g. Kruger and Shongwe, 2004; Kruger and Sekele, 2012; MacKellar *et al*., 2014; New *et al*., 2006) showed results which were in general consistent with global historical trends, i.e. a general warming over the last number of decades (Trenberth *et al*., 2007; Donat *et al*., 2013). Also observed were differences in the trends on a regional basis, with the western and eastern parts of the country exhibiting stronger warming trends than the central parts. Historical temperature trend studies were mostly confined to the period from 1961 to the last year that could be included before submission for publication, except where long-term gridded data sets were used (e.g. Jury, 2013). The selection of the start date of around 1960/61 was mainly done to include an adequate number of stations from which a general countrywide trend could be deduced, but only using those stations that did not change position, to ensure homogeneity of the time series.

To define temperature variability to a reasonable degree, Vose and Menne (2004) and Jones and Trewin (2002) recommend a station network density of 100 – 200 stations over the similar-sized United States (9,826,675 km^2) and Australia (7,692,024 km^2) respectively. Equating these recommendations to South Africa, with a surface area of 1,221,037 km^2, a network of approximately 20 stations would be needed to provide an adequate idea of the countrywide variability of the historical climate. However, South Africa exhibits a relatively complex climate in comparison to its surface area (e.g. Kruger, 2008) , and therefore one can argue that more than 20 stations are required.

Homogenisation of climate time series allows for the detection of variability in the time series which could be due to non-climatic factors. These can include non-documented changes in the exposure of the instrumentation, changes of the actual instrumentation (Quale *et al*., 1991), changes in the location of the climate station, systematic errors in the data due to e.g. instruments which are not properly calibrated, and historical errors due to incorrect measurement procedures. The latter include for example cases of measurements consistently not done at the prescribed time, parallax errors or incorrect resetting of the maximum or minimum thermometers (Trewin, 2010). In addition to the above, the homogenisation process allows for the combination of the time series of close-by weather stations through the long-term adjustment in the values of the parts of the time series forthcoming from different locations. As is the case with most meteorological services, it is sometimes inevitable to close stations with long-term records and open stations close-by. The consequence could then be that potentially useful data cannot be used to analyse long-term trends and variability, unless some form of homogenisation can be applied (Peterson *et al*., 1998).

The aim of this study is to update the state of South African trends of daily maximum and minimum temperatures and their extremes. Through proper homogenisation the common time period of the stations utilised in this study could be extended back to 1931, equating to an analysis period of 85 years to 2015. Due to the low-frequency variability of the climate, and the differences in trends detected spatially and temporally from previous research, this longer analysis period should produce results which are more robust than those based on the much shorter time series, such as in the latest studies on historical temperature trends in South Africa, by e.g. Kruger and Sekele (2012) and McKellar *et al.* (2014).

2. Data

The preparation for the development of homogenised data sets could be divided into two main activities. Firstly, the available temperature series, whether from a single station, or consisting of combinations of the data of more than one station, were identified. This would ensure that the maximum number of potential data series is considered, as the aim is to assess historical temperature trends for as far back and for as many time series as possible. The combined time series were produced from station time series which were close-by, i.e. at almost the same location or in the vicinity of the same town. In most cases there were no overlapping periods of station records, but for the small number of cases where it existed the data of the most recent time series were used.

The period for which the maximum number of time series could be identified to cover a sufficient spatial density over South Africa, i.e. to include more than 20 stations or combinations of stations well spread out over the country, has been established to be from 1931 to 2015. However, after the quality control and homogenisation processes, not all the time series go that far back, with an eventual cut-off year of 1950 selected. All the data were extracted from the climate database of the South African Weather Service.

After the initial selection of time series, the data sets were thoroughly quality controlled before homogenisation, to ensure that erroneous data values do not unduly influence the results of the homogenisation process. Here the quality control process was largely based on a range of tests developed by various authors and summarized by Trewin (2012) in the development of the Australian Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT) data set (Trewin, 2013). From an initial number of 36 stations identified, a total of 27 stations remained after the removal of probably erroneous data values identified by the quality control tests, as well as where the homogenisation process could not satisfactorily resolve periods of improbable climate shown by the original data (see Section 3 for details of station removal). The list of the stations is presented in Table I, with the numbers of combined time series and detected inhomogeneities indicated. The start year indicates the year from which at least 90% of data is available in individual years up to 2015. The height of the station indicates the range of heights from the different locations throughout the time period. The approximate locations of the stations are shown in the map in Figure 1.

3. Methodology

3.1 Quality control of data

After identification of potential stations for long-term trend analysis, the relevant time series were quality controlled. As mentioned in the previous data section, these were based on a range of tests developed by various authors and summarized by Trewin (2012). A distinction was made between short-term issues, which affect the data over a fixed relatively short term e.g. an observer error, and inhomogeneities that typically influence the climate record over the longer-term, e.g. change in exposure. In the quality control of data, two types of error can occur, and this is of specific importance to the short-term data issues: 1. Accepting a value which is incorrect and 2. Rejecting a value that is correct. The latter can have serious implications for extreme value analysis and should be minimised as much as possible. In summary, the quality control procedures of the data checked for the following:

- Internal consistency of daily maximum and minimum temperatures
- Internal consistency between hourly, and maximum and minimum temperature data
- Spatial check of monthly means
- Range checks

It was mainly the older data before the 1960's that had quality issues. Most of these issues were related to values that cannot be regarded as being within the range expected from the climate in which the stations are located. This can be attributed to thermometers that were either not properly calibrated, or measurements that did not follow the correct procedures, possibly due to lack of training of the relevant observers. Other problems included the repetition of values over unlikely long periods of time, which can possibly be attributed to observers not correctly resetting the thermometers. The consequence of the large amounts of older data not being correct or deemed to be unreliable was that the number of stations which were subsequently tested for homogeneity were decreased from 36 to 30. The six stations removed had more than 10% of the years before 1950 with less than 10% of data deemed to be correct, the criteria which were arbitrarily chosen as the limit of the number of gaps that can be accepted.

Corrections to the actual data values were in excess of 6000 values, which were either corrected from the original climate returns or removed in those cases where the values were implausible and the same on the returns.

3.2 Homogenisation of time series

The investigation of data homogeneity forms one of the key fundamental factors in data analysis before any statistical technique is applied (e.g. Trewin, 2012; 2013). This is because climate data series usually contain artificial shifts due to inevitable changes in aspects such as observing site, instruments, observer, station relocation, environment, observing practices/procedures, time, and automation i.e. changing manual to automatic stations during the period of data collection (Wang *et al*., 2010; Aguilar *et al.*, 2013).

Data homogenization is done in climate data sets in order to identify and adjust non-climatic variations which could result from the changes mentioned above (Aguilar *et al*. 2013). It is vital to identify and adjust these artificial changepoints because they could introduce significant biases in the results of climate trends, variability and extreme analysis (Wang *et al*., 2010).

Various homogenization methods have been developed (e.g. Alexanderson, 1986; Wang, 2003, 2008a, b; Wang *et al*., 2007; Vincent, 2012; Reeves *et al*., 2007), each with their own strengths and weaknesses. The performance of the homogenisation method often depends on the types and magnitude of the inhomogeneity to be detected and adjusted for. Due to the many methods developed, and the fact that it is not possible to know beforehand all the types of inhomogeneities that might be embedded in a particular climate time series, it is difficult to make an a priori decision on the most appropriate method to apply.

The World Meteorological Organization Expert Team on Climate Change Detection and Indices (WMO ETCCDI) developed a software package referred to as the RHtestsV4 which includes the provision of Quantile Matching (QM) adjustments, mean-adjustments, choice of using the whole or part of segments before and after mean-shift to estimate QM-adjustments, choice of the segment to which the base series is to be adjusted (base segment), choices of the nominal level of confidence at which to conduct the test, and the availability of a graphical user interface (GUI). This software can detect, and adjust for, multiple changepoints that could exist in data series that may have first order autoregressive errors. It is based on the penalized maximal *t*-test and the penalized maximal *F*-test which are embedded in a recursive testing algorithm with the lag-1 autocorrelation of the time series being empirically accounted for (Wand 2008a, b; Wang et al., 2007; Wang and Feng, 2013). Because the RHTestsV4 software was developed under the auspices of the WMO ETCCDI, and its compatibility to the ETCCDI RClimDex software for calculating climate extreme indices, it was preferentially considered to use in this research.

As a departure point, the track record of the RHTests4 method was investigated to obtain an impression of the performance of the homogenisation method compared to others, as well as possible shortcomings. Versions of the RHTest method has been used in many places with success (e.g. Ashcroft *et al*., 2013; Cornes *et al*., 2012; Vincent *et al*., 2012). Compared to other homogenisation methods, Reeves *et al*. (2007) indicated that the penalised maximal F-test compared favourably. However, Venema *et al*. (2012) found that the RHTestsV3 performed the worst if compared to other tests, particularly without the use of a reference series. Here it should be noted that homogenisation methods which rely on reference series should in most cases perform better than those without reference series. However, in many cases, especially in developing and/or sparsely populated countries, long term climate stations are most often very far apart, which makes the identification or construction of appropriate reference series difficult if not impossible.

As it is impossible for any homogenisation method to detect all possible inhomogeneities in all data sets, it is imperative that the outputs of the homogenisation process be properly scrutinised for false detections or omissions. Here the consultation of station metadata, if available, is imperative to contribute to an optimal homogenisation process.

Due to the limitations outlined above, the homogenisation process was not approached as an automated process, but all outputs were considered for plausibility, mostly through the interrogation of relevant metadata, but also by revisiting the data to check for any quality issues which might have affected the homogenisation process.

3.2.1. Application of the RHtestsV4 software

The RHtestsV4 software requires daily maximum and minimum temperature data (along with metadata and reference series data if available) in a specific format as inputs. These data sets are then employed by the software according to the selection of the homogenisation procedure. Due to the large distances between most of the climate stations, the homogenisation procedure with monthly mean data as input, without a reference series, was performed on the data sets. The resultant adjustments were then applied to the daily data. Alternative approaches exist, e.g. performing the homogenisation on daily data, but it was found that the consequent outputs produced, in many cases, a much larger number of inhomogeneities than performing homogenisation on monthly data. These proposed inhomogeneities could in many cases be attributed to naturally occurring warm or cold spells manifesting in the daily time series. The dates of the inhomogeneities identified were consequently looked up in the history and metadata files of the particular station, for possible verification.

Not all identified inhomogeneities were supported by the relevant metadata histories, which could be due to the causes of the inhomogeneities not documented. The identification of possible inhomogeneities in some cases revealed problems with the quality of the data sets themselves, so that additional quality control was necessary. For these cases the homogenization procedure was repeated.

In Table I the number of inhomogeneities detected by the RHTestsV4 software are indicated for the daily maximum and daily minimum temperatures. Apparent from the results is the large number of inhomogeneities identified in some of the time series. Also, for some stations discrepancies exist between the number of inhomogeneities identified in their maximum and minimum temperature series. The most probable reason is that the causes of these inhomogeneities affected the daily temperature regime in such a way that only lower or higher temperatures are significantly affected.

It is important to note that in the cases of the larger number of inhomogeneities, e.g. Cape Town International and Cape Columbine, the magnitudes of the inhomogeneities were relatively small and consequently had small effects on the eventual trend analysis. Closer inspection of the inhomogeneities detected in the time series for Cape Town revealed relatively small successive homogeneities alternating between positive and negative, with a consequently negligible effect on the trend analysis before and after homogenisation. A similar pattern of inhomogeneities was also seen in the time series of Cape Columbine. However, for other stations, e.g. Buffelspoort, inhomogeneities in the more recent part of the time series indicate large shifts in the time series that mostly coincide with the implementation of automatic weather stations. Here it should be noted that for some stations these change-overs coincided with a change in location as well, inducing relatively large inhomogeneities in the combined time series.

3.3 Extreme temperature indices

RClimDex is an R-based program that provides an easy-to-use software package for the calculation of indices of climate extremes for monitoring and detecting climate change (Zhang and Yang, 2004). It computes 27 core indices recommended by the WMO ETCCDI team as well as some other temperature and precipitation indices with user defined thresholds (Zhang and Feng, 2004). The base period, from which the percentiles were calculated, was defined as 1981-2010. The periods over which the index trends were calculated are from the start date as indicated in Table I up to 2015. The significance of the linear trends of the indices are evaluated by the *t*-test at the 5% level.

4. Results

4.1 Annual mean temperature trends

Apart from the results for the extreme temperature indices, the RClimDex software also calculates the annual mean maximum and minimum temperatures. From these data sets the annual mean temperatures were calculated, and the least-squares linear trends determined, presented in Figure 2. The overwhelming number of stations (24 out of 27) shows significantly positive trends.

4.2 Seasonal mean temperature trends

Kruger and Shongwe (2004) and McKellar *et al.* (2014) showed that the general warming trend in South Africa varies between seasons in magnitude, with the greatest in autumn and smallest trends in spring. In this study, for most stations austral summer (DJF) shows on average the largest positive deviation from the annual mean trend, i.e. 0.018°C per decade, second is autumn (MAM) with 0.007°C per decade, third winter (JJA) with an average negative deviation of -0.004°C and spring (SON) with on average the lowest trend and average negative deviation of -0.016°C per decade. However, the deviations vary considerably on a regional basis. Figure 3 presents per season, for each climate station, the seasonal ranking in trend as well as the deviation from the annual average trend. In the south-western Cape the strongest warming trend is in summer and the weakest in winter. To the east in the south-western interior the strongest trends are in autumn and the weakest in the winter, as in the south-western Cape. Further eastwards along the coast most stations show the strongest trends in summer and the weakest in autumn or spring. In the central interior the strongest trends are either in summer or autumn, and the weakest trend in winter or spring. Further to the north the strongest trends are mostly in winter, with the weakest trends in autumn or spring, which is almost the opposite than in the other parts of South Africa.

4.3 Extreme temperature trends

The results for the extreme minimum and maximum temperature indices are presented in Appendices A and B respectively. The discussion of the results is divided into cold and warm nights (represented by TN10P and TN90P), cool and hot days (TX10P and TX90P), annual extreme minimum and maximum temperatures (TNn, TNx, TXn and TXx) and cold and warm spells (CSDI and WSDI).

4.3.1 Cold and warm nights

Figure 4 presents the results for trends in cold and warm nights. All stations except one (Calvinia in the south-west Northern Cape province) experienced negative trends in cold nights, with 25 out of 27 stations significantly negative. The strongest negative trends are for stations in Gauteng, as well as Port Elizabeth in the Eastern Cape, although the strong negative trends in the former could be at least partly attributed to urbanisation. For example, the University of Pretoria Experimental Farm station is situated in what used to be the outskirts of the city of Pretoria to the east. Presently the position of the station can be regarded as relatively close to the city centre, as significant development took place up to a distance of at least 15 km eastwards.

Trends in warm nights show the opposite trend than cold nights, but in general with somewhat smaller magnitudes. Where the trend for cold nights is on average a decrease of 1.6 % per decade, the increase of warm nights is on average 1% per decade for all the stations analysed, with 22 stations being significantly positive. Most of the stations with non-significant trends are in the central interior, which also showed weaker warming trends or even cooling in previous studies (Kruger and Sekele, 2012; Mackellar *et al.*, 2014).

4.3.2 Cool and hot days

Figure 5 presents the trends in cool and hot days. There is a general decrease in cool days with all stations, except Vryburg in the North-West province showing a positive trend. A total of 20 of the 27 stations were significantly negative, with strongest decreases in the south-western Cape, Gauteng and the KwaZulu-Natal coast.

Hot days showed a general increase, with the trends of 21 stations significantly positive. The decrease of cool days and increase in warm days is on average almost equal in magnitude at about 0.8 % per decade.

4.3.3 Annual extreme temperatures

Previous studies, e.g. Kruger and Sekele (2012) showed that trends in annual extremes across South Africa do not reflect the general warming, as with the trends in days below and over the 10th and 90th percentiles of minimum and maximum temperatures. The annual extreme events represent isolated individual events on an annual basis, and positive trends will indicate that these individual events became more extreme with time, and vice versa. While it can be argued that the probabilities of extreme hot events will increase with a warming climate, the magnitudes of individual events cannot always be equated to the general warming reflected in the time series. This is especially true for relatively short time series, but longer time series should in general show positive trends. In contrast with Kruger and Sekele (2012), this was indeed found to be the case, with the overwhelming majority of stations reflecting the general warming trend in their trends of annual extreme temperatures.

Figure 6(a) presents the trends in the annual absolute minimum temperatures, indicating the temperature of the coldest night in the year. There is a general increase in values (18 stations are significantly positive), with only Pretoria showing a small negative trend. The strongest positive trends are in Gauteng province and the stations of Cape Town, Port Elizabeth and Musina in the extreme north. These stations all show trends higher than 0.3°C per decade, while the average trend for all stations is 0.2°C per decade.

Figure 6(b) presents the trends in the annual maximum of the daily minimum temperatures, indicating the temperature of the warmest night in the year. As with the annual absolute minimum a general increase in temperatures is shown, at on average the same scale of about 0.2°C per decade. However, only 15 stations are significantly positive. The strongest positive trends are almost in the same locations as the annual absolute minimum, with values higher than 0.3°C per decade.

For the daily maximum temperatures, Figure 6(c) presents the trends in the annual minimum of the daily maximums, i.e. the coolest day of the year. Only 11 stations were significantly positive, with the average trend about 0.1°C per decade. The strongest trends are to the west of Pretoria with trends at Buffelspoort and Pretoria PUR about 0.4°C per decade.

The trends in annual absolute maximum temperatures, i.e. the hottest day of the year, are presented in Figure 6(d). The strongest trends are in excess of 0.3°C per decade, and are found in the south-western cape, Northern Cape, KwaZulu-Natal coast and west of Gauteng at Buffelspoort, indicating that the trend magnitudes are not confined to a specific part of South Africa, and show a degree of randomness. However, one can conclude that there is a general tendency of increases in the annual maximum temperatures, as 21 stations showed positive trends with 13 of them significant.

4.3.4 Cold and hot spells

Figure 7(a) presents the trend in cold spells duration, which is defined as the annual number of days with at least 6 consecutive days when the daily minimum temperature is lower than the tenth percentile of daily minimum temperature values from 1981 to 2010. All stations show negative trends in the duration of cold spells, with 23 of the 27 stations statistically significant. This is consistent with the general warming trend shown by the trends of the previous indices. The strongest negative trends are at stations in Pretoria, the Northern Province and Cape Point, all of which show trends lower than -1.5 days per decade, with Pretoria University Experimental Farm a very strong decline of 8 days per decade, probably partly due to urbanisation around the station. The average trend for all stations is a much weaker trend of -1 day per decade.

Figure 7(b) presents the trends in warm spell duration, which is defined as the annual number of days with at least six consecutive days when the daily maximum temperature is higher than the 90th percentile of daily maximum values from 1981 to 2010. Here most stations show a positive trend, in contrast with the trends in cold spells, with 20 of the 27 stations positive and 8 statistically significant. The magnitude of increase is on average weaker than the decrease in cold spell duration, at 0.3 days per decade. Again, some effect of urbanisation might be visible, affecting the duration of cold spells through the moderation of minimum temperatures. The strongest increases in warm spells are found around the northern part of Gauteng and Northern Cape at Upington, which is higher than 1.6 days per decade.

4.4 Diurnal temperature range

Differences in trend magnitudes of minimum and maximum temperatures will be reflected in a trend in the diurnal temperature range, presented in Figure 8. Of the 27 stations 14 showed negative trends (12 statistically significant), and 13 positive trends (10 statistically significant).

Regionally the stations with significantly negative trends, where minimum temperatures rose faster than maximum temperatures, are mostly situated in the eastern and southern parts. The stations with significantly positive trends, where maximum temperatures rose faster than minimum temperatures, are in the western half of the country.

4.5 Temporal consistency of trends

In Kruger and Sekele (2012) the focus of the index analysis was on the period 1962 – 2009. The consistencies of the station trends over longer periods were analyzed for stations which had more data available. It could be shown that for most of these stations the warming trend was accelerating from the 1960's onward. This finding was in agreement with the mean global temperature trend, where increased warming is evident since the latter part of the 20th century, particularly from the mid-1960's (Brohan *et al.*, 2006; Smith and Reynolds, 2005; Hansen *et al.*, 2001; Lugina *et al.*, 2005).

It is argued here that climate trends are only meaningful in the context of climate change if measured over a considerable number of years, preferably 30 years or longer. We investigated how the trends in annual mean temperature changed over the last number of decades, and to compare these trends between stations. The trends over the preceding 30 years from 1980 to 2014 were calculated, i.e. time series of the consecutive linear trends for 1951-1980, 1952-1981, 1953-1982...1975-2014. Figure 9 presents the results of the trend analysis.

The mean trend of the trends is a non-significant -0.01°C.decade^{-1}.decade^{1}. However, some regional tendencies can be observed: The trends are insignificant around the south-western Cape, but negative trends are evident from Cape Agulhas eastwards along the coast. In the interior trends are positive in the south and far north, and negative in the central parts.

Figure 10 presents the mean of the average temperature (average of Tmax and Tmin) trends for the five coastal stations from Cape Agulhas eastwards, from which it can be seen that the mean 30-year trend for these stations reached a peak in 1993, with the trend in the mean temperatures for the 1964-1993 period of almost 0. 3°C per decade. Since then there was a gradual decline in trend to about 0. 1°C per decade for the most recent period of 1975-2015. This decline in trend can also be illustrated through Figure 11, which presents the annual mean temperature for the same stations since 1948, the first year when there was sufficient data for all five stations (75% of years the data was sufficient for all stations). Second-order polynomials were fitted to the time series for the individual stations (Figures 11 (a – e)), as well as the average for all the stations (Figure 11(f)), which indicate that over the period there was no increases in the annual mean temperature trends.

From the above discussion one can conclude that, while there was an acceleration of trend post 1960's to the decades prior to that at a relatively small number of stations (Kruger and Sekele, 2012), there is no evidence of a countrywide acceleration in trends for the period 1951-2015.

5. Summary and conclusions

The results of studies in historical climate trends, particularly those focusing on the instrumental period, are influenced by the period of record available for analysis. This is not only due to temporal changes in the long-term trend, but also because of the longer-term variability of most climate parameters. This analysis endeavored to extend the period of analysis as far back as possible through the homogenisation of relevant temperature time series, while still maintaining the critical spatial density of results to provide a general impression of recent temperature trends in South Africa.

For the extension of the analysis period homogenisation of the data sets was necessary due to the combinations of time series and the possibilities of inhomogeneities occurring due to changes in instrumentation, substantial changes in location and other non-climatic influences on the data sets. Most of the inhomogeneities identified occurred before around the 1960’s. Most of the smaller number of the more recent inhomogeneities can be attributed to the change of instrumentation to automatic weather stations and the changes in locations that had in some instances accompanied the instrument changes. There could be several reasons for changing the locations of the stations, e.g. the proximity to adequate power supplies, or cases where it was not necessary anymore to have the station located close to an observer. Where many inhomogeneities were identified, these were usually of smaller magnitude and accepted as is. However, where the inhomogeneities were larger, this should have been clearly shown by the data and documentation should have existed where the reasons behind the inhomogeneities could be identified. However, there were cases where the homogenisation process provided dubious results, particularly in cases where strong trends were evident in the original data.

The almost doubling of the analysis period compared to recent studies (e.g. Kruger and Sekele, 2012; McKellar *et al.*, 2014) broadly confirms their results. However, differences in some of the details came to the fore. Most importantly, the negative trends in the central interior are not confirmed by the trends over the longer period, although there is an indication that no warming or very weak trends occurred there over the analysis period.

Regional tendencies in the magnitudes of seasonal trends could be identified, while the strongest warming is confirmed to have occurred in autumn for many stations. However, the average seasonal trends show that summer is the season with the strongest warming, not autumn as concluded by Kruger and Shongwe (2004).

The trends in extreme temperatures for South Africa can be summarized as follows:

- In general, the number of days per year with low minimum temperatures have declined, while days with high minimum temperatures have increased. These trends are more pronounced in the larger centers, e.g. Cape Town, Port Elizabeth and Gauteng. Some of the time series of these stations could probably be contaminated by urbanization (also see Hughes and Balling (1996)).
- In general, the number of days per year with low maximum temperatures have declined, while days with high maximum temperatures have increased.
- In the larger centers there is a tendency for the annual absolute minimum temperatures and the annual absolute maximum daily minimum temperatures to increase.
- The annual absolute minimum daily maximum temperatures have increased at most places along the coast and some places in Gauteng, while the absolute maximum temperatures have increased for most places in the western half of the country.
- Significant decreases in cold spell duration are evident for most places in the eastern half of country as well as along the coast.
- Significant increases in warm spell duration are evident over the most of the western and northern interior.
- Increases in the mean diurnal temperature range are evident over the western interior, while decreases are evident over most places in the east and south.

Temporal changes in the warming trend through the analysis period could not be confirmed to be consistent throughout South Africa, with some regions showing an acceleration in trend and others the opposite (e.g. at most of the coastal areas). However, this finding does not imply an abatement of the general warming in some regions.

Some of the results of the trends are quite different for stations close to another, e.g. the three stations in and around Pretoria, implying that other factors other than the variability and change in the climate probably affected some of the results. These can include the effect of urbanisation, which can manifest as stronger trends than surrounding stations where the local area of measurement has changed from almost rural to urban, or a moderation in trends, where a station has always been in an urban setting compared to local changes in the land cover at stations nearby. Also, the efficiency of the homogenisation process can have a big impact on the eventual results, but it should be noted here that where particularly large trends were produced by the homogenised compared to the non-homogenised time series it was, where possible with available metadata, subjectively investigated whether the adjustments due to homogenisation were justified. Nevertheless, the results show that since at least 1931, the instrumental record confirms the impact of general global warming in South Africa, which is in all probability attributable to the anthropogenic influence of the increase in greenhouse gases. Also, it can be deduced from the results which seasons and regions displayed relatively larger trends, both results of which should have a bearing on the validation of climate models and the development of climate change adaptation scenarios.

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Table I. Long-term climate stations suitable for the analysis of temperature trends over the period 1931-2014. The number of station time series combined are shown in brackets after the station name.

Station	**No. of Time series**	**No of inhomogeneities**		**Approx. Latitude (°)**	**Approx. Longitude (°)**	**Approx. height (m)**	**Start year (after which 90% years available)**
		Tx	**Tn**				
Cape Agulhas	1	2	0	-34.83	20.02	8	1931
Cape Point	1	0	0	-34.35	18.50	208 – 227	1931
Cape St. Blaize	4	4	3	-34.18	22.15	60 – 76	1931
Cape Town International	5	0	6	-33.98	18.60	42 – 46	1939
Jonkershoek	2	3	2	-33.97	18.93	244 – 350	1936
Port Elizabeth	2	1	1	-33.98	25.60	59 – 60	1937
Langgewens	1	1	2	-33.28	18.70	175	1931
Cape Columbine	1	6	0	-32.83	17.85	63	1936
Beaufort West	7	2	3	-32.35	22.60	857 – 902	1939
Calvinia	2	0	0	-31.48	19.77	975 – 980	1941
Vanwyksvlei	2	4	2	-30.35	21.82	962	1939
Emerald Dale	1	3	3	-29.93	29.95	1189	1931
Cedara	1	0	3	-29.53	30.28	1076	1931
Mount Edgecombe	1	4	0	-29.70	31.05	91	1931
Glen College	2	1	0	-28.95	26.33	1304	1932
Upington	4	0	0	-28.45	21.25	793 – 841	1943
Cape St. Lucia	4	4	2	-28.50	32.40	3 – 107	1947
Vryburg	1	0	0	-26.95	24.63	1234	1931
Zuurbekom	2	1	0	-26.30	27.80	1578	1931
Johannesburg International	4	4	4	-26.13	28.23	1676 – 1695	1946
Buffelspoort	1	1	4	-25.75	27.48	1230	1938
Pretoria Pur	1	0	0	-25.73	28.17	1286	1937
Pretoria	4	2	2	-25.73	28.18	1300 – 1330	1939
Pretoria Univ. Exp. Farm	2	4	5	-25.75	28.27	1372	1931

Bela Bela	1	1	4	-24.90	28.33	1143	1937
Polokwane	5	0	0	-23.87	29.45	1230 – 1311	1939
Musina	2	3	1	-22.27	29.90	525	1933

Table II. List of relevant ETCCDI indices utilized in the assessment.

Index	Description	Units
TX90P	Percentage of days when TX > 90th percentile	%
TX10P	Percentage of days when TX < 10th percentile	%
TXx	Annual maximum value of TX	°C
TXn	Annual minimum value of TX	°C
WSDI	Annual number of days with at least 6 consecutive days when TX > 90th percentile	days
TNx	Annual maximum value of TN	°C
TNn	Annual minimum value of TN	°C
TN90P	Percentage of days when TN > 90th percentile	%
TN10P	Percentage of days when TN < 10th percentile	%
CSDI	Annual number of days with at least 6 consecutive days when TN < 10th percentile	days

APPENDIX A: Trend results for ETCCDI minimum temperature indices in units per decade (* indicates significance at the 5% level)

Station	**TN10P (%)**	**TN90P (%)**	**TNn (°C)**	**TNx (°C)**	**CSDI/Average Cold Spell Duration (days)**
Cape Agulhas	-2.01*	1.26*	0.21*	0.14*	-0.75*/2.69
Cape Point	-2.46*	1.38*	0.21*	0.38*	-2.27*/4.33
Cape St. Blaize	-0.91*	0.86*	0.21*	0.10*	-0.43*/1.48
Cape Town Int.	-2.44*	1.75*	0.39*	0.35*	-0.26*/0.50
Jonkershoek	-0.33	0.15	0.04	0.09	-0.31/1.01
Port Elizabeth	-3.78*	1.86*	0.53*	0.34*	-0.60*/1.42
Langgewens	-1.76*	0.63*	0.19*	0.21*	-0.92*/2.56
Cape Columbine	-0.57*	0.43*	0.07	0.09	-0.21/1.05
Beaufort West	-2.18*	0.97*	0.29*	-0.08	-0.36*/0.73
Calvinia	0.22	0.10	0.01	0.03	-0.12/1.11
Vanwyksvlei	-0.66*	0.30	0.11	0.01	-0.38*/1.47
Emerald Dale	-1.00*	0.58*	0.15	0.12*	-0.05/1.28
Cedara	-1.64*	0.98*	0.23*	0.12*	-0.78*/2.99
Mount Edgecombe	-2.97*	1.63*	0.25*	0.22*	-1.82*/5.16
Glen College	-0.76*	0.35*	0.13	0.02	-1.01*/3.40
Upington	-1.10*	0.30	0.30*	-0.01	-1.13*/4.92
Cape St. Lucia	-1.27*	1.63*	-0.01	0.12*	-0.46*/1.62
Vryburg	-0.42*	0.07	0.07	-0.06	-0.56*/3.03
Zuurbekom	-3.12*	1.24*	0.45*	0.27*	-3.39*/13.60
Johannesburg	-1.86*	2.42*	0.26*	0.41*	-0.64*/2.98
Buffelspoort	-1.78*	0.76*	0.22*	0.12	-1.66*/5.19
Pretoria Pur	-2.52*	0.38*	0.27*	0.17	-3.82*/12.43
Pretoria	-0.89*	0.54*	-0.06	0.10	-0.92*/3.47
Pretoria Univ. Exp. Farm	-4.95*	2.28*	0.46*	0.45*	-8.00*/16.30
Bela Bela	-1.11*	0.81*	0.12*	0.05	-1.06*/4.31
Polokwane	-1.55*	1.10*	0.19*	0.10*	-1.55*/4.35
Musina	-1.96*	0.92*	0.39*	0.21*	-2.72*/4.89
AVERAGE TREND	-1.70	0.95	0.21	0.15	-1.34

APPENDIX B: Trend results for ETCCDI maximum temperature indices in units per decade (* indicates significance at the 5% level)

Station	**TX10P (%)**	**TX90P (%)**	**TXn (°C)**	**TXx (°C)**	**WSDI/Average Warm Spell Duration (days)**
Cape Agulhas	-0.72*	0.47*	0.05	0.14	0.03/0.35
Cape Point	-2.75*	0.63*	0.09*	0.39*	-0.08/0.25
Cape St. Blaize	-1.01*	0.55*	0.17*	0.11	-0.06/0.10
Cape Town Int.	-1.20*	0.51*	0.02	0.23*	-0.03/0.25
Jonkershoek	-1.20*	0.68*	0.16*	0.29*	0.10/0.58
Port Elizabeth	-1.00*	0.43*	0.14*	0.15	0.00/0.00
Langgewens	-1.28*	0.75*	0.18*	0.30*	0.10/1.05
Cape Columbine	-3.06*	0.65*	0.24*	0.16	0.11/0.27
Beaufort West	-0.67*	1.17*	0.14	0.24*	0.44*/0.70
Calvinia	-0.05	0.58*	0.00	0.22*	0.13/1.08
Vanwyksvlei	-0.54*	1.18*	0.06	0.20*	0.86*/2.44
Emerald Dale	-0.09	-0.12	0.05	-0.03	-0.03/0.52
Cedara	-0.07	0.60*	-0.03	0.02	0.04/0.36
Mount Edgecombe	-1.61*	0.73*	0.13*	0.44*	0.03/0.08
Glen College	-0.37*	0.81*	0.18*	-0.05	0.54/4.47
Upington	-0.86*	1.85*	0.13	0.31*	0.61*/1.56
Cape St. Lucia	-1.29*	1.95*	0.14*	0.48*	0.27/0.49
Vryburg	0.16	-0.26	-0.06	-0.04	-1.34*/9.72
Zuurbekom	-0.53*	0.37	0.15	0.17	0.21/2.27
Johannesburg	0.14	-0.02	-0.19	-0.08	0.08/7.00
Buffelspoort	-1.51*	1.92*	0.45*	0.47*	1.34*/3.00
Pretoria Pur	-0.68*	0.02	0.38*	0.00	-0.22/2.46
Pretoria	-1.30*	2.44*	0.08	0.50*	1.83*/4.02
Pretoria Univ. Exp. Farm	-0.70*	1.21*	0.12	0.13	1.01*/3.26
Bela Bela	-0.33	0.40	0.13	0.00	-0.14/4.08
Polokwane	-0.66*	1.46*	0.18	0.16*	0.16*/1.21
Musina	-0.33	0.50*	0.03	0.05	0.11/0.51
AVERAGE TREND	-0.87	0.79	0.12	0.18	0.23

Figure captions

Figure 1. Positions of climate stations with provincial names in italics

Figure 2. Trends in annual mean temperature for the periods from the year presented in Table I to 2015 in °C per decade (filled triangles denote significance of trends at the 5% level).

Figure 3. Deviation of trends in seasonal mean temperature from trends in annual mean temperature for (a) summer, (b) autumn, (c) winter and (d) spring. The first digit indicates the rank of the specific season in comparison with the other seasons in terms of trend magnitude and the next number the deviation from the annual mean trend in °C per decade.

Figure 4. Trends in (a) TN10P, (b) TN90P for the period 1931-2015 in % per decade (filled triangles denote significant trends at the 5% level).

Figure 5. Trends in (a) TX10P, (b) TX90P for the period 1931-2015 in % per decade (filled triangles denote significant trends at the 5% level).

Figure 6. Trends in annual extreme temperatures: (a) TNn, (b) TNx (c) TXn, (d) TXx in °C per decade (filled triangles denote significant trends at the 5% level).

Figure 7. Trends in cold spells and hot spells durations in days per decade: (a) CSDI and (b) WSDI (filled triangles denote significant trends at the 5% level).

Figure 8. Trend in diurnal temperature range (DTR) for the period 1931-2015 in °C per decade (filled triangles denote significant trends at the 5% level).

Figure 9. Trends in consecutive 30 year trends from 1951-80, 1952-81 etc. to 1976-2015 in °C.decade^{-1}.decade^{-1} (* denotes significance of trends at the 5% level).

Figure 10. Mean of linear trend of average temperature (average of Tmax and Tmin) of preceding 30 years for Cape Agulhas, Cape St. Blaize, Port Elizabeth, Mount Edgecombe and Cape St. Lucia in °C per decade for 1980-2015.

Figure 11. Annual mean temperature for (a) Cape Agulhas, (b) Cape St. Blaize, (c) Port Elizabeth, (d) Mount Edgecombe, (e) Cape St. Lucia and (f) the average of stations (a) to (e) in °C (1948-2015). The red lines are the least squares second-order polynomials fitted to the time series.

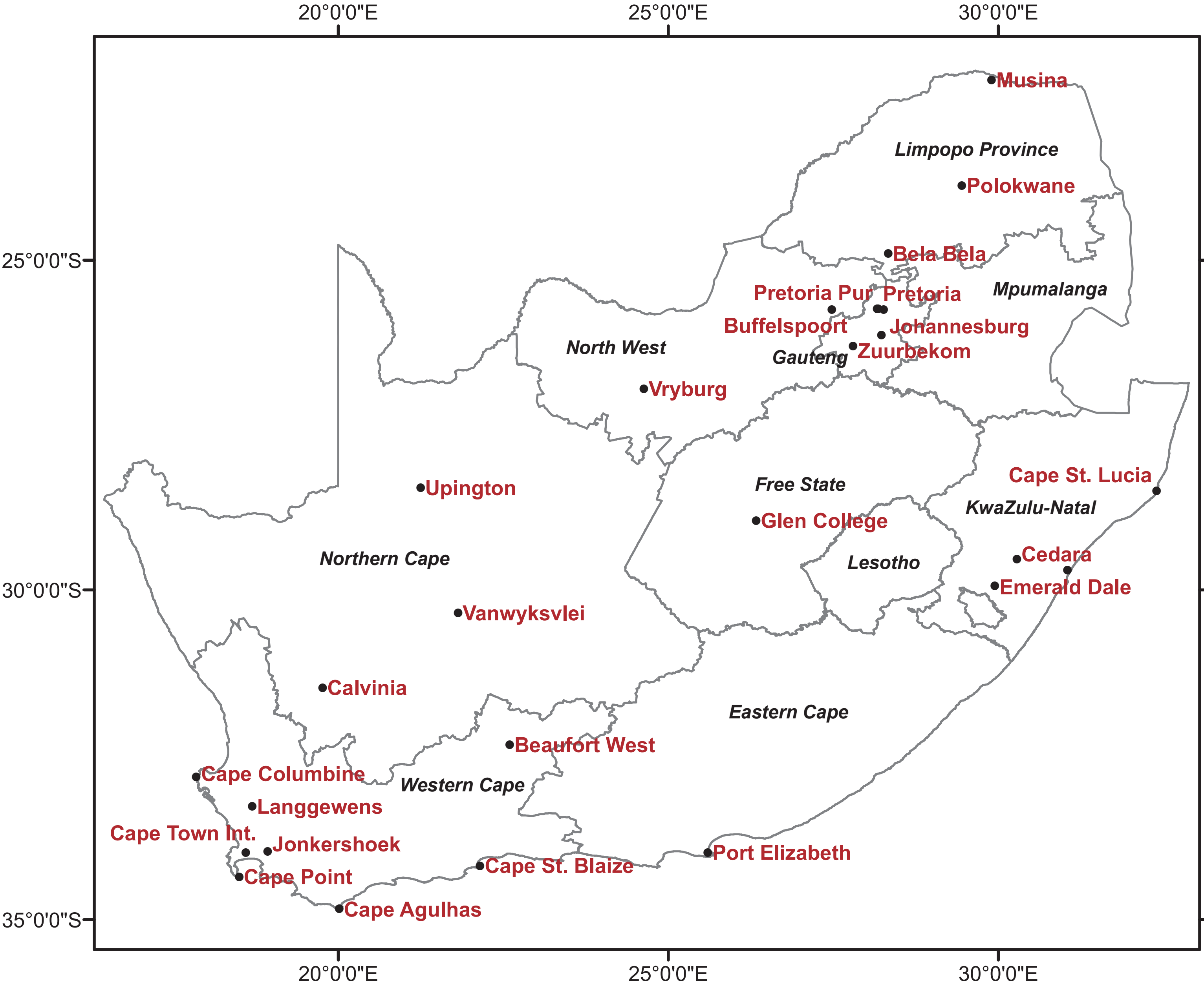
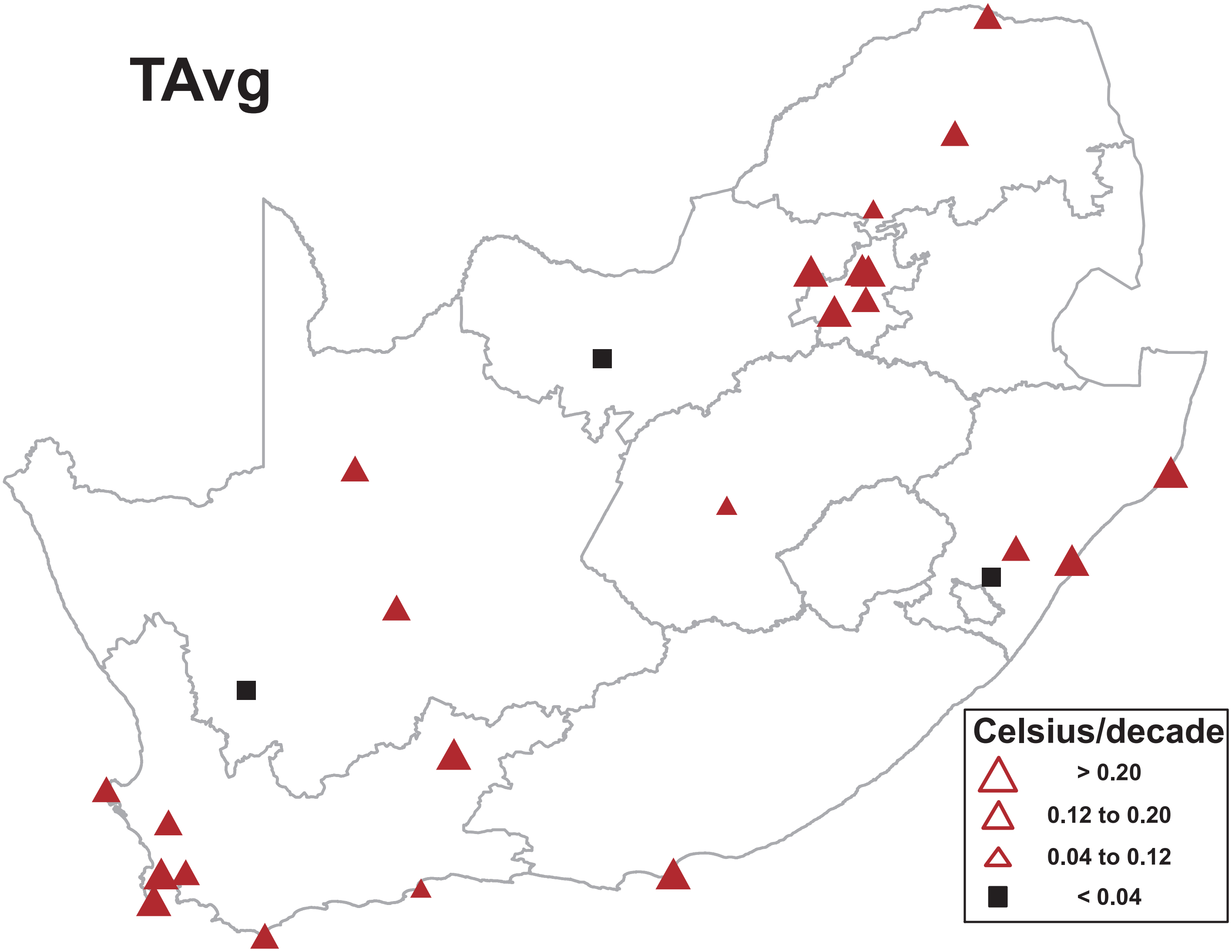


Figure 1. Positions of climate stations with provincial names in italics



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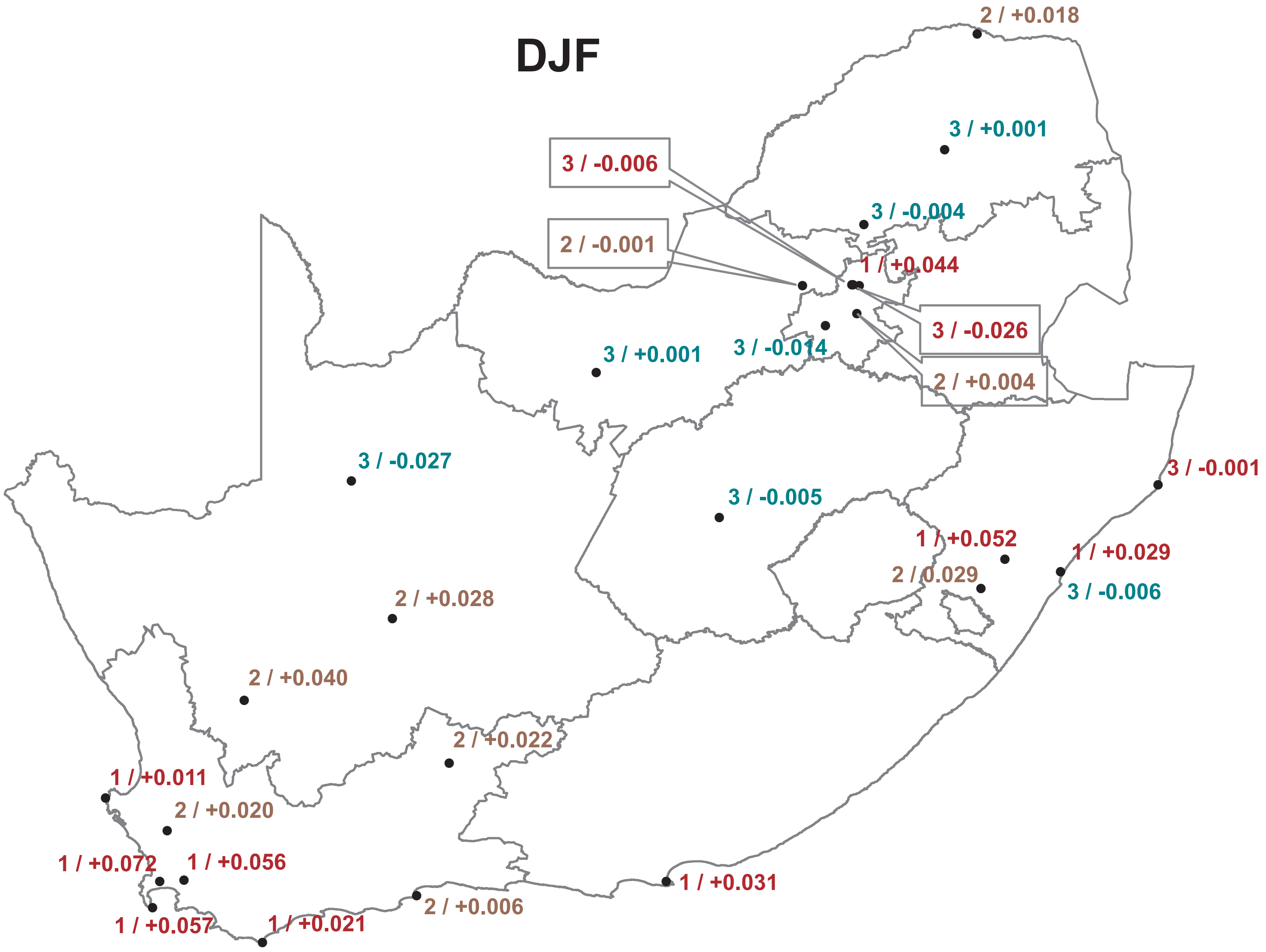


Figure 3(a). Deviation of trends in seasonal mean temperature from trends in annual mean temperature for summer, The first digit indicates the rank of the specific season in comparison with the other seasons in terms of trend magnitude and the next number the deviation from the annual mean trend in °C per decade.

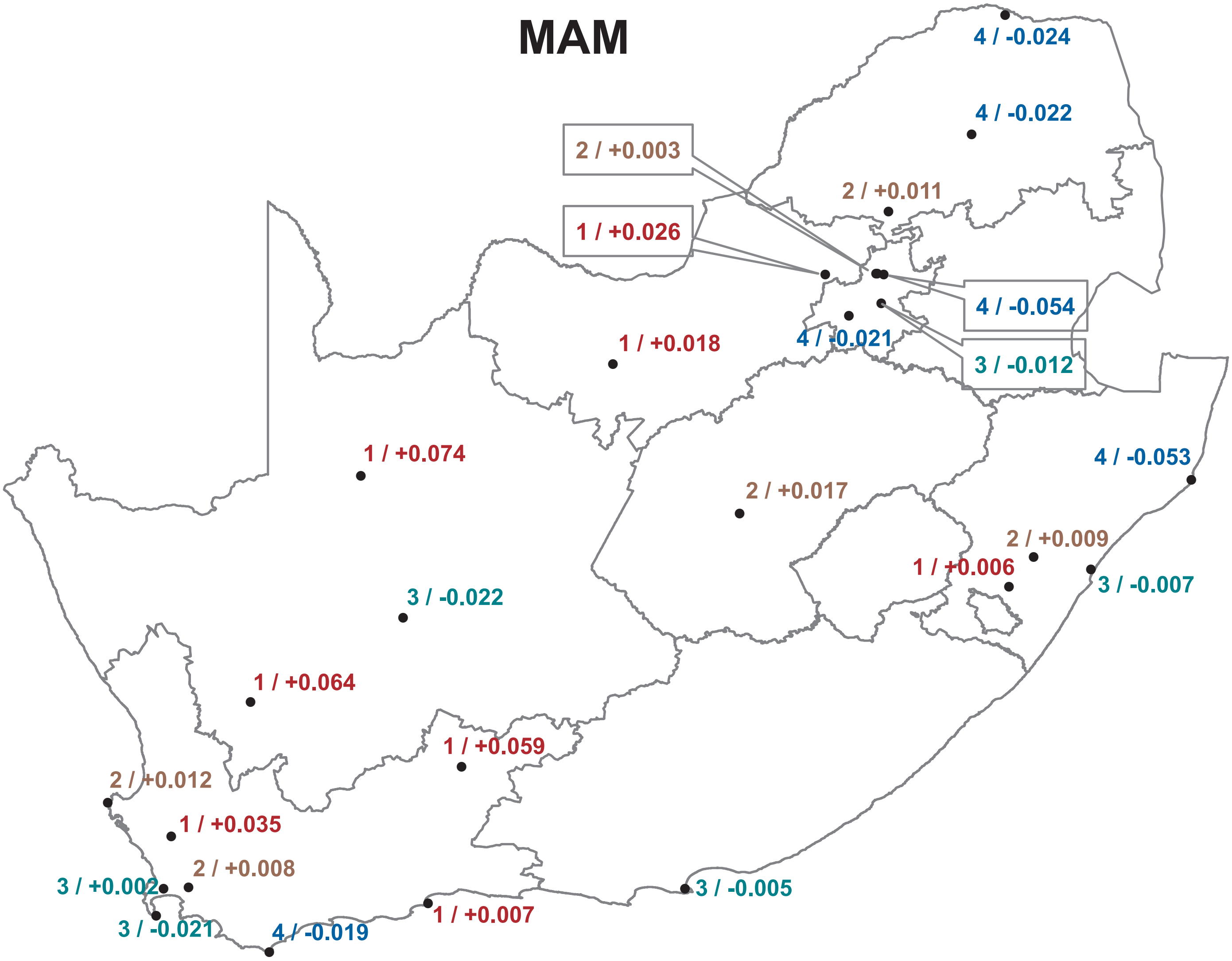


Figure 3(b). Deviation of trends in seasonal mean temperature from trends in annual mean temperature for autumn, The first digit indicates the rank of the specific season in comparison with the other seasons in terms of trend magnitude and the next number the deviation from the annual mean trend in °C per decade.

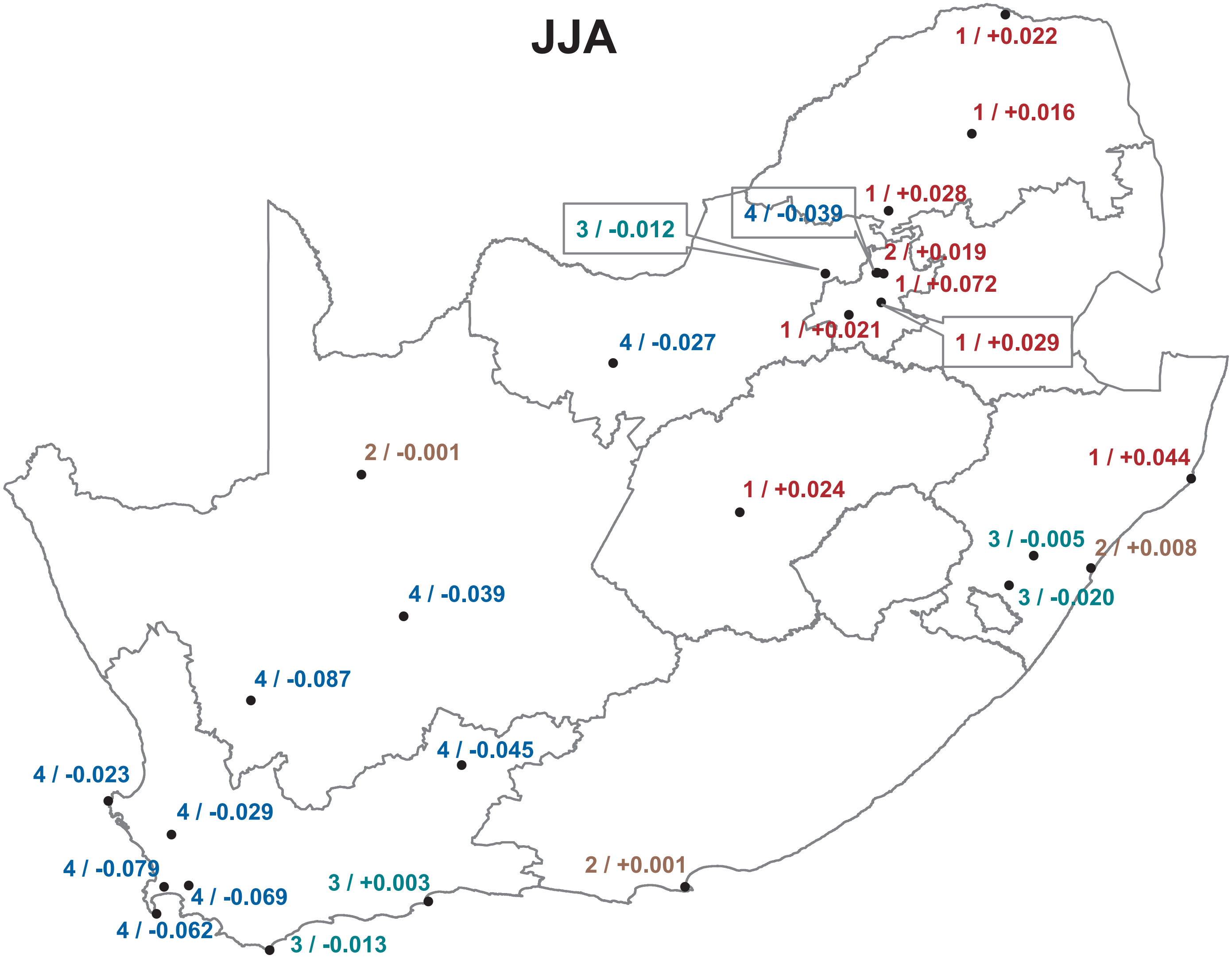


Figure 3(c). Deviation of trends in seasonal mean temperature from trends in annual mean temperature for winter, The first digit indicates the rank of the specific season in comparison with the other seasons in terms of trend magnitude and the next number the deviation from the annual mean trend in °C per decade.

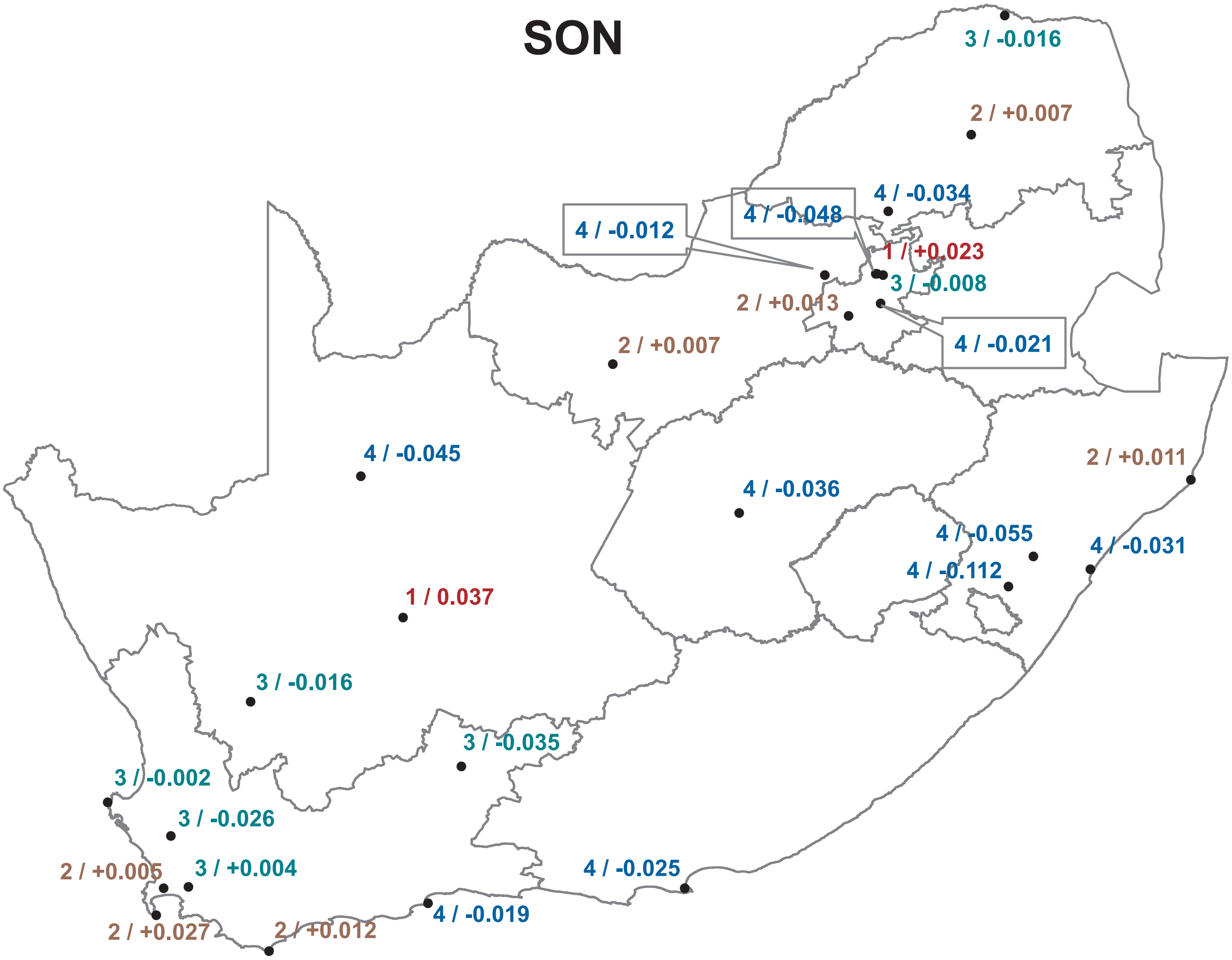


Figure 3(d). Deviation of trends in seasonal mean temperature from trends in annual mean temperature for spring, The first digit indicates the rank of the specific season in comparison with the other seasons in terms of trend magnitude and the next number the deviation from the annual mean trend in °C per decade.

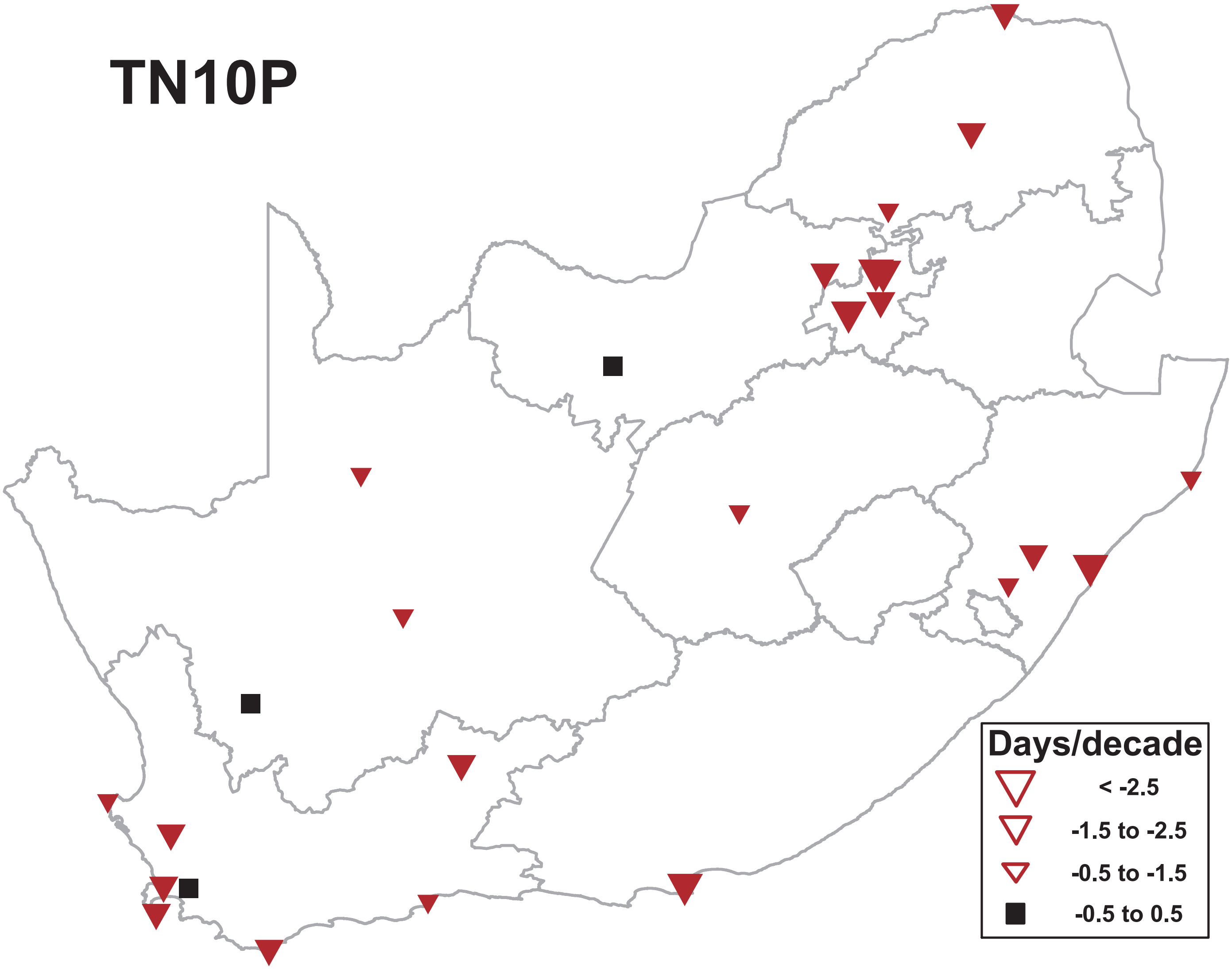


Figure 4 (a). Trends in TN10P for the period 1931-2015 in % per decade (filled triangles denote significant trends at the 5% level).

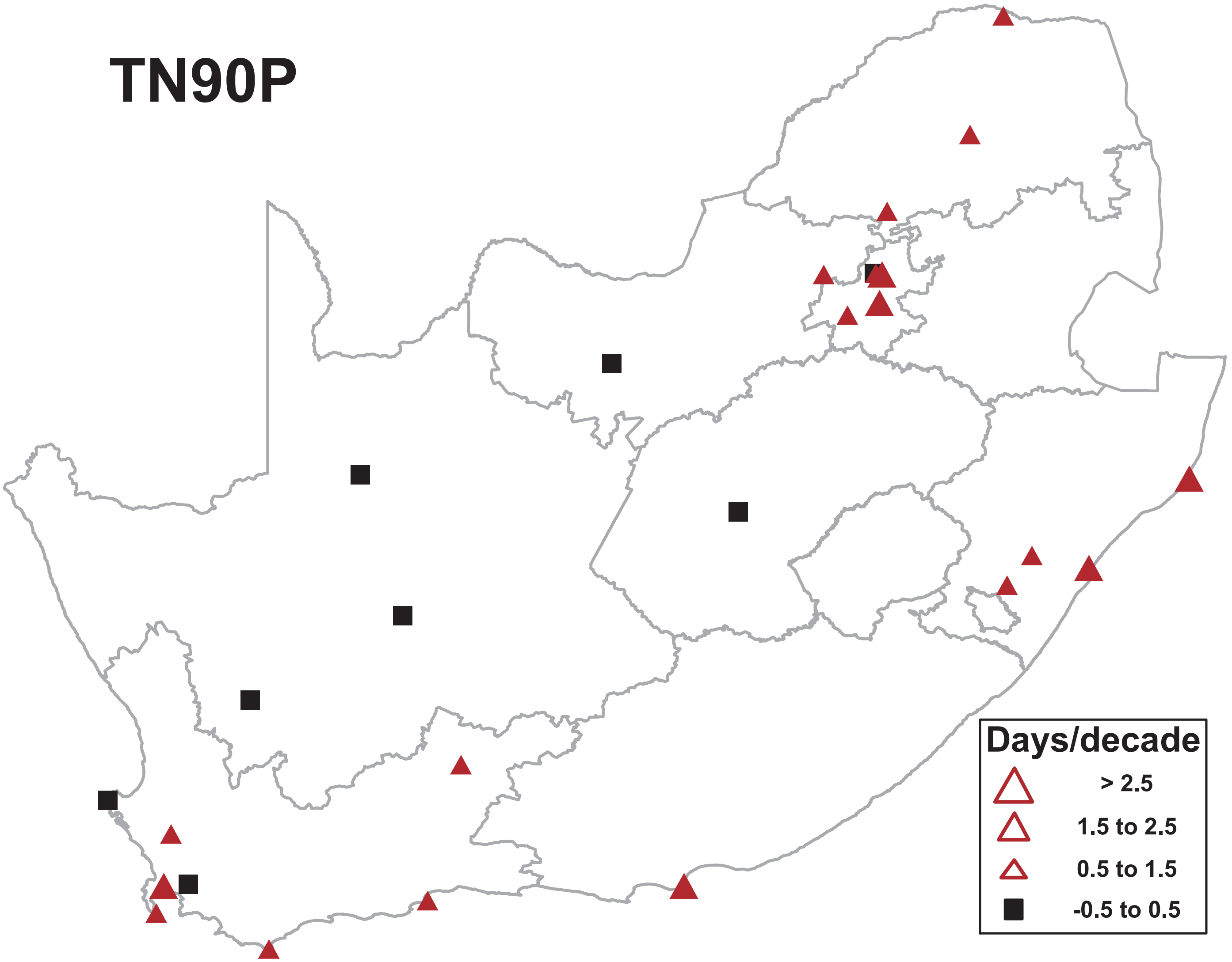


Figure 4 (b). Trends in TN90P for the period 1931-2015 in % per decade (filled triangles denote significant trends at the 5% level).

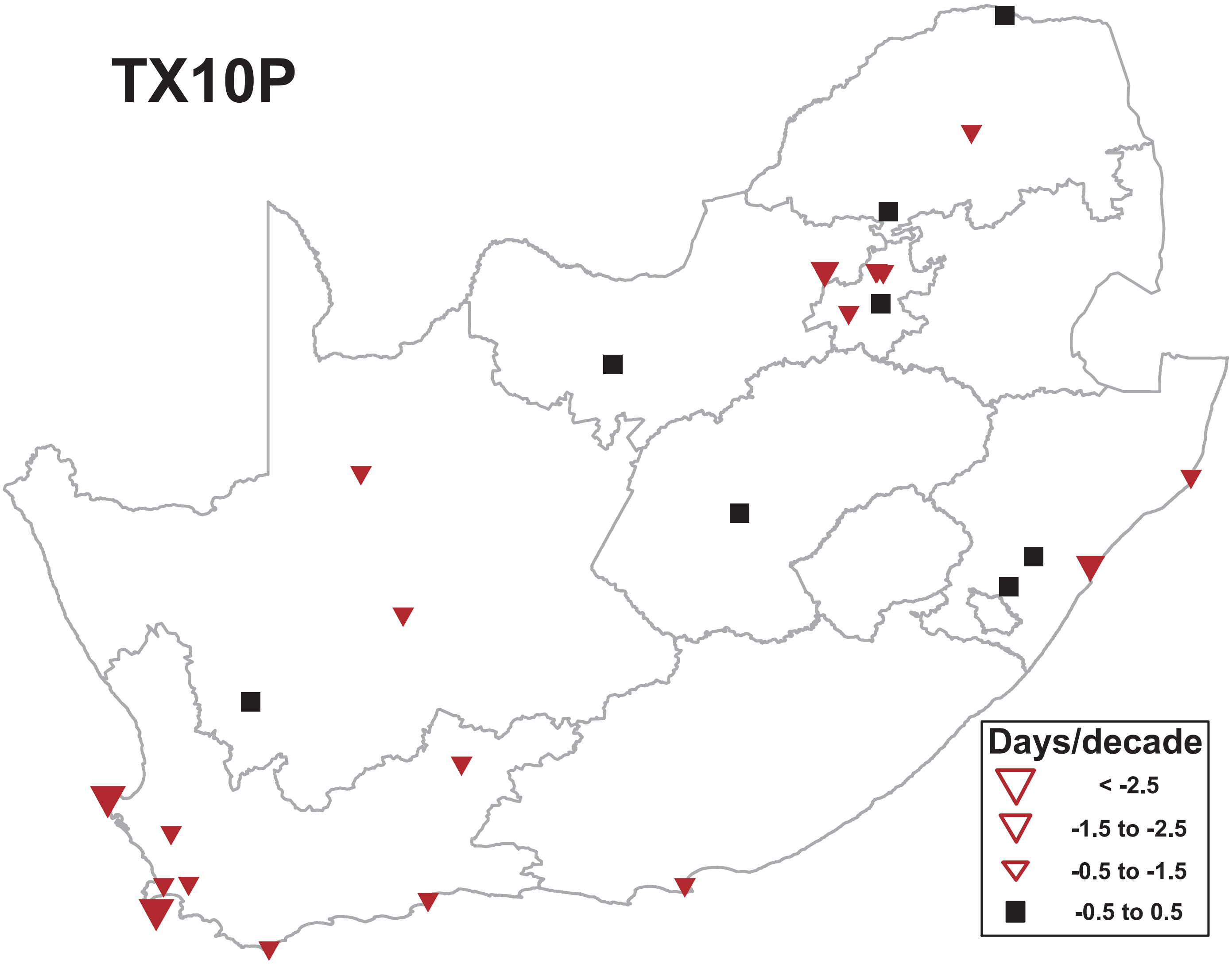


Figure 5(a). Trends in TX10P for the period 1931-2015 in % per decade (filled triangles denote significant trends at the 5% level).

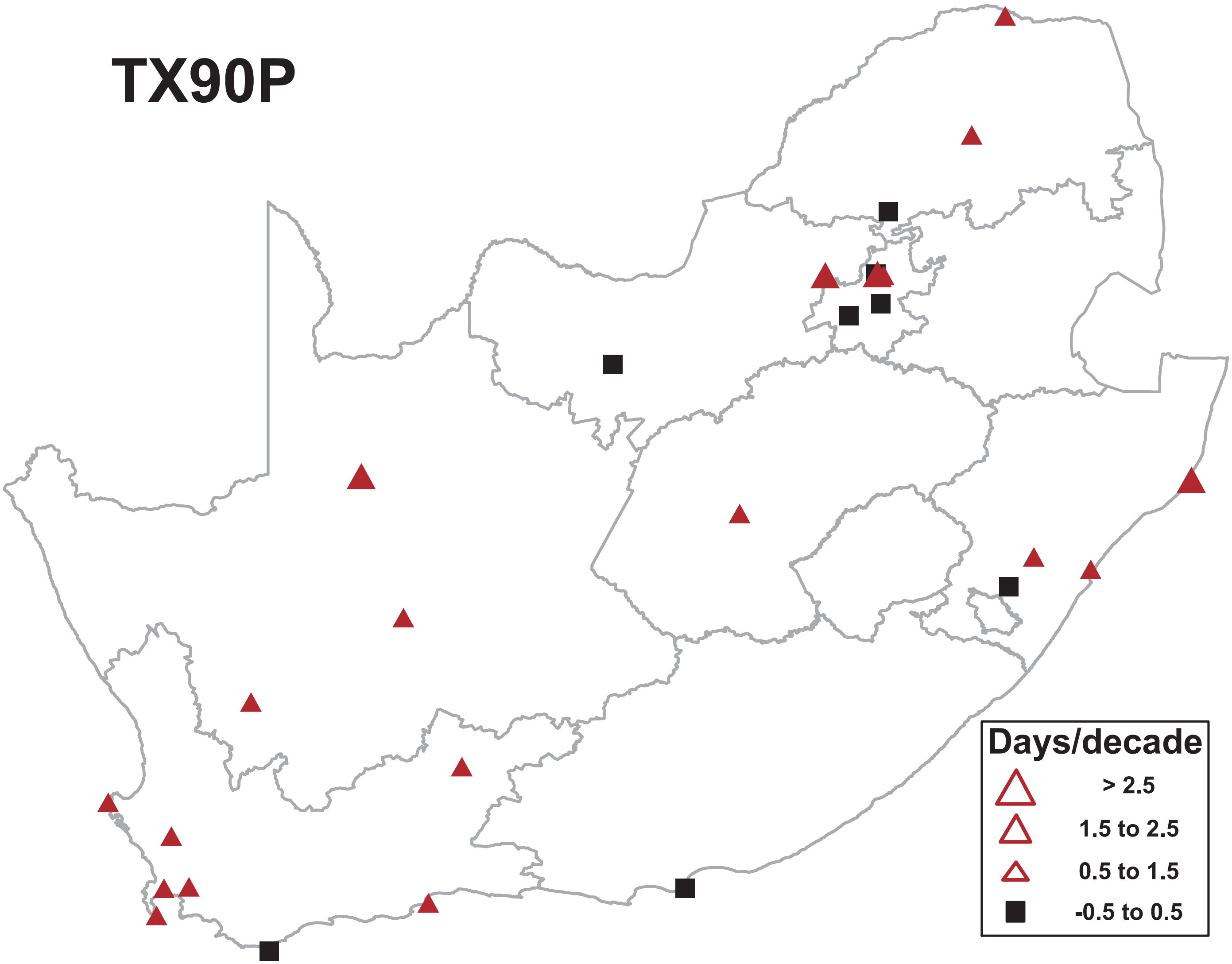


Figure 5(b). Trends in TX90P for the period 1931-2015 in % per decade (filled triangles denote significant trends at the 5% level).

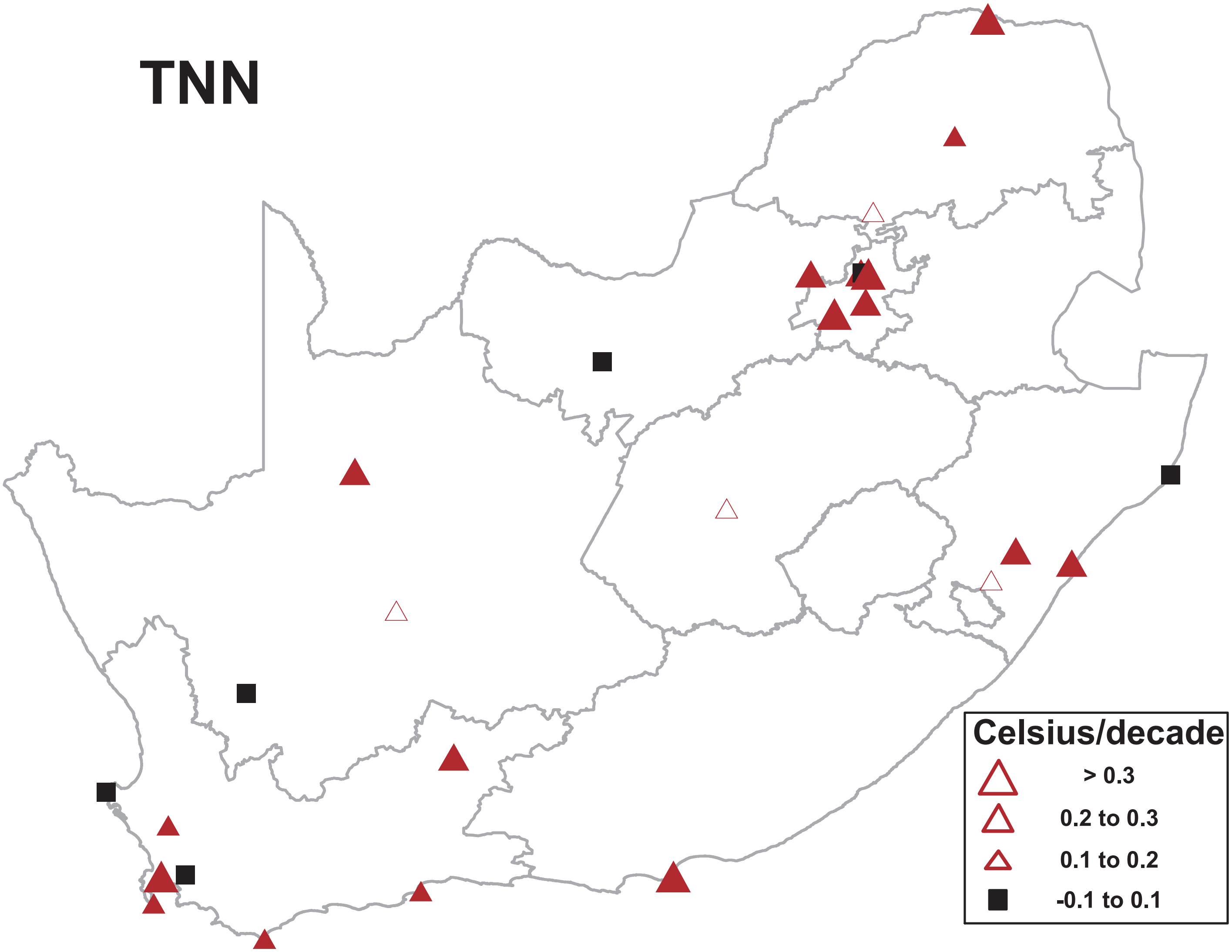


Figure 6 (a). Trends in annual extreme temperatures TNn in °C per decade (filled triangles denote significant trends at the 5% level).

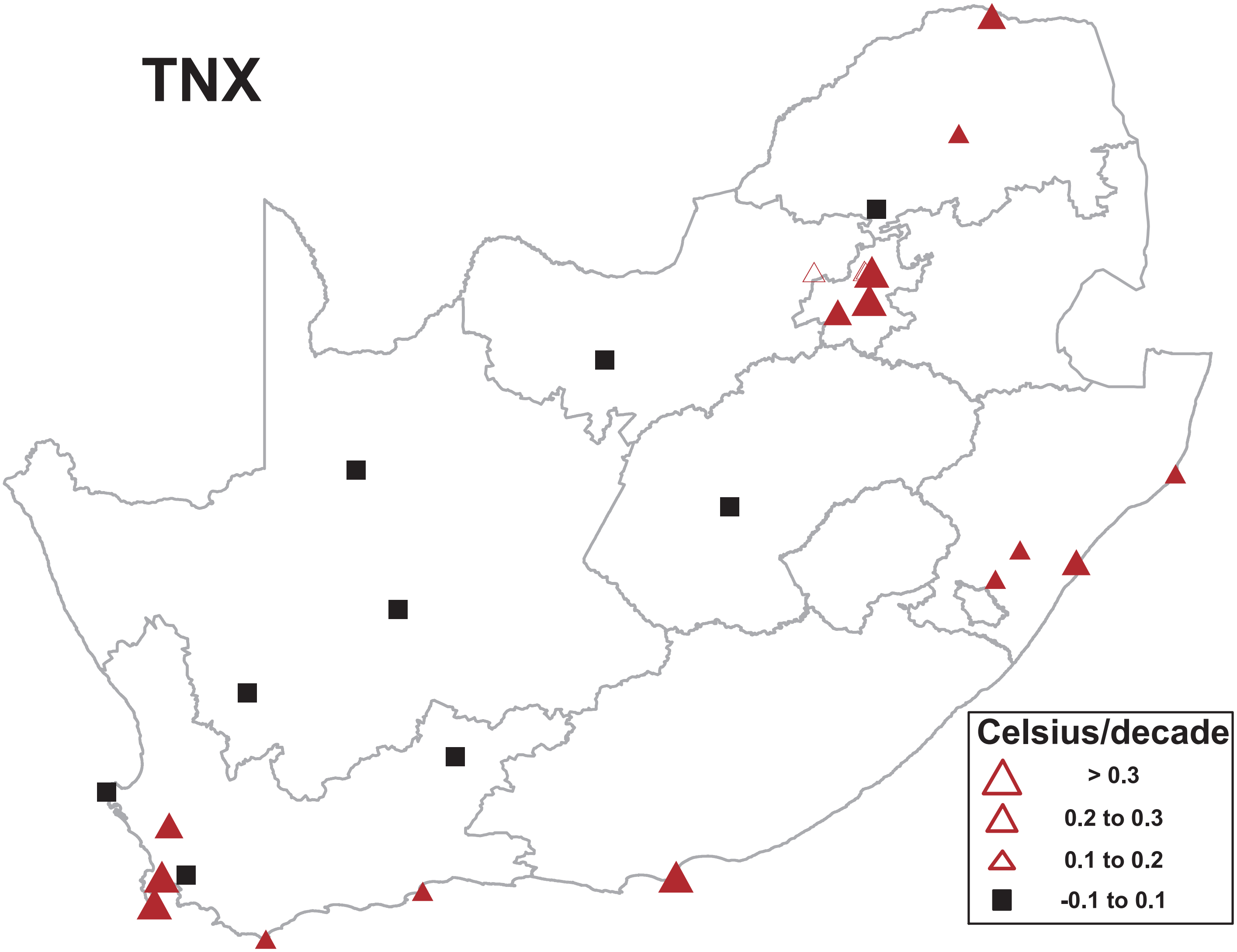


Figure 6 (b). Trends in annual extreme temperatures TNx in °C per decade (filled triangles denote significant trends at the 5% level).

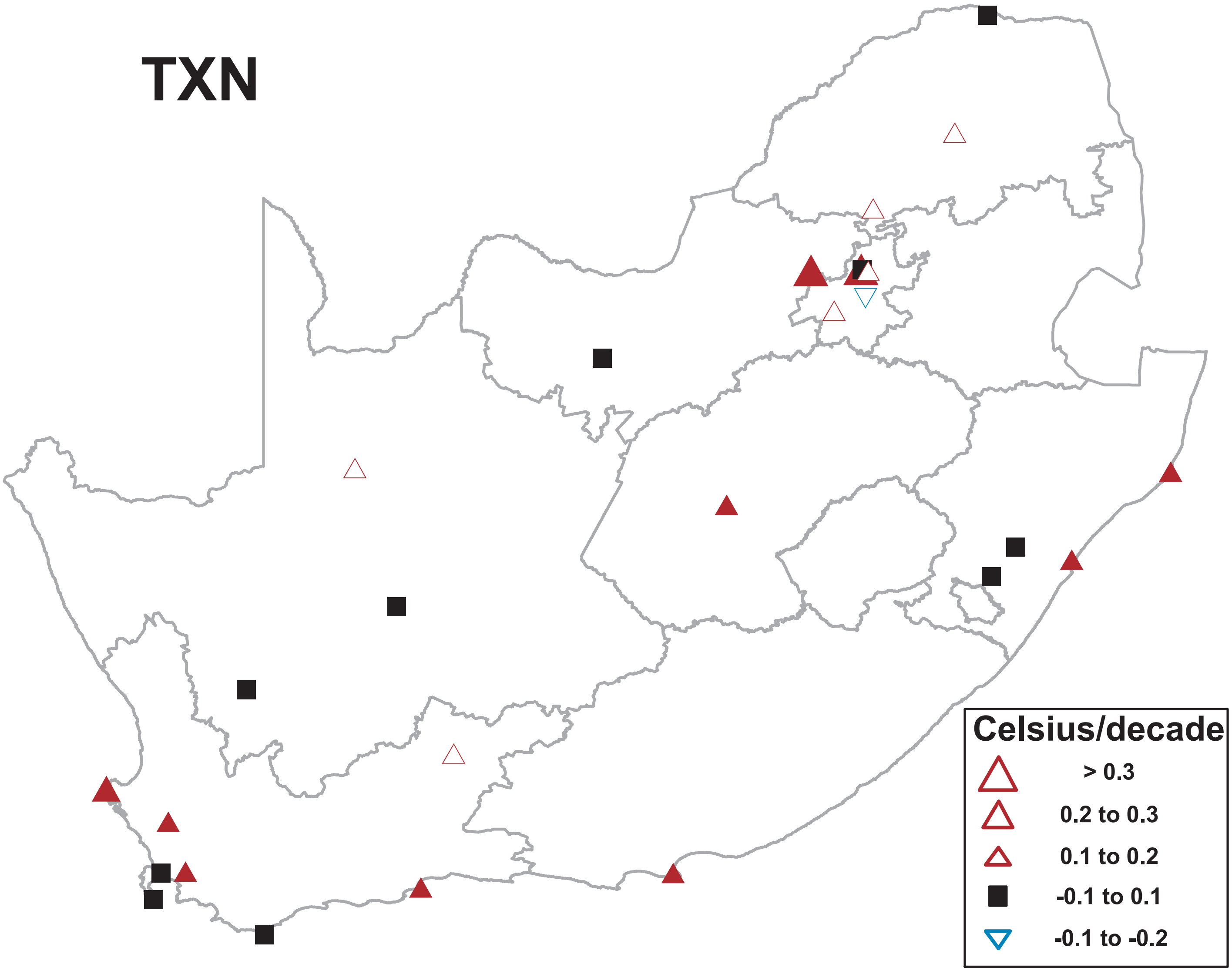


Figure 6 (c). Trends in annual extreme temperatures TXn in °C per decade (filled triangles denote significant trends at the 5% level).

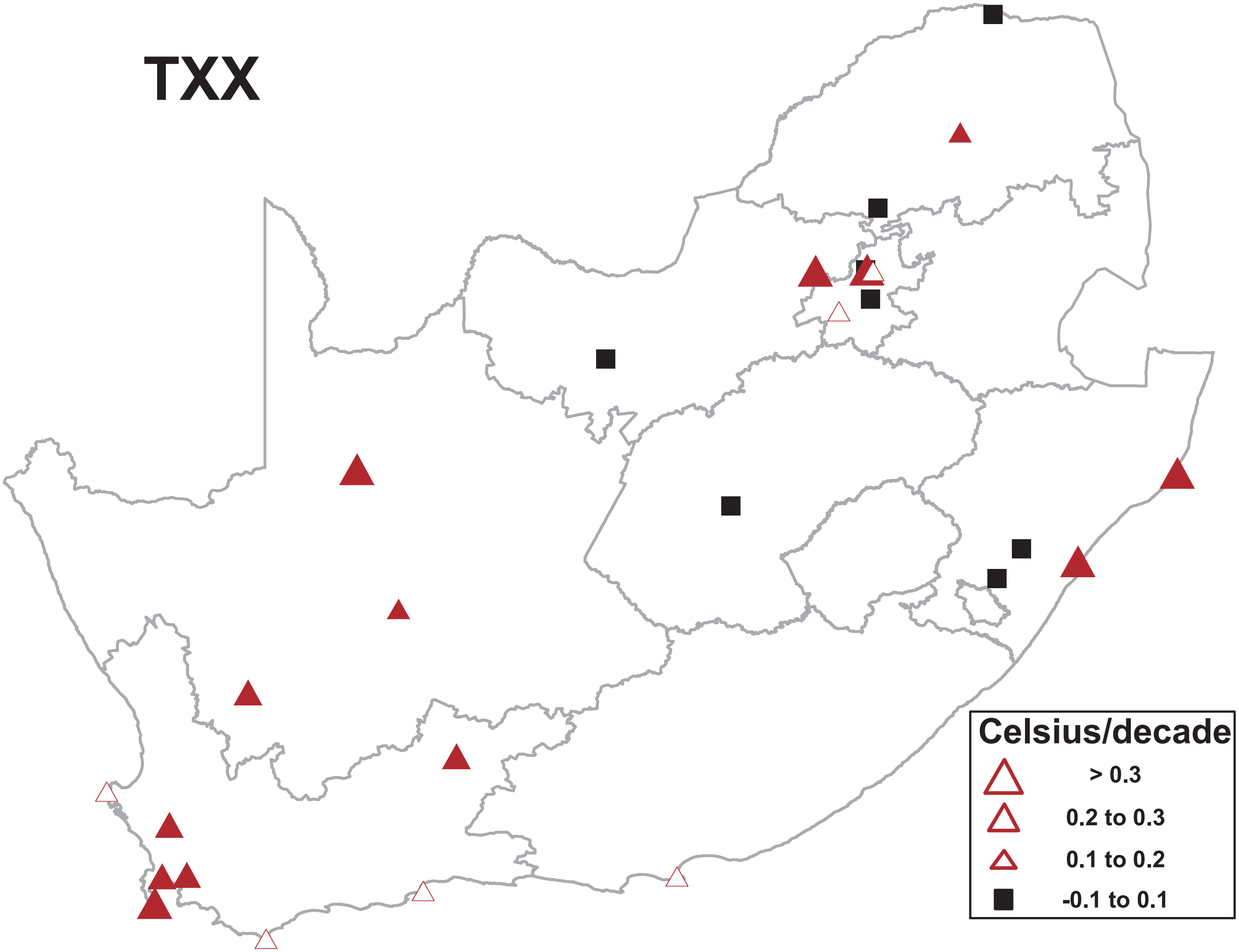


Figure 6 (d). Trends in annual extreme temperatures TXx in °C per decade (filled triangles denote significant trends at the 5% level).

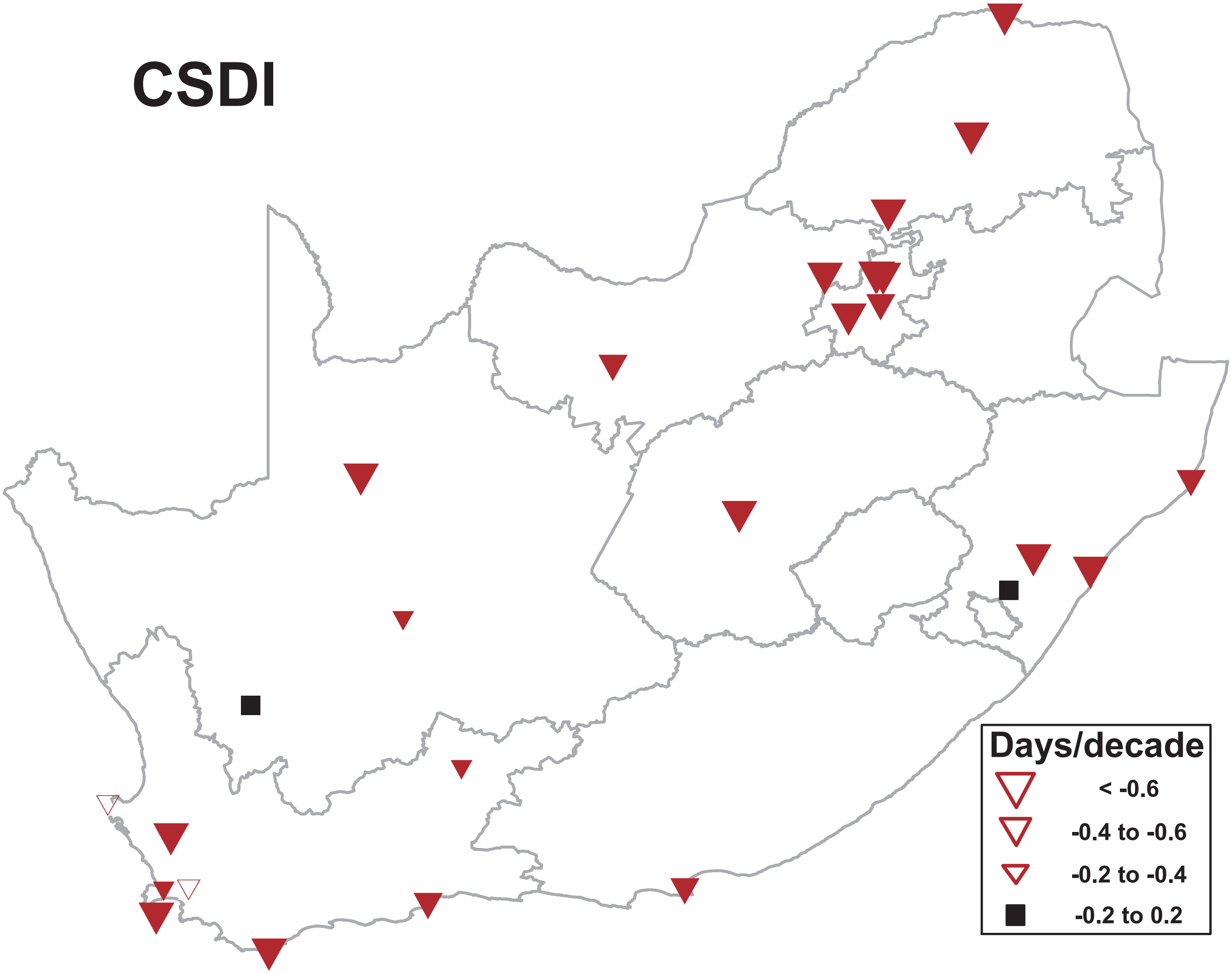


Figure 7 (a). Trends in cold spell durations in days per decade (filled triangles denote significant trends at the 5% level).

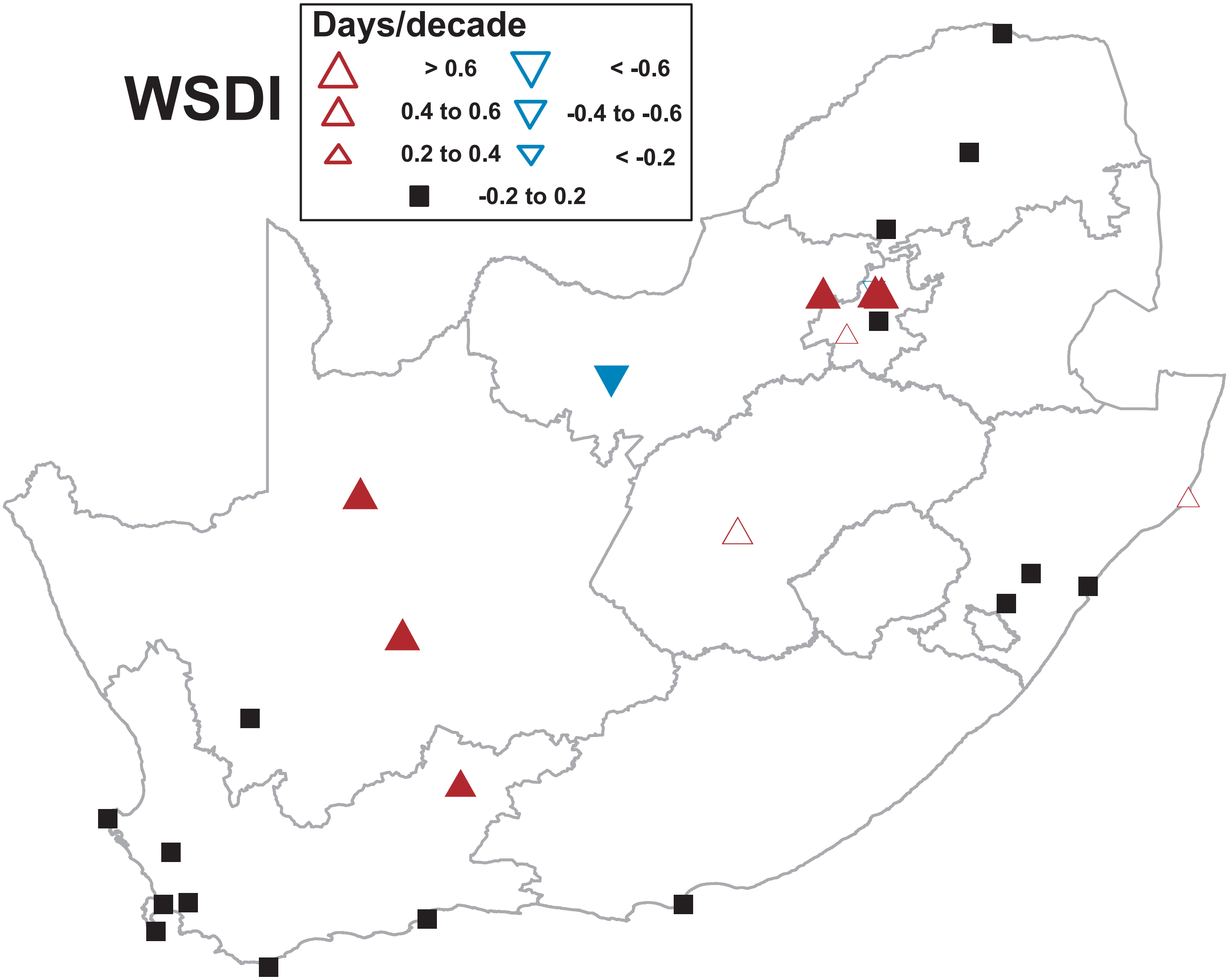
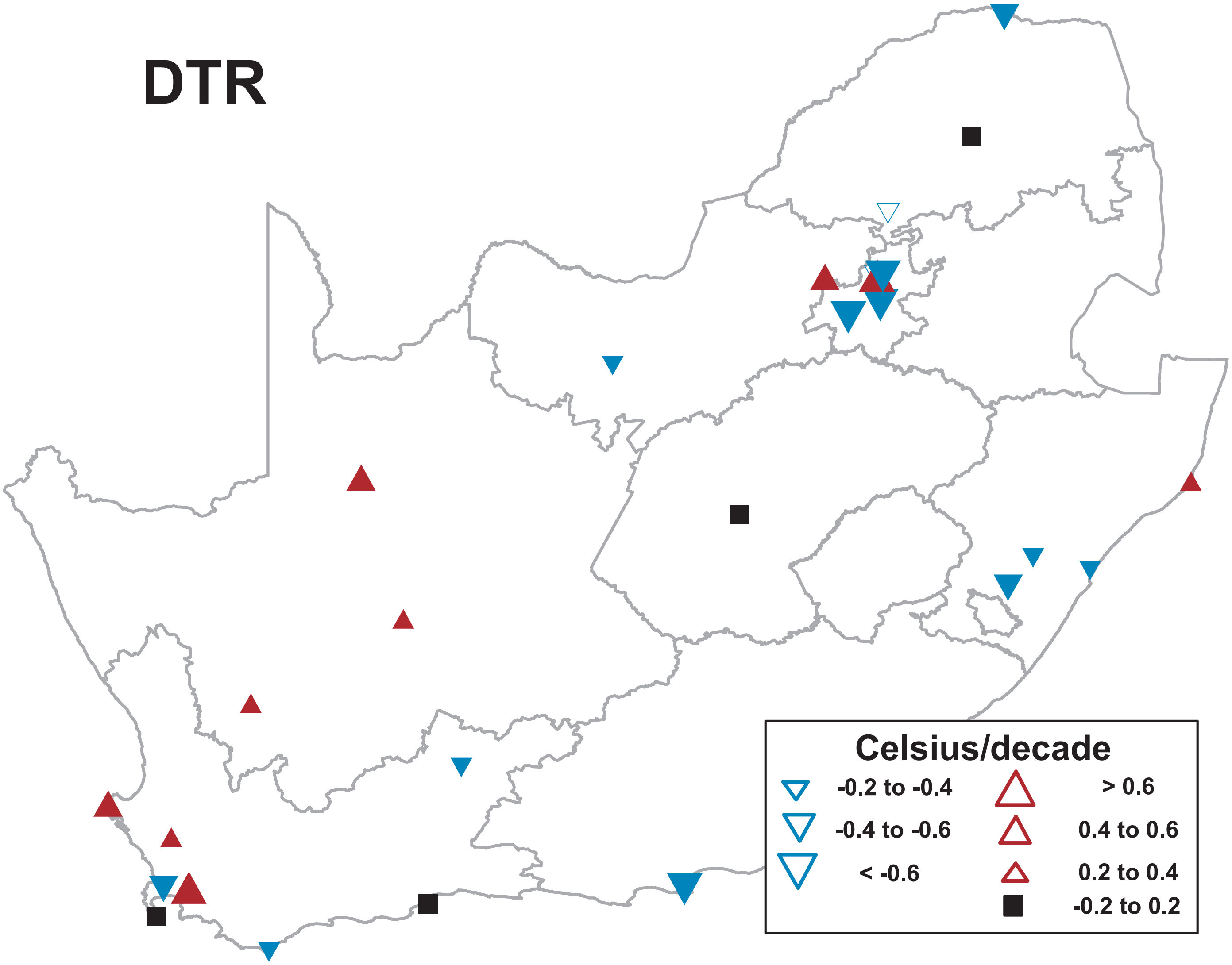


Figure 7 (b). Trends in warm spell durations in days per decade (filled triangles denote significant trends at the 5% level).



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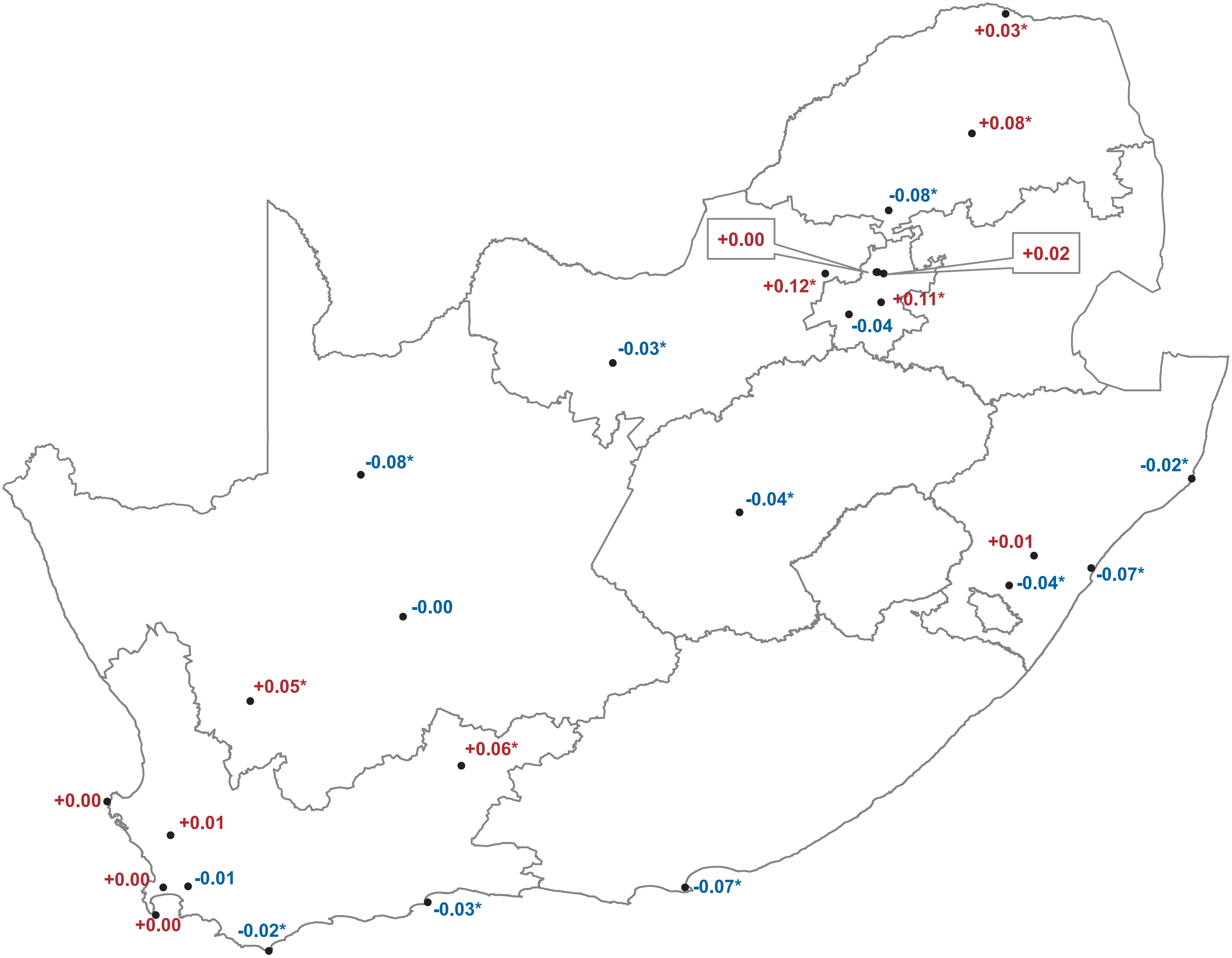

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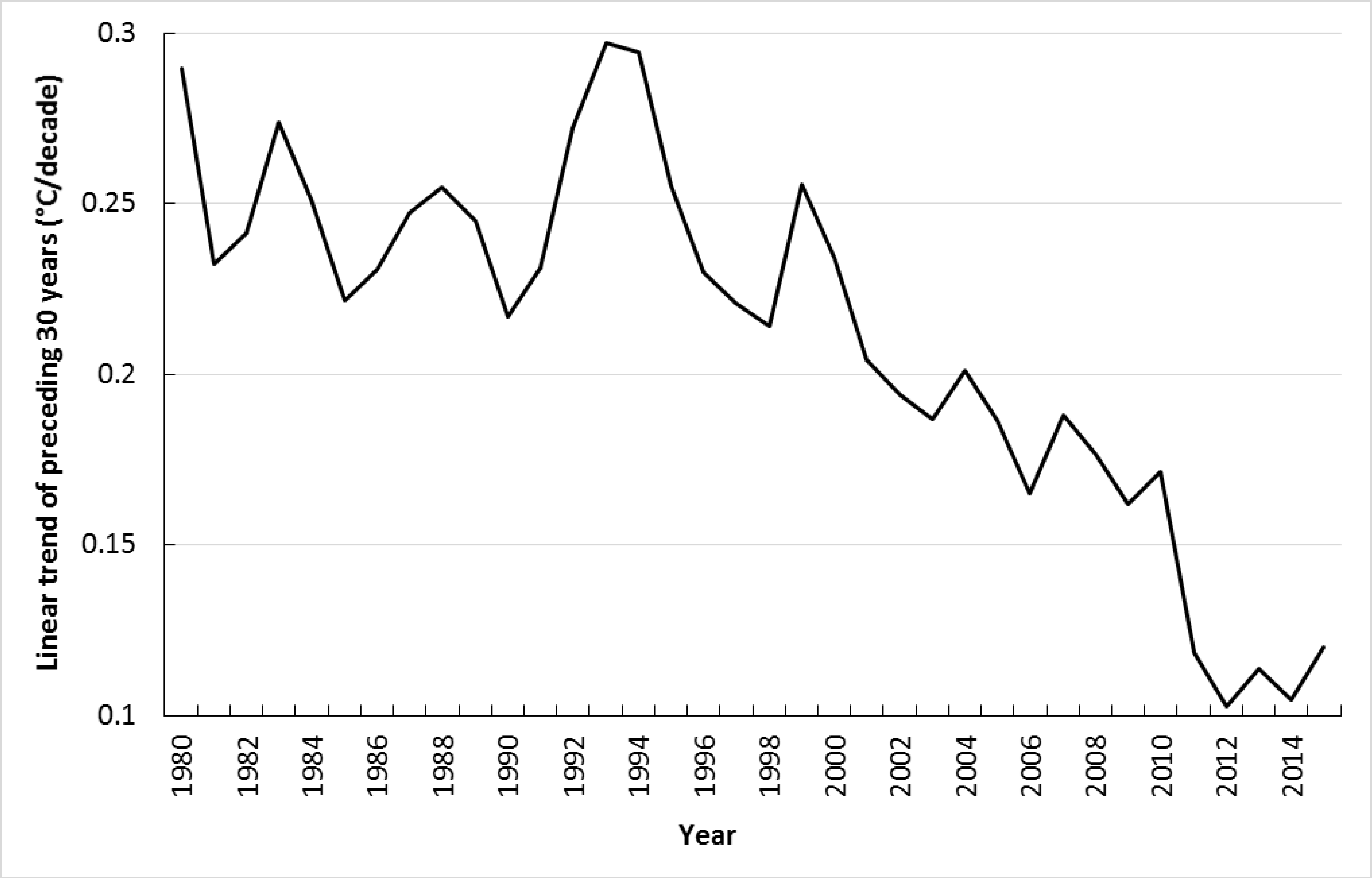

Figure 10. Mean of linear trend of average temperature (average of Tmax and Tmin) of preceding 30 years for Cape Agulhas, Cape St. Blaize, Port Elizabeth, Mount Edgecombe and Cape St. Lucia in °C per decade for 1980-2015.

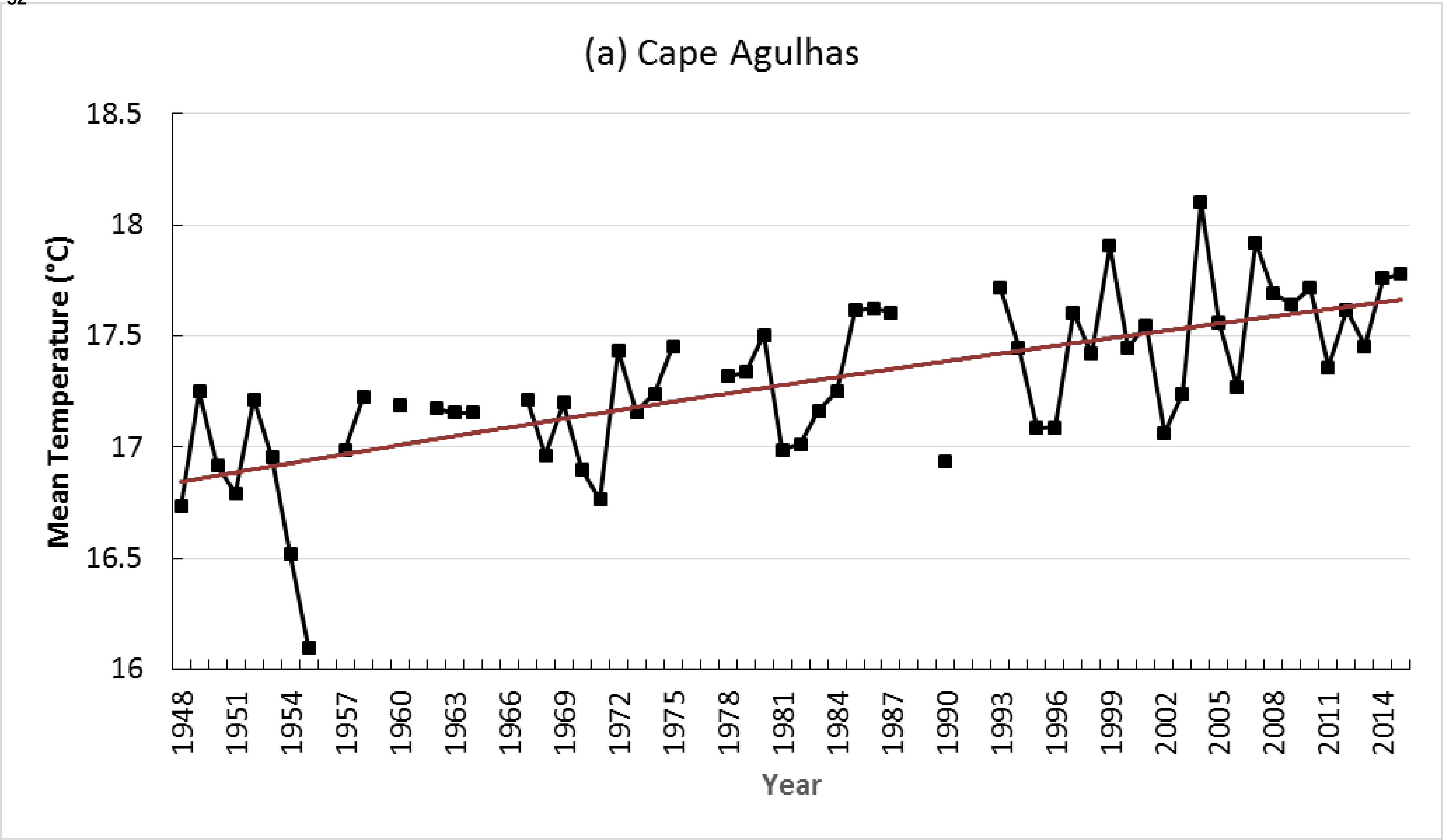

Figure 11 (a). Annual mean temperature for Cape Agulhas in °C (1948-2015). The red line is the least squares second-order polynomial fitted to the time series.

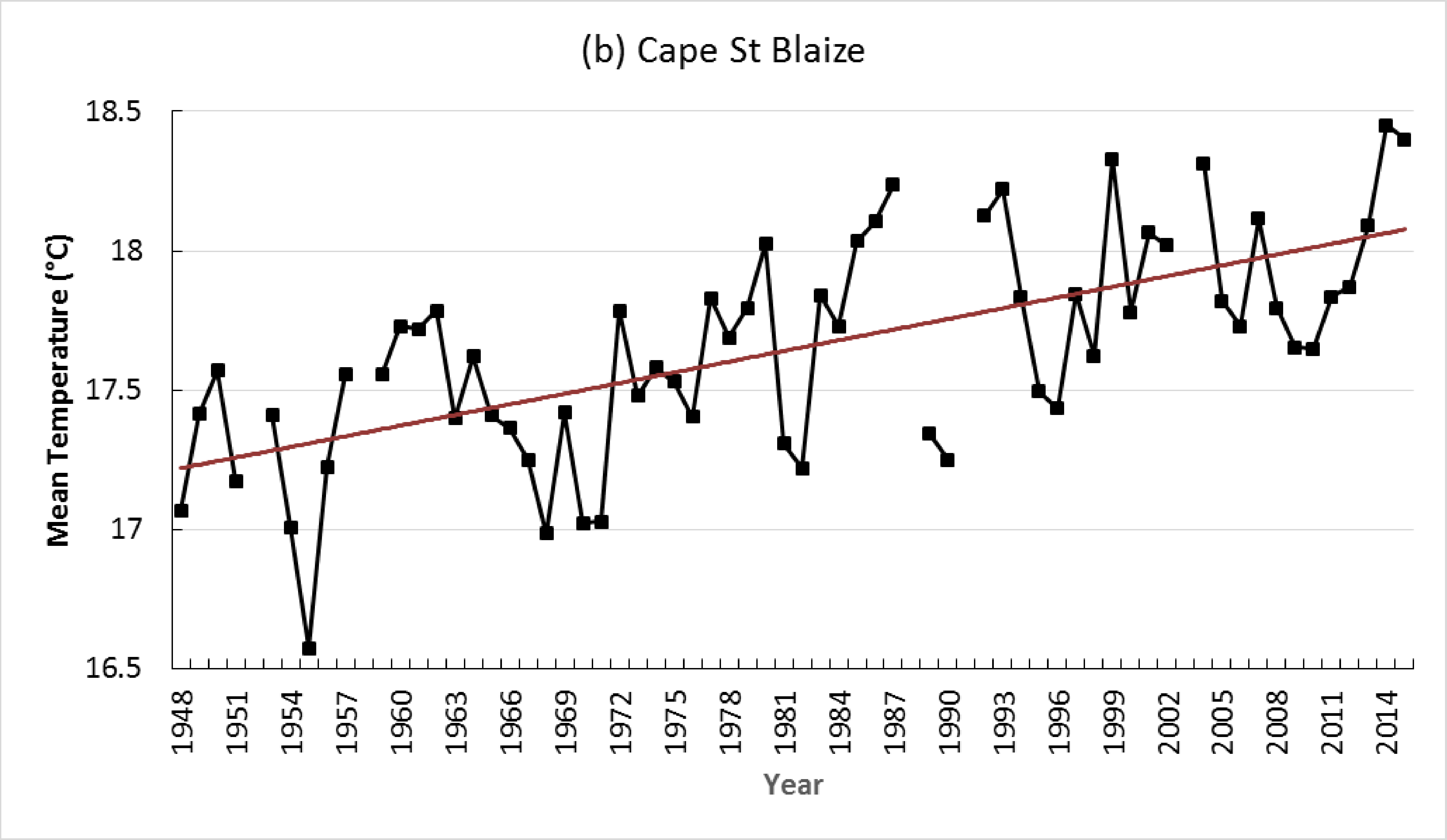

Figure 11 (b). Annual mean temperature for Cape St. Blaize in °C (1948-2015). The red line is the least squares second-order polynomial fitted to the time series.

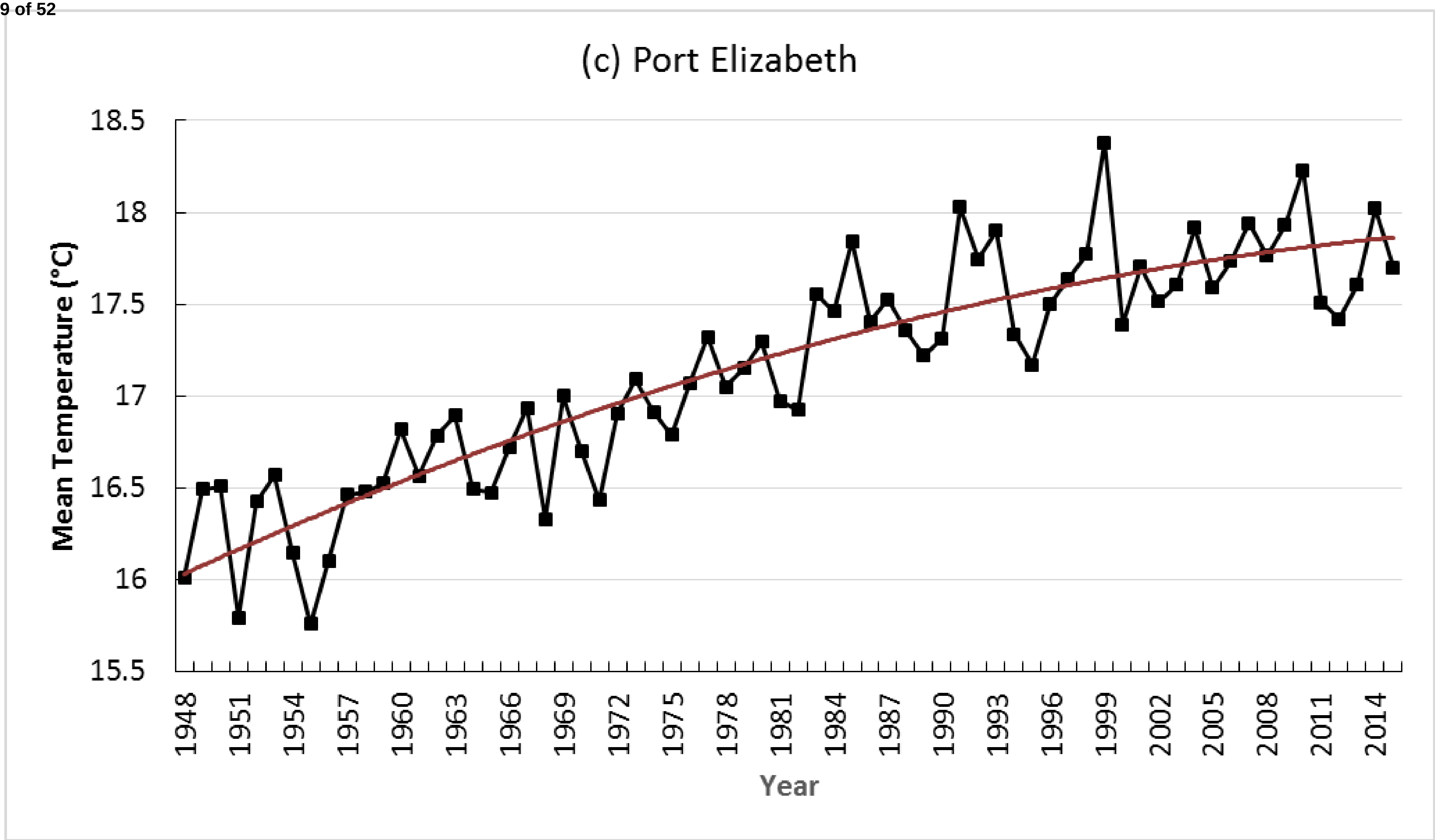

Figure 11 (c). Annual mean temperature for Port Elizabeth in °C (1948-2015). The red line is the least squares second-order polynomial fitted to the time series.

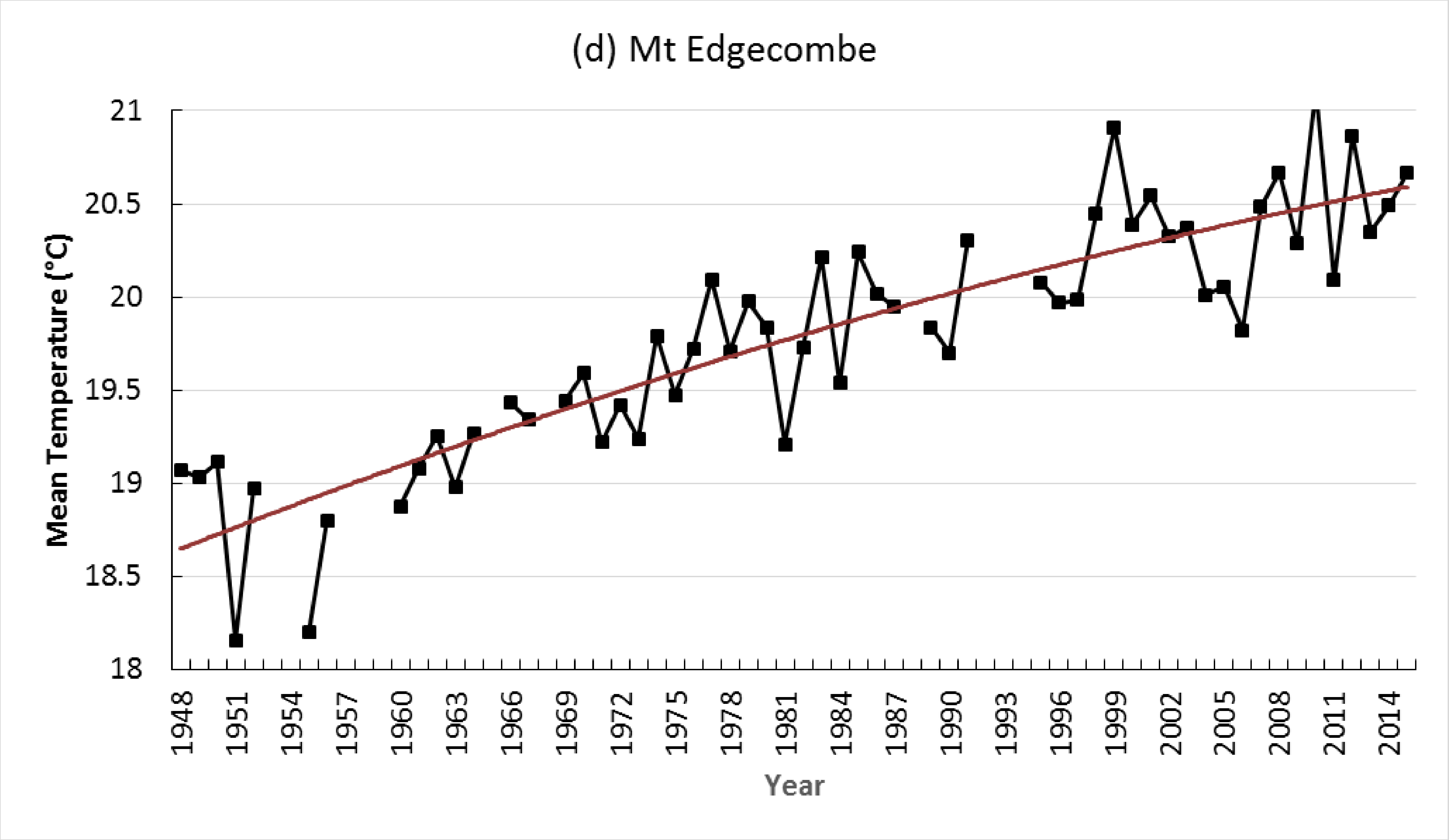

Figure 11 (d). Annual mean temperature for Mt. Edgecombe in °C (1948-2015). The red line is the least squares second-order polynomial fitted to the time series.

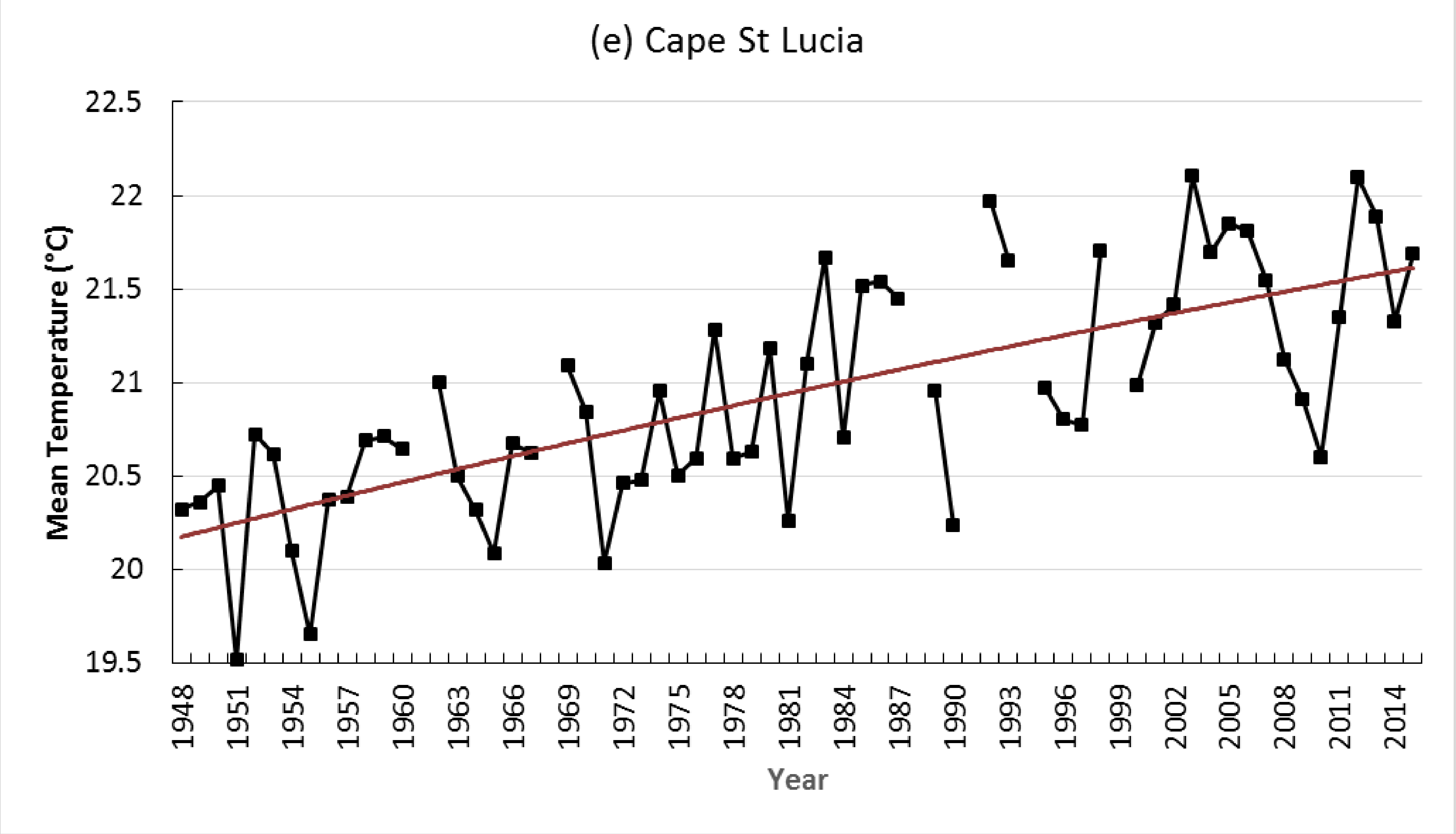

Figure 11 (e). Annual mean temperature for Cape St. Lucia in °C (1948-2015). The red line is the least squares second-order polynomial fitted to the time series.

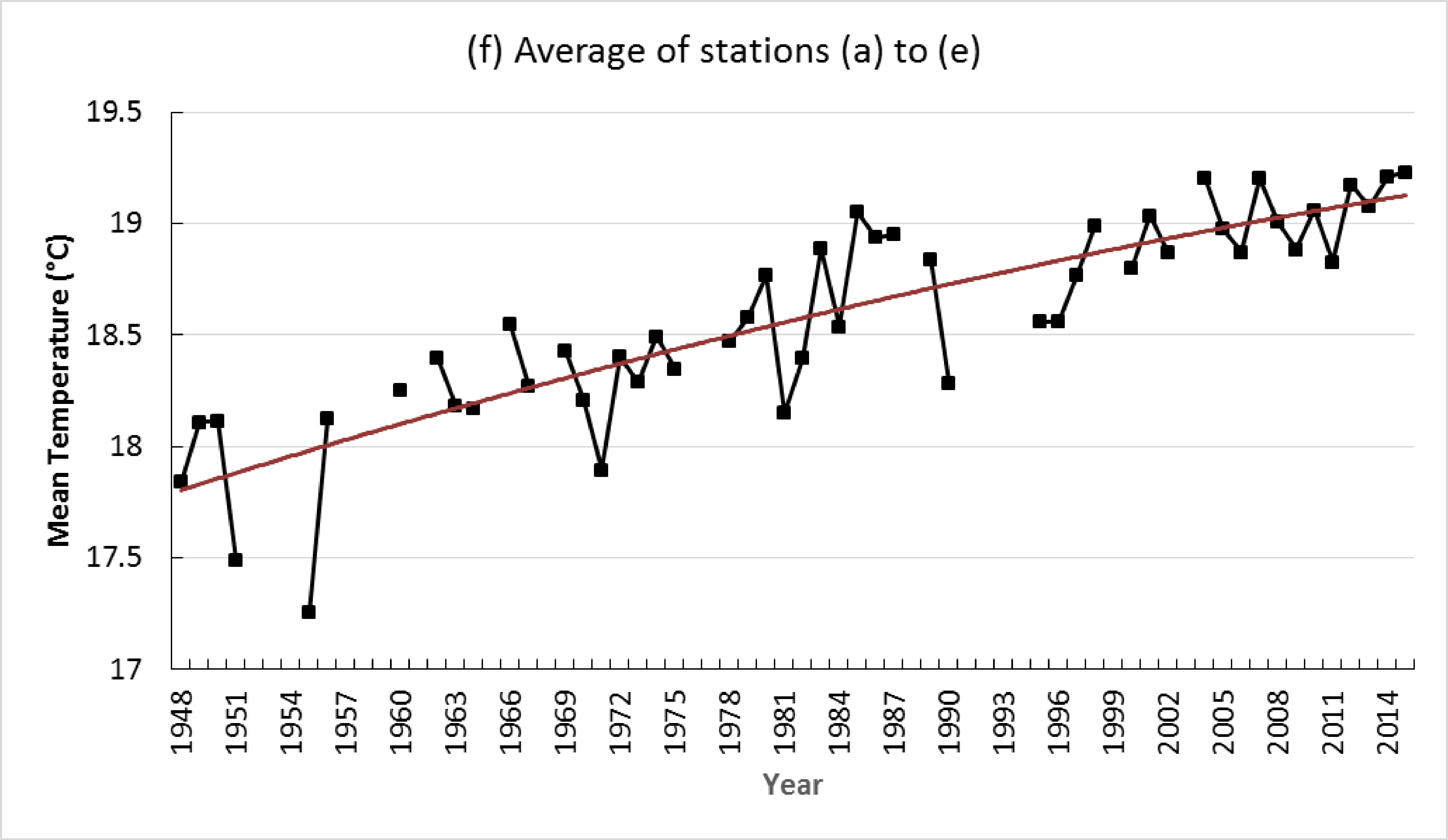

Figure 11 (f). Annual mean temperature for Cape Agulhas, Cape St. Blaize, Port Elizabeth, Mount Edgecombe and Cape St. Lucia in °C (1948-2015). The red line is the least squares second-order polynomial fitted to the time series.