# Statistical Analysis to Detect Climate Change and Its Implications on Water Resources

By
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# ABSTRACT

Climate change has affected diverse physical and biological systems worldwide. The impact of climate change on water resources is one of the most important. Even though the world's water resources are rapidly deteriorating due to the combined effects of climate change, population growth and fast urban development, climate change has been posing new challenges to water resources managers. Uncertainty of the climatic pattern is a major challenge for water authorities to formulate effective water management policies according to the prevailing and future climatic conditions.

Statistical analysis is a useful technique which can be used to detect the climatic patterns and changes in the past. There are two types of changes observed in climatic variables, which are abrupt change and trend (gradual change). Abrupt change means that the climatic pattern has changed from one pattern to another pattern. Trend means that value of the climatic variable has been gradually increasing or decreasing. To detect these changes, a number of statistical tests were selected. The most accurate tests from amongst them were chosen for each type of change based on an analysis carried out using hypothetical data. The change detection for real data was carried out using these tests.

Even though there are several hydro-climatic variables impacted by climate change, only two major influencing variables, rainfall and temperature, were selected for this study. The Yarra River catchment was selected as the case study catchment because it is a major source of water supply for Melbourne. Any changes in rainfall and temperature over this catchment would have implications for the management of water resources within the catchment.

Change analysis (abrupt change and trend) was carried out for historical rainfall and temperature data at different timescales to identify the pattern of change. Measurement stations were selected so that they were representative of the urban, rural and forested parts of the Yarra River catchment. For the change analysis of rainfall, there were two major climatic shifts identified in the last century, the first occurred in the middle of the century and the second one was in the last decade. The first one was step-up change and the second one was a step-down change. For most stations within the catchment, the first change was more statistically significant than the second one. Although the annual rainfalls have decreasing trends, the heavy precipitation days on the other hand are increasing in urban areas and decreasing in rural areas.

For the temperature analysis, a major step-up change occurred in the period between 1950 and 1960. After this change, temperature has been rising over the entire catchment. This pattern was more apparent in urban areas than rural or forest areas. The number of very cold days exhibited a statistically significant decreasing trend from the middle of the last century, while number of very hot days has increasing trends since the last decade.

These change analysis results have identified the past changes that occurred in the climatic system as well as the current climatic conditions. Based on the current trends, this study suggests a warmer, drier and more extreme climate over the catchment. The reducing trends in rainfall indicate that the current Drought Response Plans (DRP) will need to be considered for further review. Decreasing rainfall patterns may also have led to reduced health of waterways due to changes in base flows. This could lead to negative water quality impacts in Port Phillip Bay due to increased concentration of pollutants and higher water temperatures in the Bay. The increase in extreme rainfall events could lead to more frequent flash floods in urban areas, as the stormwater drainage system may not be able to cope with the increased flows.

The results presented in this study may have resulted from possible climate change and/or from the impact of other human activities. However, this study did not attempt to reveal the possible causes of the observed trends, which will have to be addressed in future studies. Nevertheless, the results presented here will be useful as an initial step towards further investigation of the impact of climate change and human induced activities on hydrological processes within the Yarra River catchment.

# DECLARATION

I, Sithranjan Shanmugasundram, declare that the Master by Research thesis entitled "Statistical analysis to detect climate change and its implications on water resources" is no more than 60,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work

[redacted]

31.08.2012

Signature Date

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# LIST OF ABBREVIATIONS

IPCC: Intergovernmental Panel on Climate Change

MK: Mann Kendall test

SR: Spearman Rho test

LR: Linear Regression test

MCP: Median Change Point test

RS: Rank Sum test

ST: Student’s t test

WL: Worsley Likelihood ratio test

RSS: Residual sum of squares

MSE: Mean square error

MRO: Melbourne Regional Office

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# 1 INTRODUCTION

## 1.1 Background

Climatic events such as excessive rainfall, extended droughts and extreme temperatures have played an important role in the history of mankind and they are still important in the modern world. The change in global climate is impacting on every aspect of our life. Our limited agricultural land and water resources are under severe pressure.

Over the past century, there has been a significant decrease in the frequency and intensity of extreme precipitation events in the southwest region of Western Australia and a significant increase in the proportion of total precipitation from extreme events in eastern Australia (Haylock & Nicholls 2000). In Southeast Australia, the average annual rainfall is decreasing and extreme rainfall events and flooding are becoming more frequent. This changing environment is one of the major challenges in the irrigated and non-irrigated agricultural catchments of Southeast Australia. It has major implications for our current water resources and engineering water management strategies. Therefore, the accurate understanding of changes in climate and the prediction of such climatic events are necessary for the well being of the human society.

Flooding and extreme temperatures have become a major catastrophic events all around the world including Australia. As indicated in a study conducted by the Department of Primary Industries and Energy (1992), flood damage costs Australia around 300 million dollars per year with about 200,000 urban properties prone to flooding due to a 100-year flood. Flooding not only causes direct accountable property damage, but also creates major social problems due to relocation, emotional disturbances, loss of important records/articles and in some cases loss of human life. Furthermore, flooding also causes environmental problems such as the destruction of native vegetation and extinction of some wildlife species (Department of Primary Industries and Energy, 1992).

On the other hand, reduction in amount of rainfall for extended periods would cause drought. Increasing temperature is exacerbating the situation. In Australia, many parts of its land suffer from frequent droughts. Australia is often referred to as the driest inhabited continent on earth and this is evident when rainfall and run-off are compared with other countries. It has also been seen that many parts of Australia have experienced their worst single and multi-year droughts on record over the last decade (Tan & Rhodes 2008). These recent frequent droughts have severely stressed water supply systems and the community that depends on them.

Regional studies across the Asia-Pacific area (Manton et al. 2001) have shown statistically significant increases in occurrences of hot days and warm nights and decreases in cold days and cold nights over the past few decades. Continuing dry and warm weather as well as prevailing extended drought are causes for bushfires in southeast Australia, which made significant impact on the society in terms of fatalities and monetary losses (Murphy & Timbal 2008). Estimated annual monetary loss due to bushfires in Australia is AUD$ 8,500 million which is approximately 1.15% of Australia's Gross Domestic Product (Ashe et al. 2006).

Due to the increasing awareness of climate change, in 1979 the first world climate conference organized by the World Meteorological Organization expressed concern that human activities may cause significant regional or global changes to climate. Today initial concerns have evolved into international policy to reduce global green house gas emission (i.e. Kyoto Protocol) and the broader establishment of international working groups such as the Intergovernmental Panel on Climate Change (a joint collaboration between the World Meteorological Organization and the United Nations Environment Program) dedicated to synthesizing scientific information on climate change including environmental and socioeconomic impacts.

The climate is a dynamical system influenced by immense external factors, such as solar radiation or the topography of the surface of the solid earth. As there are numerous uncertainties involved in the climatic system, statistical methods are suitable tools to understand the climatic system. If we knew all the factors affecting the climate system and the state of the full climate system (including the atmosphere, the ocean, the land surface, etc.) at a given time in full detail, then there would not be room for statistical uncertainty. But, we don't know all factors that control the climate in its enormously large phase space. Thus, it is not possible to map the state of atmosphere, the ocean, and the other components of the climate system in full detail. Even though climate is controlled by innumerable factors, only a small portion of these factors can be considered, while the rest are necessarily interpreted as background noise (Storch & Zwiers 1999). Therefore, to get an understanding of the climate change, major influencing parameters have to be considered for any climate change analysis studies.

Better understanding of climate change would help to forecast the future climatic events in terms of the timing and the severity. This would immensely help to take precautionary actions as well as prevent the huge amount of losses in lives and economy.

## 1.2 Aims of the Study

The main aim of this research was to understand and detect the changes in climatic variables, especially those which are more closely related to water resources of the Yarra River catchment. This catchment was selected as the case study catchment because it is a major source of water supply for Melbourne. Thus, any changes in climatic variables over this catchment would have implications for the management of water resources within the catchment. Any detected changes in climatic variables will not only help to understand the past climatic conditions and timing and severity of extreme events, but also would support to forecast the future climatic conditions, extreme events and its severity.

The tasks that were carried out in this study to achieve the above aim are described below. The following description also briefly describes the methodology used in this study.

1) **Data collection** – Rainfall and temperature were identified as suitable climatic variables for change analysis in this study. Time series data were collected from the stations throughout Yarra catchment.

2) **Identifying types of changes and change detection techniques –** This task involved conducting an exhaustive literature review to identify the types of changes that can occur in climatic variables and also to identify the statistical techniques

used by researchers to detect those changes. Two types of changes, namely trend and step change (or abrupt change in mean) have been identified in various change detection studies. Various statistical techniques (both parametric and non-parametric) have been used in past studies to detect trends and also to identify the step change point.

3) **Selecting most suitable techniques using hypothetical data analysis** – The aim of this task was to identify the best technique for each type of change from among all reviewed statistical techniques. Hypothetical datasets were developed to represent all possible types of changes in real rainfall and temperature datasets. The hypothetical datasets had known change points and trends and thus using them led to identify which of the statistical techniques are able to accurately locate the known change points and trends.

4) **Formulating a technique to detect abrupt change in slope** – From the analysis presented in the above two tasks, it was also identified that climatic data may have abrupt changes in slope, not just abrupt changes in mean. Past climate change studies that were reviewed considered only abrupt change in mean (i.e. step change) but not abrupt change in slope. Therefore, an important contribution of this study is that it proposes a technique to detect abrupt changes in slope.

5) **Developing a methodology for change analysis of real datasets** – Based on the statistical techniques identified for different types of changes using hypothetical data analysis, a methodology has been developed in this study for the analysis of change detection in real datasets of rainfall and temperature. This analysis was classified into two categories, standard value analysis and extreme values analysis. The standard value analysis consisted of longer timescales, annual and monthly timescales being used in this study. For the extreme value analysis, few indices were used for detection of change.

## 1.3 Significance of the Study

Australia's population and agricultural production are highly concentrated in the southeast of the country. Rainfall variability over these parts and over most of the continent in recent decades was very high (Murphy & Timbal 2008). Mean rainfall of southeast region was below long term average since 1996 till the end of 2006. Drought is recurring problem in this part of the country and many systems have to be designed to cope with this variability. Generally, Australians rely on wet years to compensate for drought in the agricultural sector. But, the current extended dry period has led to numerous extreme impacts in this region. The continuing dry and warm weather has also had an impact on bushfires in the southeast. A recent example is the major bushfire that broke out in Victoria in February 2009, which had taken over 200 lives (Hogan 2009).

Melbourne's drinking water is one of the best in the world in terms of quality (Melbourne Water 2010). But, recent climate change, increasing population and rapidly growing urbanization have put more pressure on the water supply of Melbourne, which has led to imposition of water restrictions. Planning to ensure that the water supply is able to cope with the demands of the growing metropolis also has to be taken into account. A greater awareness of the potentially significant implications of climate change on the water supply system has to be generated.

Some of these impacts of the last decade's drought and warm weather in Victoria are unprecedented in historical records. With these extreme conditions, there is an urgent need to better understand the climate variability and the uncertainty in climate change over the region in order to provide greater certainty in planning and decision making.

This study also proposes that for detection of change in historical time series datasets of rainfall and temperature, along with detection of abrupt changes in mean, abrupt changes in slope should also be detected. This is important because climatic variables also exhibit abrupt changes in mean, which may not be detected by step change detection techniques.

## 1.4 Outline of the Thesis

This thesis consists of six chapters, with this chapter presenting the background and need for this study, along with the aims, brief methodology and the significance of this study.

The Chapter 2 describes the climate change in terms of rising temperature, changing rainfall pattern, and frequent extreme events. Different types of changes and the statistical techniques that have been used in past climatic studies to identify those changes are also reviewed in this chapter.

Chapter 3 mainly describes the study area and methodology that was followed in this research. Details of the case study catchment (the Yarra River catchment) and its different land use patterns, availability of time series data for selected variable and the station selection criteria are also discussed in this chapter. To select the best technique for each type of change, hypothetical datasets were developed and the hypothetical data analysis is presented in this chapter.

Change analysis of one of the selected climatic variable, rainfall is presented in Chapter 4. Eleven rainfall stations from three different land use areas are considered for the analysis. Detection of change in both standard value and extreme value rainfall events are described in this chapter.

Similar to the rainfall analysis described in Chapter 4, analysis of standard value and extreme value temperature events are described in Chapter 5. Only three stations were considered for temperature analysis, mainly since temperature variation over the catchment was not much. The details of the stations and the results are presented in this chapter.

A summary, conclusion, implications of the detected changes in climatic variables (rainfall and temperature) on water resources and recommendations for future research drawn from this study are finally presented in Chapter 6.

# 2 LITERATURE REVIEW

## 2.1 Introduction

The main objective of this chapter was to conduct an exhaustive literature review of past climate change studies with the aim of identifying the types of changes in climatic data and the change detection techniques used to detect those changes. The literature review also helped in getting a comprehensive knowledge of past work done locally and internationally to address the problem of change detection in climatic data and the impact of such changes on water resources.

Climate change is one of the greatest economic, social and environmental challenges of our time (Parkinson 2009). One of the most important implications of climate change is the alterations in regional hydrologic cycles and subsequent effects on the quantity and quality of water resources (Gleick 1989). This in turn affects the water supply, which for a specific region, has to be determined according to its prevailing climatic conditions.

During the last centuries natural factors such as volcanic eruptions or the amount of energy released from the sun have affected the climate of earth on a smaller scale. The composition of the atmosphere has changed since the beginning of the $19^{th}$ century due to human activities associated with emissions of carbon dioxide and other greenhouse gases (Karoly et al. 2003). The scientific community has reached consensus that this changes cause a warming of the atmosphere and therefore influencing the Earth's climate. In order to better understand the physical nature of these changes, as well as their possible environmental and socio-economic impacts, the Intergovernmental Panel on Climate Change (IPCC) was established in 1988 through the World Meteorological Organization (WMO) and the United Nations Environmental Programme. Working Group 1 of the IPCC was charged with the task of assessing the available scientific information on climate change and their first, second and third assessment reports form a comprehensive review of current scientific understanding (Houghton et al. 2001; Houghton et al. 1990; Houghton et al. 1996). In 1996, the IPCC concluded that 'the balance of evidence suggests a discernible human influence on global climate'. This position was strengthen by the assessment (IPCC 2001) to include that 'there is new and stronger evidence that most of the warming observed over that last 50 years is attributable to human activities'. To predict the future climate change expected to occur over the next 100 years, highly sophisticated climate models are used. Prediction of global warming up to the year 2100 depends upon different scenarios as shown in Figure 2.1.

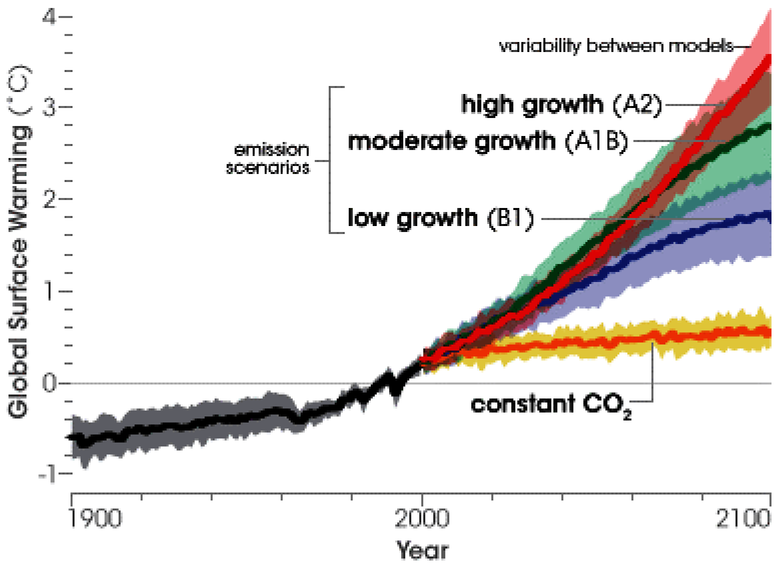



Figure 2.1.Prediction of global warming until the year 2100 (from IPCC 2007)

The comprehensive assessment of World Meteorological Organization on Fresh Water Resources of the World (World Meteorological Organisation 1997), estimated in 1997 that approximately a third of the world's population was living in countries deemed to be suffering from water stress: they were withdrawing more than 20% of their available water resources. At present, 1.4 billion people out of total world population of 6.8 billion suffer through water scarcity (Thomasson 2009). By 2025, it is estimated that 5 billion people out of total population of 8 billion will experience water scarcity due to climate change (Arnell 1999). Climate change due to an increasing concentration of greenhouse gases is likely to affect the volume and timing of rainfall, groundwater recharge and river flows, and thus affect the numbers and distribution of people affected by water scarcity (World Meteorological Organisation 1997). global population growth and climate change scenarios at the 0.5° x 0.5° scale, showing that next 25 years climate change would have lass effect on change in water resources stresses than population and water demand growth (Vorosmarty et al. 2000). However, they did not explicitly compare the future situation with and without climate change.

Although climate change is a global phenomenon, the changes and implications on hydrologic regimes may vary in a local scale (Sharma & Shakya 2006). In Australia, some regions have been studied comprehensively than others. There is no significant comprehensive climatic study carried out in south-eastern Australia when compared with the studies carried out in Western Australia (Nicholls 2006). Therefore, there is an immediate need for future change detection studies on climatic variables in a local scale along the east coast and stretching inland from the coast which consists of a large proportion of Australia's population and economic value (Nicholls 2006). Victoria is one of the three states located in east coast of Australia, which represents only 3% of Australia's total land area, but contains 25% of Australia's total population (Whetton et al. 2001). As a result of low rainfall occurred in the last decade (1997-2006) in Victoria, water inflows to catchments reduced and major urban areas faced water restrictions.

This chapter first describes the climate change in terms of rise in temperature, changes in rainfall patterns and increase in extreme events and its effects on water resources as well as on the society. Then the types of changes in climatic variables based on studies carried out in past are described, followed by the statistical techniques (which includes parametric and non-parametric techniques) used for change detection are presented. Finally, a summary is presented at the end of this chapter.

### 2.1.1 Rise in temperature

The Earth's climate has changed many times during the planet's history, with events ranging from ice ages to long periods of warmth. The most dramatic variability is displayed in the glacial-interglacial cycle where global temperature varies from 5 to 7 °C between long cold periods and shorter warm periods on scales of around 100,000 years (Imbrie & Imbrie 1979). Over the last 10,000 years since the end of last glaciations, changes in the global scale temperature have been much less dramatic. While there is evidence of relatively large regional scale changes in the range of less than 2 °C; it is unlikely that these fluctuations occurred on a global scale (Folland et al. 1990).

Global average surface temperature has increased by 0.6°C since the 19th century and continuation of greenhouse gas emissions can result in additional warming over the 21st century up to 4.5 °C by 2100 (Houghton et al. 2001; Zereini & Hötzl 2008). According to the recent record, 1998 has remained the warmest year and 1998-2007 was the warmest decade (Hogan 2009; Richard 2007). Australia has warmed by 0.8°C over the last century with minimum temperature increasing faster than maximum temperature (Hughes 2003). Victoria has warmed at the rate of 1.06°C per century since 1950 (Howe et al. 2005). This warming will have severe consequences for the water cycle of the world, because with the warming will come changes in precipitation patterns with increased risk of droughts and floods.

### 2.1.2 Changes in rainfall pattern

In many regions, precipitation and temperature are in general inversely correlated (Nicholls 2004). There was a shift to wetter conditions in late 1940s and recently a jump to drier conditions in 1990s in Victoria (Howe et al. 2005). Mean rainfall has been below long term average in the last decade, in southeast Australia (Murphy & Timbal 2008). Similar shift has occurred in 1974/75 and 1996/97 in southwest of Western Australia, and annual inflows to Perth dams have reduced by 48% and 64% respectively when compared with annual average inflow between 1911-1974 (Gill 2006).

### 2.1.3 Frequent and severe extreme events

Extreme climatic events have received attention recently as they have caused exponential increases in economic losses, often leading to a large number of fatalities (Karl & Easterling 1999). This increased attention raises the question as to whether extreme weather and climate events are truly increasing, whether this is only a perceived increase exacerbated by enhanced media coverage, or both (Karl & Easterling 1999). Only in developed countries, it appears to be an increase in media coverage, but in other parts of the world no increase was evident. Extreme events can be defined, in terms of values such as “extreme daily temperature, extreme daily rainfall, and unusual monthly temperature or storm events", or impact which the event has on the society such as "excessive loss of life, excessive monetary loss, or both" (Easterling et al. 2000). Population and infrastructure continues to increase in areas that are vulnerable to extreme such as flooding, storm damage, and extreme heat or cold. Statistics related to extreme events play a major role in engineering practice for water resources design and management (Katz et al. 2002). Lack of long term climatic data suitable for analysis of extremes is the biggest obstacle to quantifying whether extreme events have changed over the twentieth century, either worldwide or on a more regional basis (Easterling et al. 2000).

Continuing dry and warm weather as well as prevailing extended drought are causes for bushfires in southeast Australia, which made significant impact on the society in terms of fatalities and monetary losses (Murphy & Timbal 2008). Estimated annual monetary loss due to bushfires in Australia is AUD$ 8,500 million which is approximately 1.15% of Australia's Gross Domestic Product (Ashe et al. 2006). In the last 100 years (excluding 2009 and 2010), 54% of the total Australian bushfire fatalities occurred in Victoria (Haynes et al. 2008).

The excessive intensity of rainfall causes flooding as capacity of the drainage system is inadequate to sustain the extreme intensity of rainfalls (Howe et al. 2005).

Based on the above literature review and, prevailing extreme and uncertain climatic conditions in southeast Australia, there is an urgent need to better understand climate change and the uncertainty due to climate change over southeast Australia, in particular in Victoria, in order to provide greater certainty in planning and decision making. The trend and step change analysis of climatic variables will give a better understanding of current climatic pattern and help to effectively forecast the future climate.

## 2.2 Detection of Climate Change

As water resources and water infrastructure are affected by climate change, better understanding of occurred change in climate pattern is necessary to safeguard the water resources. This can be done through identifying clear and concise indices of climatic variables (e.g. annual rainfall, annual monthly rainfall, minimum annual daily temperature, maximum annual daily temperature, etc.), and analysing them to reveal the changes in climatic pattern. There are two major patterns of changes (presented in Figure 2.2) identified in climatic variables (Kundzewicz & Robson 2004):

1) Trend (gradual change)

2) Step change (abrupt change)

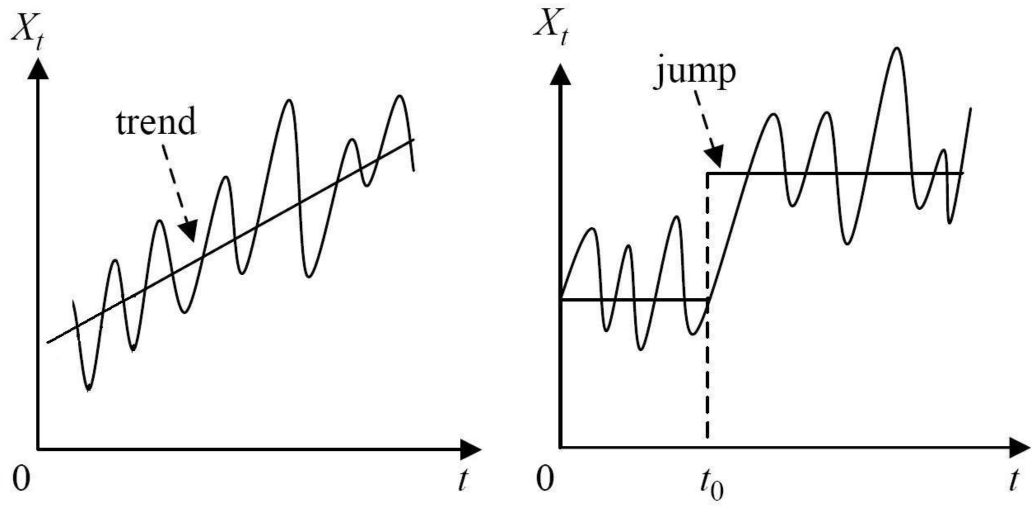



Figure 2.2 Two types of changes in climatic data: Trend and Step change

Trend is expected to continue in future, but the step change is that change in which the climate system has already shifted to a new pattern, and which will likely to remain relatively constant until a new shift occurs (McCabe & Wolock 2002).

Various timescales of climatic variables are required for different kinds of applications. Observations are taken on short timescales such as hourly or daily over the fixed time interval such as monthly or annually to obtain a single extreme value. Observations are taken for longer consistent timescales are suitable for understand the long term climatic analysis (Storch & Zwiers 1999).

In change analysis of rainfall, monthly is used for precipitation distribution on land and ocean (Barrett 1970), seasonal is used for water allocation and supply operation (Folland et al. 1991) and yearly for water supply planning (Turkes 1996). Several timescales have also been used in analysis of extreme value events. Highest annual daily rainfall and heavy precipitation days, which was defined by Bureau of Meteorology (2010) using daily rainfall exceeding 10mm. Highest annual daily rainfall and heavy precipitation days would help in flood forecasting (Toth et al. 2000).

For temperature analysis, the timescales of minimum and maximum daily are used to find the spatial trend (Karl et al. 1993), mean monthly temperature is used to find the heat stress on society in terms of mortality rate (Larsen 1990), and seasonal is used to check the water chemistry variation (Xia et al. 1997). For extreme value temperature analysis, annual very hot days, which are number of days in a year recorded maximum temperature more than 40˚C and annual very cold days, which is number of days in a year recorded minimum temperature less than 2˚C. Annual very hot days would help to asses the risk level of the bushfires (Schär et al. 2004) and annual very cold day would help to estimate the near-surface humidity (Kimball et al. 1997).

### 2.2.1 Step change

Step change can occur in the climatic variables due to natural climatic variations and/or due to construction of large scale water resource projects such as dam construction (Xiong & Guo 2004). If any step change occurs in climatic pattern of a specific area, then all water related policies and management strategies will have to be revised.

### 2.2.2 Trend

In climate change studies, trend detection is the demonstration that a change has occurred in a defined statistical sense (Houghton et al. 2001). This has been widely used to assess the potential implications of climate change and variability on climatic variables in various parts of the world. Different types of trends on each variable interpret different implications on water resources. For instance, increasing trend in temperature will enhance the evaporation, which will reduce in water storage; decreasing trend in precipitation will result in drought and catchment drying.

## 2.3 Statistical Tests for Change Detection

There are statistical techniques to detect the changes. Change analysis techniques are classified into non-parametric tests and parametric tests, which are defined as detecting the change by rank-based methods and data-driven methods respectively.

Parametric test and non-parametric test are defined by “a test of a hypothesis about the parameters of a population distribution” and “a test of a hypothesis about some features of a population distribution other than its parameters” respectively (Argyrous 2000). Parametric tests use data-driven methods, require many assumptions and are sensitive to outliers. On the other hand non-parametric tests use rank based methods, require fewer assumptions and less sensitive to outliers (Hamed 2007; Katz et al. 2002; Khaliq et al. 2006; Zhang et al. 2004). But parametric tests are more powerful than nonparametric tests (Kundzewicz & Robson 2004). Power of the test determined by “the probability of rejecting the null hypothesis when it actually false and should be rejected” (Levin & Fox 2000).

Nonparametric statistical tests are more suitable than parametric tests for trend detection studies as non-normally distributed data and missing data are frequently encountered in climatic time series (Yue et al. 2002).

### 2.3.1 Step change detection techniques

Step change analysis will help to make sure, whether the available water management policies are still applicable or reformations of the policies are required. The step change has to be proved with defined statistical sense. Kundzewicz & Robson (2004) have listed few statistical tests for step change analysis, which are as follows:

i. Median change point test (MCP)

ii. Rank-sum test (RS)

iii. Worsley likelihood ratio test (WL)

iv. Student’s t test (ST)

v. Cumulative Sum test (CUSUM)

Various characteristics of these five techniques are presented in Table 2.1.

Table 2.1.Charecteristics of the five step change detection techniques

| **Test characteristics** | **Name of test** | | | | |
|---|---|---|---|---|---|
| | **Median change point test** | **Rank-sum test** | **Likelihood ratio test** | **Student's t test** | **CUSUM test** |
| **Mean/Median based** | *Median* | *Median* | *Mean* | *Mean* | *Mean* |
| **Known/Unknown Change point** | *Unknown change point* | *Known change point* | *Unknown change point* | *Known change point* | *Unknown change point* |
| **Parametric/Non-parametric** | *Non-parametric* | *Non-parametric* | *Parametric* | *Parametric* | *Parametric* |
| **Data-driven/Rank-based** | *Rank-based* | *Rank-based* | *Data-driven* | *Data-driven* | *Data-driven* |
| **Sensitivity to outliers** | *Less sensitive to outliers* | *Less sensitive to outliers* | *Sensitive to outliers* | *Sensitive to outliers* | *Sensitive to outliers* |

As seen in Table 2.1, only MCP and RS are rank based non-parametric tests, while other three tests are data driven parametric tests. MCP, WL and CUSUM tests can be used for an unknown change point in the time series data, while RS and ST can be used only for known change points in the time series (Kundzewicz & Robson 2004).

MCP is used to detect the change in median of a series (Pettitt 1979; Siegel & Castellan 1956). MCP is considered robust to changes in the distributional form and relatively powerful among other tests available for step change detection (Kundzewicz & Robson 2004). RS can be used to detect the change point in median. CUSUM test method is a parametric approach and is considered as easy to handle among other change point detection techniques (Inclan & Tiao 1994). It has been utilised for testing for a change in mean (Bai 1994). ST and WL are mean based parametric tests.

#### 2.3.1.1 Median change point test

This is a rank based test for checking the change of median in time series data. This test is considered to be powerful and robust to distributional form changes in dataset (Kundzewicz & Robson 2004). This technique was invented by Pettitt (1979).

Consider a sequence of random variables $X_1, X_2, ..., X_T$ and it is said to have a change point, where X is the magnitude of the observation and T is number of observations in the sample. The distributions function before the change point is denoted as $F_1(X)$ and after the change point is denoted as $F_2(X)$. Sum of nominal measurement $V_t$,

$$V_t = \sum_{j=1}^{T} sign(X_t - X_j) \tag{2-1}$$

where $t$ is an arbitrary observation point between 1 and T.

$$sign(X) = \begin{cases} 1 & if \quad X > 0 \\ 0 & if \quad X = 0 \\ -1 & if \quad X < 0 \end{cases} \tag{2-2}$$

Equation (2-3) also can be used to find $V_t$, where $R_t$ is the rank of $X_t$ in the sample of T observations. If there are ties in the data, average of the ranks will be used.

$$V_t = T + 1 - 2R_t \tag{2-3}$$

After finding $V_t$, the statistic $U_t$ is to be calculated as given in Equation (2-4),

$$U_t = U_{t-1} + V_t \qquad \text{For t=2,…, T.} \tag{2-4}$$

$$U_1 = V_1 \tag{2-5}$$

$U_T = 0$ always. (2-6)

In other words, $U_t$ is the cumulative sum of $V_t$.

To test the hypothesis, maximum absolute value of $U_t$ to be calculated. It is denoted by $K$, as presented in Equation (2-7).

$$K = \max_{1 \le t \le T} |U_t| \tag{2-7}$$

The observation point at where $\max|U_t|$ occurs will be the change point of the time series data.

There are two possible step changes, which are step up change and step down changes. Following method will be used to determine which type of change has occurred in the sample:

$$K^+ = \max_{1 \le t \le T} U_t \tag{2-8}$$

$$K^- = -\min_{1 \le t \le T} U_t \tag{2-9}$$

$K^+$ and $K^-$ are the maximum of $U_t$ and minimum of $U_t$ multiplied by -1 respectively.

$K^+$ would be large if $F_1(X) \le F_2(X)$ which is step up change and $K^-$ would be large if $F_1(X) \ge F_2(X)$ which is a step down change. Hence

$$K = \max(K^+, K^-) \tag{2-10}$$

Z value (the standardized value of *K*) will be calculated as;

$$Z = \frac{K}{T}\sqrt{\frac{3}{(T+1)}} \tag{2-11}$$

Standard normal distribution table will be used to find the significance of change.

### 2.3.1.2 Rank sum test

This is one of the frequently used powerful non-parametric tests to detect the change point (Black 1999). This test developed by Wilcoxon (1945) and Mann & Whitney (1947).

This is a rank based test and checking whether the sum of the ranks of one sample is sufficiently different from overall mean of the ranks to indicate that it is not part of a common population. Sampling distribution assumes that any sample from a population will have a sum of ranks close to the population mean, but not identical. Large samples' (which are considered as 10 or more) distributions of sum of ranks assumed to be normal with population mean (Black 1999).

Rank all data, from 1 (smallest) to $n_1 + n_2$ (largest). In the case of ties (equal data values), use average of the ranks.

Where two samples are spread evenly through the rank ordering, the rank sums for either sample will be equal to mean of rank sums;

$$\mu_w = n_1 \frac{(n_1 + n_2 + 1)}{2} \tag{2-12}$$

The standard error mean (SEM) of the sampling distribution of rank sums;

$$SEM = \sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}} \tag{2-13}$$

Where $n_1$ is number of samples of smaller rank sum and $n_2$ is number of sample of higher rank sum. In this test, minimum 25 is the sufficient sample size to use existing tables for normal distribution to test the hypothesis.

Z test will be used to find the probability of step change.

Test statistic z will be calculated as follows;

$$z = \frac{W - \mu_w}{SEM} \tag{2-14}$$

Where W is smaller of the two rank sums.

This test was used by Yue & Wang (2002) to analyse the influence of serial correlation on the accuracy of the test.

#### 2.3.1.3 Likelihood ratio test

This method tests whether the means in two parts of a record are different (for an unknown time of change). The test assumes that the data are normally distributed. This test had been developed by Hawkins (1977) and Worsley (1979).

Suppose that $X = X_1, X_2 ...., X_n$ is a sequence of random variables. Mean of first k observations denoted by $\bar{X}_k$ and the mean of last n-k observations by $\bar{X}_k'$. Sum of the squares of observations difference for a group split at k is given by;

$$S_k^2 = \sum_{i=1}^{k} (X_i - \bar{X}_k)^2 \tag{2-15}$$

And the normalised sum of squares between the groups given by;

$$T_k^2 = \frac{k(n-k)}{n} (\bar{X}_k - \bar{X}_k')^2, \quad \text{k=1,…,n-1} \tag{2-16}$$

Let $S^2 = S_n^2$ (2-17)

To get test statistic;

$$V = \max_{1 \le k \le n-1} \left| T_k \right| \frac{1}{S} \tag{2-18}$$

Since test static is given by;

$$W = \frac{V\sqrt{(n-2)}}{\sqrt{1-V^2}} \tag{2-19}$$

This test was used by Chiew & McMahon (1996) to detect trends in historical streamflow records.

#### 2.3.1.4 Student *t* test

It is a parametric test. This method tests whether the means of time series before and after the known change point are different. The test assumes that the data are normally distributed. This test introduced by Fisher (1925).

The Student's t test statistic t is (critical test statistic values for various significance levels can be obtained from Student's t statistic tables) calculated as follows;

$$t = \frac{(\bar{X}_1 - \bar{X}_2)}{S_{X_1X_2}\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}} \tag{2-20}$$

Where;

$$S_{X_1X_2} = \sqrt{\frac{(n_1-1)S_{X_1}^2+(n_2-1)S_{X_2}^2}{n_1+n_2-2}} \tag{2-20a}$$

Where $\bar{X}_1$ and $\bar{X}_2$ are the means of the first and second periods respectively, and $n_1$ and $n_2$ are the number of observations in the first and second periods respectively, and $S_{X_1X_2}$ is the sample standard deviation (of the entire $n_1$ and $n_2$ observations). Above formula is created for unequal sample size and equal variance. If it become equal, both $n_1$ and $n_2$ will be replaced by n.

(n-1) is the number of freedom for either group and $n_1 + n_2 - 2$ is the total number of degrees of freedom.

For this test, we have to input the suspected year of change to check the significance level of change.

This test used by McCabe & Wolock (2002) to analyse the step increase in streamflow in the United States.

#### 2.3.1.5 CUSUM test

This method tests whether the means of two parts, before and after the unknown change point of a time series data are different. The test assumes that the data are normally distributed. This method developed by Litchfield & Wilcoxon (1949).

It is assumed that this test is to detect a change in the mean of a time series data after 'm' observations;

$$E(X_i) = \mu \qquad i = 1, 2, 3...., m \qquad (2\text{-}21)$$

$$E(X_i) = \mu + \Delta \qquad i = m+1, m+2,...., n \qquad (2\text{-}22)$$

Where; $\mu$ : Mean prior to the change

$\Delta$ : The change in the mean.

The cumulative deviations from the means are calculated as;

$$S_0^* = 0 \qquad S_k^* = \sum_{i=1}^{k} (X_i - \bar{X}) \qquad k = 1, 2, 3, ...., n \qquad (2\text{-}23)$$

And the rescaled adjusted partial sums are obtained by dividing the $S_k^*$ values by the standard deviation;

$$S_k^{**} = S_k^* / D_x \tag{2-24}$$

$$D_x^2 = \sum_{i=1}^{n} \frac{(X_i - \bar{X})^2}{n} \tag{2-25}$$

The test statistic $Q$ is given by;

$$Q = \max \left| S_k^{**} \right| \tag{2-26}$$

It is calculated for each year and the highest value indicating the change point.

### 2.3.2 Trend detection techniques

There are several statistical tests available for trend detection. Kundzewicz & Robson (2004) are listed few statistical tests that can be used for trend analysis as follows;

i. Mann-Kendall test (MK)

ii. Spearman's rho test (SR)

iii. Linear regression test (LR)

MK and SR are rank based non-parametric tests to detect monotonic trend in time series data (Lehmann & D'Abrera 1975; Sneyers 1990). MK test has been popularly used to asses the trend in hydro-meteorological time series, but SR is seldom used (Hirsch et al. 1982). LR is parametric test and it assumes data are normally distributed (Kundzewicz & Robson 2004).

The outcome of trend analysis would help to formulate the effective water management policies as well as develop suitable mitigation measures to safeguard the water resources. In details, the outcome of extreme value trend analysis would help to forecast the pattern and severity of the future extreme events. This would facilitate to develop effective safety precautionary measures such as (i) for flooding, to increase the drainage capacity and redesign the stormwater drainage systems and (ii) for bushfire, to evacuate the people from fire prone area.

Various characteristics of these three test techniques are presented in Table 2.2.

Table 2.2.Characteristics of the three trend detection techniques

| **Test characteristics** | **Name of test** | | |
|---|---|---|---|
| | **Mann-Kendall** | **Spearman Rho** | **Linear Regression** |
| **Parametric/Non-parametric** | *Non-parametric* | *Non-parametric* | *Parametric* |
| **Data-driven/Rank-based** | *Rank-based* | *Rank-based* | *Data-driven* |
| **Sensitivity to outliers** | *Less sensitive to outliers* | *Less sensitive to outliers* | *Sensitive to outliers* |

### 2.3.2.1 Mann-Kendall test

Mann-Kendall test is a non-parametric test for identifying trends in time series data. This test compares the relative magnitudes of data rather than the data values themselves (Gilbert 1987). One of the benefits of this test is that the data need not to confirm to any particular distribution. Moreover, data reported as non-detects can be included by assigning them a common value that is smaller than the smallest measured value in the data test. This test assumes that there exists only one data value for a time period. When multiple data points exist for a single time period, the median value will be used.

The data values are evaluated as ordered time series. Each data value is compared to all subsequent data values. The initial value of the Mann-Kendall statistic S is assumed to be 0. If a data value from a later time period is higher than a data value from an earlier time period, S is increased by 1. On the other hand, if the data value from the later time period is lower than a data valued sampled earlier, is decreased by 1. The net result of increments and decrements yields the final value of S.

Let $x_1, x_2, x_3, \ldots, x_n$ represent n data points, then the Mann-Kendall test statistic S is given by;

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \tag{2-27}$$

Where $x_j$ are the sequential data values, n is the length of the data set, and

$$\mathrm{sgn}(x_j - x_i) = \begin{cases} 1 & if \quad x_j - x_i > 0 \\ 0 & if \quad x_j - x_i = 0 \\ -1 & if \quad x_j - x_i < 0 \end{cases} \tag{2-27a}$$

Mann (1945) and Kendall (1975) have documented that when n≥8, the statistic S is approximately normally distributed with the mean and variance as follows:

$$E(S) = 0 \tag{2-28}$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p - 1)(2t_p + 5)}{18} \tag{2-29}$$

where n is the number of data points, g is the number of tied groups (a tied group is a set of data having the same value), and $t_p$ is the number of data points in the $p^{th}$ group.

The standardized test statistic Z is computed by

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, & S < 0 \end{cases} \tag{2-30}$$

The standardized statistic Z follows the standard normal distribution with mean of zero and variance of one.

MK was used in trend detection works of Hirsch et al (1982), Chiew & McMahon (1993), Zhang et al (2004) and Yue et al (2002).

#### 2.3.2.2 Spearman Rho test

It is a non-parametric test.

This is a rank-based test that determines whether the correlation between two variables is significant. In trend analysis, one variable is taken as the time itself and the other as the corresponding time series data. This test had been developed by David (1951) and Kendall (1949).

Like the Mann-Kendall Test, the n time series values are replaced by their ranks.

Let $\{X_i, i = 1, 2, ...n\}$ be the dataset with $n$ number of data.

Null hypothesis $H_0$ assumes that there is no trend. Alternative hypothesis is that $X_i$ increases or a decrease with $i$, which means trend exists. The test statistic is given by (Sneyers 1990);

$$D = 1 - \frac{6\sum_{i=1}^{n}[R(X_i) - i]^2}{n(n^2 - 1)} \qquad (2\text{-}31)$$

Where $R(X_i)$ is the rank of $X_i$ in n dataset.

Distribution of D is asymptotically normal with the mean and variance as follows under null hypothesis (Lehmann & D'Abrera 1975; Sneyers 1990);

$$\mu(D) = 0 \qquad (2\text{-}32)$$

$$V(D) = \frac{1}{n-1} \tag{2-33}$$

Probability value of test statistic D is estimated using cumulative distribution function (CDF) as its statistics are fairly normally distributed with mean of zero and variance of $V(D)$.

Standardized statistic Z which follows standard normal distribution will be calculated using following standardization;

$$Z = \frac{D}{\sqrt{V(D)}} \tag{2-34}$$

The standardized statistic Z follows the standard normal distribution with mean of zero and variance of one.

Two of the few examples which used SR in their work are of Hipel & McLeod (1994) and McLeod et al (1983).

#### 2.3.2.3 Linear regression test

This is a parametric test which assumes the data are normally distributed. It tests whether there is a linear trend by examining the relationship between time $(X)$ and the variable of interest $(Y)$. This technique was developed by Sir Francis Galton (1894).

For given the dataset $(X_i, Y_i)$ with n data points, the regression gradient $(m)$ and the y-intercept $(b)$ are determined as follows;

The regression gradient "m" is given by the equation:

$$m = \frac{n\sum_{i=1}^{n} X_i Y_i - \sum_{i=1}^{n} X_i \sum_{i=1}^{n} Y_i}{n\sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i\right)^2} \tag{2-35}$$

and the y-intercept “b” is given by the equation:

$$b = \frac{\sum_{i=1}^{n} Y_i - m\sum_{i=1}^{n} X_i}{n} \tag{2-36}$$

The correlation coefficient R is:

$$R = \frac{n\sum_{i=1}^{n} X_i Y_i - \sum_{i=1}^{n} X_i \sum_{i=1}^{n} Y_i}{\sqrt{\left[n\sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i\right)^2\right]\left[n\sum_{i=1}^{n} Y_i^2 - \left(\sum_{i=1}^{n} Y_i\right)^2\right]}} \tag{2-37}$$

Where R, the correlation coefficient, gives a measure of the reliability of the linear relationship between x and y values.

The linear regression test assumes that the data are normally distributed and that the errors (deviations from the trend) are independent and follows the same normal distribution with zero mean.

## 2.4 Summary

A literature review climate change, the types of change that occur in climatic data and the statistical tests used to detect those changes are presented in this chapter. Mathematical statistics provides powerful tools which are invaluable for study of the changes in climatic variables.

This chapter presented five statistical techniques for step change analysis and three techniques for trend detection. Both parametric and non-parametric tests were used in this study. Although parametric tests are more powerful, they require more assumptions and they are sensitive to outliers than non-parametric tests. Non-parametric tests are less powerful, but they require fewer assumptions and are less sensitive to outliers. All the selected techniques were programmed in Microsoft Excel spreadsheets.

# 3 STUDY AREA AND METHODOLOGY

## 3.1 Introduction

This chapter first describes the case study catchment that has been used in this study, which is the Yarra River catchment. This section also describes the importance of this catchment for the management of Melbourne's water resources.

Even though several other hydro-climatic variables such as streamflow, evaporation, humidity, soil moisture etc. influence the water resources, temperature and rainfall have the maximum influence. Increase in temperatures will contribute to evaporation, which in turn will leads to the dangerous reduction in water levels of reservoirs. This when combined with reduction in rainfall will only exacerbate the problem. Therefore, rainfall and temperature were selected for change analysis in this study. The next section in this chapter presents the criteria and assumptions used for selecting the rain gauge and temperature measuring stations.

This is followed by the methodology, which includes the application of trend and abrupt change detection techniques on hypothetical datasets. To represent all possible types of changes in the selected climatic variables, hypothetical datasets were developed to test the suitability of the change detection techniques. The hypothetical data analysis is also presented in this section.

Based on this hypothetical data analysis, the methodology for analysis of change in real climatic datasets is then presented. Finally, a summary is presented at the end of this chapter.

## 3.2 The Case Study Catchment

The Yarra River catchment was considered in this study, since it is one of the important water catchments in Victoria. This is because it provides 70% of Melbourne's drinking water. Furthermore, more than one-third of Victoria's population live in this catchment and over one-third of Victoria's native plant and animal species can be found within this catchment (Melbourne Water 2010).

The Yarra River and its tributaries drain a catchment of approximately 3,755 $km^2$, extending from the headwaters in the Great Dividing Range to Port Phillip Bay. The upper reaches of the catchment have been reserved for water supply purposes for more than 100 years (Melbourne Water 2010). Most of the land along rivers and creeks in the middle and lower sections has been cleared for agriculture or urban development. As given in Figure 3.1, the catchment can be divided into three general sections based on its landuse pattern, which are forest, rural and urban areas. From the Great Dividing Range to the Warburton Gorge, the catchment consists of mainly dense and extensive forested area with less human population, which is defined as forest area. The area with limited urban development, from the Warburton Gorge to Warrandyte along the Yarra River, consists mainly of rural flood plains and valleys are defined as rural area. Finally, the area located downstream of Warrandyte along the Yarra River, which mainly consists of built-up surfaces (of Melbourne) such as paved roads, roofs, car parks, and residential and commercial buildings is defined as urban area (Pettigrove 1990). The catchment supports a range of uses valued by the Victorian community, including urban water supply, agricultural and horticultural industries. Therefore, the management of water resources within the Yarra River catchment is of great importance.

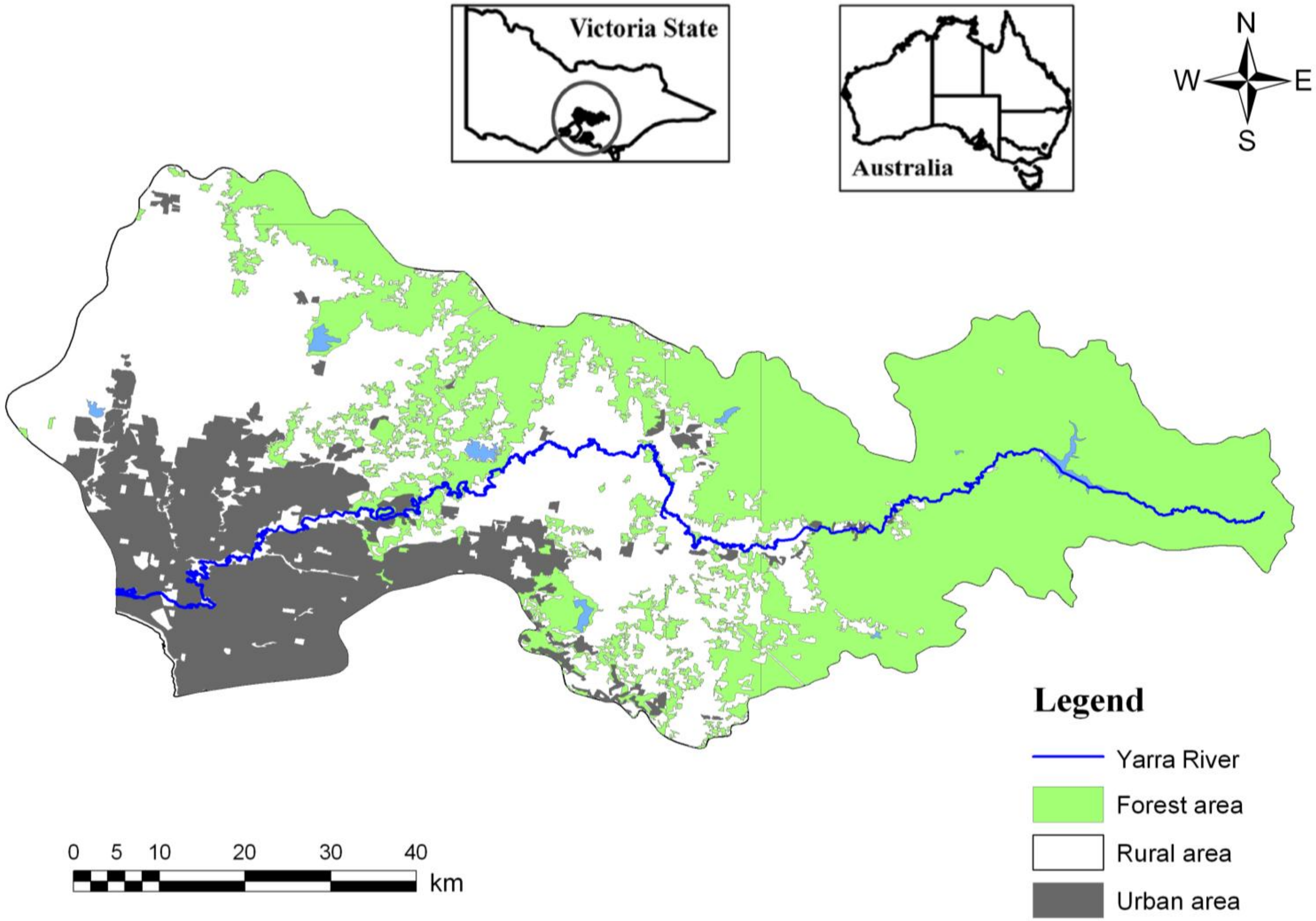



Figure 3.1 Land use pattern of Yarra River catchment

The annual rainfall in the catchment varies with altitude, from 1200 mm in the forested upper reaches of the catchment to around 660 mm in Melbourne (Pettigrove 1990). Maximum rainfall occurs during late autumn (May) and from late winter to early spring (August to September). Minimum rainfall occurs in the catchment from mid-summer to early autumn (January to March) (Sokolov & Black 1999). January and February are hottest months throughout the Yarra catchment, with average maximum temperature about 26˚C. In winter, the maximum temperature ranges from below 10°C in the high country to 13°C in coastal areas (Australia Travel Search 2008).

## 3.3 Criteria and Assumptions in Selection of Rainfall and Temperature Stations

Historic data of selected variables were acquired from the Bureau of Meteorology (Australia) database and the landuse and topographic data were obtained from Geosciences Australia.

Weather observation stations were selected across the Yarra River catchment to represent the three different landuse patterns. The catchment has its rain gauge stations which record 24-hour rainfall totals. For the better interpretation of the climate change in terms of significant slope or step change, long records of time series data are suitable. Since, a large number of rainfall stations which are located in all three different land use patterns consist of less than 80 years of data, the initial criterion considered for selecting the rain gauge stations was the length of dataset. From the original 180 rain gauge stations for which data was available, 129 stations were rejected as the available data duration was less than 80 years. The remaining 51 stations were considered for further analysis to select the most appropriate stations for this study.

The daily rainfall records of these rain gauge stations had days where data were either missing or were recorded as an accumulated value over several days. In Australia, there has been an increasing tendency for accumulated totals over recent decades, especially on weekends. Previous studies have used different methods for dealing with such accumulations and missing values. Suppiah and Hennessy (1996) distributed accumulations evenly over the preceding missing days and Hennessy et al. (1999)

rejected stations with a large number of accumulations or missing days in time series data. Karl et al. (1995) and Karl & Knight (1998) filled missing values by generating artificial rainfall amounts based on distribution of past rainfall at the same period of previous year. Suppiah & Hennessy (1996) found that, for stations with many accumulations, there is an impact on trends in percentiles when accumulations are either distributed or ignored.

In this study, the aim was to use more accurate and consistent dataset with minimal artefacts. Therefore, any accumulations were defined as missing data in this study. Then, from the remaining set of 51 rain gauge stations, only those stations were selected which had less than 300 days of missing data for the whole period of dataset and length of successive missing data was less than 30 days. By the use of these two criteria, 14 stations were selected.

Missing data were filled by the same daily rainfall recorded at the adjacent station according to the assumption that closer stations also had a similar rainfall pattern (Paterson et al. 1998). Out of the 14 selected stations, three stations were removed as each of them has a close station with better quality data. The removed three stations were Melbourne botanical garden, Doncaster and Warburton East. Melbourne botanical garden station is just 2 km away from Melbourne regional office station. Its data started from 1964 and there are consecutive 6 years of missing data between 1994 and 1999. Similarly, Doncaster station is just 4km Eltham station, data started from 1986 and consecutive 3 years of data missing between 1997-1999. But Warburton East doesn't have any missing data. Even though, compare with Warburton station which is just 4km away, Warburton east station's data length is too short (reading started from 1985).

As presented in Figure 3.2, the 11 rain gauge stations finally selected were spread over the three land use areas; five stations in urban, three in rural and three in forest. The name, numbers, geographical coordinates, altitude, land use pattern, data availability of the rain gauge stations and details of missing data that were filled using data from adjacent station are presented in Table 3.1. As can be seen in this table, the Melbourne Regional Office (MRO) rain gauge (Station no. 86071) has the longest rainfall dataset (from 1855 till date) with no missing data.

For the temperature analysis, 180 temperature measuring stations which record daily maximum and minimum temperature were selected within the Yarra River catchment. Compared with rainfall data, length of the temperature data availability was much lesser for all stations except Melbourne Regional Office. It was decided to choose one station per land use area as temperature variation between the adjacent stations is negligible. For urban land use area, Melbourne Regional Office was selected and for rural and forest land use area, Epping and Maroondah were selected respectively. These stations are presented in Figure 3.3 and their details are provided in Table 3.2.

Similar to the rainfall data, missing data of selected temperature gauging stations were filled by the data which was recorded at the adjacent station.

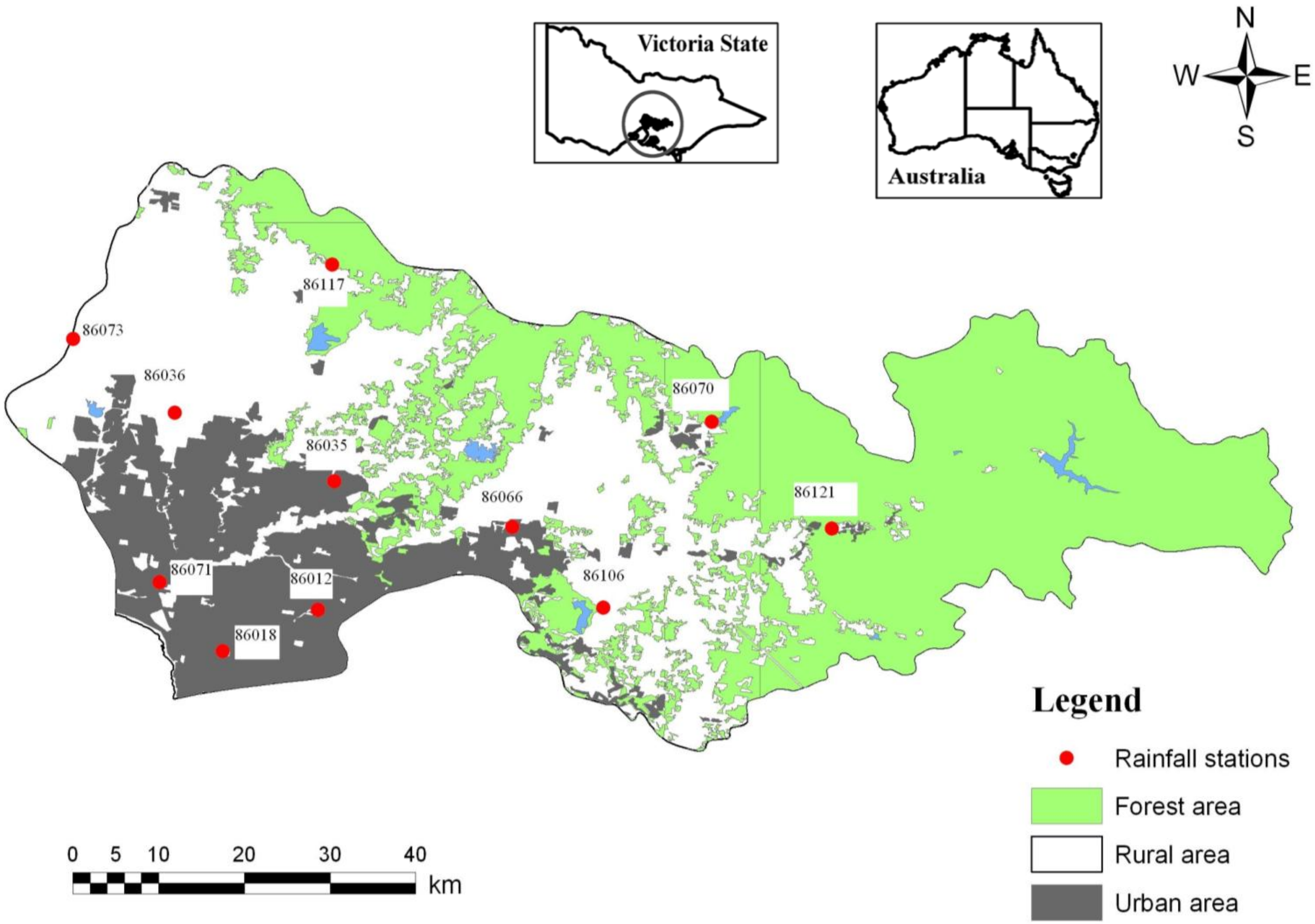



Figure 3.2.Yarra River Catchment showing selected rain gauge stations (with their station numbers)

Table 3.1. Description of rainfall gauge stations

| Station Number | Station Name | Latitude | Longitude | Height above MSL | Data availability | | Land-use pattern | Adjacent station used to fill data | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | From | To | | Station name | Distance (km) | Number of days of filled data | Percentage of missing data |
| 86071 | Melbourne (MRO) | -37.8075 | 144.9700 | 31.2 | 1856 | 2007 | Urban | N/A | N/A | 0 | 0.00% |
| 86018 | Caulfield | -37.8792 | 145.0361 | 48.8 | 1888 | 2006 | Urban | Hawthorn | 3.7 | 82 | 0.19% |
| 86012 | Box Hill | -37.8364 | 145.1364 | 97.0 | 1921 | 2004 | Urban | Mitcham | 5.3 | 125 | 0.41% |
| 86035 | Eltham | -37.7025 | 145.1533 | 35.0 | 1907 | 2006 | Urban | Manningham | 3.8 | 136 | 0.38% |
| 86066 | Lilydale | -37.7503 | 145.3403 | 113.0 | 1886 | 2007 | Urban | Montrose | 4.9 | 276 | 0.62% |
| 86036 | Epping | -37.6311 | 144.9858 | 140.0 | 1907 | 2007 | Rural | Preston | 8.2 | 189 | 0.52% |
| 86073 | Mickleham | -37.5547 | 144.8794 | 270.0 | 1903 | 2007 | Rural | Greenvale | 9.1 | 146 | 0.38% |
| 86106 | Silvan | -37.8339 | 145.4356 | 259.0 | 1921 | 2004 | Rural | Monbulk | 4.8 | 82 | 0.27% |
| 86117 | Toorourrong | -37.4769 | 145.1514 | 219.0 | 1893 | 2007 | Forest | Upper Plenty | 10.3 | 56 | 0.13% |
| 86121 | Warburton | -37.7517 | 145.6758 | 170.0 | 1879 | 2006 | Forest | Arrabri | 4.0 | 201 | 0.43% |
| 86070 | Maroondah | -37.6408 | 145.5497 | 149.0 | 1893 | 2007 | Forest | Prahran | 4.8 | 195 | 0.47% |

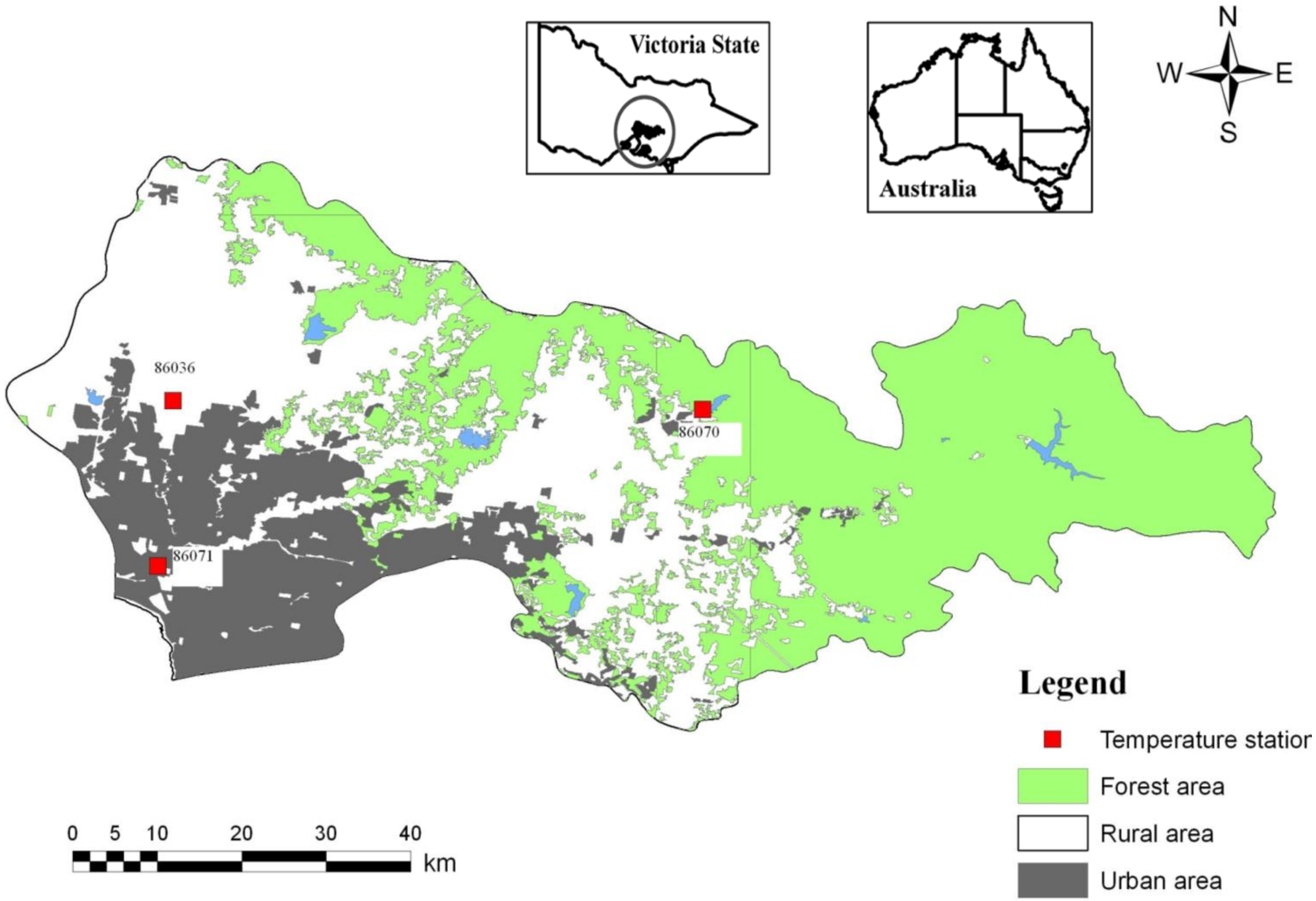



Figure 3.3.Yarra River Catchment showing selected temperature stations

Table 3.2.Description of temperature measuring stations

| Station Number | Station Name | Latitude | Longitude | Height above MSL | Data availability | | Land-use pattern | Adjacent station used to fill data | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | From | To | | Station name | Distance (km) | Number of filled data | Percentage of missing data |
| 86071 | Melbourne (MRO) | -37.8075 | 144.9700 | 31.2 | 1856 | 2008 | Urban | N/A | N/A | 0 | 0.00% |
| 86036 | Epping | -37.6311 | 144.9858 | 140.0 | 1979 | 2008 | Rural | N/A | N/A | 0 | 0.00% |
| 86070 | Maroondah | -37.6408 | 145.5497 | 149.0 | 1965 | 2006 | Forest | Prahran | 4.8 | 21 | 0.14% |

## 3.4 Methodology

To identify the changes in the selected variables, statistical methods were chosen as appropriate tools. For the accurate outcome from the statistical analysis, high quality historical dataset is necessary, which were available from Bureau of Meteorology databases. Statistical tests were used to check for the existence of change in the selected climatic variables.

The analysis for each of the two selected climatic variables was divided into two categories, namely, standard value and extreme value analysis. The analysis on standard (or regular) values of the variable was defined as standard value analysis. Observations taken for longer consistent timescales are suitable for standard value analysis (Storch & Zwiers 1999). For example, monthly rainfall trend is used for rainfall distribution on land and ocean (Barrett 1970) and annual rainfall for water supply planning (Turkes 1996). Minimum and maximum annual daily temperature trend are used to find spatial trend (Karl et al. 1993) and mean monthly temperature is used to find heat stress on society in terms of mortality rate (Larsen 1990). On the other hand, extreme value analysis can be defined as the analysis on extreme events in terms of their values, such as "extreme daily temperature, extreme daily rainfall, and unusual monthly temperature or storm events", or impact which the event has on the society, such as "excessive loss of life, excessive monetary loss, or both" (Easterling et al. 2000). Statistics related to extreme events play a major role in engineering practice for water resources design and management (Katz et al. 2002). As the smallest timescales of temperature and rainfall in both standard value and extreme value analysis were daily, data were downloaded at a daily timescale and then transformed in to monthly and annual timescales, as required.

The timescales compiled for standard value rainfall analysis in this study are monthly rainfall and annual rainfall. For standard value temperature analysis; minimum annual daily, maximum annual daily, mean monthly maximum and mean monthly minimum temperature are compiled. The timescales compiled for extreme value rainfall analysis in this study are highest annual daily rainfall and heavy precipitation days, which is defined as number of days per year with daily rainfall exceeding 10 mm by Bureau of Meteorology (2010). For extreme value temperature analysis, annual very hot days, which are number of days in a year which recorded maximum temperature more than

40˚C and annual very cold days, which is number of days in a year that recorded minimum temperature less than 10˚C are compiled.

As stated in Section 2.2, two types of changes in climatic variables have been reported in past studies, namely, step change (i.e., the changes that have occurred abruptly) and trend (i.e., changes that have occurred gradually) (Kundzewicz & Robson 2004). In addition to these two types of changes, there is another type of abrupt change that can occur in climatic time series data, which is an abrupt change in slope. The magnitude of the slope in a dataset might be different before and after a certain point. In this study, such a change is defined as "slope change" and the point at which slope change occurs is identified as the "break point".

In other words, an abrupt change can be either an abrupt change in mean (i.e., a step change) or an abrupt change in slope (called slope change). When an abrupt change occurs, a 'change point' can be identified, which is the time at which the slope or step change occurred. As presented in Figure 3.4, the first task entails identification of existence of abrupt change (which can either be a slope change or step change). If statistically significant abrupt change exists in a time series data, temporal trend analysis would be carried out for the broken dataset, i.e., separately for the period before and after the change point. If no statistically significant abrupt change exists, temporal trend analysis would be carried out for the whole unbroken period of time series data.

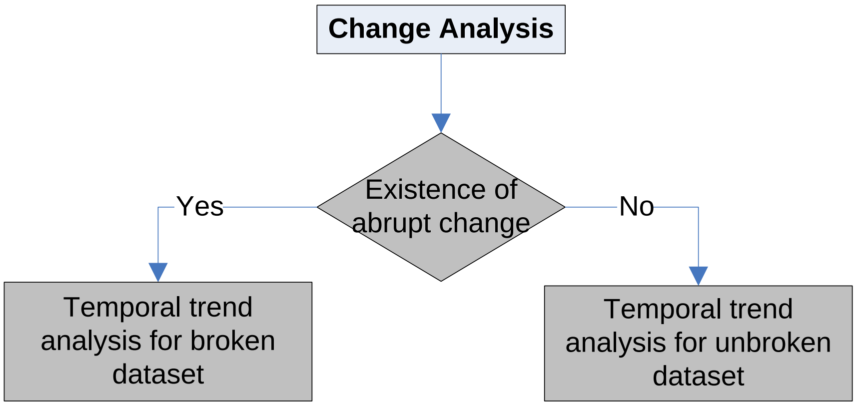



Figure 3.4.Flow chart of broad methodology

To locate the break point at which an abrupt slope change in time series data occurs, a technique called "Break point test" is proposed in this study. This test is an modification of a parametric test that was developed by Jones & Molitoris (1984) to detect the break point of two lines. The modified test is presented in the next sub-section.

### 3.4.1 Slope change detection using break point test

The problem of finding the break point of two straight lines joined at some unknown point has a long statistical history. Sprent (1961) and Shaban (1980) presented a common method to find the division of the points into two groups which gives the smallest residual sum of squares when a different lines are fit into each group. Rate of that change in time series data is represented by the slope of the best fit line. If there are two different rate of change (i.e. slopes) occurring before and after a particular point, it would affect the accuracy of forecast of that variable. This change point where the slope changes is called as the "break point" of the time series data.

Break point test would be able to locate the break point in time series data, the steps for which are presented below.

If $x_0$ is the position of the unknown break point, the equations of the two lines are

$$y = \beta_0 + \beta_1 x \qquad x \le x_0 \qquad (3\text{-}1)$$

and

$$y = \beta_2 + \beta_3 x \qquad x > x_0 \qquad (3\text{-}2)$$

Adding the following constraints forces the lines to join at $x_0$,

$$\beta_0 + \beta_1 x_0 = \beta_2 + \beta_3 x_0 \qquad (3\text{-}3)$$

One of the constants can be eliminated by solving this equation for $\beta_2$,

$$\beta_2 = \beta_0 + \beta_1 x_0 - \beta_3 x_0$$

Now the two equations are

$$y = \beta_0 + \beta_1 x \qquad x < x_0 \tag{3-4}$$

$$y = \beta_0 + \beta_1 x_0 + \beta_3 (x - x_0) \qquad x \geq x_0 \tag{3-5}$$

Residual sum of squares (RSS) is a measure of discrepancy between the actual data and an estimated model. In this study, straight line represents the estimated model. The estimated model which gives the lowest RSS is called as “best fit line”. The method is to be used to searches for the value of $x_0$ that minimizes the RSS for the above three parameter linear regression.

$$RSS = \sum_{i=1}^{n} (y_i - f(x_i))^2 \tag{3-6}$$

This is actually a four parameter regression involving three linear parameters, $\beta_0, \beta_1$ and $\beta_3$, and one nonlinear parameter, $x_0$. For each value of this parameter, a linear regression problem is solved and the RSS calculated. Different values of $x$ are tried until the value that minimizes the RSS in found. Then the break point will be calculated. When the break point is found, the mean square error (MSE) is calculated as

$$MSE = RSS_{\min} / (n - 4), \tag{3-7}$$

Where n is the number of observations. The degrees of freedom are $n-4$ since three linear parameters and one non-linear parameter $(x_0)$ have been estimated.

Since this is nonlinear regression, statistical tests are approximate rather than exact. An approximate F test can be calculated to test whether the broken line is a significantly better fit than a single straight line. Fit a single straight line to the data, and let the residual sum of squares be $RSS_s$. The F test has 2 and $n-4$ degrees of freedom. This test can be regarded as comparison of two different populations. The test statistic of F test is the ratio of two scaled RSS reflecting different sources of variability. These RSS are constructed so that the statistic tends to be greater when the null hypothesis is not true. RSS should be statistically independent in order for the statistic to follow the F-distribution. Hence,

$$F_{2,n-4} = (RSS_s - RSS_{\min})/(2MSE) \qquad (3\text{-}8)$$

A significant F indicates that the broken line is a better fit than a single straight line.

For a given climatic time series data, the point at which $RSS_{min}$ occurs can be calculated. Using that $RSS_{min}$ point, the break point can be calculated using the time series data. The break point would be the point where the two lines are forced to join ( $x_0$ in the above analysis). When the break point and the $RSS_{min}$ point are close to each other, it can be said that there is an existence of abrupt slope change.

### 3.4.2 Testing of abrupt change and trend analysis techniques using hypothetical datasets

Testing and validation of the statistical techniques prior to the application in real datasets (in this case, the datasets of climatic variables) is important to determine whether these statistical techniques are acceptable for what they are intended to be used (Law & Kelton 1991). To test and validate the selected statistical test methods, well behaved datasets with known characteristics of changes (i.e. slope change, step change and trend) was necessary. This was achieved by constructing hypothetical datasets, as discussed in following sub-sections.

#### 3.4.2.1 Construction of hypothetical datasets

Several hypothetical time series datasets were generated to cover all possible types of changes that may occur in real rainfall and temperature datasets and the change characteristics such as abrupt change and trend. The types of developed hypothetical datasets are as follows:

i. One constant mean to another constant mean (an abrupt step change)
ii. Constant mean to trend (an abrupt slope change)

iii. One trend to another trend (an abrupt slope change)

Hypothetical data representing annual rainfall were developed for each type of the above mentioned three changes. These datasets represent standard values with an annual timescale. However, once the techniques are tested and validated, they will be equally valid for the standard value analysis with any timescale (annual, monthly or daily timescales). Similarly, they will be valid for extreme value analysis. Furthermore, once the techniques are tested and validated for hypothetical data representing annual rainfall data, they are also valid for temperature datasets. In these hypothetical data tests, data will be merely considered as numbers, irrespective of variable (rainfall or temperature), timescale, or the kind of analysis (standard or extreme value).

Hundred years of hypothetical annual data were created for each type of change. As described in Section 2.2, a minimum of 10 data points is a sufficient sample size to use existing statistical tables for normal distribution to test a hypothesis (Black 1999). Hypothetical data for each of the three hypothetical cases were created to span between years 1900 and 1999 with the abrupt change in the year 1945.

In each hypothetical dataset, initial dataset was developed without any variation (or fluctuation). However, in reality, there will be variations in the dataset of any climatic variable. Therefore, to produce realistic hypothetical datasets similar to real datasets and to improve the quality of the validation, two types of variations, uniform variation and random variation, were also considered in each hypothetical dataset. In uniform and random variations, the means were kept same as that in the dataset with no variation.

Figure 3.5 represents the hypothetical case developed to represent one constant mean to another constant mean type of change (which is an abrupt step change). This dataset shows a constant mean value of 200 mm from 1900 to 1945, a jump of 100 mm and then a constant mean value of 300 mm between 1946 and 1999. Uniform variation demonstrates a fluctuation of 40 mm up and down from the mean in the dataset without fluctuation. Random variation was developed by generating evenly distributed random real number within 40 mm up and down to preserve the fixed mean values. Figure 3.6 presents a real data example of mean change which occurred in the annual rainfall at

Box Hill station. Annual rainfall data considered was between 1921 and 1990 and the step change was observed at 1948.

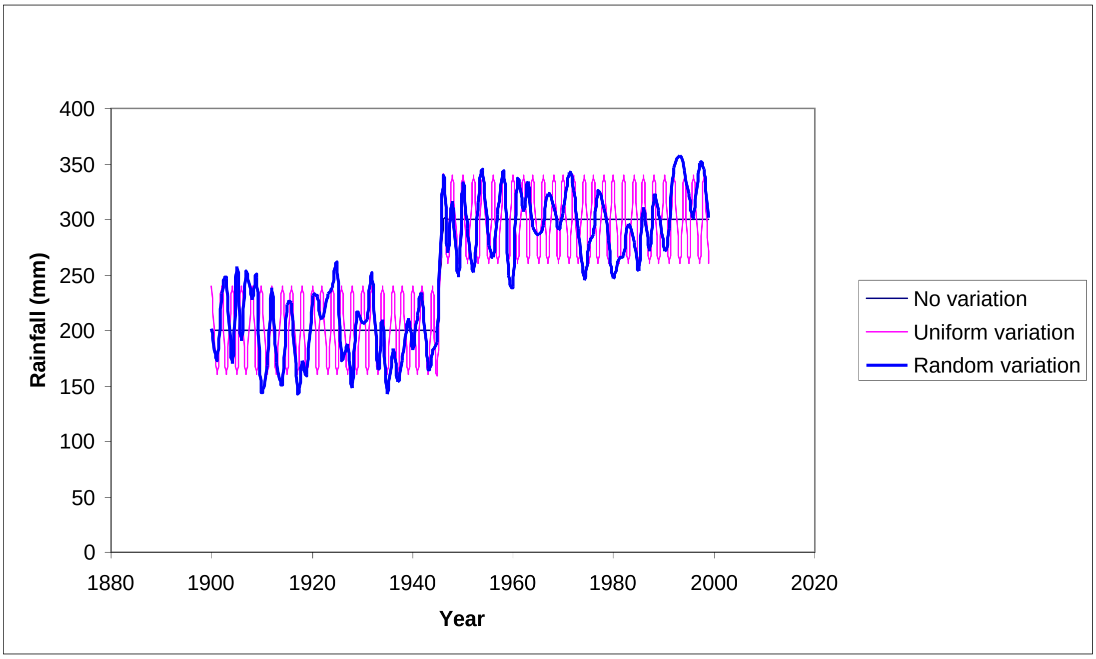



Figure 3.5 Hypothetical dataset with one constant mean to another constant mean

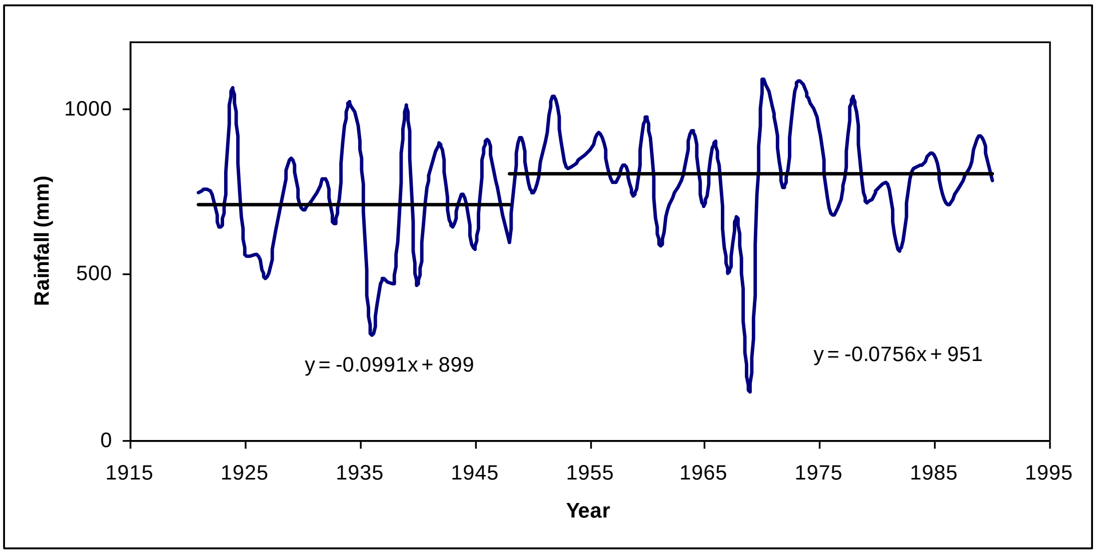



Figure 3.6 Annual rainfall at Box Hill with a step change in 1948

Figure 3.7 represents the hypothetical dataset developed to represent one constant mean to a trend type of change. Before the change point in 1945, the data are similar to that in Figure 3.5. From 1946 to 1999, a constant increasing trend of 4 mm/year was considered. Uniform and random variations were considered as in Figure 3.5. Figure 3.8

presents a real example of this case, which is the annual highest temperature at Melbourne Regional Office, with a change in 1996.

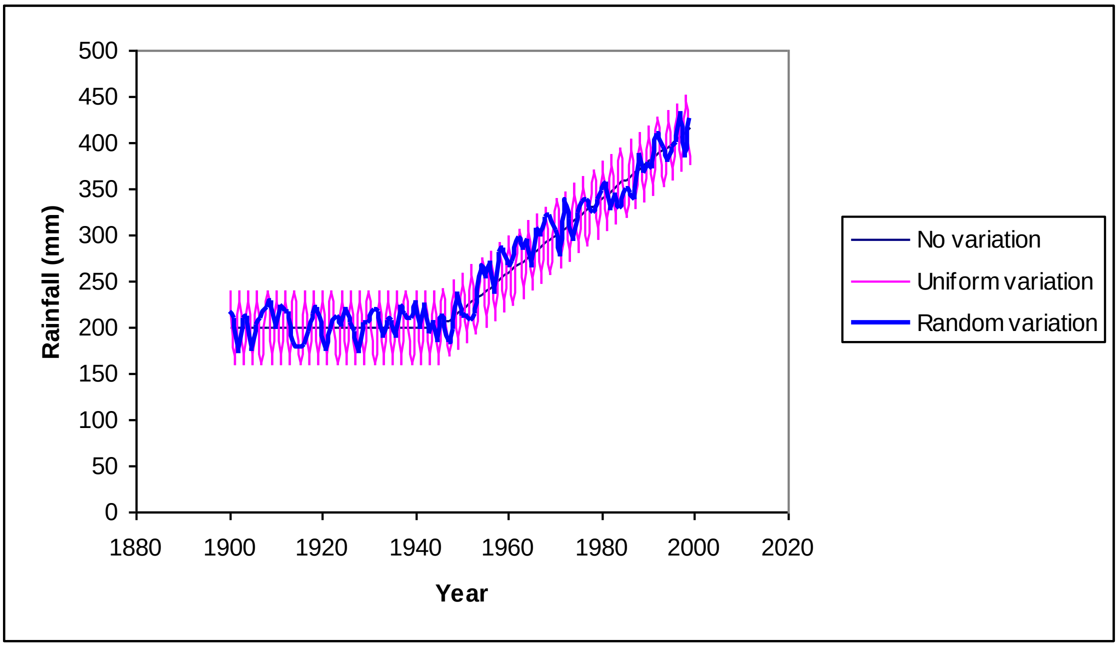



Figure 3.7 Hypothetical dataset with one constant mean to trend

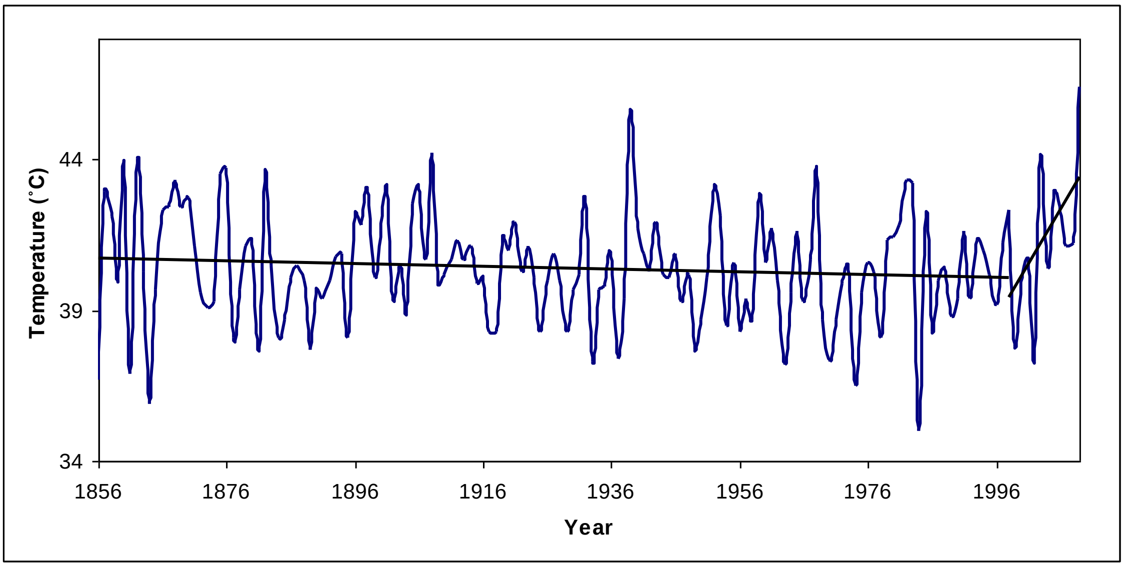



Figure 3.8 Annual highest temperatures at MRO with an abrupt slope change in 1996

Figure 3.9 represents the third hypothetical case developed to represent one increasing trend to another increasing trend (which is an abrupt slope change). This dataset is similar to that of Figure 3.7, except that the constant increasing trend of 2 mm/year is introduced to the data from 1900 to 1945 and for data from 1946 to 1999, an increasing trend of 8 mm/year is introduced. Also uniform variation's fluctuation value was kept as 80 mm. Random variations were considered as done before. Figure 3.10 presents a real data example of this case, which was observed in the annual lowest temperatures at the station in Epping with an abrupt slope change in 1981.

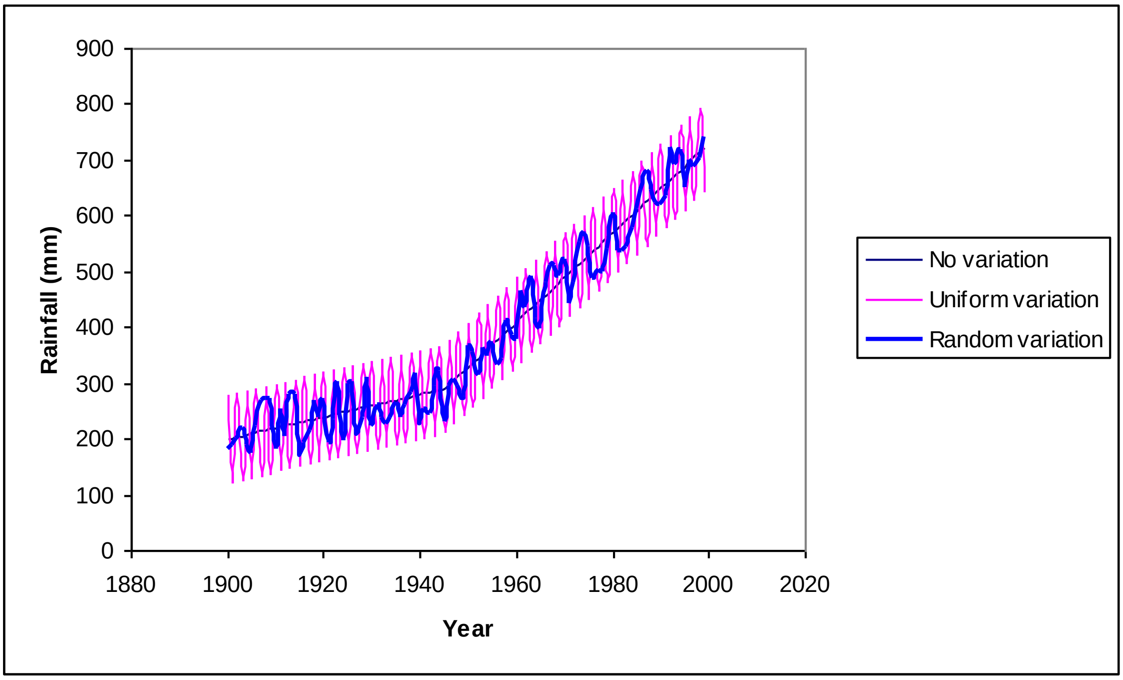



Figure 3.9 Hypothetical dataset with one increasing trend to another increasing trend

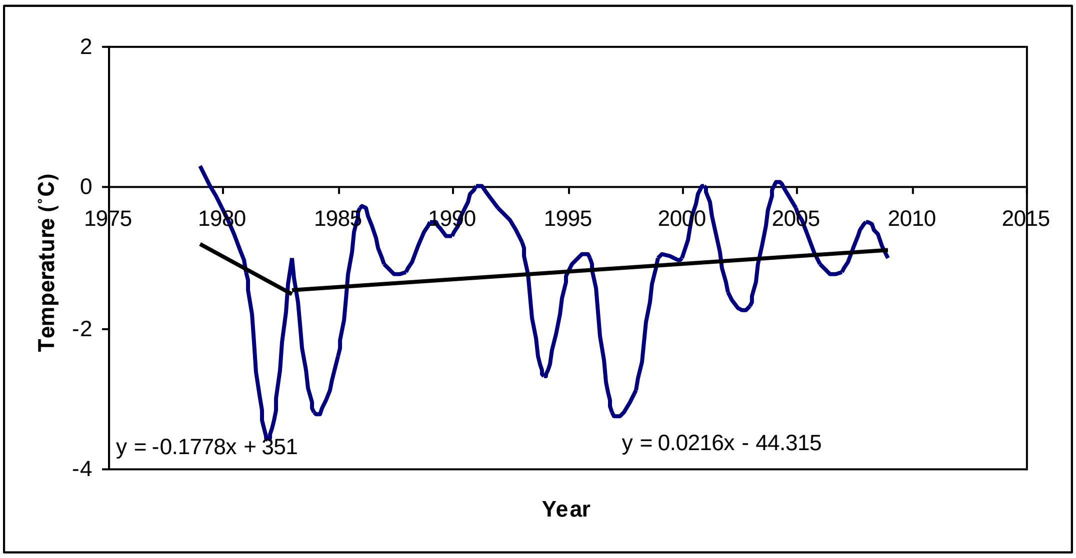



Figure 3.10 Annual minimum temperatures at Epping with a slope change in 1981

### 3.4.2.2 Testing of abrupt change analysis techniques

Statistical techniques for slope change and step change detection, as described in Section 2.2 were used to locate the change point for all three hypothetical data cases (Figure 3.5, Figure 3.7 and Figure 3.9). Table 3.3 presents the results of the analysis of using the statistical techniques on the hypothetical datasets, which provide the detected change point. As mentioned in Section 2.2, Median change point test and Rank-sum test are rank based tests and, Likelihood ratio test and Student t test are data driven tests. Rank-sum test and Student t test were given the maximum statistical significant level (99%) step change at the years are selected by Median change point test and Likelihood ratio test respectively for all types of hypothetical datasets.

Table 3.3. Change points of abrupt change analysis on hypothetical dataset

| **Hypothetical dataset** | | **Methods tested** | | | |
|---|---|---|---|---|---|
| | | **Median Change point** | **Likelihood Ratio** | **CUSUM** | **Break point method** |
| Mean Change (Figure 3.5) | No variation | 1945 | 1945 | 1945 | N/A |
| | Uniform variation | 1945 | 1945 | 1945 | N/A |
| | Random variation | 1945 | 1945 | 1945 | N/A |
| Constant mean to trend (Figure 3.7) | No variation | 1950 | 1965 | 1959 | 1945 |
| | Uniform variation | 1959 | 1965 | 1959 | 1944 |
| | Random variation | 1954 | 1958 | 1953 | 1947 |
| One trend to another trend (Figure 3.9) | No variation | 1949 | 1961 | 1957 | 1945 |
| | Uniform variation | 1955 | 1961 | 1957 | 1944 |
| | Random variation | 1956 | 1957 | 1957 | 1948 |

All the techniques detected the change points as given in Table 3.2 with 99% or more significance level. From the results given in the table, for the first hypothetical case of mean change, the change point is accurately located by all methods while for the other two hypothetical cases, the change point is most closely located by the Break point technique.

### Conclusion

The basic assumption of all step change detection techniques was that the mean of the dataset is constant before and after the step change. The point where the maximum jump occurred is defined as change point. For slope change, rate of increase or decrease of magnitude of the data in a dataset is different before and after the change point. Based on these assumptions, hypothetical dataset were developed and analysed.

For the first hypothetical case of abrupt step change, all techniques correctly detected the change point as 1945. For the second and third hypothetical cases of constant mean to trend and one trend to another trend, change points were detected later than 1945 (as observed in Table 3.2). So, according to the test results, it is obvious that maximum jump occurred at the years as mentioned in Table 3.2, which was not at 1945. But, for those two hypothetical cases, 1945 was the year when the actual change occurred. The Break point method is the only technique which has closely picked the change points for all three hypothetical cases.

Hence, abrupt change analysis has to be started with Break point test. If that abrupt change is not abrupt slope change, then abrupt step change analysis should be carried out using Median change point test since, it was proven as a best abrupt step change detection technique among others.

## 3.4.2.3 Testing of trend analysis techniques

Similar to the testing of abrupt change detection techniques, trend detection techniques also were tested for all three cases of hypothetical data (Figure 3.5, Figure 3.7 and Figure 3.9). There are three statistical techniques which are Mann-Kendall test, Spearman Rho test and Linear Regression test were selected for trend detection analysis. Among these techniques, as mentioned Section 2.2, Mann-Kendall test and Spearman Rho tests are non-parametric tests while Linear Regression test is a parametric test. Trend analysis was carried out on three different sets of data, which are; whole 100 years of data, first 45 years (1900-1945) and remaining 55 years (1946-1999) of data.

Table 3.4 presents the trend analysis results of developed hypothetical cases. Only 99% statistically significant trend and non-statistically significant trend were detected by selected trend detection techniques.

Table 3.4.Trend analysis result of hypothetical data

| Hypothetical dataset | | Methods tested | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Mann Kendall | | | Spearman Rho | | | Linear Regression | | |
| | | Full | Before 1945 | After 1945 | Full | Before 1945 | After 1945 | Full | Before 1945 | After 1945 |
| Mean Change | No variation | 99% | NS | NS | 99% | 99% | 99% | 99% | 99% | 99% |
| | Uniform variation | 99% | NS | NS | 99% | 99% | 99% | 99% | NS | NS |
| | Random variation | 99% | NS | NS | 99% | NS | NS | 99% | NS | NS |
| Constant mean to trend | No variation | 99% | NS | 99% | 99% | 99% | 99% | 99% | 99% | 99% |
| | Uniform variation | 99% | NS | 99% | 99% | 99% | 99% | 99% | NS | 99% |
| | Random variation | 99% | NS | 99% | 99% | NS | 99% | 99% | NS | 99% |
| One trend to another trend | No variation | 99% | 99% | 99% | 99% | 99% | 99% | 99% | 99% | 99% |
| | Uniform variation | 99% | 99% | 99% | 99% | 99% | 99% | 99% | 99% | 99% |
| | Random variation | 99% | 99% | 99% | 99% | 99% | 99% | 99% | 99% | 99% |

NS: Non Significant

## Conclusion

All three techniques revealed that there were increasing trends at 99% significance level when whole 100 years of data was taken into account. It means, if there is a significant increasing or decreasing values at the initial and later part of dataset, all three techniques would conclude that there is a significant trend, regardless of the pattern of variation of the dataset.

Then these techniques are applied to the datasets which occurred before and after 1945. As presented Table 3.3, Mann-Kendall test did not detect any trend when mean value in the dataset remains constant. It has only detected the trend when the dataset consists of increase in the mean value. From the above given testing results, it is revealed that Spearman Rho test has shown significant trend even when the mean value remains constant. Therefore, this test is not suitable especially in situations when the mean value does not change. As far as Linear Regression test is considered, it has the same problem as Spearman Rho test when the mean value of the data is constant, i.e., it detects a significant trend when none exists.

Thus, all the selected trend detection techniques are validated with the following special characteristics individually:

- Mann-Kendall test is only able to detect increasing or decreasing trend.

- On the other hand, both Spearman Rho test and Linear Regression test wrongly detect a significant trend even when the data has a constant mean. Both these tests detect increasing and decreasing trends correctly.

So, as our aim of the study was detecting the changes, Spearman Rho and Linear Regression tests are not suitable. Hence, since the Mann-Kendall test is able to detect the trends correctly for all the hypothetical cases, this technique will be used for trend analysis in the real dataset.

### 3.4.3 Methodology to analyse real climatic data

Based on the analysis for hypothetical datasets presented in the previous section, the methodology for change analysis of real climatic dataset was developed, which is presented in Figure 3.11.

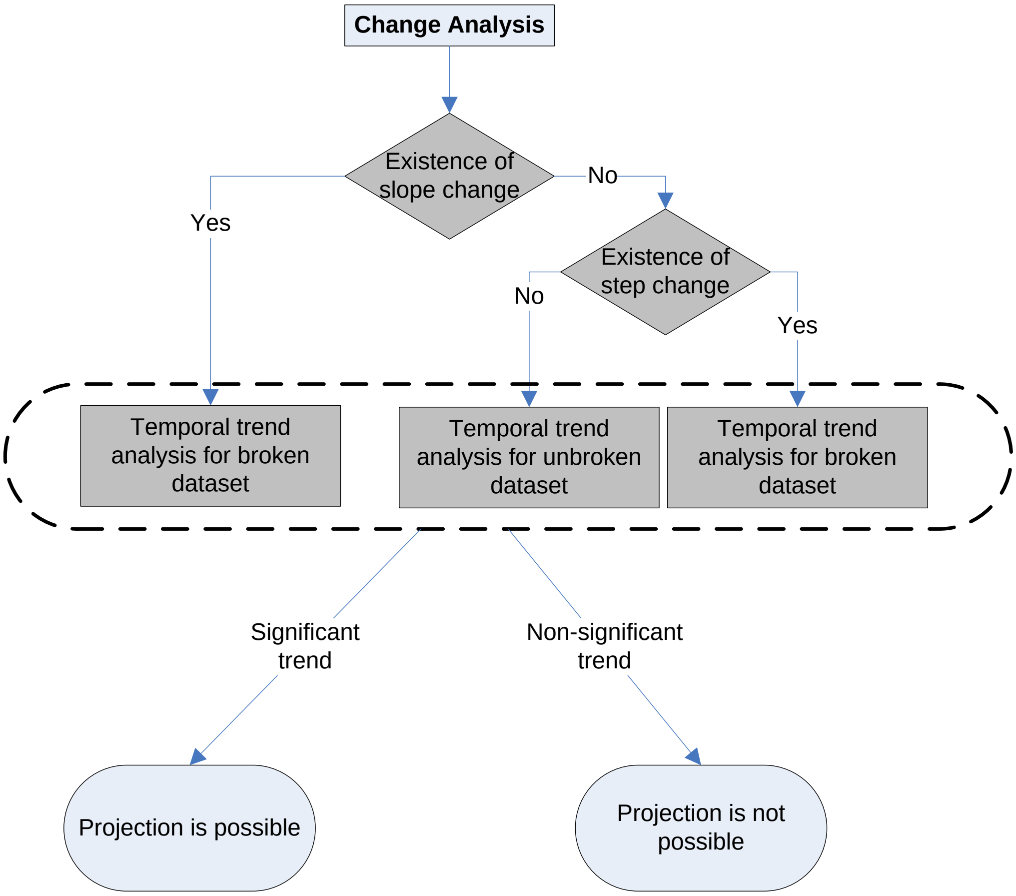



Figure 3.11 Flowchart presenting methodology for change analysis of real dataset

As presented in Figure 3.11, change detection analysis should start with checking for the occurrence of abrupt change in dataset. To check for occurrence of abrupt change, the break point method would be first applied to check for existence of slope change. As mentioned in Section 2.2, minimum RSS point and break point would be calculated. If these two points are close together, then that change is a slope change and if those are apart, that change is considered a step change and step change analysis has to be conducted.

For step change analysis, the Median change point test will be applied to check for a significant step change. Median change point test was selected for the step change detection because this method identified the step change most accurately in the hypothetical data analysis. As mentioned in Section 2.2, if a significant abrupt change (either slope change or step change) is detected in a climatic variable, it is assumed that the climatic pattern of that region has changed from one to another. That pattern will remain till the next occurrence of another abrupt change. So, if a significant abrupt change is detected, the dataset should be split into two sets, one before and the other after the change point, for trend analysis since the climatic pattern is different before and after the change point. Then the trend analysis will be carried out using the Mann-Kendall test on the split dataset before and after the change point. As mentioned in Section 2.2, if a significant trend is detected, it is assumed that trend will continue in the future. Hence, projection of the climatic pattern is possible.

If the step change is not significant, trend analysis has to be carried out for the unbroken dataset. As before, if the trend is significant, forecasting is possible and vice versa.

## 3.5 Summary

To detect the climate change and its implications on water resources, the Yarra River catchment was selected as the study area since it is the most important catchment for Melbourne. This is so because majority of the water requirements of Melbourne is being provided by this catchment. To identify the climate change, it is necessary to identify the changes in climatic variables related to water resources. Even though there are numerous climatic variables existing, only temperature and rainfall were selected for this study as these are the major variables that influence a catchment's water resources.

There are three types of changes, which are slope change, step change and trend that can occur in real climatic data. In climate change studies, that change detection is the demonstration that the change has occurred in a defined statistical sense. So, to identify the changes, Break point test to detect the slope change, five statistical techniques, which are Median Change Point test, Rank Sum test, Likelihood Ratio test, Student t test and CUSUM test for step change detection and three statistical techniques for trend detection, which are Mann-Kendall test, Spearman Rho test and Linear regression test were selected. To test and validate these methods, it is necessary to develop well behaved datasets with the characteristics of change (i.e. slope change, step change and trend) well defined. There are nine different hypothetical datasets were developed with these characteristics. To validate these techniques, abrupt change detection techniques were used to locate the change point and the trend detection techniques were used to detect the trend of the developed hypothetical datasets.

From the hypothetical data analysis, it was revealed that the Break point method accurately detects abrupt changes in slope and the Median change point test is the most accurate of all techniques for detecting abrupt step changes. As far as detection of trends is concerned, the Mann-Kendall test correctly detected the trends for all hypothetical cases. Thus, these techniques which have been successfully tested for the hypothetical datasets would be used for the change analysis of the real climatic datasets.

# 4 CHANGE DETECTION IN RAINFALL

The effects of long term natural climate variability and human induced climate change on rainfall variability have become the focus of much concern and recent research efforts. All water that sustains human life ultimately comes from rainfall. Latent heating from rainfall is the main driver of the atmospheric water cycle, which strongly influences the Earth's weather and climate.

As described in Section 2.1, Victoria has warmed at the rate of 1.06°C per century since 1950 and this warming will have severe consequences for the water cycle since it will bring changes in precipitation patterns with increased risk of droughts and floods. Statistical analysis is an appropriate tool to reveal these changes. Since various timescales are required for different kinds of applications, this chapter presents the results of statistical analysis of observed temporal variability of rainfall at different timescales within the Yarra River catchment. This analysis uses rainfall data at annual and monthly timescales**.** Data were collected from stations located in each of the three land use areas within the Yarra River catchment, namely, urban, rural and forest areas. The analysis presented in this chapter aims to analyse and detect the type of change in historical rainfall (whether abrupt change or trend) that had occurred in the catchment and also to investigate if there is a significant difference in the detected changes between the three land use areas.

The statistical techniques used for change detection in this chapter are those that were selected based on the hypothetical data analysis presented in Chapter 3. The technique selected to detect abrupt change in slope was the Break Point method, whereas abrupt step change would be detected using the Median Change Point test. Trends in the data would be detected using the Mann-Kendall test.

This chapter initially describes the standard value analysis of historic rainfall data, which includes both abrupt change (slope as well as step change) and trend analysis. Along the same lines, change analysis for extreme values of rainfall is then presented. Based on the analysis and results, conclusions are finally drawn at the end of this chapter.

## 4.1 Standard Value Analysis

Standard value analysis means that observed regular values of the variable are analysed to detect any changes. For standard value analysis, longer timescales are taken into consideration and in this study, annual and monthly timescales of historic rainfall data are used. Since the timescales are long, they are able to reveal the notable or significant changes in long-term climatic pattern. Standard value rainfall analysis would provide insight into both the spatial and temporal distribution of rainfall, which in turn would support the long term water allocations and supply operations.

Historic rainfall data from all the 11 stations which were selected to represent the three different land use areas within the Yarra catchment are used for the analysis. Annual rainfall data were derived from the available data that was at a daily timescale. Time series plots of annual rainfall data for urban, rural and forest stations are presented in Figure 4.1, Figure 4.2 and Figure 4.3 respectively. In the same way, monthly rainfall data for the twelve months were also derived from daily data for all the 11 stations.

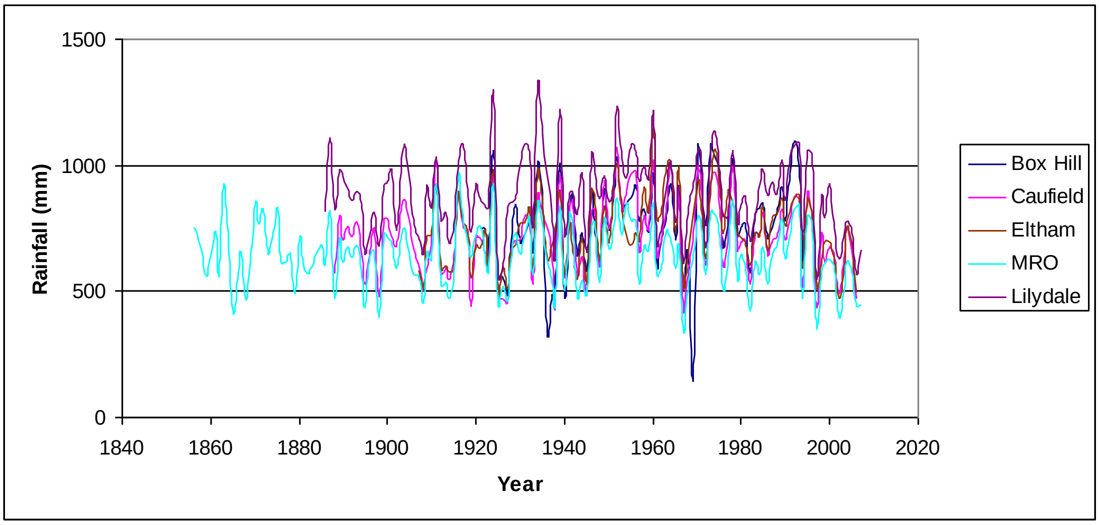



Figure 4.1 Annual rainfalls for stations located in urban areas

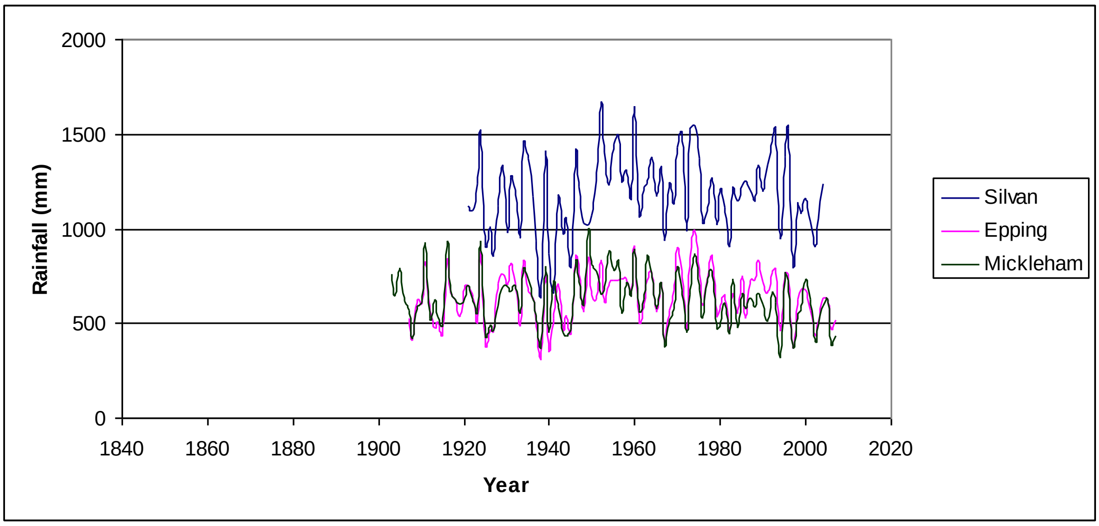



Figure 4.2 Annual rainfalls for stations located in rural areas

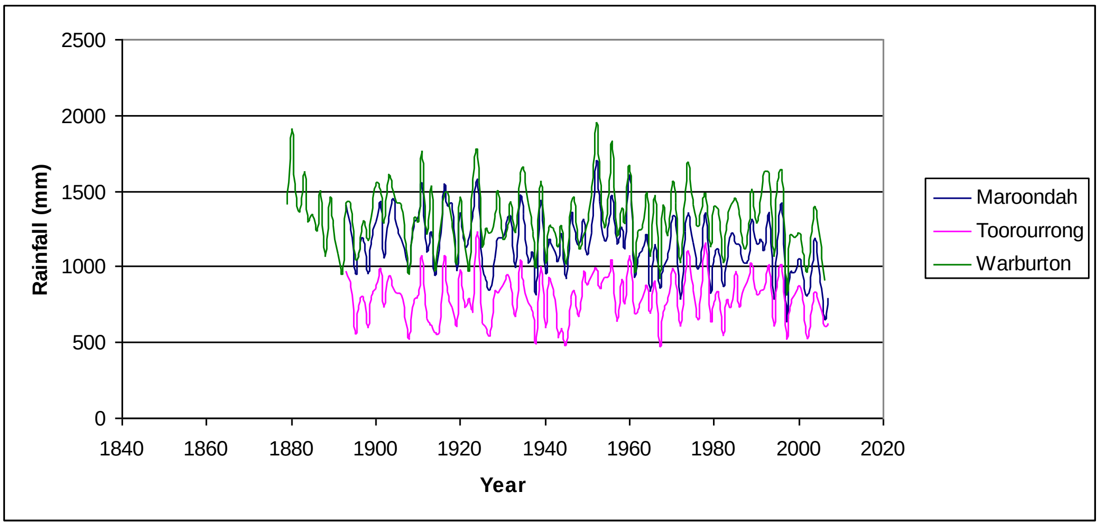



Figure 4.3 Annual rainfalls for stations located in forest areas

The following sub-sections present the analysis and results for detecting abrupt change (which includes slope and step change) and trend for the 11 rainfall measuring stations.

### 4.1.1 Slope change analysis

This section aims to detect if an abrupt change has occurred in the slope of rainfall data and if it has occurred, then to identify the point at which the change occurred, which is defined as the slope change point. In this analysis, the Break point method was used to locate the slope change point in the rainfall data at two timescales, which are annual and monthly timescales.

#### 4.1.1.1 Analysis for annual rainfall

As mentioned in Section 2.2.1, in the Break point method, the first step is to locate the minimum RSS point and the break point for each station. The minimum RSS points and the break points for the 11 stations are presented in Table 4.1.

Table 4.1 Slope change analysis for annual rainfall data

| Station | Min RSS point | Break point | Existence of Slope change |
|---|---|---|---|
| Box Hill | 1971 | 1994 | No |
| Caulfield | 1948 | 1978 | No |
| Eltham | 1957 | 1973 | No |
| MRO | 1996 | 1955 | No |
| Lilydale | 1996 | 1981 | No |
| Silvan | 1950 | 5570 | No |
| Epping | 1945 | 2104 | No |
| Mickleham | 1945 | 2037 | No |
| Maroondah | 1945 | 2124 | No |
| Toorourrong | 1948 | 2045 | No |
| Warburton | 1996 | 2031 | No |

According to the results presented in Table 4.1, most of the stations (6 out of 11 stations) had the minimum RSS point at around 1945 and other three stations had 1996 as the minimum RSS point. But none of the break points are close to the corresponding minimum RSS points. Hence, it can be concluded that no abrupt slope change had occurred in the annual rainfall data for all the 11 stations.

#### 4.1.1.2 Analysis for monthly rainfall

Similar to the slope change analysis for annual rainfall, analysis is carried out for monthly rainfall data. Break point analysis results (i.e. the minimum RSS point and the break point) for all 12 months at each of the 11 stations are presented in Table 4.2.

Table 4.2 Slope change analysis for monthly rainfall data

| Stations | Jan | | Feb | | Mar | | Apr | | May | | Jun | | Jul | | Aug | | Sep | | Oct | | Nov | | Dec | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP |
| Box Hill | 1969 | 1990 | 1964 | 1990 | 1969 | 1948 | 1969 | 1917 | 1947 | 1963 | 1979 | 1932 | 1950 | 1965 | 1950 | 1985 | 1949 | 1988 | 1946 | 1905 | 1948 | 1963 | 1963 | 1977 |
| Caulfield | 1969 | 1988 | 1917 | 1956 | 1914 | 1948 | 1914 | 1973 | 1950 | 1958 | 1911 | 1933 | 1944 | 1973 | 1950 | 1997 | 1949 | 1958 | 1946 | 1955 | 1938 | 1949 | 1945 | 1989 |
| Eltham | 1920 | 1948 | 1973 | 1966 | 1996 | 1926 | 1996 | 1945 | 1948 | 1915 | 1974 | 1949 | 1944 | 1963 | **1950** | **1949** | 1951 | 1926 | 1946 | 1874 | 1933 | 1948 | 1963 | 1926 |
| MRO | 1874 | 1955 | 1915 | 1928 | 1932 | 1988 | 1932 | 1963 | 1948 | 1917 | 1955 | 1933 | 1966 | 1949 | 1950 | 1963 | 1924 | 1988 | 1894 | 1969 | 1893 | 1959 | 1993 | 1968 |
| Lilydale | 1905 | 1956 | 1973 | 1955 | 1933 | 1922 | 1933 | 1963 | **1947** | **1948** | 1911 | 1918 | 1966 | 1932 | 1950 | 1935 | 1949 | 1922 | 1958 | 1925 | 1938 | 1956 | 1936 | 1922 |
| Silvan | 1925 | 1966 | 1973 | 1955 | 1960 | 1998 | 1960 | 1999 | 1950 | 1935 | 1979 | 1917 | 1945 | 1918 | **1950** | **1951** | 1951 | 1998 | 1958 | 1948 | 1944 | 1988 | 1983 | 1998 |
| Epping | 1952 | 1926 | 1945 | 1959 | 1932 | 1956 | 1932 | 1973 | 1948 | 1958 | 1986 | 1932 | 1944 | 1915 | 1951 | 1973 | 1940 | 1956 | 1990 | 1975 | 1944 | 1990 | 1945 | 1956 |
| Mickleham | 1975 | 1988 | 1963 | 1945 | 1918 | 1966 | 1918 | 1973 | 1970 | 1983 | 1958 | 1970 | 1965 | 1932 | 1948 | 1915 | 1966 | 2011 | 1963 | 1948 | 1959 | 1978 | 1935 | 1966 |
| Maroondah | 1955 | 1922 | 1963 | 1950 | 1949 | 1965 | 1949 | 1915 | 1973 | 1964 | 1922 | 1960 | 1965 | 1933 | 1923 | 1973 | 1924 | 1955 | 1957 | 1969 | 1910 | 1966 | 1992 | 1965 |
| Toorourrong | 1969 | 1998 | 1962 | 1948 | 1933 | 1922 | 1933 | 1874 | 1950 | 1973 | 1911 | 1973 | 1946 | 1960 | 1952 | 1912 | 1925 | 1666 | 1915 | 1926 | 1938 | 1999 | 1951 | 1922 |
| Warburton | 1969 | 1922 | 1964 | 1929 | 1950 | 1988 | 1950 | 1975 | 1983 | 1963 | 1976 | 1945 | 1992 | 1933 | 1993 | 1955 | 1980 | 1998 | 1958 | 1996 | 1978 | 1945 | 1928 | 1988 |

Shaded months are 99% statistically significant
RSS – The minimum RSS point
BP – The break point

From the results presented in Table 4.2, it can be observed that only Eltham, Lilydale and Silvan are showing statistically significant slope change for monthly rainfall. Eltham and Silvan had break points in the rainfall for the month of August in 1949 and 1951 respectively, while Lilydale had the break point for the rainfall in May in 1948. All these three slope changes are 99% statistically significant changes. The time series plots of monthly rainfalls indicating the significant slope changes are presented in Figure 4.4, Figure 4.5 and Figure 4.6 for Eltham, Lilydale and Silvan respectively.

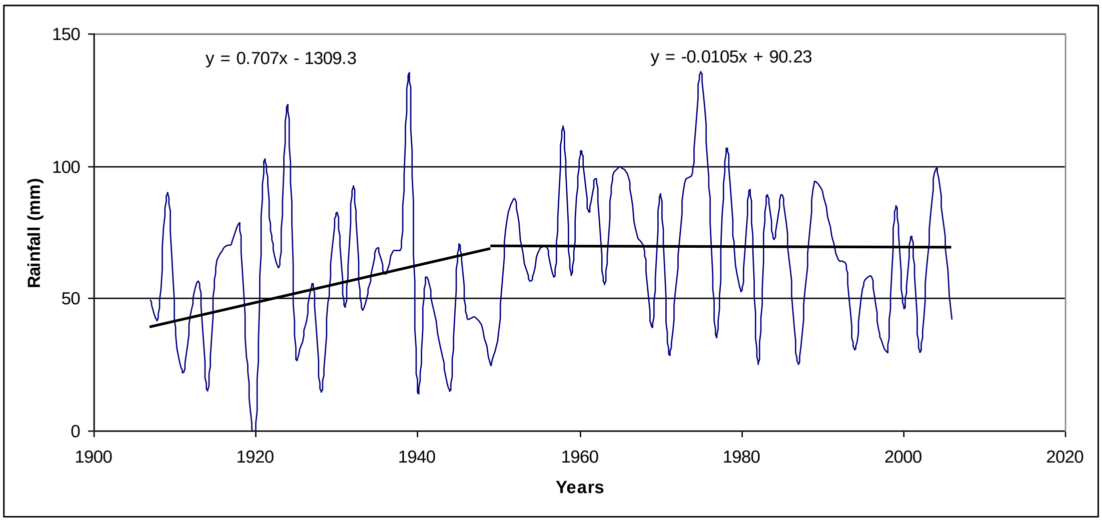



Figure 4.4 Monthly rainfalls for August at Eltham with slope change in 1949

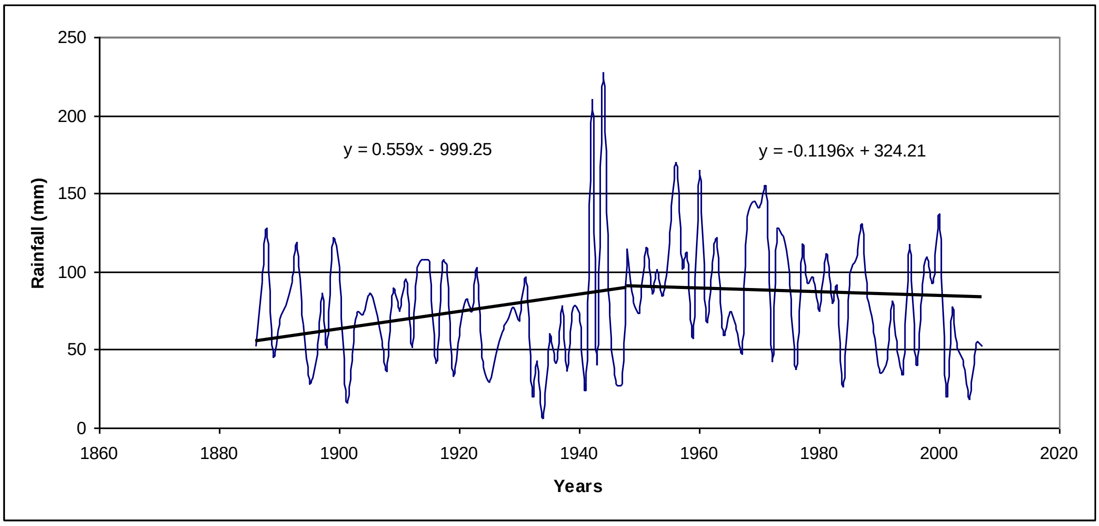



Figure 4.5 Monthly rainfalls for May at Lilydale with slope change in 1948

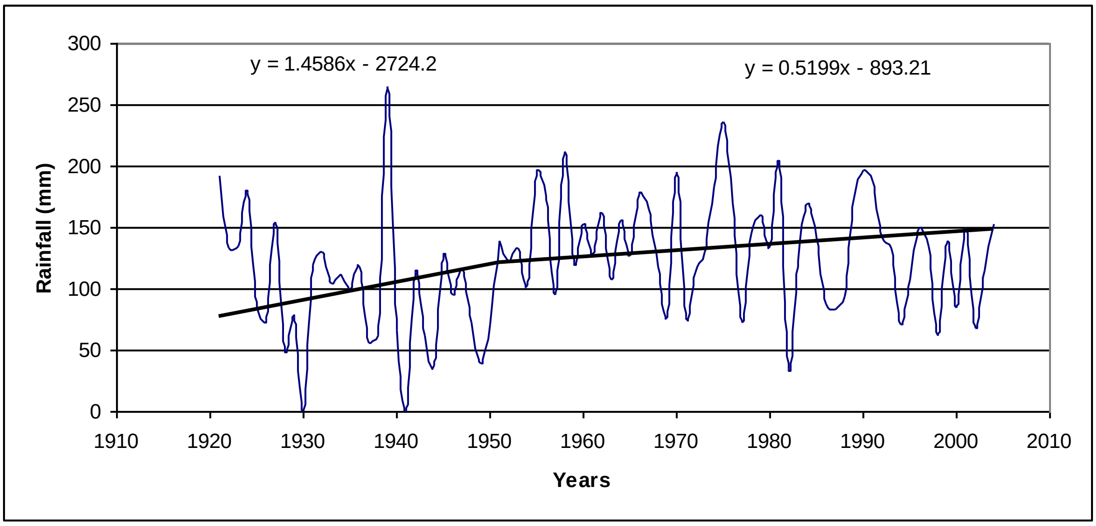



Figure 4.6 Monthly rainfalls for August at Silvan with slope change in 1951

### 4.1.1.3 Discussion

The slope change analysis for annual rainfalls at all the 11 stations indicated that there was no abrupt slope change at any of the stations. Thus, the next step would be to check for the existence of abrupt step change.

As far as the slope change analysis for monthly rainfalls is concerned, Eltham and Silvan indicated abrupt slope changes in August of 1949 and 1951 respectively. A third station, Lilydale had a slope change in May of 1948. In all these three cases, as can be observed in Figures 4.4 – 4.6, the monthly rainfall slopes were increasing before the change point, but change to close to zero for Eltham and Silvan and to a negative slope for Lilydale. The change in monthly rainfall for August seems to be most abrupt for Eltham, with a slope of 0.707 before 1949 changing to -0.0105 after 1949. These values of slopes can be observed in Figure 4.4 from the equations of the best fit lines before and after the change point.

For the monthly rainfalls at all the other stations, where no abrupt slope change was detected, the step change analysis would be conducted to detect the existence of any abrupt step change.

### 4.1.2 Step change analysis

The analysis presented in this section aims to detect the presence of abrupt step changes in the annual as well as monthly rainfall data. This step change analysis was carried out using the same time series data for which the slope change analysis was done, but for only those data which did not exhibit any statistically significant abrupt slope change.

Even though, initially five different statistical techniques were selected for the detection of abrupt step change, based on the analysis on hypothetical data, only Median change point test was selected as the most accurate method. The hypothetical data analysis that was used for the selection of the Median change point test from amongst the five initially selected techniques was presented in the methodology in Section 3.4.

The following sub-sections present the analysis that was carried out using the Median change point test to locate the abrupt step change point in annual and monthly rainfall data from the selected 11 stations.

#### 4.1.2.1 Analysis for annual rainfall

The results of the analysis for the detection of abrupt step change point in the annual rainfall data are presented in Table 4.3. This table presents two change points, namely, the 'primary change point' and the 'secondary change point'. The primary change point is the point where the maximum step change had occurred and the secondary change point is the point where the second maximum step change occurred.

In Table 4.3, the highlighted cells are those where the step change point is statistically significant at either 95% or 90% significance level. Out of the 11 stations, only 5 stations, namely Box Hill, Eltham, Maroondah, MRO and Silvan have shown statistically significant step change in annual rainfall data. All the statistically significant step changes occurred in middle of the century, except for MRO where the step change occurred in 1996.

Table 4.3 Abrupt step change points for annual rainfall data

| Land use | Station | Primary change point | Secondary change point |
|---|---|---|---|
| Urban | Box Hill | 1948 [1] | 1969 |
| | Caulfield | 1945 | 1996 |
| | Eltham | 1945 [1] | 1957 |
| | MRO | 1996 [2] | 1945 |
| | Lilydale | 1930 | 1996 |
| Rural | Silvan | 1950 [1] | 1996 |
| | Epping | 1958 | 1996 |
| | Mickleham | 1978 | 1945 |
| Forest | Maroondah | 1960 [2] | 1996 |
| | Toorourrong | 1948 | 1996 |
| | Warburton | 1996 | 1950 |

[1] At 90% statistical significance level
[2] At 95% statistical significance level

Figure 4.7 presents both the primary and secondary step change points for all stations on a radar plot. A pattern can be observed in the primary and secondary step change points, even though most of those change points are not statistically significant. The observed pattern is that if a primary step change occurred during the period 1940-1950, then a secondary change point occurred during the period 1990-2000 or vice versa. Thus, it can be concluded that there were two step changes that occurred in the annual rainfall over the catchment, the first occurred in the middle of the century and the second step change occurred during the last decade of the century.

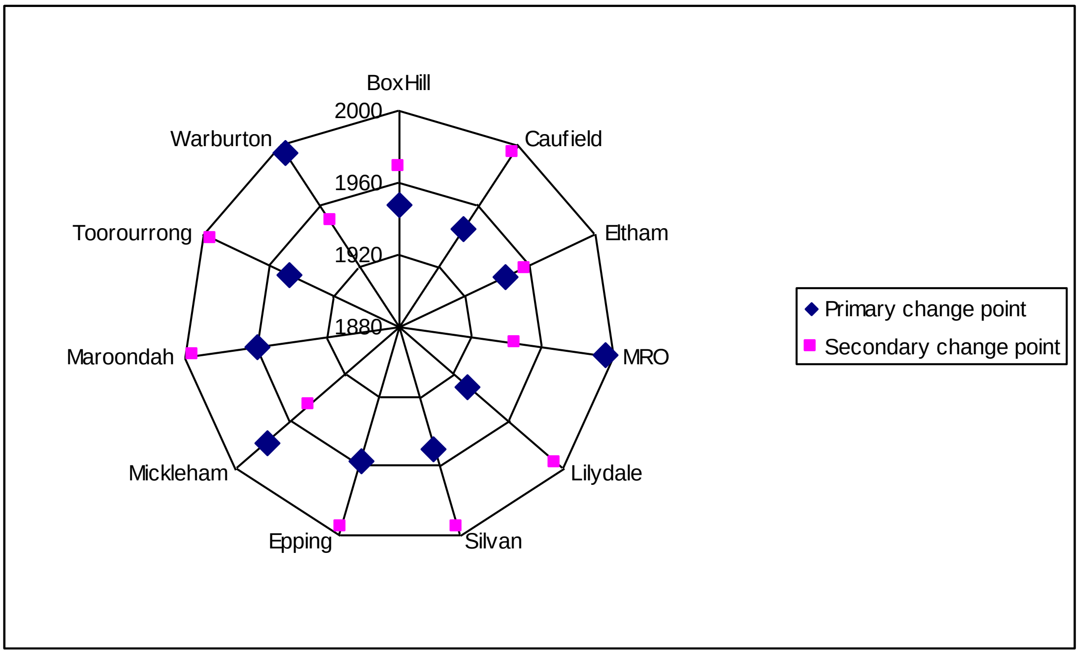



Figure 4.7 Primary and secondary step change points for annual rainfall

The time series plots of annual rainfall for the 5 stations that exhibited a significant step change are presented in Figure 4.8 – Figure 4.12.

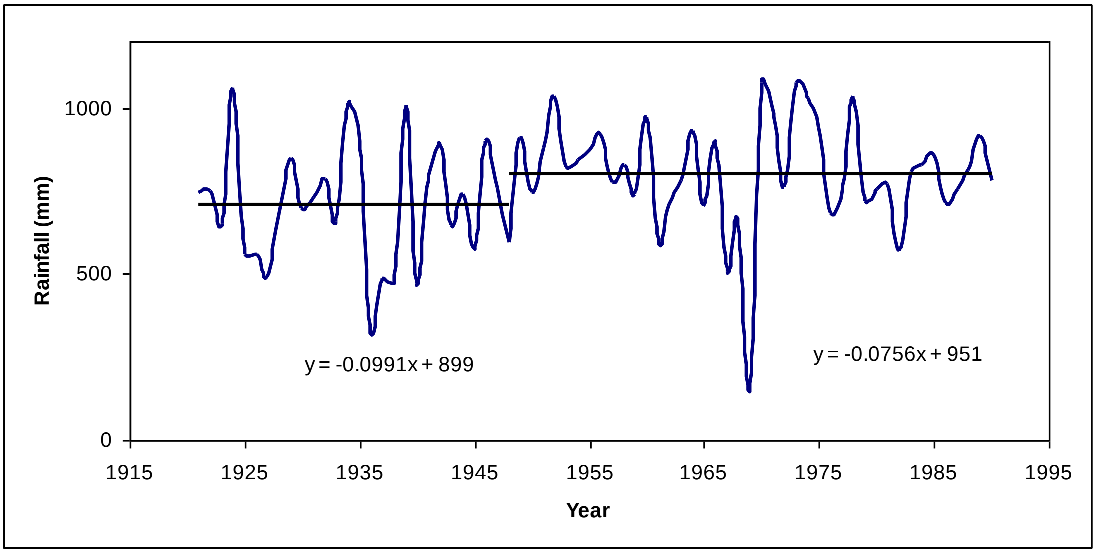



Figure 4.8 Annual rainfall at Box Hill with a step change in 1948

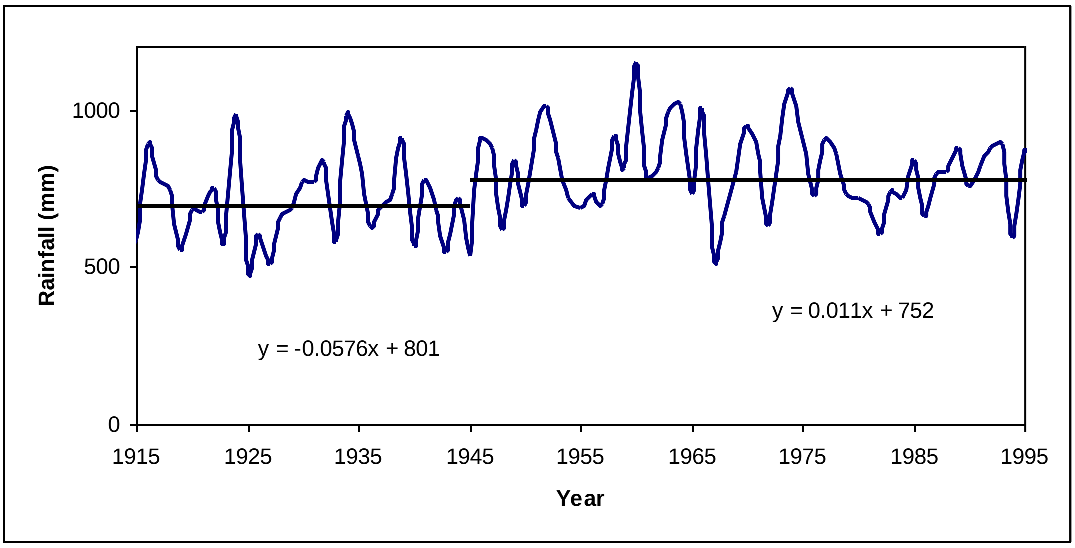



Figure 4.9 Annual rainfall at Eltham with a step change in 1945

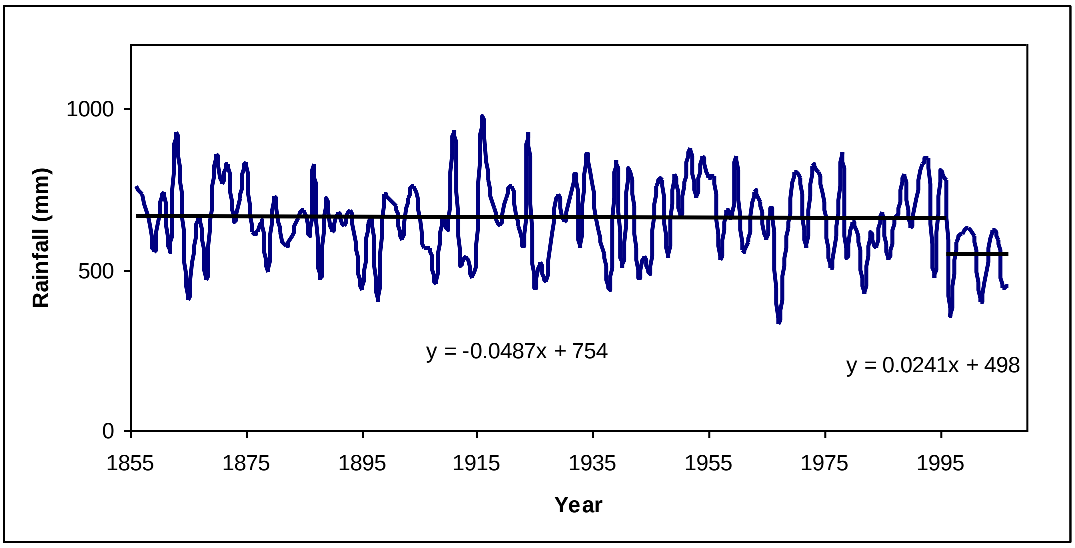



Figure 4.10 Annual rainfall at MRO with a step change in 1996

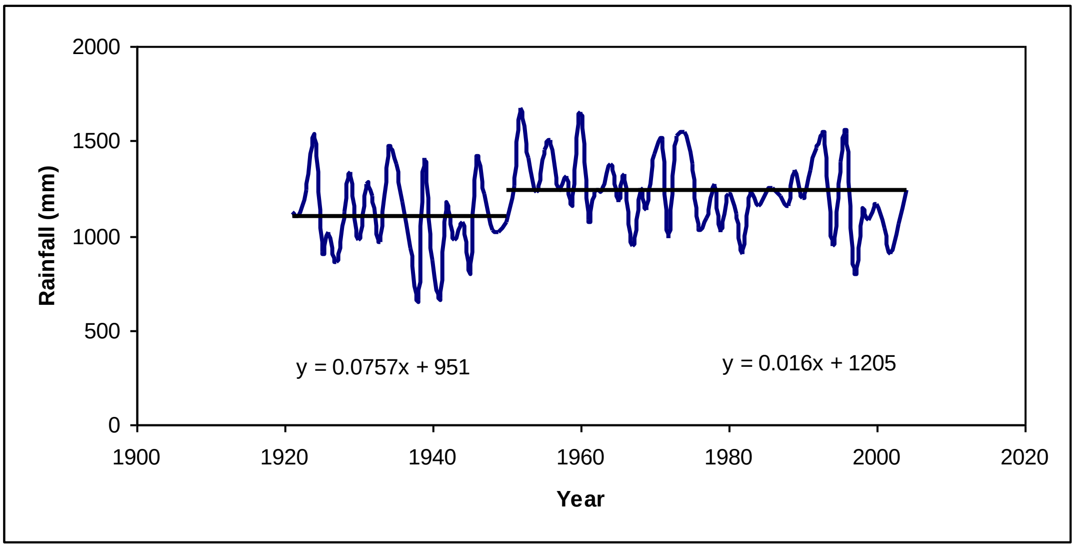



Figure 4.11 Annual rainfall at Silvan with a step change in 1950

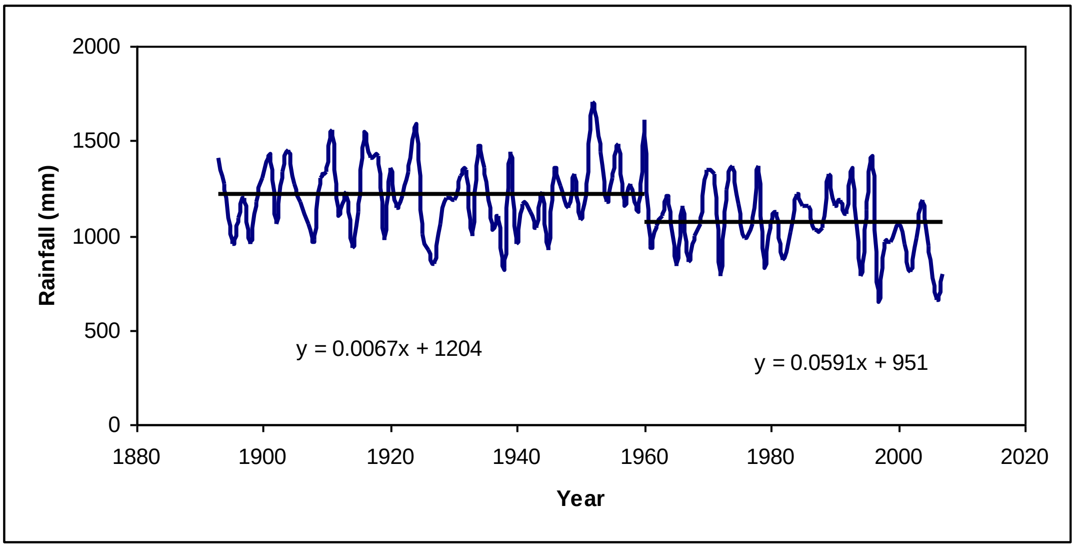



Figure 4.12 Annual rainfall at Maroondah with a step change in 1960

From Figure 4.8 – Figure 4.12, it is interesting to note that the significant step changes that were detected in the middle of the 20$^{th}$ century were step up changes, whereas the change points in the end of the century were step down changes.

### 4.1.2.2 Analysis for monthly rainfall

Similar to the step change analysis for annual rainfall data, the Median change point test was used to locate the abrupt step change points for monthly rainfall data. As described in Section 3.4.3, the datasets which exhibited statistically significant slope change were not considered for the step change analysis. The results of monthly rainfall analysis are presented in Table 4.4. This table presents the primary and secondary change points (denoted by 1$^{st}$ and 2$^{nd}$ in the table) for each month at all the stations. The statistically significant step change points are shaded in this table. Time series plots for all the months that exhibited a statistically significant step change point are presented in Appendix A. The mean of the data before and after the step change are also presented in the figures in Appendix A.

Table 4.4 Abrupt step change points for monthly rainfall

| Stations | Jan | | Feb | | Mar | | Apr | | May | | Jun | | Jul | | Aug | | Sep | | Oct | | Nov | | Dec | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Summer months | | | | Autumn months | | | | | | Winter months | | | | | | Spring months | | | | | | Summer | |
| | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd |
| **Box Hill** | 1969 | 1948 | 1964 | 1942 | 1969 | 1947 | 1969 | 1970 | 1947[1] | 1969 | 1979 | 1940 | 1950 | 1975 | **1950[1]** | 1972 | 1949[1] | 1966 | 1946 | 1955 | 1948 | 1988 | 1963 | 1938 |
| **Caulfield** | 1969 | 1906 | 1917 | 1934 | 1914 | 1932 | 1914 | 1901 | 1950 | 1939 | 1911 | 1956 | 1944 | 1895 | 1950[1] | 1985 | 1949 | 1993 | 1946 | 1915 | 1938 | 1992 | 1945 | 1902 |
| **Eltham** | 1920 | 1932 | 1973 | 2004 | 1996 | 1988 | 1996 | 1928 | 1948 | 1982 | 1974 | 1918 | 1944 | 1991 | N/A | N/A | 1951 | 1961 | 1946 | 1914 | 1933 | 1960 | 1963 | 1993 |
| **MRO** | 1874 | 1969 | 1915 | 1973 | 1932 | 1996 | 1932 | 1928 | 1948 | 1989 | 1955 | 2001 | 1966 | 1991 | 1950 | 1993 | 1924 | 1993 | 1894 | 1946 | 1893 | 1969 | 1993 | 1906 |
| **Lilydale** | 1905 | 1946 | 1973 | 1920 | 1933 | 1949 | 1933 | 1948 | N/A | N/A | 1911 | 1941 | 1966 | 1895 | 1950 | 1915 | 1949 | 1999 | 1958 | 2001 | 1938 | 1922 | 1936 | 1994 |
| **Silvan** | 1925 | 1960 | 1973 | 1992 | 1960 | 1933 | 1960 | 1974 | 1950 | 1939 | 1979 | 1951 | 1945 | 1965 | N/A | N/A | 1951[1] | 1987 | 1958 | 1924 | 1944 | 2003 | 1983 | 1928 |
| **Epping** | 1952 | 1939 | 1945 | 1970 | 1932 | 1968 | 1932 | 1978 | 1948 | 1940 | 1986 | 1911 | 1944 | 1991 | 1951[1] | 1990 | 1940 | 1924 | 1990 | 2005 | 1944 | 1928 | 1945 | 1964 |
| **Mickleham** | 1975 | 1939 | 1963 | 1955 | 1918 | 1931 | 1918 | 1978 | 1970 | 1940 | 1958 | 1904 | 1965 | 1990 | 1948 | 1985 | 1966 | 1920 | 1963 | 1980 | 1959 | 1937 | 1935 | 1984 |
| **Maroondah** | 1955 | 1902 | 1963 | 1973 | 1949 | 1932 | 1949 | 1900 | 1973 | 1982 | 1922[1] | 1909 | 1965 | 1994 | 1923 | 1990 | 1924 | 1960 | 1957[2] | 1975 | 1910 | 1978 | 1992 | 1897 |
| **Toorourrong** | 1969 | 1904 | 1962 | 1928 | 1933 | 1950 | 1933 | 1901 | 1950 | 1981 | 1911 | 1974 | 1946 | 1979 | 1952 | 1900 | 1925 | 1979 | 1915 | 1958 | 1938[1] | 1960 | 1951 | 1928 |
| **Warburton** | 1969 | 1940 | 1964 | 1973 | 1950 | 1920 | 1950 | 1996 | 1983 | 1941 | 1976 | 2003 | 1992 | 1945 | 1993 | 1954 | 1980 | 1951 | 1958 | 1928 | 1978 | 1918 | 1928 | 1993 |

[1] At 90% statistical significance level
[2] At 95% statistical significance level

Shaded boxes with double borders indicates statistically significant step up changes

It can be observed in Table 4.4 that all the statistically significant step changes had occurred in winter (June, July and August) and spring (September, October and November) months, except at Box Hill which had a significant step change for the monthly rainfall in May. The month of August had significant step changes for three stations, which are Box Hill, Caulfield and Epping in the years of 1950, 1950 and 1951 respectively. All these changes were step up changes, as seen in the plots in Appendix A. Similarly, September's rainfall had experienced step up changes in Box Hill and Silvan, both of which again were in the middle of the century (1949 and 1951 respectively). Maroondah has step down changes in the monthly rainfalls of June and October in the years of 1922 and 1957 respectively. Toorourrong experienced a step up change in November's rainfall for the year 1938.

A switching pattern was observed between the primary and secondary step change points, especially for winter and spring months. Box Hill station most prominently showed this switching pattern in the change points for all 12 months, as shown in the radar plot in Figure 4.13. In other words, if the primary significant change point in Box Hill was from 1940 - 1950, then the secondary significant change point was around 1960 and vice versa. The radar plots of primary and secondary step change points for the other stations are presented in Appendix B.

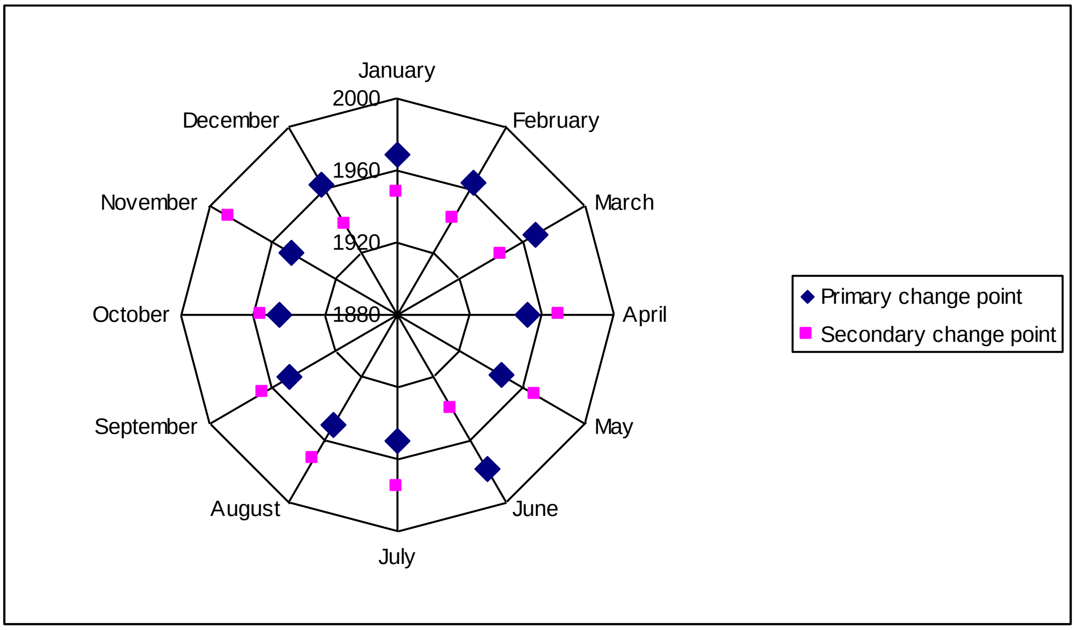



Figure 4.13 Primary and secondary step change points of monthly rainfall at Box Hill

### 4.1.2.3 Discussion

From the step change analysis presented above, it can be observed that there was a step up change from drier conditions to wet conditions in the middle of the 20th century and then a step down change, again to drier conditions in the end of the century. This is prominently seen in the annual rainfalls. With respect to monthly rainfalls, the step change in the middle of the century (1940 - 1950) were step-up changes (please refer to Appendix A).

## 4.1.3 Trend analysis

If a climatic trend is observed in a particular region, it is assumed that the trend will continue in the future to some extent. Hence, trend detection would help to forecast the future climatic conditions as well.

As presented in Section 3.3.1.3, Mann-Kendall test was selected as the best method for this study based on the results from the hypothetical data analysis. Most of the datasets were analysed as unbroken, while other datasets which consisted of statistically significant abrupt changes were separated into two parts, one before and the other after the abrupt change point. The Mann-Kendall trend analysis was conducted only for the later part of the dataset, i.e., for the part after the abrupt change point. This was so because these trends would be the current ones and thus of relevance.

### 4.1.3.1 Analysis for annual rainfall

The trend analysis results for annual rainfalls at all 11 rainfall stations are presented in Table 4.5.

Table 4.5 Annual rainfall trends

| Land use area | Station | MK test trends | |
|---|---|---|---|
| | | **Z** | **Significance** |
| Urban | Box Hill | 2.343 | 95% |
| | Caulfield | 0.802 | NS |
| | Eltham | -2.35 | 95% |
| | MRO | -2.97 | 99% |
| | Lilydale | 0.035 | NS |
| Rural | Silvan | 0.927 | NS |
| | Epping | 0.86 | NS |
| | Mickleham | -1.47 | NS |
| Forest | Maroondah | -3.33 | 99% |
| | Toorourrong | 0.3 | NS |
| | Warburton | -0.9 | NS |

Statistically significant Mann-Kendall statistics are shaded

Statistically significant step change was detected for the stations at Box Hill, Eltham, Maroondah, MRO and Silvan. So, for these stations, the trend analysis was carried out for the dataset after the step change year.

As can be observed in Table 4.5, Box Hill was showing 95% statistically significant increasing trend while Eltham, Maroondah and MRO were showing statistically significantly decreasing trend with 95%, 99% and 99% statistical significance, respectively.

#### 4.1.3.2 Analysis for monthly rainfall

The trend analysis for monthly rainfall has been carried out for the selected 11 rainfall stations and presented below separately for each of the three land use areas.

The trend detection results for rainfall stations in urban area are presented in Tables 4.6 - 4.10.

Table 4.6 Monthly rainfall trend at Box Hill

| Station | MK test trends | |
|---|---|---|
| | Z | Significance |
| January | 0.714 | NS |
| February | -0.88 | NS |
| March | 1.106 | NS |
| April | -0.28 | NS |
| May | 1.764 | 90% |
| June | 0.845 | NS |
| July | 1.437 | NS |
| August | 2.184 | 95% |
| September | 2.725 | 99% |
| October | 0.112 | NS |
| November | 1.246 | NS |
| December | 2.081 | 95% |

Table 4.8 Monthly rainfall trend at Eltham

| Station | MK test trends | |
|---|---|---|
| | Z | Significance |
| January | 1.346 | NS |
| February | -0.07 | NS |
| March | -0.81 | NS |
| April | 0.745 | NS |
| May | 0.107 | NS |
| June | 1.158 | NS |
| July | 0.31 | NS |
| August | 1.736 | 90% |
| September | 0.953 | NS |
| October | 0.211 | NS |
| November | 0.828 | NS |
| December | 0.098 | NS |

Table 4.7 Monthly rainfall trend at Caulfield

| Station | MK test trends | |
|---|---|---|
| | Z | Significance |
| January | 0.606 | NS |
| February | 1.81 | 90% |
| March | -0.74 | NS |
| April | 0.239 | NS |
| May | -0.08 | NS |
| June | -1.13 | NS |
| July | 0.271 | NS |
| August | 2.213 | 95% |
| September | 0.113 | NS |
| October | 0.903 | NS |
| November | 1.194 | NS |
| December | 0.409 | NS |

Table 4.9 Monthly rainfall trend at MRO

| Station | MK test trends | |
|---|---|---|
| | Z | Significance |
| January | 0.139 | NS |
| February | 0.487 | NS |
| March | -2.09 | 95% |
| April | -0.47 | NS |
| May | -0.15 | NS |
| June | -1.13 | NS |
| July | 0.024 | NS |
| August | 1.322 | NS |
| September | -1.05 | NS |
| October | -0.99 | NS |
| November | 0.164 | NS |
| December | 0.177 | NS |

Table 4.10 Monthly rainfall trend at Lilydale

| Station | MK test trends | |
|---|---|---|
| | Z | Significance |
| January | 0.115 | NS |
| February | 0.341 | NS |
| March | -1.7 | 90% |
| April | -0.51 | NS |
| May | 2.664 | 99% |
| June | -0.96 | NS |
| July | -0.35 | NS |
| August | 1.299 | NS |
| September | -0.05 | NS |
| October | -0.5 | NS |
| November | 1.297 | NS |
| December | -0.34 | NS |

Among these stations, only Box Hill has shown statistically significant increasing trends for four months. In Victoria, late winter and early spring months are considered as wet months. So, increasing trends in August and September rainfall would significantly contribute to increase in the annual rainfall of Box Hill. Caulfield has shown statistically significant increasing trend in February and August rainfall, Eltham has increasing trend in August rainfall and MRO has exhibited decreasing trend in March rainfall. Interestingly, Lilydale has shown decreasing trend in March and increasing trend in May. Urban area's monthly rainfall trends for the month of August appeared to be consistently showing increasing trends: three stations with statistically significant trends and two with non-statistically significant trends.

Trend analysis results for the 3 stations located in rural area are presented in Table 4.11 - Table 4.13.

Table 4.11 Monthly rainfall trend at Silvan

| Station | MK test trends | |
|---|---|---|
| | **Z** | **Significance** |
| January | 0.375 | NS |
| February | -1.32 | NS |
| March | 0.618 | NS |
| April | 0.042 | NS |
| May | 0.498 | NS |
| June | 2.152 | 95% |
| July | 0.576 | NS |
| August | 1.792 | 90% |
| September | 2.148 | 95% |
| October | -1.04 | NS |
| November | 0.135 | NS |
| December | 0.769 | NS |

Table 4.12 Monthly rainfall trend at Epping

| Station | MK test trends | |
|---|---|---|
| | **Z** | **Significance** |
| January | 1.611 | NS |
| February | 0.073 | NS |
| March | -0.57 | NS |
| April | 0.775 | NS |
| May | 0.405 | NS |
| June | 0.194 | NS |
| July | 0.329 | NS |
| August | 2.581 | 99% |
| September | 0.511 | NS |
| October | -0.36 | NS |
| November | 1.092 | NS |
| December | 0.497 | NS |

Table 4.13 Monthly rainfall trend at Mickleham

| Station | MK test trends | |
|---|---|---|
| | Z | Significance |
| January | 0.731 | NS |
| February | -0.68 | NS |
| March | -0.56 | NS |
| April | 0.617 | NS |
| May | -1.53 | NS |
| June | -1.19 | NS |
| July | -0.37 | NS |
| August | 0.083 | NS |
| September | -1.4 | NS |
| October | -1.75 | 90% |
| November | -0.09 | NS |
| December | -0.5 | NS |

Similar to the results for urban area stations, monthly rainfall in August has shown increasing trends (two stations were statistically significant and one was non-statistically significant). For Silvan, two winter months and a spring month has shown statistically significant increasing trend. August monthly rainfall was significantly increasing at Epping, while October monthly rainfall was reducing at Mickleham.

The trend analysis results for stations located in forest area are presented in Table 4.14 - Table 4.16.

Table 4.14 Monthly rainfall trend at Maroondah

| Station | MK test trends | |
|---|---|---|
| | Z | Significance |
| January | -0.46 | NS |
| February | 0.01 | NS |
| March | -1.64 | NS |
| April | -0.59 | NS |
| May | -1.33 | NS |
| June | -2.63 | 99% |
| July | -2.23 | 95% |
| August | -0.49 | NS |
| September | -2.01 | 95% |
| October | -1.94 | 90% |
| November | 0.773 | NS |
| December | -0.55 | NS |

Table 4.15 Monthly rainfall trend at Toorourrong

| Station | MK test trends | |
|---|---|---|
| | Z | Significance |
| January | -0.21 | NS |
| February | 0.135 | NS |
| March | -0.34 | NS |
| April | 0.541 | NS |
| May | 0.027 | NS |
| June | -0.89 | NS |
| July | 1.228 | NS |
| August | 0.914 | NS |
| September | -0.55 | NS |
| October | -0.13 | NS |
| November | -1.92 | 90% |
| December | 0.44 | NS |

Table 4.16 Monthly rainfall trend at Warburton

| Station | MK test trends | |
|---|---|---|
| | Z | Significance |
| January | 0.202 | NS |
| February | -1.21 | NS |
| March | -0.75 | NS |
| April | -1.87 | 90% |
| May | -0.79 | NS |
| June | 0.159 | NS |
| July | -0.37 | NS |
| August | -0.62 | NS |
| September | -0.52 | NS |
| October | -2.26 | 95% |
| November | -1.26 | NS |
| December | 0.192 | NS |

In forest area, all of the statistically significant trends are decreasing trends. Maroondah has shown that two winter months and two spring months have decreasing trends. November rainfall was decreasing at Toorourrong station, whereas April and October rainfall were decreasing for Warburton station.

#### 4.1.3.3 Discussion

There were similarities between the annual and monthly rainfall trends. Box Hill was the only station that exhibited increasing trends in annual rainfall. For monthly rainfalls, Box Hill shows increasing significant trends for 4 months, and most other months also had increasing trends (although not statistically significant). Most of the monthly rainfalls at Caulfield and Eltham also exhibited increasing trends.

For stations located in rural areas, Silvan and Epping had increasing trends in most of the months, whereas Mickleham had decreasing trends of monthly rainfalls for most months. Similar trends were observed for the annual rainfall at these 3 stations, although they were not statistically significant.

As far as stations in the forest area are concerned, the monthly rainfall was reducing for most of the months, some being statistically significant and some not. Maroondah is the other station (other than Box Hill located in urban area) that exhibited maximum number of months (4 months) with significant trends, which were all decreasing trends. Most other months in Maroondah also had decreasing trends, though not significant. Annual rainfalls for Maroondah were also decreasing at 99% significance level.

Interestingly, it is also observed that the monthly rainfall in August has shown increasing trends at all stations, except 2 stations in the forest area.

## 4.2 Extreme Value Analysis

Due to the global climate change, it was expected that the extreme events would become more severe and also more frequent. Extreme rainfall events and the resulting floods usually cause a lot of damage to life and property. Determination of frequencies and magnitudes of these events are very important for flood plain management and designs of hydraulic structures, civil protection plans, etc. However, length of available records are not large enough for risk analysis. Therefore results from trend analysis would be quite useful.

In this study, two indices were selected for extreme value analysis of rainfall. These are:

1) Annual highest daily rainfall – This index is the highest daily rainfall for each year. The time series plots for the highest daily rainfall for all three different land use areas are presented in Figure 4.14 - Figure 4.16.

2) Heavy precipitation days – This is the annual count of days with daily precipitation greater than 10 mm. The time series plots for heavy precipitation days are presented separately for each land use area in Figure 4.17 - Figure 4.19.

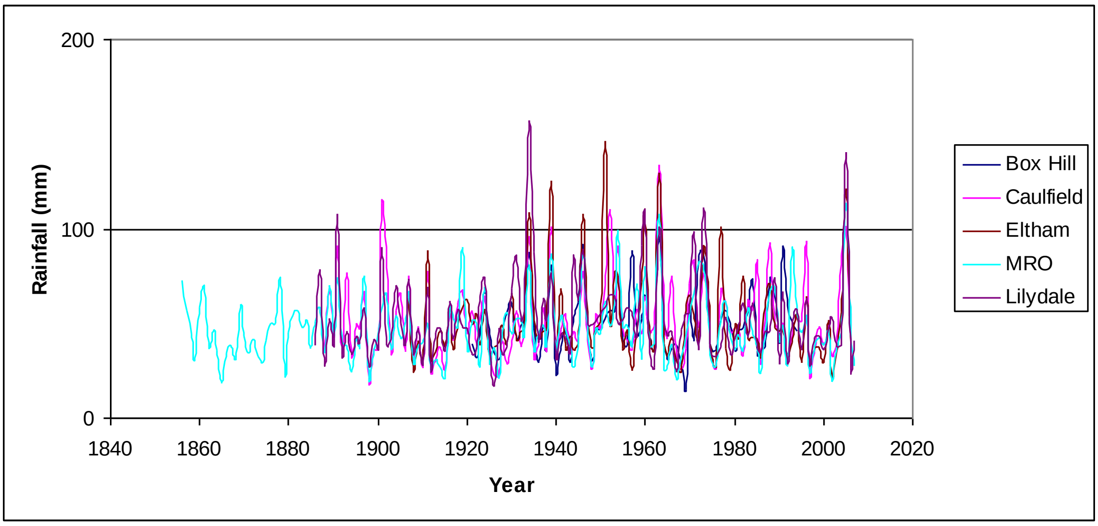



Figure 4.14 Highest daily rainfalls in urban area

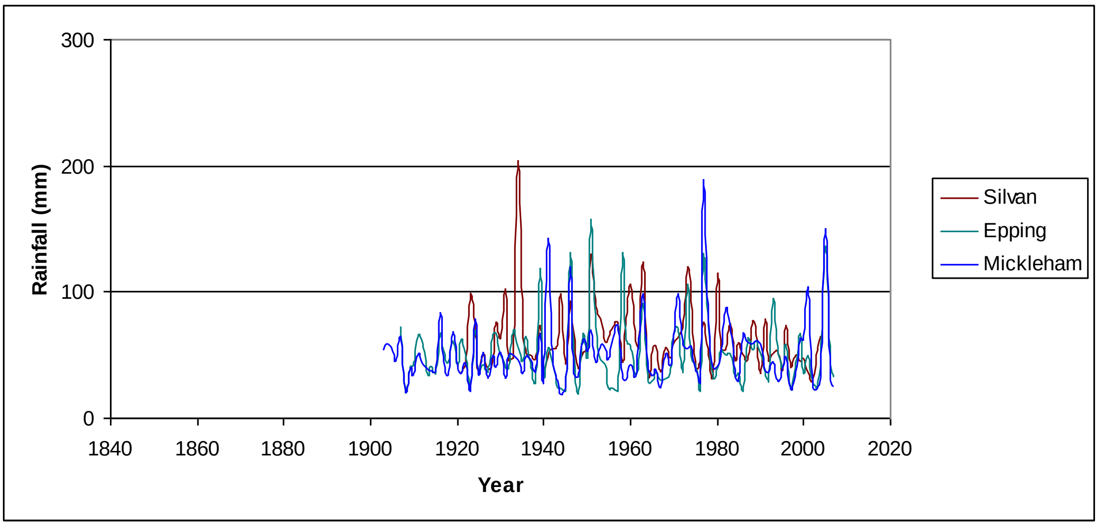



Figure 4.15 Highest daily rainfalls in rural area

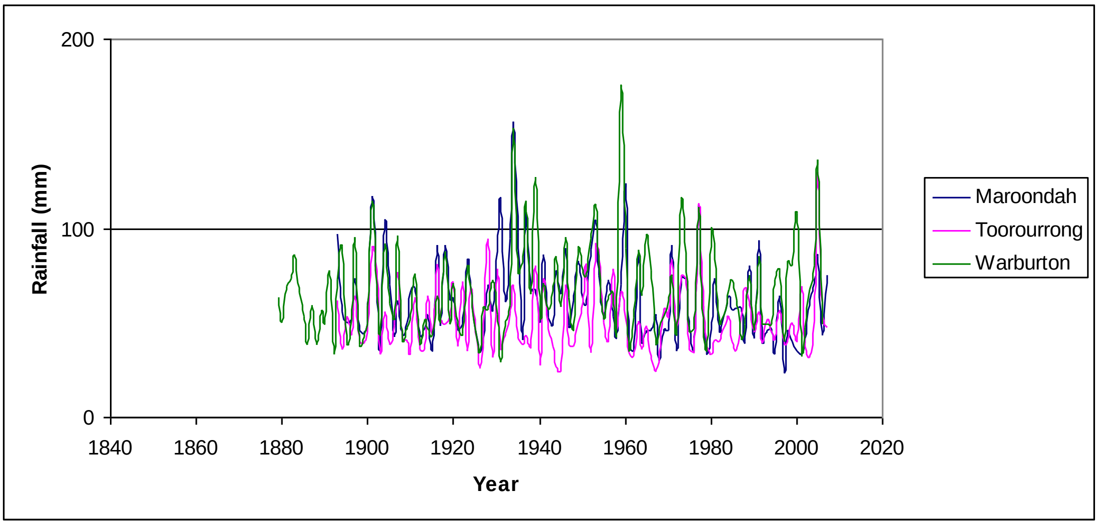



Figure 4.16 Highest daily rainfalls in forest area

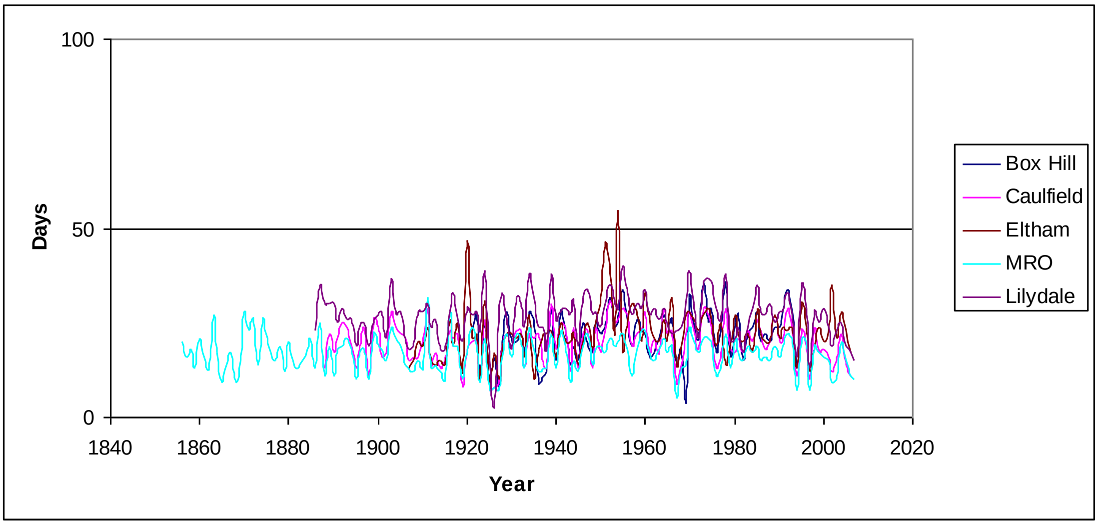



Figure 4.17 Heavy precipitation days in urban area

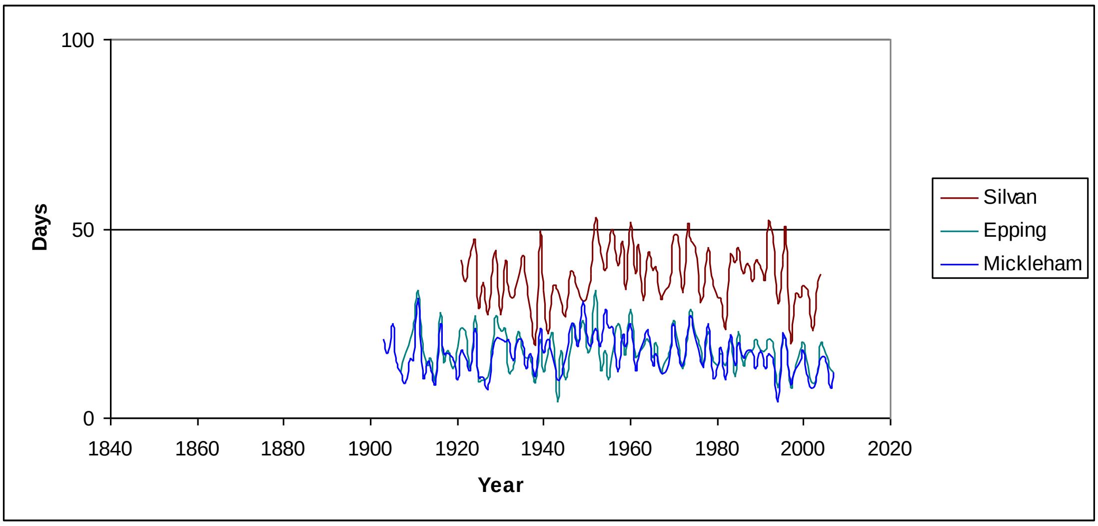



Figure 4.18 Heavy precipitation days in rural area

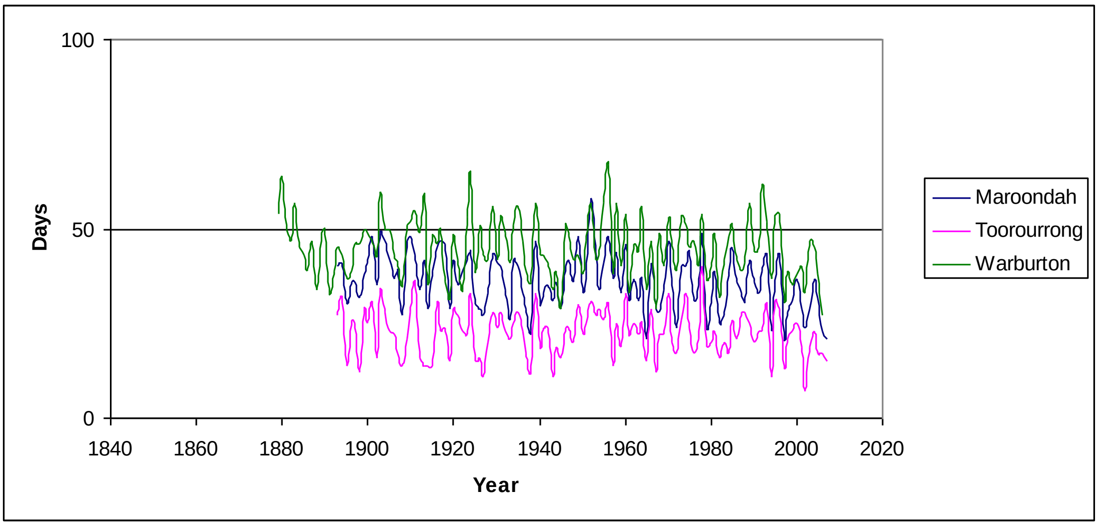



Figure 4.19 Heavy precipitation days in forest area

The following sub-sections present the abrupt change analysis (slope and step change analysis) and trend analysis for the two extreme value indices.

### 4.2.1 Slope change analysis

The same rainfall stations and the same length of dataset as in standard value analysis have been used for this analysis as well. Break point test was used for the detection of the abrupt slope change point. The slope change analyses for the two indices are presented in the following sub-sections.

#### 4.2.1.1 Analysis for highest daily rainfall

The slope change analysis results of highest daily rainfall are presented in Table 4.17.

Table 4.17 Break points of highest daily rainfall data

| Station | Min RSS | Break point | Existence of slope change |
|---|---|---|---|
| Box Hill | 1963 | 2040 | No |
| Caulfield | 1996 | 2003 | No |
| Eltham | 1978 | 1999 | No |
| MRO | 2004 | 2006 | No |
| Lilydale | 1928 | 1888 | No |
| Silvan | 1934 | 1927 | No |
| Epping | 2004 | 2006 | No |
| Mickleham | 2004 | 2006 | No |
| Maroondah | 1935 | 1924 | No |
| Toorourrong | 2004 | 2006 | No |
| Warburton | 1933 | 3011 | No |

From the results in Table 4.17, it is observed that there were no statistically significant abrupt slope change points in the highest daily rainfall data at all stations within the catchment. Hence, data from all stations were considered for abrupt step change analysis.

### 4.2.1.2 Analysis for heavy precipitation days

Table 4.18 presents the slope change analysis results of annual heavy precipitation days.

Table 4.18 Break points of annual heavy precipitation days

| Station | Min RSS | Break point | Existence of slope change Status |
|---|---|---|---|
| Box Hill | 1927 | 1923 | No |
| Caulfield | 1950 | 1974 | No |
| Eltham | 1938 | 1924 | No |
| MRO | 1941 | 1909 | No |
| Lilydale | 1930 | 1970 | No |
| Silvan | 1950 | 1781 | No |
| Epping | 1958 | 1867 | No |
| Mickleham | 1945 | 1978 | No |
| Maroondah | 1935 | 1899 | No |
| Toorourrong | 1911 | 1909 | Yes |
| Warburton | 1988 | 1996 | No |

Shaded cell indicates break point at 99% significance level

Among all the stations, only Toorourrong has shown a 99% statistically significant slope change in 1911 for the annual heavy precipitation days, time series plot for which is presented in Figure 4.20. For Box Hill station also, the Minimum RSS point and break point are very close to each other, but those points are just two points away from the starting point of the time series data. So, this break point for Box Hill was not eligible to be considered as an abrupt slope change point.

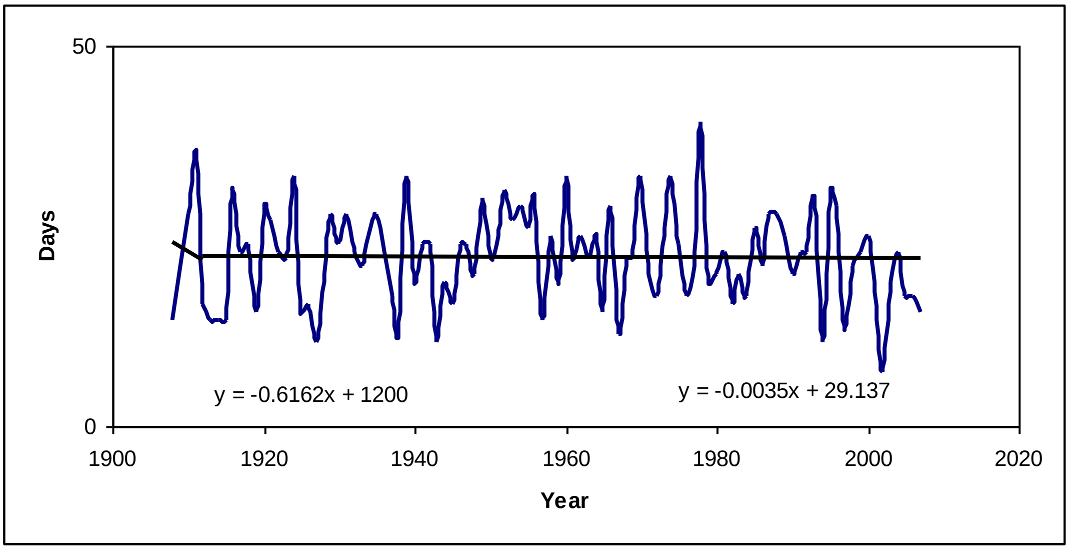



Figure 4.20 Annual heavy precipitation days at Toorourrong

#### 4.2.1.3 Discussion

All the 11 stations did not exhibit an abrupt slope change for the 2 indices for extreme rainfall. The only exception was Toorourrong station, which had an abrupt slope change for annual heavy precipitation days.

### 4.2.2 Step change analysis

Similar to the abrupt slope change, abrupt step change analysis of extreme value events would help to find out abrupt changes in the pattern of change in extreme value events and the point in time when it occurred. If abrupt step change has occurred in an extreme value event, it reveals that the severity of the extreme event has suddenly jumped to another level of severity, either a step-up or a step-down change.

As before, the Median change point test has been used for the detection of any abrupt step change. The analyses for the two selected indices are presented below.

#### 4.2.2.1 Analysis for highest daily rainfall

The results for abrupt step change analysis of highest daily rainfall data are presented in Table 4.19. The table also presents the primary and secondary change points, which are also plotted using a radar plot in Figure 4.21 to check if any patterns exist between both the change points.

Table 4.19 Abrupt step change points for highest daily rainfall data

| Land use | Station | Primary change point | Secondary change point |
|---|---|---|---|
| Urban | Box Hill | 1969 | 1987 |
| | Caulfield | 1948 | 2006 |
| | Eltham | 1974 | 1963 |
| | MRO | 1915 | 2004 |
| | Lilydale | 1929 | 1995 |
| Rural | Silvan | 1974 | 1996 |
| | Epping | 1939 | 2004 |
| | Mickleham | 1948 | 1992 |
| Forest | Maroondah | 1960[1] | 1996 |
| | Toorourrong | 1968 | 2004 |
| | Warburton | 1933[1] | 1990 |

[1] At 90% significance level

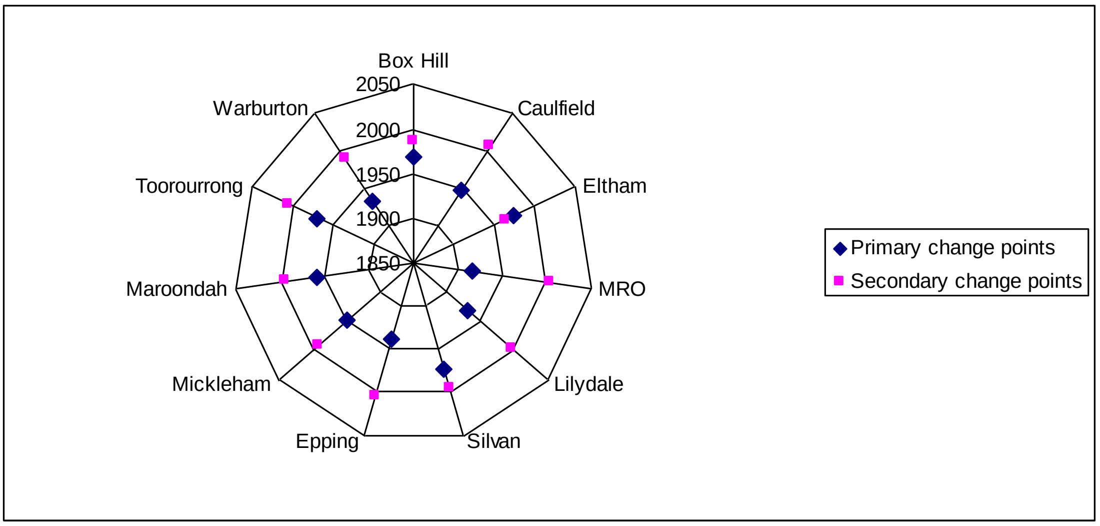



Figure 4.21 Radar plot for abrupt step change points of highest daily rainfall

From the analysis of the results, it is observed that only Maroondah and Warburton stations have exhibited significant change points at years 1960 and 1933 respectively. Maroondah had step down change while Warburton experienced a step up change, as can be observed in the time series plots presented in Figure 4.22 and Figure 4.23. In an overall sense, most of the primary change occurred in middle of the century while the secondary change has occurred in the later part of the 20th century or in early 21st century. This pattern can also be observed from the radar plot presented in Figure 4.21.

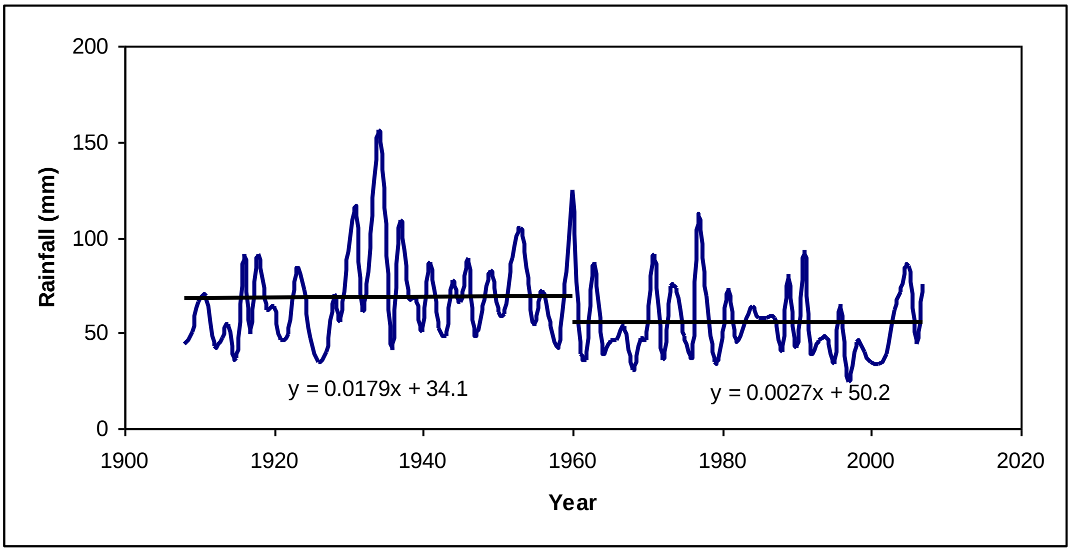



Figure 4.22 Highest daily rainfall at Maroondah with step change in 1960

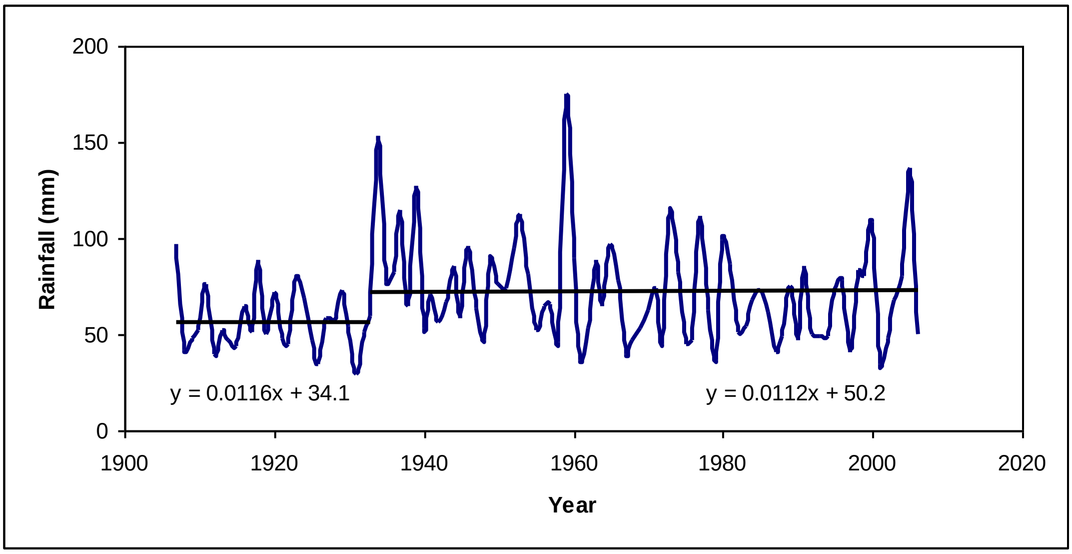



Figure 4.23 Highest daily rainfall at Warburton with step change in 1933

### 4.2.2.2 Analysis for heavy precipitation days

For this index, datasets from all stations have been used for the step change analysis except that for Toorourrong station because an abrupt slope change was detected in the dataset for this station.

The abrupt step change analysis results of heavy precipitation days are presented in the Table 4.20. As before, the primary and secondary change points are also presented using a radar plot in Figure 4.24 to detect any patterns between the primary and secondary abrupt step change points.

Table 4.20 Abrupt step change points of heavy precipitation days

| Land use | Station | Primary change point | Secondary change point |
|---|---|---|---|
| Urban | Box Hill | 1948[1] | 1987 |
| | Caulfield | 1938[1] | 1993 |
| | Eltham | 1948[2] | 1995 |
| | MRO | 2006 | 1996 |
| | Lilydale | 1930 | 1996 |
| Rural | Silvan | 1950 | 1996 |
| | Epping | 2006 | 1978 |
| | Mickleham | 1927 | 1988 |
| Forest | Maroondah | 1924 | 1996 |
| | Toorourrong | N/A | N/A |
| | Warburton | 2006 | 1996 |

[1] At 90% statistical significance
[2] At 95% statistical significance

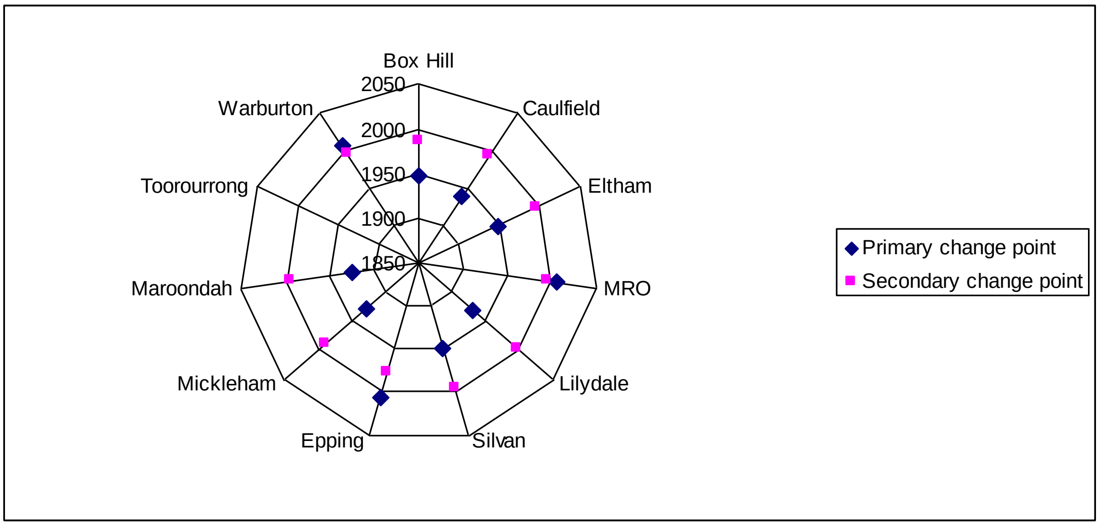



Figure 4.24 Radar plot for abrupt step change points of heavy precipitation days

According to the results presented in Table 4.20, three urban area stations, namely Box Hill, Caulfield and Eltham had shown significant abrupt step change in the middle of the century. As can be observed in Figure 4.25 – Figure 4.27 for these three stations respectively, the abrupt step changes were all step-up changes. Epping, MRO, Toorourrong and Warburton had shown step down change at the end of the century, but those are not statistically significant. From the radar plot in Figure 4.24, urban area stations (except MRO) revealed a switching pattern between primary and secondary change points, with the primary change point being in the middle of the 20th century and the secondary change point in the later part of the century or vice versa.

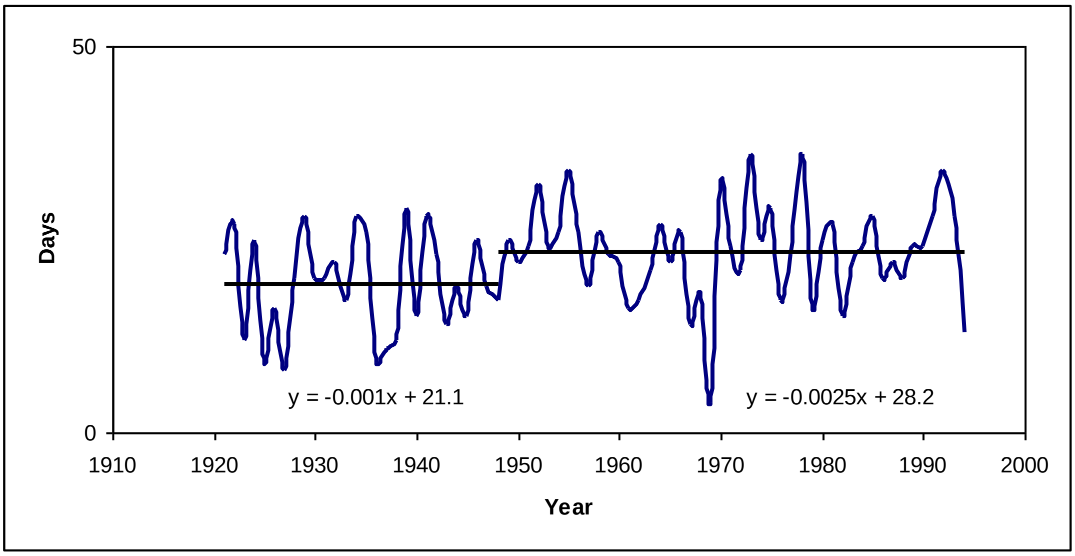



Figure 4.25 Heavy precipitation days at Box Hill with step change in 1948

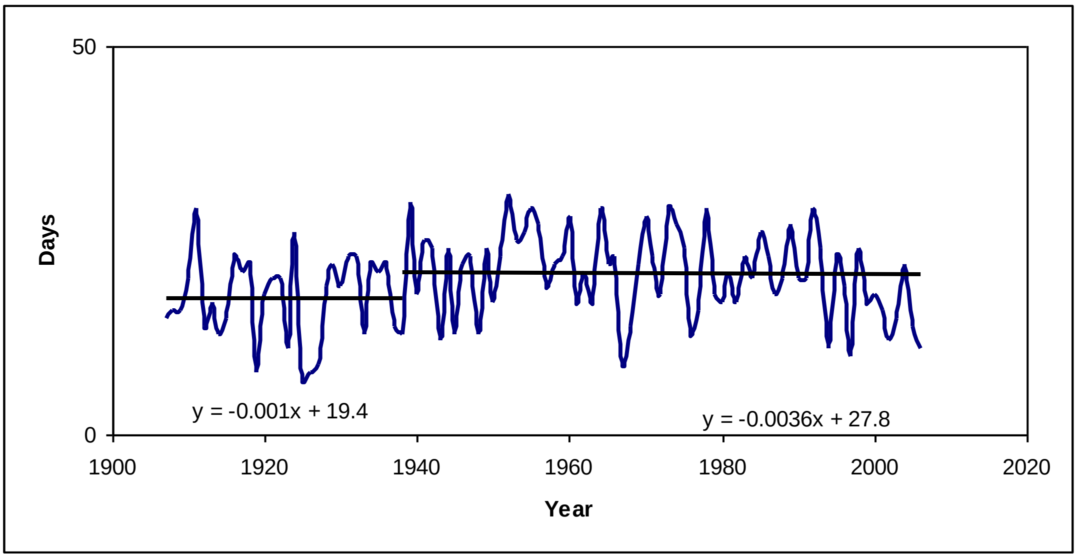



Figure 4.26 Heavy precipitation days at Caulfield with step change in 1938

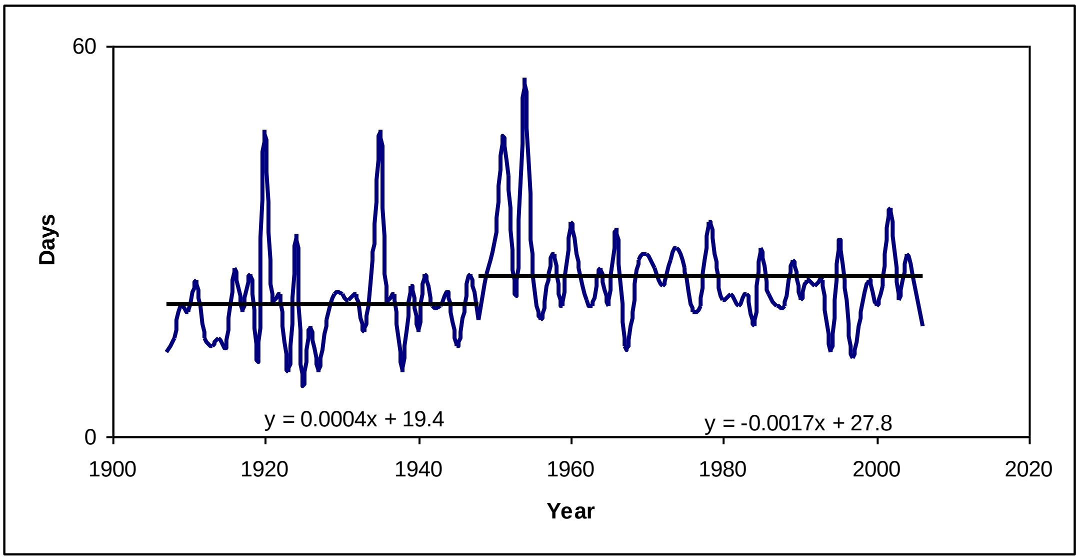



Figure 4.27 Heavy precipitation days at Eltham with step change in 1948

### 4.2.2.3 Discussion

It can be observed that most stations had exhibited an abrupt step change in the extreme rainfall indices, once in the middle of the 20$^{th}$ century and another in the end or in early 21$^{st}$ century. The step changes in the end of the 20$^{th}$ century were step down changes while most step changes in the middle of the century were step up changes.

## 4.2.3 Trend analysis

Trend analysis of extreme value rainfall data would help to understand the severity of extreme rainfall events in past and also would support to forecast the severity of the events in the future.

Similar to the trend analysis for standard values, Mann-Kendall test was used to analyse the extreme value rainfall data. Also, most of the datasets used for trend analysis are unbroken datasets, since they did not exhibit any abrupt change point. For few stations which had statistically significant abrupt slope change or step change, the later part of the broken dataset, i.e., the dataset after the change point was considered for trend analysis.

#### 4.2.3.1 Analysis for highest daily rainfall

The trend analysis results of annual highest daily rainfall data is given in Table 4.21.

Table 4.21 Trend of annual highest rainfall

| **Land use** | **Station** | **MK test trends** | |
|---|---|---|---|
| | | **Z** | **Significance** |
| Urban | Box Hill | 0.915 | NS |
| | Caulfield | 1.061 | NS |
| | Eltham | -0.77 | NS |
| | MRO | 0.237 | NS |
| | Lilydale | 0.046 | NS |
| Rural | Silvan | -0.9 | NS |
| | Epping | -0.68 | NS |
| | Mickleham | 0.053 | NS |
| Forest | Maroondah | -2.02 | 95% |
| | Toorourrong | -0.17 | NS |
| | Warburton | 1.138 | NS |

From the analysis of results presented in Table 4.21, only Maroondah shows statistically significant decreasing trend throughout the study period, while other stations did not show any statistically significant trend. Majority of the urban area stations exhibited statistically non-significant increasing trend while, majority of the rural and forest stations had shown decreasing trends in the highest daily rainfall.

#### 4.2.3.2 Analysis for heavy precipitation days

The trend analysis results of heavy precipitation days are presented in Table 4.22.

Table 4.22 Trend of annual heavy precipitation days

| Land use | Station | MK test trends | |
|---|---|---|---|
| | | Z | Significance |
| Urban | Box Hill | 2.039 | 95% |
| | Caulfield | 0.469 | NS |
| | Eltham | 2.514 | 95% |
| | MRO | -0.51 | NS |
| | Lilydale | -0.03 | NS |
| Rural | Silvan | 0.452 | NS |
| | Epping | -0.87 | NS |
| | Mickleham | -1.14 | NS |
| Forest | Maroondah | -3.17 | 99% |
| | Toorourrong | -0.98 | NS |
| | Warburton | -1.61 | NS |

Two urban area stations, which are Box Hill and Eltham have shown statistically significant increasing trends throughout the study period, while forest land use area station Maroondah has shown statistically significant decreasing trend.

#### 4.2.3.3 Discussion

Similar patterns are observed at all stations for the trends in the 2 extreme rainfall indices. Majority of the urban area stations have shown increasing trends for both the indices, even though not all stations had exhibited statistically significant trends. Furthermore, for majority of the rural and forest stations, the trends of both the indices were decreasing, but most were not statistically significant.

## 4.3 Conclusions

Climate change has posed an imminent challenge to the existing water management practices in Melbourne. Rapid urbanization and environmental degradation are additional challenges other than that of climate change. Due to the scarcity of water resources in the Yarra river catchment, climate change studies have been paid much attention by local and international experts. Also variability and recent changes in rainfall patterns have implied that a systematic framework is critical for detecting abrupt changes and trends that may arise from climate change. Therefore, in this study, a combined analysis of abrupt change detection and trend detection was carried out.

From the results of the analysis, there were two major climatic shifts, one in the middle of the $20^{th}$ century and the other during the last decade of the century that occurred over the Yarra river catchment. Earlier one was step up change and the later one was identified as step down. Melbourne was affected severely by this rainfall reduction during the last decade.

In terms of extreme events, the stations which are located in urban area have shown increasing trends while the stations in rural and forest areas have exhibited decreasing trends. This change may have been because of the rapid urbanization that occurred during the recent decades.

# 5 CHANGE DETECTION IN TEMPERATURE

Global and regional climate changes and variability may influence the long term climatic variable patterns and as a consequence, last few years were experienced frequent droughts and increase in temperatures temperatures. As discussed in Section 2.1, investigations of these changes have received more attention in recent years and studies have demonstrated that global average surface temperature has increased over the last few decades. A recent study carried out at national scale showed that the mean temperature for Australia as a whole has been increasing and the warming has accelerated in recent decades (Murphy & Timbal 2008). However, this change has not been either spatially or temporarily uniform (Houghton et al. 2001).

The Yarra river catchment and south east Australia as a whole has experienced frequent drought occurrences, hindering the economic progress of the region. However, there are no previous studies that have provided detailed analysis of change in temperature patterns at a local scale over the Yarra river catchment. The work presented in this chapter aims to understand the spatial and temporal patterns of changes in temperature over the Yarra river catchment. Three stations were selected for the analysis, one from each of the three land use areas, as presented in the methodology (Section 3.2). The three stations were MRO for urban area, Epping for rural and Maroondah for forest area. The analysis of temperature at these three different stations will provide insight into any spatial patterns in the temperature change and also if the land use has any impact on the observed changes.

As done for the change analysis for rainfall in Chapter 4, standard value as well as extreme value analysis has been carried out for temperature data also. The following sub-sections of this chapter present the standard value analysis and the extreme value analysis, respectively.

## 5.1 Standard value analysis

For the standard value analysis of temperature, data at two different timescales were selected, namely annual and monthly. Two indices were selected for each of the annual and monthly timescales, which are as follows:

i) Annual maximum temperature

ii) Annual minimum temperature

iii) Mean monthly maximum temperatures

iv) Mean monthly minimum temperatures

The first 2 indices were for the annual timescale data and the last 2 for monthly timescale.

The time series plots of the annual maximum temperature and the annual minimum temperature for the selected three stations are presented in Figure 5.1 and Figure 5.2 respectively. Among these three stations, MRO has the longest dataset, which starts from 1856. Temperature data for the other two stations, Epping and Maroondah, start from 1979 and 1965 respectively.

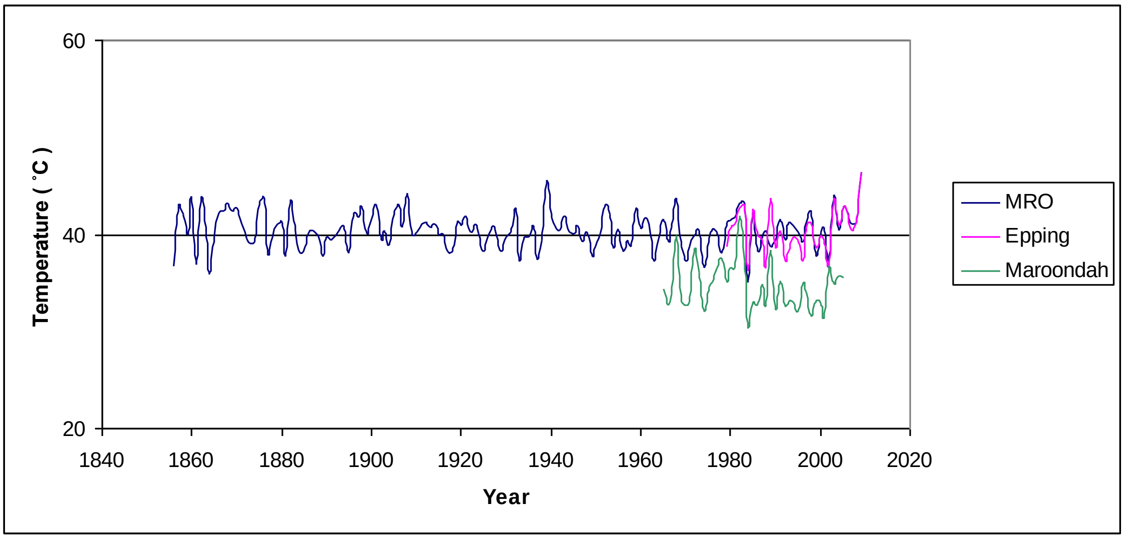



Figure 5.1 Annual maximum temperatures

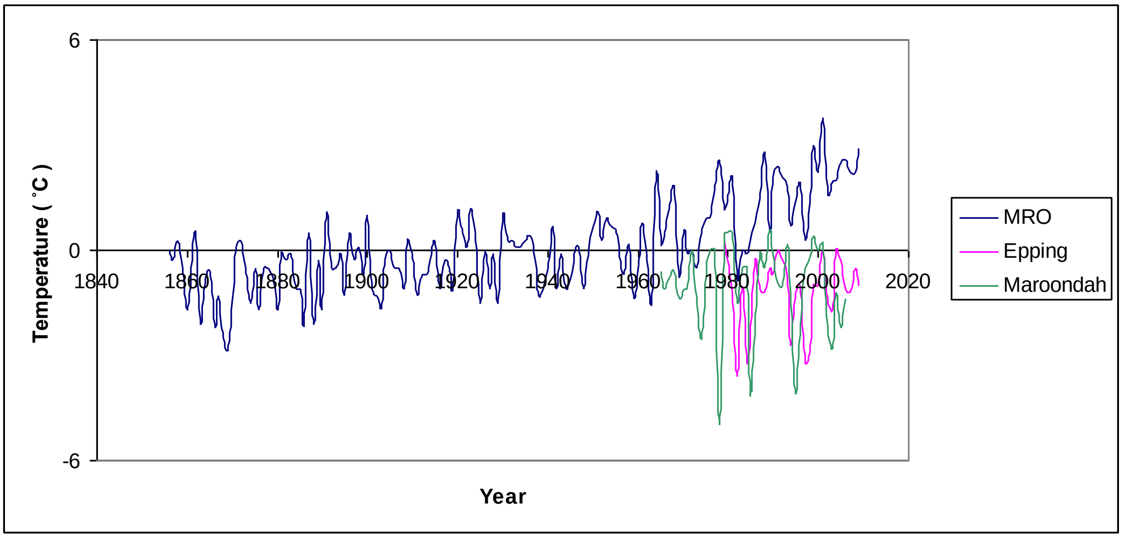



Figure 5.2 Annual minimum temperatures

A visual analysis of the annual maximum temperature does not reveal any abrupt changes, but from the annual minimum temperature plot, it can be clearly seen that the minimum annual temperature at MRO has exhibited an abrupt increase from around 1950. The analysis presented below will help to pin-point in a statistical sense the exact year when the abrupt increase in trend started.

The following sub-sections present the slope change, step change and the trend analysis for the two annual and two monthly indices.

## 5.1.1 Slope change analysis

Similar to the rainfall change analysis, Break point test was used to check for the existence of abrupt slope change in the datasets of the 4 standard value temperature indices. The analysis is presented in the following sub-sections:

### 5.1.1.1 Analysis of annual maximum temperature

The Break point test results for the annual maximum temperature, which are the minimum RSS points and break points for datasets from the 3 stations, are presented in Table 5.1.

Table 5.1 Break point analysis for annual maximum temperature

| Station | Min RSS | Break point | Existence of slope change |
|---|---|---|---|
| MRO | 2002 | 2010 | No |
| Epping | 2002 | 1991 | No |
| Maroondah | 1983 | 1946 | No |

From Table 5.1, it is observed that there was no abrupt slope change in annual maximum temperatures at any of the 3 stations.

### 5.1.1.2 Analysis of annual minimum temperature

Break point analysis results for annual minimum temperatures are given in Table 5.2, which shows an abrupt slope change in 1981 for Epping.

Table 5.2 Break points of annual minimum temperatures

| Station | Min RSS | Break point | Existence of slope change |
|---|---|---|---|
| MRO | 1936 | 2011 | No |
| Epping | 1982 | 1981[1] | Yes |
| Maroondah | 2001 | 2009 | No |

[1] At 99% statistical significance level

A time series plot indicating the significant abrupt slope change for Epping is presented in Figure 5.3.

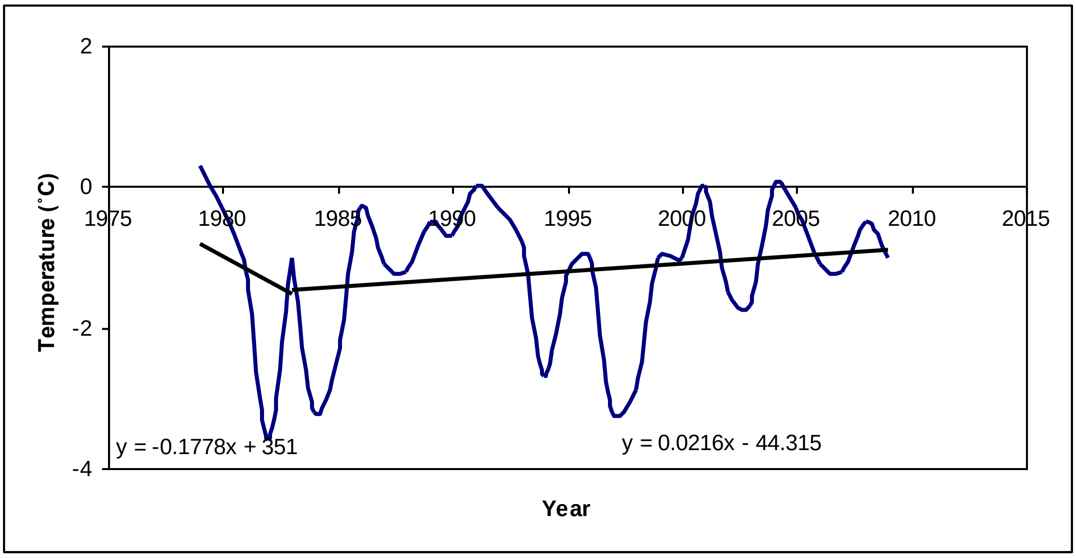



Figure 5.3 Annual minimum temperatures at Epping with a slope change in 1981

#### 5.1.1.3 Analysis of mean monthly maximum temperature

Break point analysis results of mean monthly maximum temperature given in Table 5.3. As seen in this table, MRO and Maroondah had statistically significant (at 99% level) abrupt slope changes for a month each, MRO in January of 1908 and Maroondah in October of 2003. The station in rural area, Epping had significant abrupt slope changes for 3 months, namely, September, November and December in the years 1986, 1993 and 1985 respectively. It can also be observed that all the 5 significant abrupt slope changes in mean monthly maximum temperature have occurred in spring and summer months only.

The time series plots for these 5 statistically significant abrupt slope changes are presented in Figure 5.4 – Figure 5.8. It can be seen that all the abrupt slope changes lead to increase in temperatures. In other words, the trend after the abrupt slope change point is increasing for all the 5 months.

Table 5.3 Break points of mean monthly maximum temperatures

| Stations | Jan | | Feb | | Mar | | Apr | | May | | Jun | | Jul | | Aug | | Sep | | Oct | | Nov | | Dec | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Summer months | | | | Autumn months | | | | | | Winter months | | | | | | Spring months | | | | | | Summer | |
| | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP | RSS | BP |
| **MRO** | 1909 | 1908 | 1996 | 2006 | 1940 | 1917 | 1994 | 2001 | 1939 | 1880 | 2000 | 2006 | 1976 | 1991 | 1992 | 1973 | 1997 | 2042 | 1940 | 1876 | 1970 | 1980 | 1994 | 1999 |
| **Epping** | 1982 | 1979 | 1996 | 2035 | 2005 | 2012 | 2009 | 1935 | 1998 | 1974 | 2005 | 2009 | 1998 | 2009 | 1992 | 1984 | 1988 | 1986 | 2004 | 2012 | 1991 | 1993 | 1987 | 1985 |
| **Maroondah** | 1983 | 2009 | 1996 | 2005 | 1972 | 1964 | 1999 | 2017 | 1970 | 1961 | 1980 | 1993 | 1976 | 1959 | 1983 | 2017 | 1996 | 1267 | 2002 | 2003 | 1987 | 1998 | 1994 | 1999 |

Shaded months are 99% statistically significant
RSS - The minimum RSS point
BP- The break point

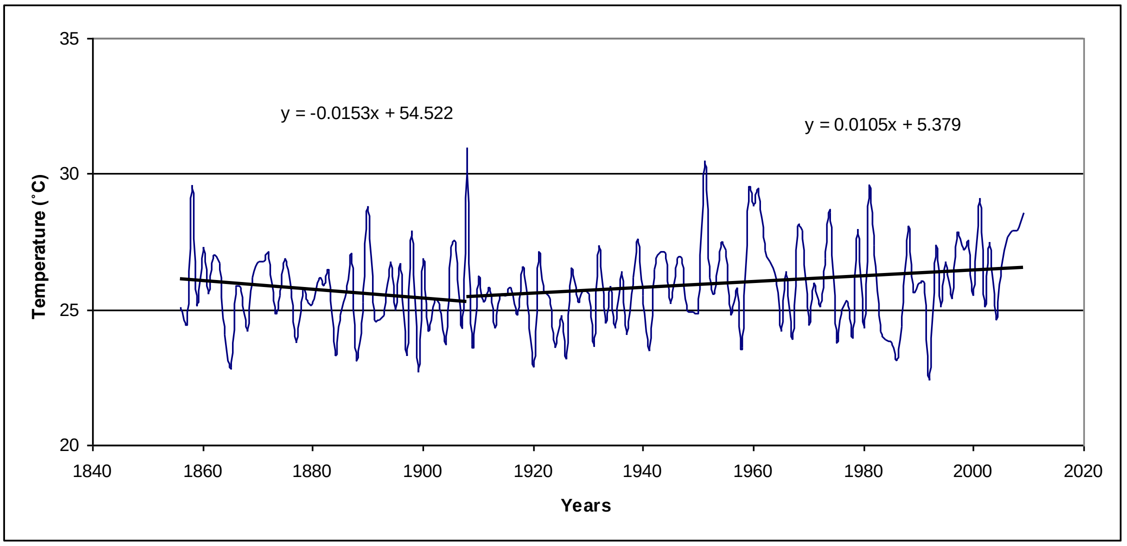



Figure 5.4 Mean monthly maximum temperatures for January at MRO with slope change in 1908

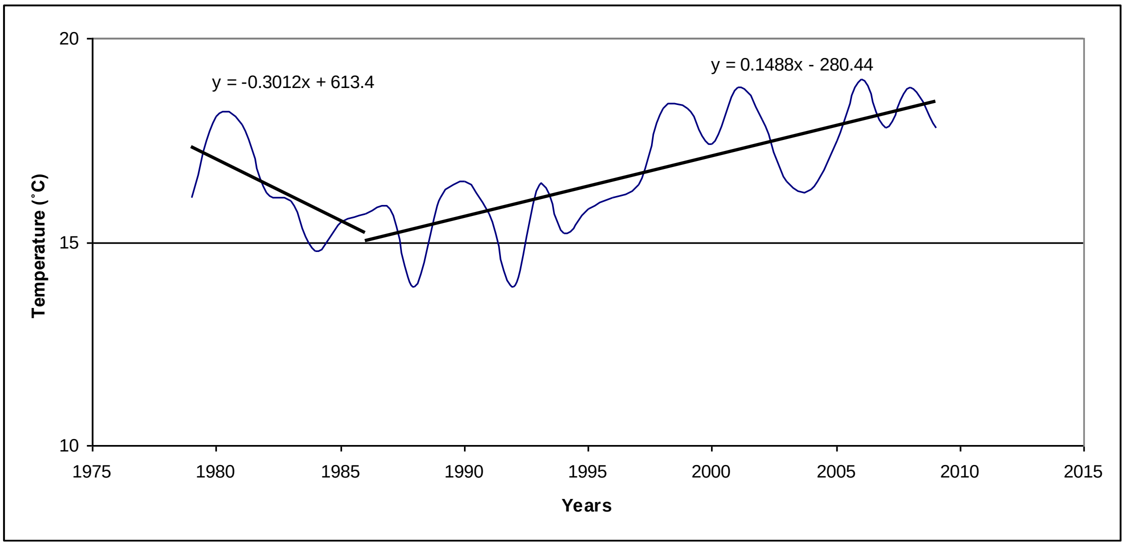



Figure 5.5 Mean monthly maximum temperatures for September at Epping with slope change in 1986

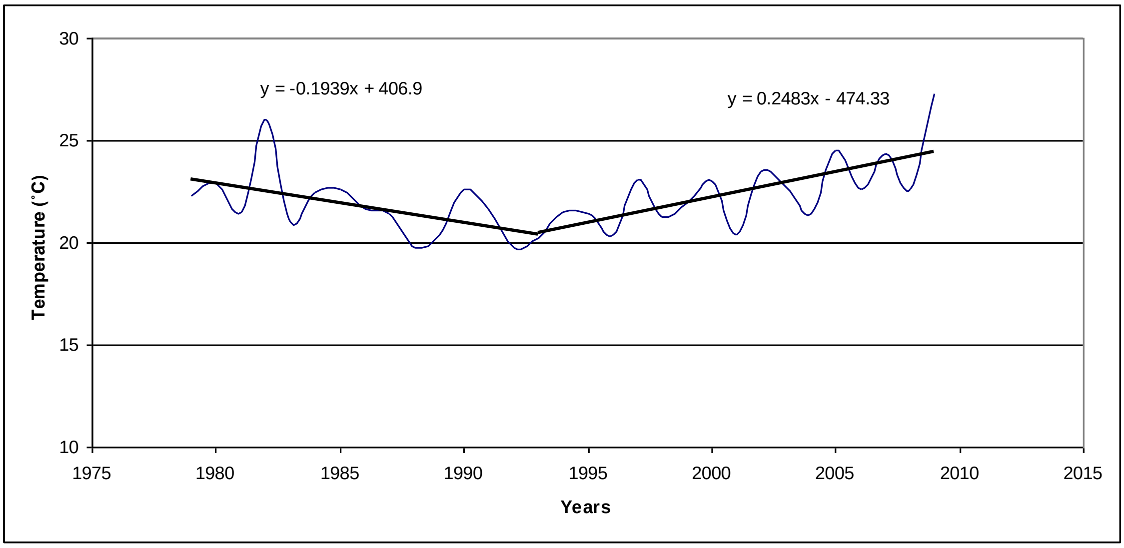



Figure 5.6 Mean monthly maximum temperatures for November at Epping with slope change in 1993

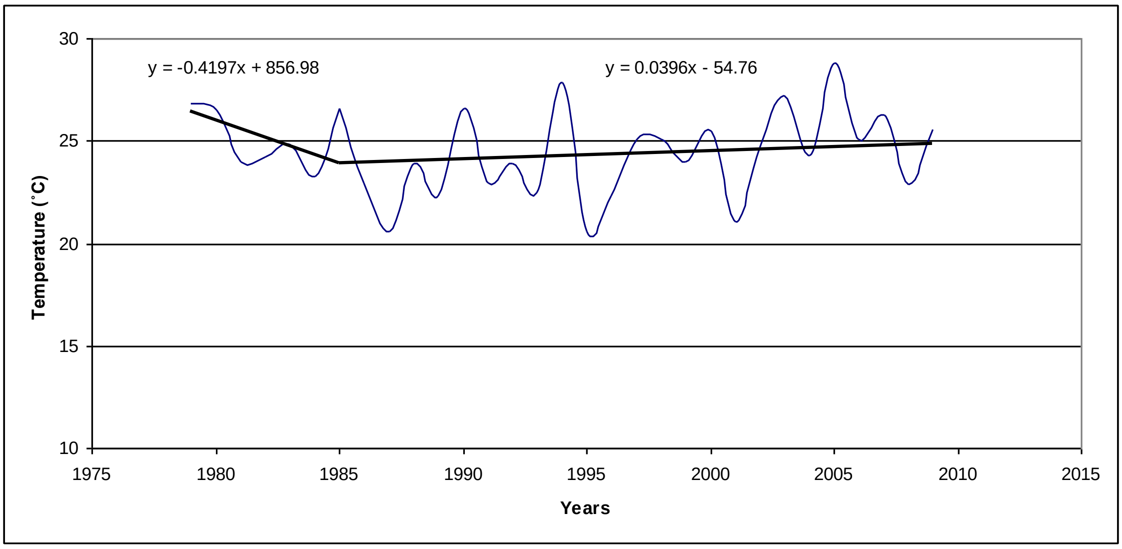
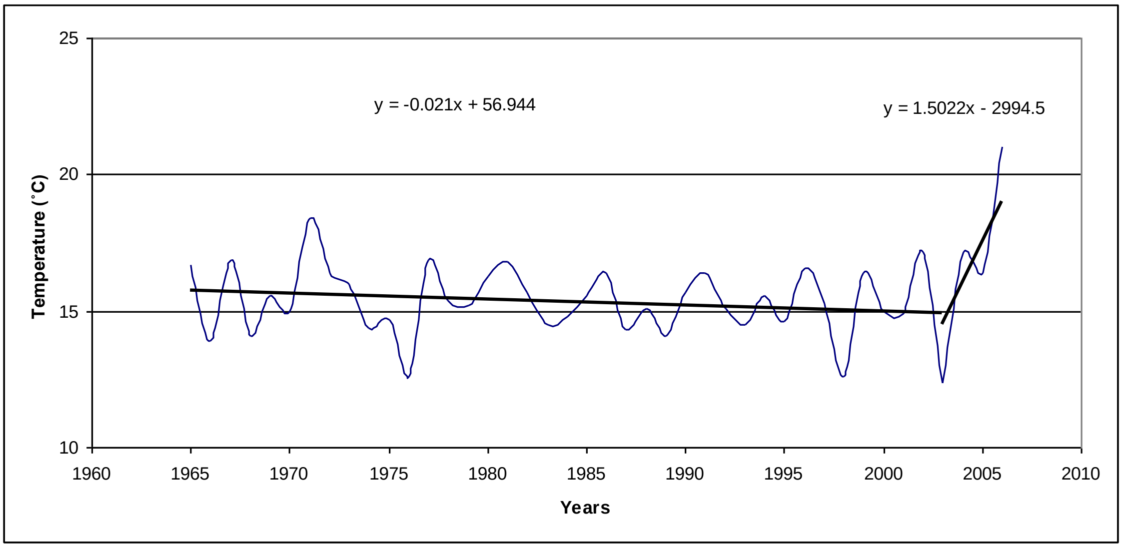



Figure 5.7 Mean monthly maximum temperatures for December at Epping with slope change in 1985




### 5.1.1.4 Analysis of mean monthly minimum temperature

Break point analysis results for mean monthly minimum temperature at the 3 stations are given in Table 5.4. As seen in this table, there were no statistically significant slope change points detected in any of the time series data.

Table 5.4 Break points of mean monthly minimum temperatures

| Stations | Jan | | Feb | | Mar | | Apr | | May | | Jun | | Jul | | Aug | | Sep | | Oct | | Nov | | Dec | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **RSS** | **BP** | **RSS** | **BP** | **RSS** | **BP** | **RSS** | **BP** | **RSS** | **BP** | **RSS** | **BP** | **RSS** | **BP** | **RSS** | **BP** | **RSS** | **BP** | **RSS** | **BP** | **RSS** | **BP** | **RSS** | **BP** |
| **MRO** | 1958 | 1917 | 1930 | 1972 | 1954 | 1926 | 1966 | 2152 | 1962 | 1926 | 1950 | 1929 | 1931 | 1831 | 1942 | 1952 | 1959 | 1939 | 1930 | 1863 | 1957 | 1938 | 1958 | 1934 |
| **Epping** | 1982 | 1979 | 1992 | 1980 | 1993 | 2007 | 1999 | 1904 | 2006 | 2008 | 2005 | 2009 | 1995 | 2022 | 2003 | 2000 | 1981 | 1976 | 2006 | 2008 | 1999 | 1992 | 1994 | 2021 |
| **Maroondah** | 1974 | 1968 | 1998 | 2003 | 1973 | 1957 | 1994 | 2024 | 1989 | 1984 | 1972 | 1967 | 2001 | 2006 | 2002 | 2008 | 1971 | 1965 | 1971 | 1965 | 1974 | 1934 | 1994 | 2012 |

RSS- The minimum RSS point
BP- The break point

#### 5.1.1.5 Discussion

From the analysis above, it is important to note that all the statistically significant slope changes have been from decreasing to increasing slopes. This indicates that the change in slope has always led to increasing trends in temperature after the change point. Later in this chapter, the Mann-Kendall test will be used to identify if these increasing trends were statistically significant or not.

Also seen in the above slope change analysis was that only Epping had a significant slope change in annual minimum temperatures. Moreover, Epping had also exhibited abrupt slope changes for the maximum number of months, namely, for 3 months in the mean monthly maximum temperature analysis.

### 5.1.2 Step change analysis

To detect any abrupt step changes, the Step change analysis was carried out on the same datasets which were used for the slope change analysis. Since the abrupt slope change point was already detected for some of the datasets, the abrupt step change analysis was not carried out for those datasets.

As before, Median change point test was used for the step change analysis. The analysis for the 4 selected indices is presented in the following sub-sections.

#### 5.1.2.1 Analysis of annual maximum temperature

Step change analysis results of annual maximum temperature are given in the Table 5.5. The primary and secondary change points are presented in this table.

Table 5.5 Step change points of annual maximum temperature

| Station | Primary change point | Secondary change point |
|---|---|---|
| MRO | 2002 | 1914 |
| Epping | 2002[1] | 1983 |
| Maroondah | 1983[1] | 2002 |

[1] At 90% statistical significance level

As seen in Table 5.5, Epping and Maroondah had statistically significant Primary change points in the years 2002 and 1983, respectively. The time series plots indicating these abrupt step changes are presented in Figure 5.9 and Figure 5.10. The time series plots indicate that Epping had a step-up change in 2002, whereas the change in Maroondah was a step-down change in 1983.

It is interesting to note that all the 3 stations had step-up changes in 2002, two of which were primary change points and the third was secondary. Also, 1983 was observed to be a change point for two stations, both of which were step-down change points.

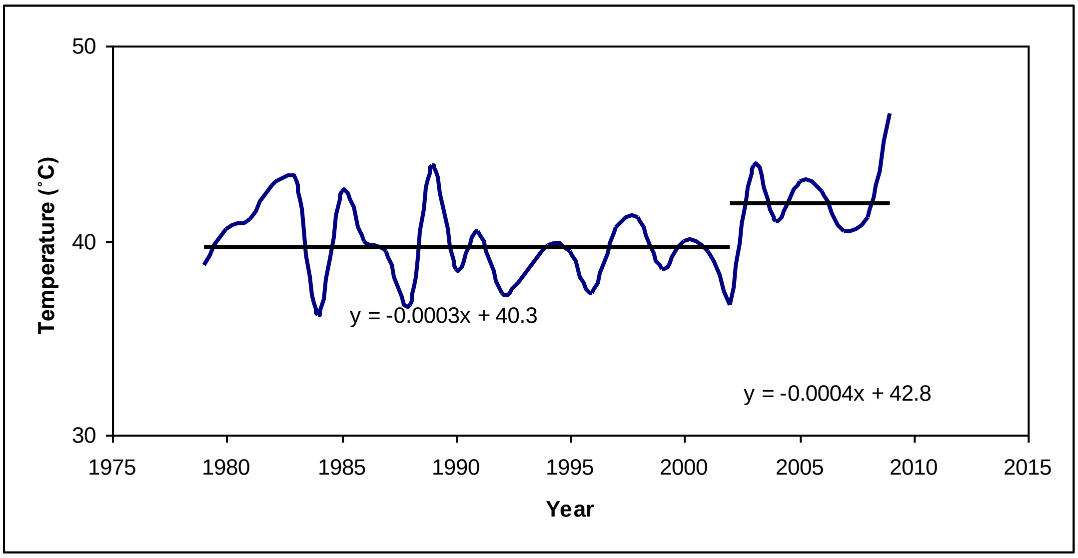



Figure 5.9 Annual maximum temperatures at Epping with a step change in 2002

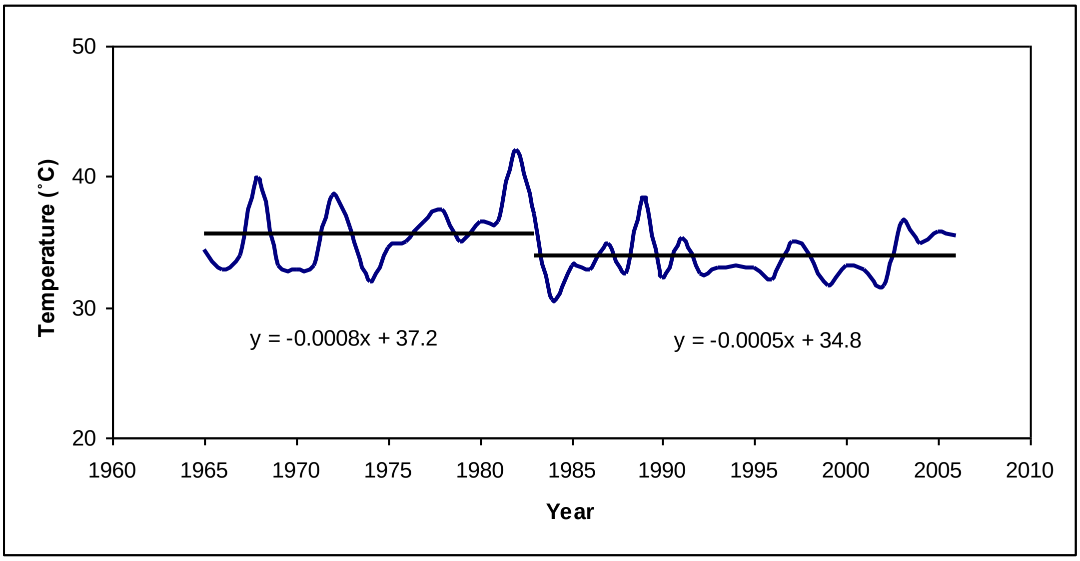



Figure 5.10 Annual maximum temperatures at Maroondah with a step change in 1983

### 5.1.2.2 Analysis of annual minimum temperature

Step change analysis results of annual minimum temperature are given in the Table 5.6. Since Epping had an abrupt slope change for annual minimum temperatures, it has not been considered for the step change analysis.

Table 5.6 Step change points of annual minimum temperature

| Station | Primary change point | Secondary change point |
|---|---|---|
| MRO | 1949[1] | 1983 |
| Epping[2] | N/A | N/A |
| Maroondah | 2001 | 1978 |

[1] At 99% statistical significance level
[2] Epping not considered as abrupt slope change point detected in 1981 (Table 5.2)

As can be seen in Table 5.6, MRO had a statistically significant abrupt step change in 1949 (at 99% significance level). A time series plot indicating this statistically significant abrupt step change is presented in Figure 5.11, from which it is seen that the step change was a step-up change.

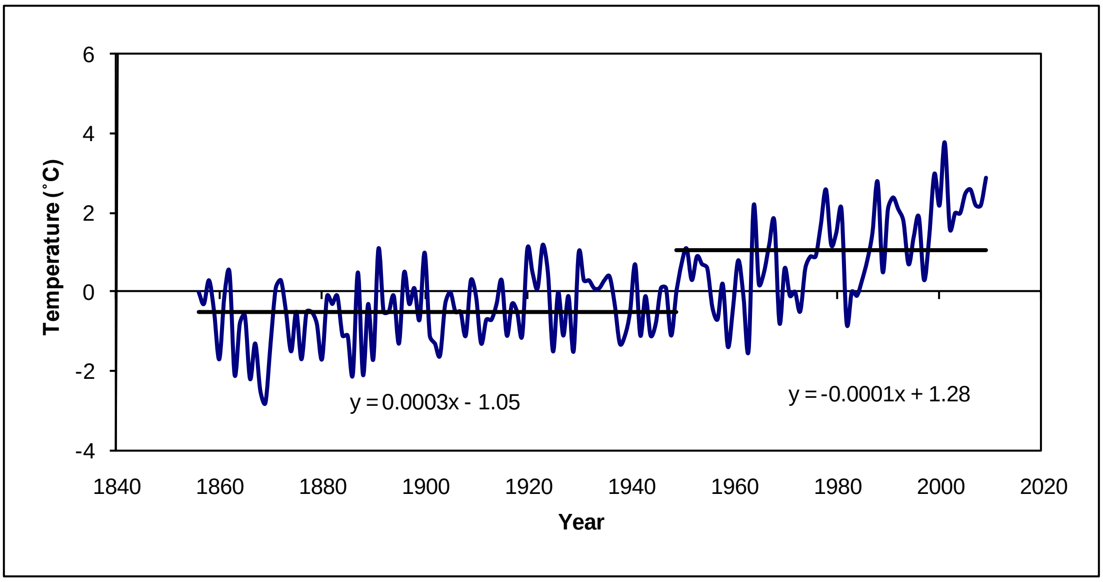



Figure 5.11 Annual minimum temperatures at MRO with a step change in 1949

### 5.1.2.3 Analysis of mean monthly maximum temperature

Step change analysis results for mean monthly maximum temperature are given in the Table 5.7. The statistically significant step changes in this table are shaded dark, with the statistical significance level indicated in the table footnote. The time series plots for all these significant step changes are presented in Appendix C.

It can be observed in Table 5.7 that for MRO's mean monthly maximum temperature, almost all the months except January (for which a slope change is already detected in 1908, presented earlier in Table 5.3) and December have experienced statistically significant step change. All these significant step changes at MRO occurred in the later half of the 20$^{th}$ century. Moreover, as can be observed in the time series plots in Appendix C, all these step changes are step-up changes.

As far as Epping and Maroondah are concerned, all the change points for these two stations occurred between 1992 and 1998. And the time series plots from Appendix C indicate that all the step changes for these two stations were also step-up changes.

Table 5.7 Step change points of mean monthly maximum temperature

| Stations | Jan | | Feb | | Mar | | Apr | | May | | Jun | | Jul | | Aug | | Sep | | Oct | | Nov | | Dec | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd |
| **MRO** | N/A | N/A | 1966[2] | 1897 | 1950[1] | 1933 | 1952[2] | 1890 | 1971[3] | 1939 | 1956[3] | 1873 | 1968[3] | 1914 | 1979[2] | 1885 | 1995[2] | 1966 | 1976[1] | 1940 | 1978[1] | 1893 | 1996 | 1894 |
| **Epping** | 1996[1] | 1983 | 1996 | 1984 | 1997[1] | 1986 | 1999 | 1982 | 1998 | 1984 | 1995[2] | 1991 | 1998[2] | 1987 | 1997 | 1982 | N/A | N/A | 2003 | 1991 | N/A | N/A | N/A | N/A |
| **Maroondah** | 1994 | 1982 | 1996 | 1983 | 1995 | 1972 | 1999 | 1973 | 1970 | 2003 | 1995[1] | 1975 | 1998[1] | 1976 | 1992[1] | 1983 | 1995[1] | 1981 | N/A | N/A | 1994[1] | 1983 | 1996 | 1970 |

[1] At 90% significance level
[2] At 95% significance level
[3] At 99% significance level
Months with N/A are those for which significant abrupt slope change point is already calculated

### 5.1.2.4 Analysis of mean monthly minimum temperature

Step change analysis results for mean monthly minimum temperature are given in the Table 5.8, in which the statistically significant step changes are shaded dark. The time series plots for those months that exhibited significant step changes are presented in Appendix D.

From Table 5.8, it is observed that MRO exhibited statistically significant abrupt step changes in all months, which occurred between 1945 and 1966. From the time series plots in Appendix D, it can be observed that all these abrupt step changes were step-up changes.

Epping exhibited step changes for 2 months and Maroondah for just a single month of the year. All these changes occurred in the end of the $20^{th}$ century and the time series plots again indicate that they were step-up changes.

Table 5.8 Step change points of mean monthly minimum temperature

| Stations | Jan | | Feb | | Mar | | Apr | | May | | Jun | | Jul | | Aug | | Sep | | Oct | | Nov | | Dec | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd |
| **MRO** | 1958[3] | 1890 | 1954[3] | 1911 | 1955[3] | 1914 | 1966[3] | 1939 | 1962[3] | 1911 | 1950[3] | 1921 | 1945[3] | 1912 | 1963[3] | 1919 | 1959[3] | 1921 | 1959[3] | 1931 | 1957[3] | 1901 | 1959[3] | 1912 |
| **Epping** | 1994[1] | 1982 | 1996 | 1983 | 1989 | 1981 | 1990 | 1999 | 1983 | 2006 | 1999 | 1987 | 1987 | 1995 | 1984 | 2004 | 1997 | 1981 | 2003 | 1993 | 1999[1] | 1984 | 2001 | 1994 |
| **Maroondah** | 1982 | 2001 | 1983 | 2001 | 1993 | 1973 | 1994 | 1971 | 1973 | 1993 | 1989 | 2003 | 1987[1] | 2001 | 1988 | 2000 | 1971 | 2001 | 1992 | 1972 | 1990 | 1974 | 1994 | 1969 |

[1] At 90% significance level
[2] At 95% significance level
[3] At 99% significance level

#### 5.1.2.5 Discussion

From the step change analysis presented above, it is clear that all the three stations over the Yarra river catchment experienced considerable step-up change in temperatures, especially in the end of the century. Moreover, the most significant step changes have occurred in the station located in urban area, which is MRO. Both the monthly timescale indices (i.e., mean monthly maximum and minimum temperatures) at MRO exhibited abrupt step-up changes in all months. The maximum temperatures at MRO seem to have experienced a step-up more towards the end of the 21$^{st}$ century, whereas the minimum temperatures had a step-up in the middle of the century (around 1945 - 1960).

The other 2 stations, Epping and Maroondah also experiences step-up changes, although not as prominent as in MRO. The step-up changes at these 2 stations were observed to be more towards the end of the last century. Contrary to all the other step-up changes, Maroondah experienced a step-down change in its annual maximum temperatures in 1983.

### 5.1.3 Trend analysis

As in the rainfall analysis, trend analysis was carried out for temperature data also with the Mann-Kendall test. For those stations which experienced an abrupt change, broken dataset (i.e., dataset after the abrupt change) were used in the trend analysis.

#### 5.1.3.1 Analysis of annual maximum temperature

Trend analysis results of annual maximum temperature are given in Table 5.9.

Table 5.9 Trend analysis for annual maximum temperatures

| Station | Mann-Kendall test | |
|---|---|---|
| | Z | Significance |
| MRO | -0.373 | NS |
| Epping | 0.619 | 90% |
| Maroondah | 0.67 | NS |

As seen in the table, Epping exhibited a statistically significant upward trend (at 90% significance level) in its annual maximum temperatures after 2002. As presented earlier, it had experienced a step-up change in its annual maximum temperature in 2002.

#### 5.1.3.2 Analysis of annual minimum temperature

Trend analysis results of annual maximum temperature are given in Table 5.10. It can be observed in this table that MRO had significant upward trend (at 99% significance level) after 1949, when it had experienced an abrupt step-up in its annual minimum temperatures.

Table 5.10 Trend analysis for annual minimum temperatures

| Station | Mann-Kendall test | |
|---|---|---|
| | Z | Significance |
| MRO | 5.097 | 99% |
| Epping | 1.05 | NS |
| Maroondah | -0.347 | NS |

#### 5.1.3.3 Analysis of mean monthly maximum temperature

Table 5.11, Table 5.12 and Table 5.13 present the trend analysis results of mean monthly maximum temperature at stations MRO, Epping and Maroondah respectively.

Table 5.11 Mean monthly maximum temperature trend at MRO

| Station | MK | |
|---|---|---|
| | **Z** | **Significance** |
| January | 2.137 | 95% |
| February | 0.01 | NS |
| March | 0.702 | NS |
| April | 0.818 | NS |
| May | 1.089 | NS |
| June | 2.85 | 99% |
| July | 2.438 | 99% |
| August | 1.887 | 95% |
| September | 1.584 | 90% |
| October | 2.224 | 95% |
| November | 2.351 | 99% |
| December | 1.375 | 90% |

Table 5.12 Mean monthly maximum temperature trend at Epping

| Station | MK | |
|---|---|---|
| | **Z** | **Significance** |
| January | 1.588 | 90% |
| February | -0.25 | NS |
| March | 1.647 | 95% |
| April | 0.816 | NS |
| May | 0.306 | NS |
| June | 0.594 | NS |
| July | -0.27 | NS |
| August | 1.615 | 90% |
| September | 3.721 | 99% |
| October | 1.479 | 90% |
| November | 2.554 | 99% |
| December | 1.565 | 90% |

Table 5.13 Mean monthly maximum temperature trend at Maroondah

| Station | MK | |
|---|---|---|
| | **Z** | **Significance** |
| January | 0.444 | NS |
| February | -0.28 | NS |
| March | 0.769 | NS |
| April | 0.499 | NS |
| May | 1.17 | NS |
| June | 0.823 | NS |
| July | -0.41 | NS |
| August | 1.287 | 90% |
| September | 0.891 | NS |
| October | 1.019 | NS |
| November | 1.891 | 95% |
| December | 1.30 | 90% |

In the mean monthly maximum temperature trend analysis presented in Tables 5.11 – 5.13, it is observed that MRO had shown statistically significant increasing trends for all months except 4 months around autumn. MRO exhibited statistically significant increasing trends for 8 months, Epping for 7 and Maroondah for 3 months. Considering statistically significant as well as non-significant trends, it is also observed that MRO had increasing trends in all months, whereas Epping and Maroondah had decreasing trends for 2 months each.

#### 5.1.3.4 Analysis of mean monthly minimum temperature

Similar to mean monthly maximum temperature analysis, Table 5.14, Table 5.15 and Table 5.16 present the trend analysis results of mean monthly minimum temperatures at the 3 stations respectively.

From Tables 5.14 – 16, it can be observed that the mean monthly minimum temperature trends for MRO had shown statistically significant increasing trends for all months except April. On the contrary, Epping had shown significant increasing trends for only the month of November, whereas Maroondah for only June.

From the trend analysis for all the 3 stations, there was only one statistically significant decreasing trend identified, which was at Maroondah for the month of May. Considering statistically significant as well as non-significant trends for the mean monthly minimum temperatures, it is also observed that MRO had decreasing trends for 1 month, Epping for 4 and Maroondah for 9 months.

Table 5.14 Mean monthly minimum temperature trend at MRO

| Station | MK | |
|---|---|---|
| | Z | Significance |
| January | 2.036 | 95% |
| February | 2.375 | 99% |
| March | 2.606 | 99% |
| April | -0.38 | NS |
| May | 2.498 | 99% |
| June | 3.514 | 99% |
| July | 4.523 | 99% |
| August | 2.824 | 99% |
| September | 3.687 | 99% |
| October | 2.892 | 99% |
| November | 3.582 | 99% |
| December | 2.217 | 95% |

Table 5.15 Mean monthly minimum temperature trend at Epping

| Station | MK | |
|---|---|---|
| | Z | Significance |
| January | 1.081 | NS |
| February | 1.139 | NS |
| March | -0.39 | NS |
| April | -1.10 | NS |
| May | -1.25 | NS |
| June | 1.088 | NS |
| July | 0.255 | NS |
| August | -0.76 | NS |
| September | 0.68 | NS |
| October | 0.187 | NS |
| November | 1.713 | 95% |
| December | 0.204 | NS |

Table 5.16 Mean monthly minimum temperature trend at Maroondah

| Station | MK | |
|---|---|---|
| | Z | Significance |
| January | -0.31 | NS |
| February | -0.80 | NS |
| March | -1.47 | 90% |
| April | -0.57 | NS |
| May | 0.379 | NS |
| June | 1.528 | 90% |
| July | -1.006 | NS |
| August | -0.73 | NS |
| September | 0.347 | NS |
| October | -1.127 | NS |
| November | -0.921 | NS |
| December | -0.9 | NS |

#### 5.1.3.5 Discussion

From the trend analysis presented above, it is clear that the urban area station, MRO had exhibited statistically significant increasing trends, especially in its minimum temperatures. As presented in the abrupt change analysis previously, these increasing trends had started after step-up changes that occurred around the middle of the last century.

On the other hand, the station located in forest area, namely Maroondah exhibited decreasing trends in its minimum temperatures, observed both at the annual and monthly timescales.

## 5.2 Extreme Value Analysis

Extreme temperature events can cause severe social and environmental impacts on society. Extreme temperature events have received attention recently as they have caused exponential increase in economic losses, often leading to large number of fatalities (Karl & Easterling 1999). Statistics related to extreme climatic events plays major role in engineering practice and water management.

In this study, the following two indices were selected for extreme value temperature analysis:

i) Annual very hot days - Annual count of days with maximum daily temperature over 40° C.

ii) Annual very cold days - Annual count of days with minimum daily temperature less than 2° C.

Similar to standard value analysis, same stations and same length of dataset were used in extreme value analysis. The extracted dataset of all three selected stations for annual very hot days and annual very cold days are presented in Figure 5.12 and Figure 5.13.

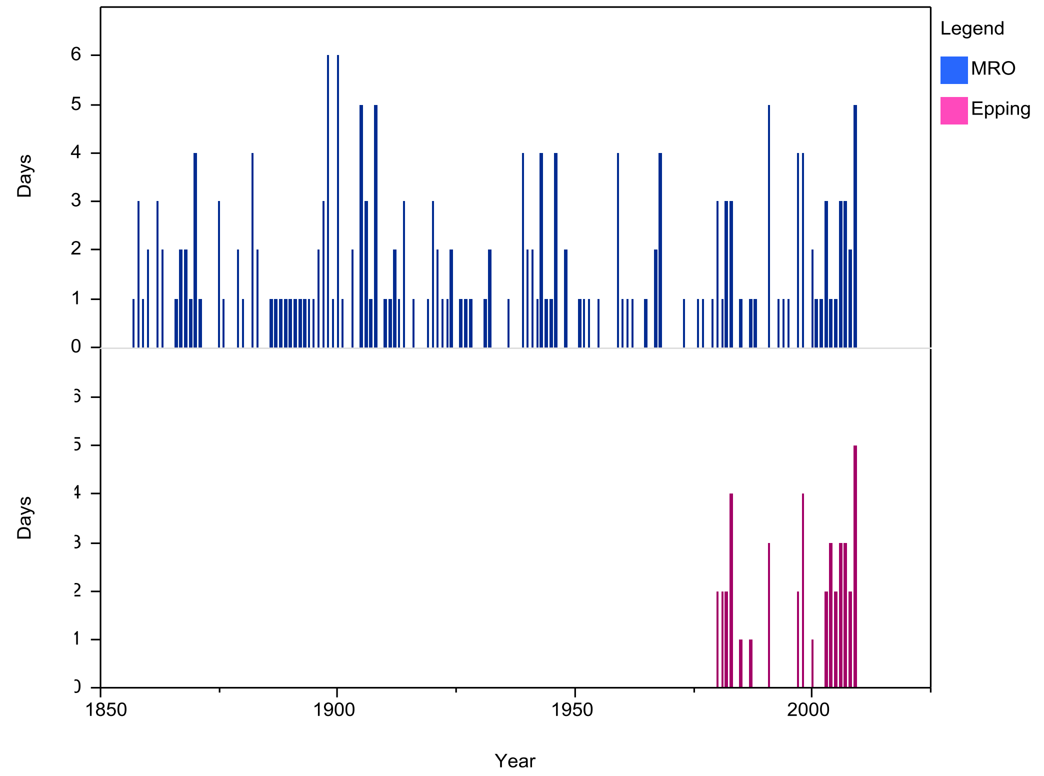



Figure 5.12 Annual count of very hot days

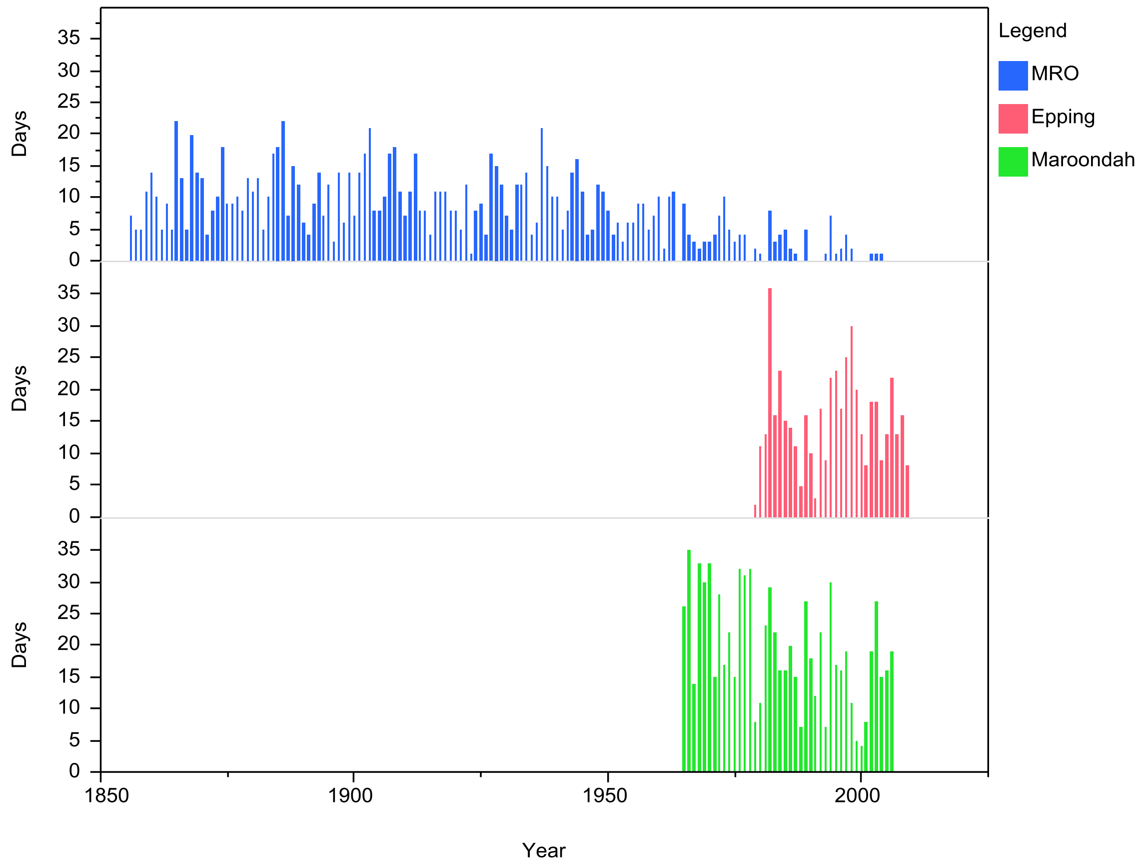



Figure 5.13 Annual count of very cold days

Interestingly, Maroondah never had a maximum temperature over 40° C and therefore is not presented in Figure 5.12. From the plots for annual very cold days, just a visual examination reveals that the number of very cold days has been drastically reducing at all the 3 selected stations and is most prominent at the MRO. The following statistical analysis will provide actual change points and the trends.

## 5.2.1 Slope change analysis

As mentioned in Section 4.2.1.1, similar to standard value analysis, slope change in extreme value analysis is important as it would help to identify the actual pattern of change in each extreme event. Due to the global climate change, it was expected to increase the severity of extreme events.

### 5.2.1.1 Analysis of annual very hot days

The results of slope change analysis for Annual very hot days using Break point test are presented in Table 5.17. From this table, it can be seen that none of the stations experiences an abrupt slope change in annual very hot days.

Table 5.17 Break points of annual very hot days

| Station | Min RSS | Break point | Existence of slope change |
|---|---|---|---|
| MRO | 1909 | 1948 | No |
| Epping | 1983 | 1977 | No |
| Maroondah[1] | N/A | N/A | N/A |

[1] Maroondah has never experienced very hot days

### 5.2.1.2 Analysis of annual very cold days

Slope change analysis results of annual very cold days are presented in Table 5.18. Again, none of the stations experienced an abrupt slope change for this index.

Table 5.18 Break points of annual very cold days

| Station | Min RSS | Break point | Existence of slope change |
|---|---|---|---|
| MRO | 1926 | 1899 | No |
| Epping | 1982 | 1980 | No |
| Maroondah | 1998 | 2002 | No |

#### 5.2.1.3 Discussion

Since no abrupt slope changes were detected for both the indices, the following step change analysis to detect abrupt changes will be important.

### 5.2.2 Step change analysis

As before, the Median change point test was used to locate the abrupt step change point. Since there were no abrupt slope changes for both the time series data, the same dataset which used in slope change analysis were used in this analysis also.

#### 5.2.2.1 Analysis of annual very hot days

Detected primary and secondary change points of annual very hot days are presented in the Table 5.19.

Table 5.19 Change points of annual very hot days

| Station | Primary change point | Secondary change point |
|---|---|---|
| MRO | 1996[1] | 1948 |
| Epping | 2002[1] | 1983 |
| Maroondah | N/A | N/A |

[1] At 99% statistically significant level

It can be observed that MRO exhibited a step change of annual very hot days in 1996 and Epping in 2002. From the time series plots presented in Figure 5.14 and Figure 5.15, it can be observed that both these step changes were step-up changes.

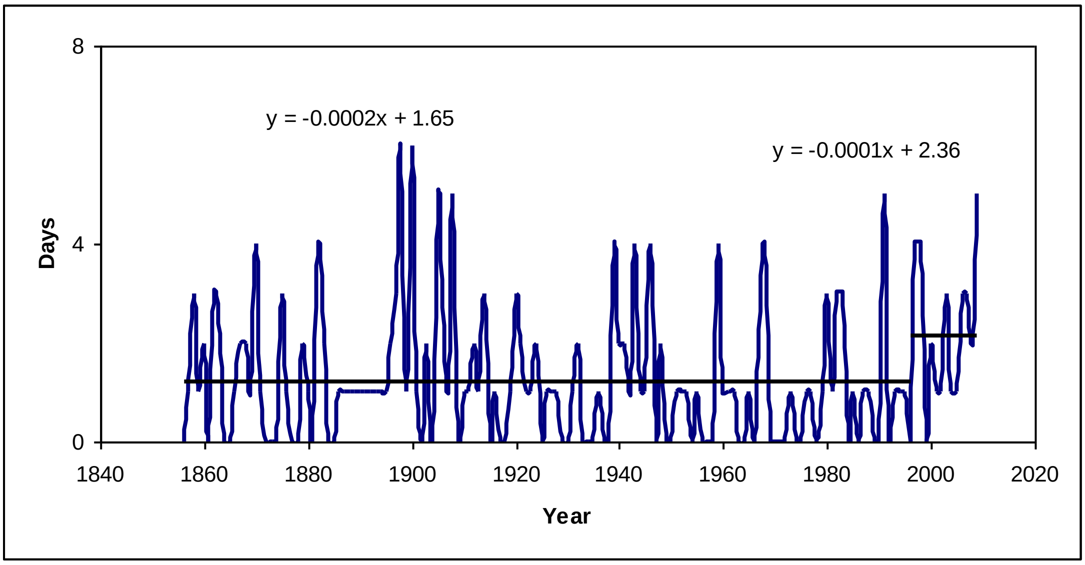



Figure 5.14 Annual very hot days at MRO with a step change in 1996

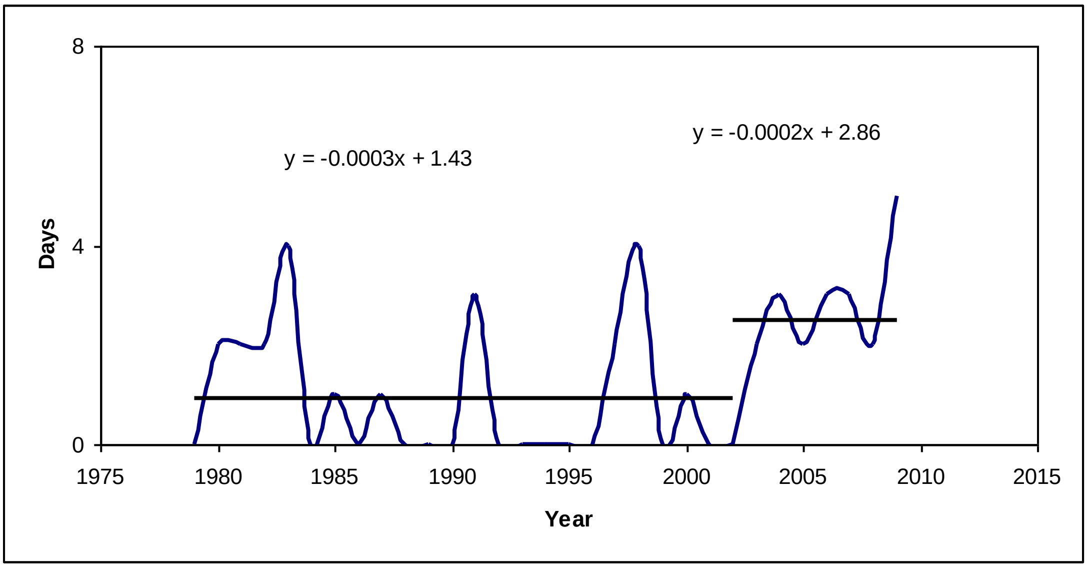



Figure 5.15 Annual very hot days at Epping with a step change in 2002

### 5.2.2.2 Analysis of annual very cold days

The detected primary and secondary step change points of annual very cold days are presented in the Table 5.20. The table reveals that there were statistically significant abrupt step changes in the number of annual very cold days at MRO and Maroondah, in the years 1950 and 1978 respectively. The time series plots for these 2 stations are presented in Figure 5.16 and Figure 5.17, which reveal that both these significant step changes were step-down changes.

Table 5.20 Change points of annual very cold days

| Station | Primary change point | Secondary change point |
|---|---|---|
| MRO | 1950[1] | 1923 |
| Epping | 1993 | 1984 |
| Maroondah | 1978[2] | 1994 |

[1] At 99% statistically significant level
[2] At 90% statistically significant level

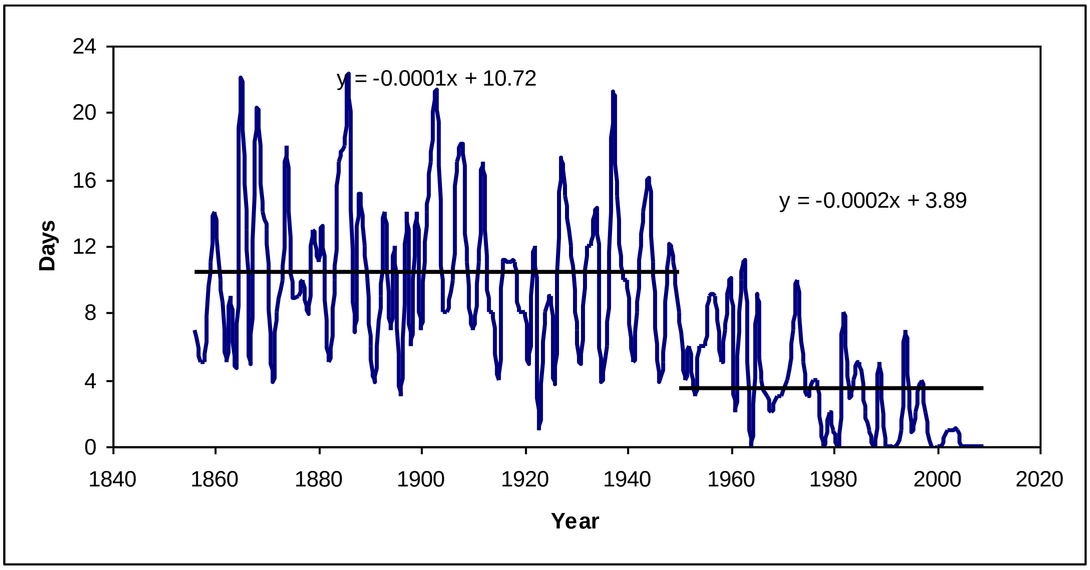



Figure 5.16 Annual very cold days at MRO with a step change in 1950

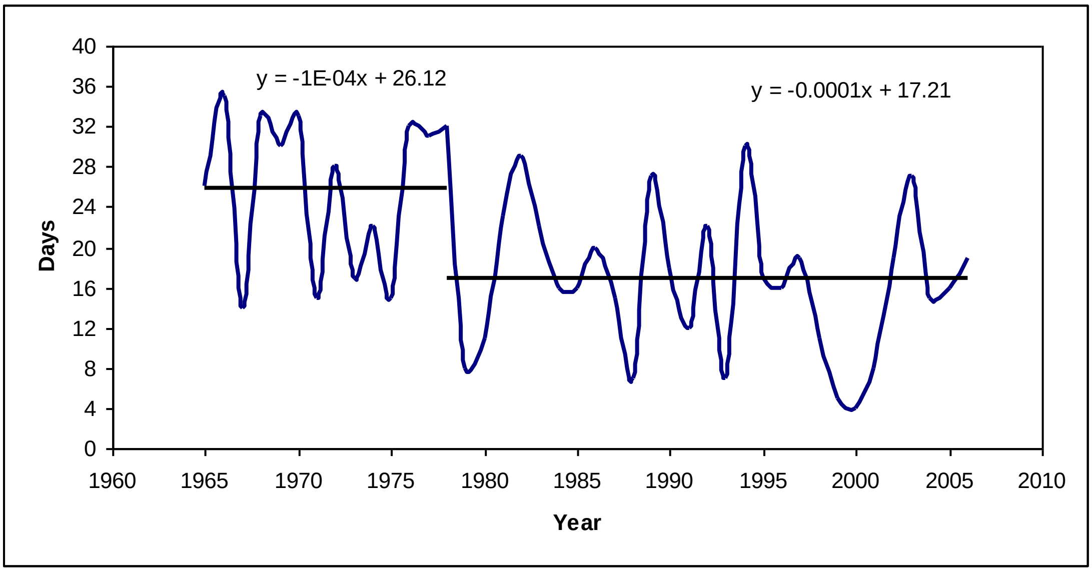



Figure 5.17 Annual very cold days at Maroondah with a step change in 1978

#### 5.2.2.3 Discussion

From the step change analysis, it can be observed that the very hot days over the catchment exhibited a step-up change during the end of the last century. Whereas the very cold days exhibited a step-down change, indicating that the cold days are reducing; this in turn indicates warming temperatures. MRO exhibited the reduction in cold days during the middle of the last century, whereas Maroondah in 1978.

### 5.2.3 Trend analysis

As before, the Mann-Kendall test was used to analyse the trends in the extreme value temperature indices.

#### 5.2.3.1 Analysis of annual very hot days

In the trend analysis for annual very hot days, MRO and Epping datasets are considered after 1996 and 2002 respectively as abrupt step changes were identified in those years. The trend analysis results of annual very hot days are presented in Table 5.21

Table 5.21 Trend of annual very hot days

| Station | Mann-Kendall test | |
|---|---|---|
| | Z | Significance |
| MRO | 1.095 | 90% |
| Epping | 1.608 | 99% |
| Maroondah[1] | N/A | N/A |

[1] Maroondah has never experienced very hot days

It can be observed from the above table that MRO and Epping have both experienced statistically significant increasing trends in the annual count of very hot days.

#### 5.2.3.2 Analysis of annual very cold days

Similar to trend analysis for annual very hot days, for the trend analysis of annual very cold days, the datasets for MRO and Maroondah were considered only after 1950 and 1978 respectively. The trend analysis results of annual very cold days are presented in Table 5.22.

Table 5.22 Trend of annual very cold days

| Station | Mann-Kendall test | |
|---|---|---|
| | Z | Significance |
| MRO | -5.338 | 99% |
| Epping | 0.374 | NS |
| Maroondah | -1.125 | NS |

From Table 5.22, it can be observed that only MRO has experienced a statistically significant decrease in trends for the annual count of very cold days.

#### 5.2.3.3 Discussion

From the analysis for trends, it is observed that MRO, representing the urban area within the Yarra river catchment has experienced increase in very hot days, starting from the end of the last century. On the other hand, MRO experienced decrease in very cold days, starting from the middle of the 20$^{th}$ century. This seems to indicate that the summers are becoming hotter and the winters are also becoming warmer.

Similar trends are also observed at the other stations, though not as prominent as in MRO.

## 5.3 Conclusion

The Yarra River catchment lies in the north-east of Melbourne in Victoria and its water resources support a range of uses valued by Melbourne's community, including urban water supply, agricultural and horticultural industries, and downstream user requirements as well as flow requirements for maintaining environmental flows. Any climatic changes will have important implications for water resources of this catchment. No previous studies have provided a detailed analysis of changes in temperature patterns specific to the Yarra River catchment, which was the main motivation for conducting the analysis presented in this chapter.

From the analysis presented in this chapter, it is clear that the temperatures over the Yarra river catchment are increasing. The increase in temperature is more pronounced in urban areas, whereas in the forest areas, represented by the station at Maroondah, the increase is not very prominent. On the contrary, the minimum temperatures in Maroondah have exhibited decreasing trends, observed in both annual and monthly timescales.

The increasing trends in temperature at MRO have been observed both in the maximum and minimum temperatures, but the increase in the minimum temperatures is much more prominent. It is interesting to note that the maximum temperatures at MRO have exhibited the increase towards the end of the last century, whereas the minimum temperatures had increased in the middle of the century. These have been observed in both the standard value and extreme value analysis.

# 6 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Summary

Climate change is one of the greatest economic, social and environmental challenges of our time. Climate variability has a large impact on water resources since fundamental drivers of hydrological cycle get affected. Increase in temperatures will contribute to evaporation, which in turn will leads to the dangerous reduction in water levels of reservoirs. This when combined with reduction in rainfall will only exacerbate the problem.

Climate change is typically discussed in global terms, yet its effects vary quite dramatically among different regions of earth. This is because, although climate change is a global phenomenon, the trends and its impacts may be different from one location to the other due to the variations of hydro-climatic variables from one region to the other. The main aim of this research was to understand the changes in climatic variables that have occurred at a regional scale in and around Melbourne. The Yarra River catchment was selected as the case study catchment because it is a major source of water supply for Melbourne. Thus, any changes in climatic variables at a local scale over this catchment would have implications for the management of water resources within the catchment. Two climatic variables, rainfall and temperature were selected in this study for change detection.

With the aim of detecting changes in rainfall and temperature data over the Yarra River catchment, this study was classified into two parts:

1) **Selection of most suitable techniques** - There are two types of changes that have been reported in climate change studies, namely, step change (abrupt change) and trend (gradual change). There are numerous statistical techniques that have been used in literature to detect each of these changes.

To choose the best statistical technique from the many available techniques for each of the two types of change, hypothetical data analysis was conducted. Hypothetical datasets were developed with known abrupt change points and trends, which was then used to select the statistical technique that most accurately detected the change points and trends.

2) **Detection of change in rainfall and temperature** - These data were required to understand the climate change in this catchment. There were 11 stations selected for rainfall analysis and 3 stations for temperature analysis, which were selected to represent all three different landuse areas.

## 6.2 Conclusions

The conclusions that can be drawn from this study are as follows:

1) **Hypothetical data analysis** - It was concluded from the hypothetical analysis that the Break Point test was most accurately able to detect the known change point for all the considered hypothetical data cases. Thus, it was proposed to start the change analysis for real climatic data sets by first using the Break Point test to detect the abrupt slope change point test. If a slope change point was not detected, then the Median change point test should be applied as it was the most accurate amongst the step change detection techniques. The Mann-Kendall test should be used for the detection of trends as it was most accurate in detecting trends in the hypothetical data analysis.

2) **Real data analysis** - The conclusions that can be drawn from the second part of the study, namely change detection in rainfall and temperature over the Yarra River catchment are as follows:

i) There were two shifts that occurred in the rainfall over the catchment. The first shift occurred in middle of the century (1940-1960) and second one occurred at the end of the century. First shift was a step-up change and the second one was a step-down change. This indicates that the first half of the century was a dry period, which was followed by a wet period and then changed to dry again.

ii) All statistically significant step changes for monthly rainfall were in the winter and spring months, except one month where the change was in late autumn (please refer to Table 4.4, page 65).

iii) There are statistically significant decreasing trends identified in annual rainfall of all 11 stations over the catchment, except Boxhill (Table 4.5, page 68). Boxhill also had the maximum number of months with increasing trends in monthly rainfall (as indicated in Table 4.6, page 69).

iv) With respect to extreme rainfall, the heavy precipitation days have exhibited statistically significant abrupt step-up changes in the middle of the century for 3 out of 5 urban stations (Table 4.20, page 81).

v) The number of heavy precipitation days has increasing trend in most urban area stations, while in most forest and rural area stations, it has decreasing trends (Table 4.22, page 85).

vi) With respect to temperatures, for MRO, both mean monthly minimum and maximum temperatures have experienced step up change in almost all months in middle of the century (mostly between 1950-1960) (Tables 5.7 and 5.8 on pages 101 and 103 respectively).

vii) Annual minimum temperature of MRO has got statistically significant step-up change in 1949 (Table 5.6, page 99) and is also showing statistically significant increasing trends (Table 5.10, page 105).

viii) Annual very hot days in urban and rural areas have experienced a statistically significant step-up change during the last decade (Table 5.19, page 112).

ix) On the other hand, annual very cold days have exhibited statistically significant step down changes, which in turn indicated warming temperatures (Table 5.20, page 114).

## 6.3 Implications on Water Resources

The Yarra River catchment is important for Melbourne as most of its water resources come from this catchment. In the last decade, this catchment has experienced a long-term drought and it is of interest to water resource professionals to know if this drought is part of a short-term climatic cycle or a decline in long-term rainfall brought on by global climate change.

As far as rainfall is concerned, any changes in rainfall pattern would have affects on water availability, which in turn affects urban water supply and agricultural, residential and industrial water uses. As was seen in this study, decreasing rainfall trends (in annual rainfall) are observed over the Yarra River catchment. Thus the changing scenario of water availability needs to be properly taken into account for the long-term catchment scale water management. If this reducing trend continues, then the severity and duration of droughts can be expected to increase and more frequent droughts can be expected in the future than in the past. The reducing trends in rainfall observed in this study indicates that the current Drought Response Plans (DRP) (Melbourne Water, 2007) will need to be considered for further review. Tan and Rhodes (2008) have also suggested timely review of DRP taking into account the climate change affects for its effective application.

In the Yarra River catchment, the most important sectors that are likely to be affected due to changing rainfall patterns are urban water supply, maintaining environmental flow which is important to save the unique and rich flora and fauna, water quality and irrigation. The urbanized lower part of the catchment is highly dependent on water supply from the storage reservoirs located in the upper and middle reaches of the catchment. Therefore, this region is more likely to be the risk-prone region. Decreasing rainfall patterns may also have led to reduced health of waterways due to changes in base flows. This could lead to negative water quality impacts in Port Phillip Bay due to increased concentration of pollutants and higher ambient water temperatures in the Bay.

There will also be increased risk of bushfires in the catchment areas with associated risk of decreased streamflows. Therefore, effective measures should be taken to reduce possible damage due to the reduction in rainfall patterns.

From an urban drainage point of view, the increase in extreme rainfall events could lead to more frequent flash floods in urban areas, as the urban drainage system may not be able to cope with the increased flows. Sustaining an acceptable risk of urban flooding is one of the key objectives in operational planning and management of urban drainage systems. This is because flooding causes multi-dimensional damages which include social discomfort, economical cost and even political loss. Therefore, there is a need to assess the flooding impact of climate change on urban drainage systems so that appropriate risk management strategies can be applied.

On the other hand, the increasing trends in temperature over the catchment will only further exacerbate the problem, thus making the water resources increasingly vulnerable to climate change. At the same time, demand for water is growing as a result of increasing population, which when combined with increasing temperatures (and consequent high evaporation rate) will necessitate the need for effective water supply and demand management and also for the application of Water Sensitive Urban Design (WSUD).

## 6.4 Recommendations for Future Research

The following are recommendations that can be taken up in future research studies:

1) This study considered only two variables for change detection, namely rainfall and temperature. There is another significant variable, streamflow, which would also have been impacted by climate change. Change detection for this parameter would immensely support in getting a more comprehensive impact of climate change on water resources.

2) Spatial analysis of change in climatic variables was not considered in this study. Such a study will help to get a better understanding of possible anthropogenic

causes of change in climatic variables, which may be due to activities like urbanisation, land clearance, etc.

3) There is a strong belief that decadal or multi-decadal climatic variations would also have an influence on current climatic changes. Such a study will be quite useful as the understanding of long term cyclic variations would help to understand possible causes of climate change, which may either be due to natural variations or anthropogenic factors or a combination of both.

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# Appendix A

## * Step change points for monthly rainfall

* Please refer to Section 4.1.2.2, Table 4.4

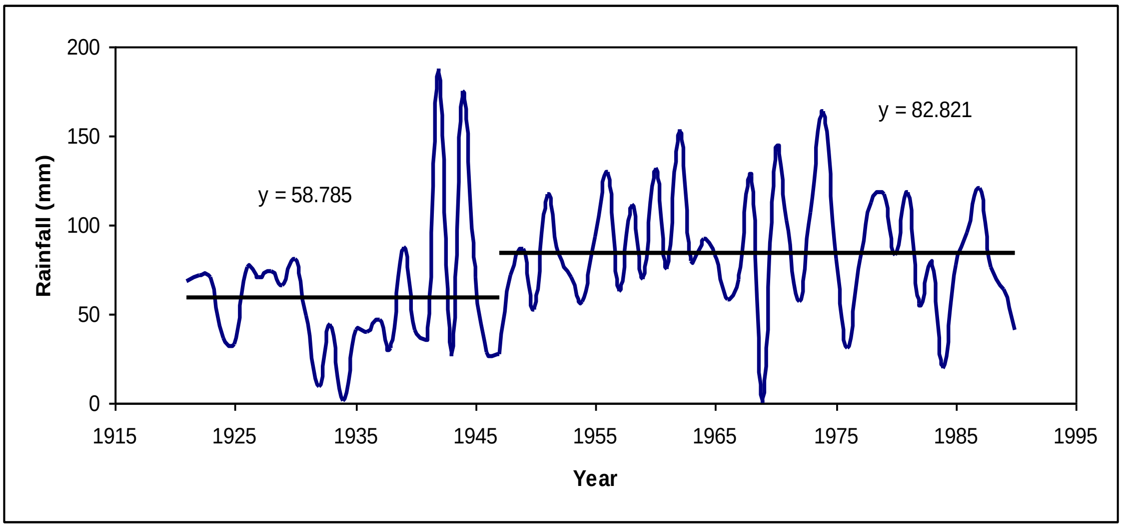


Figure A1 Monthly rainfall for May at Box Hill with a step change in 1947

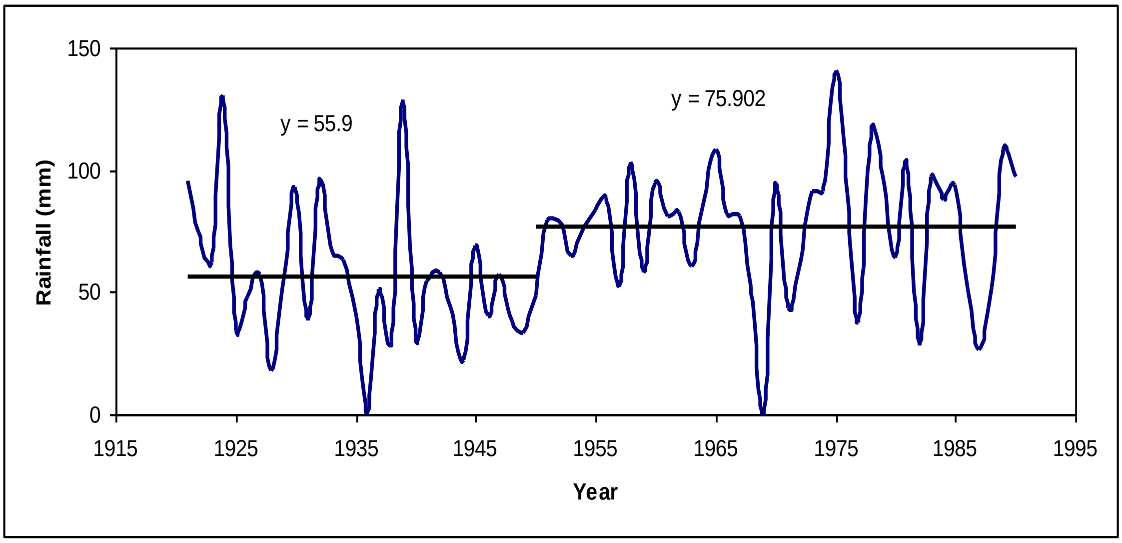


Figure A2 Monthly rainfall for August at Box Hill with a step change in 1950

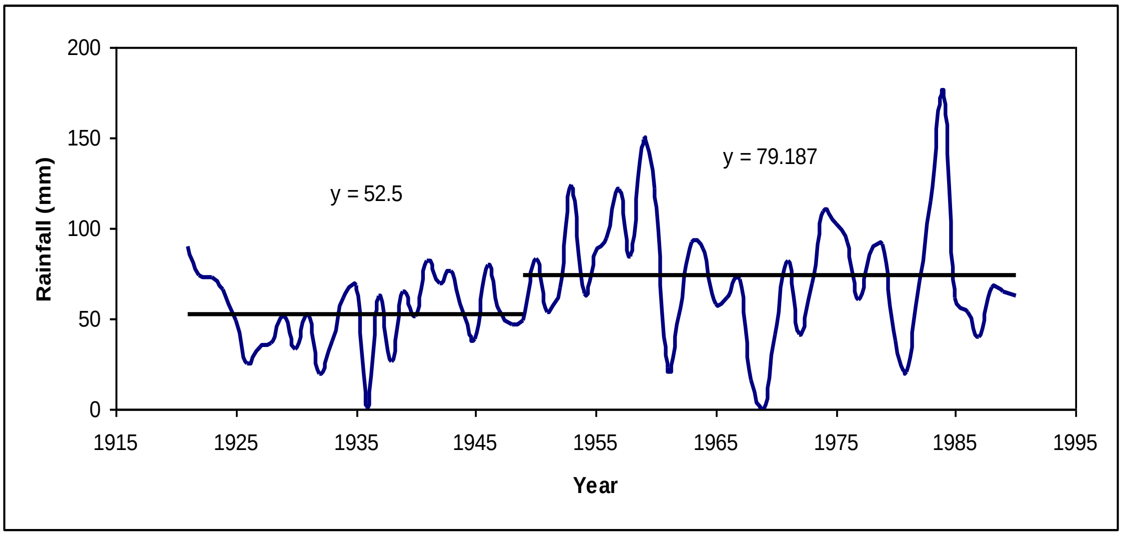


Figure A3 Monthly rainfall for September at Box Hill with a step change in 1949

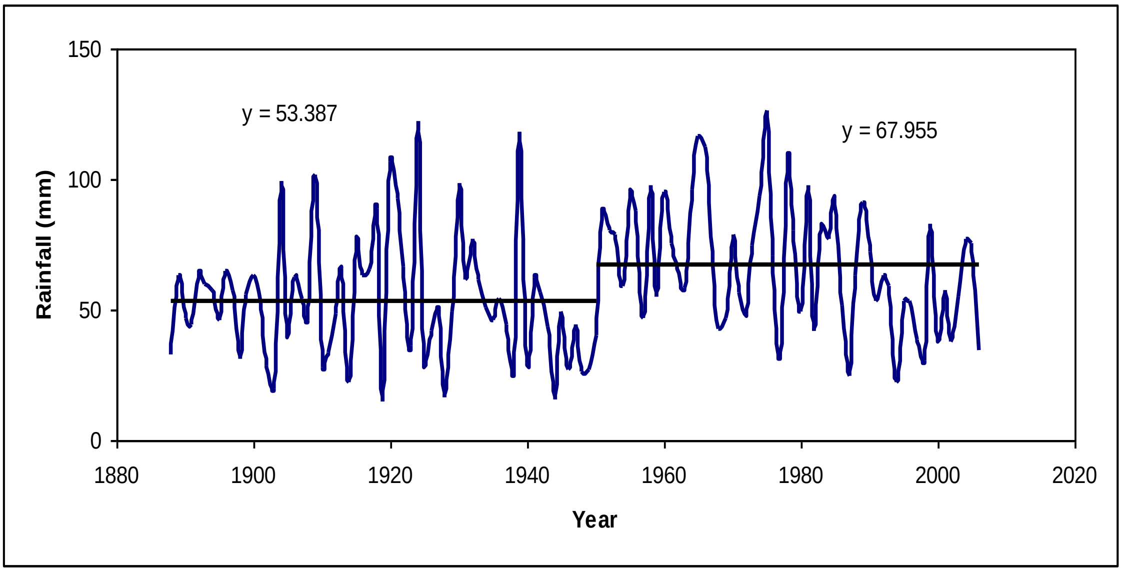


Figure A4 Monthly rainfall for August at Caulfield with a step change in 1950

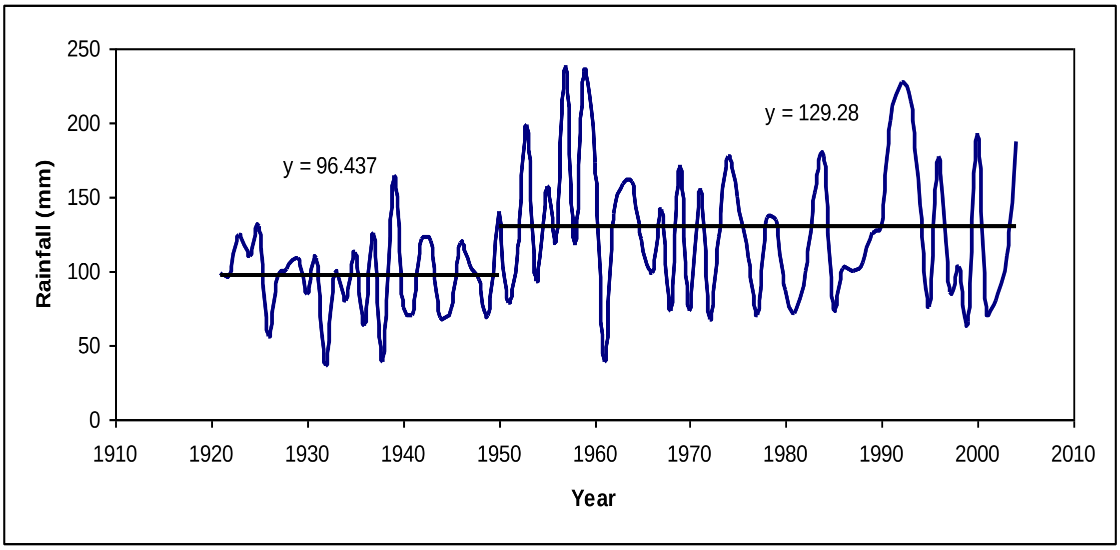


Figure A5 Monthly rainfall for September at Silvan with a step change in 1951

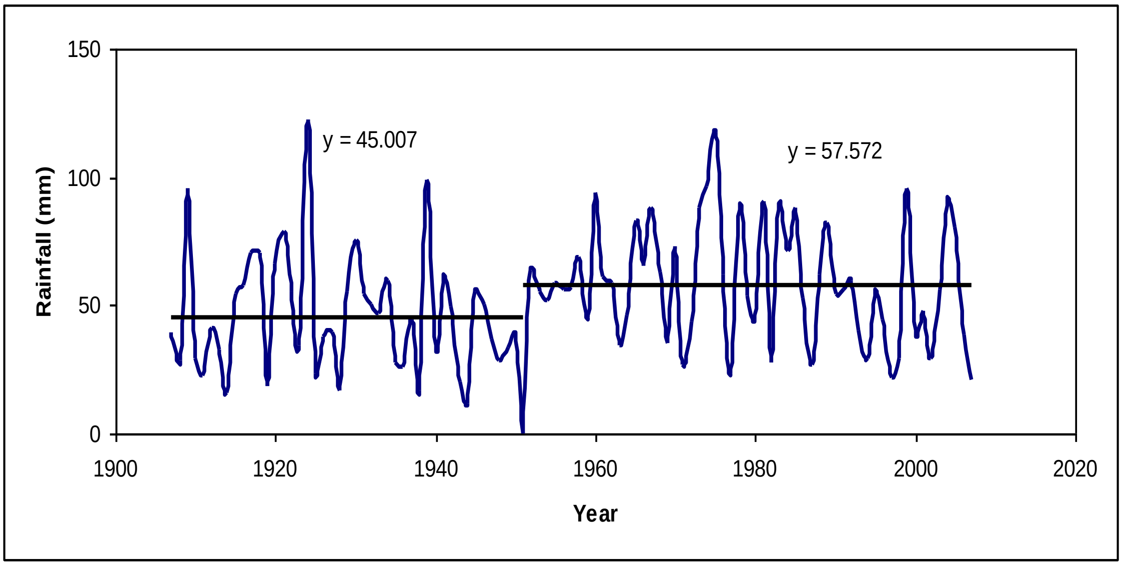


Figure A6 Monthly rainfall for August at Epping with a step change in 1951

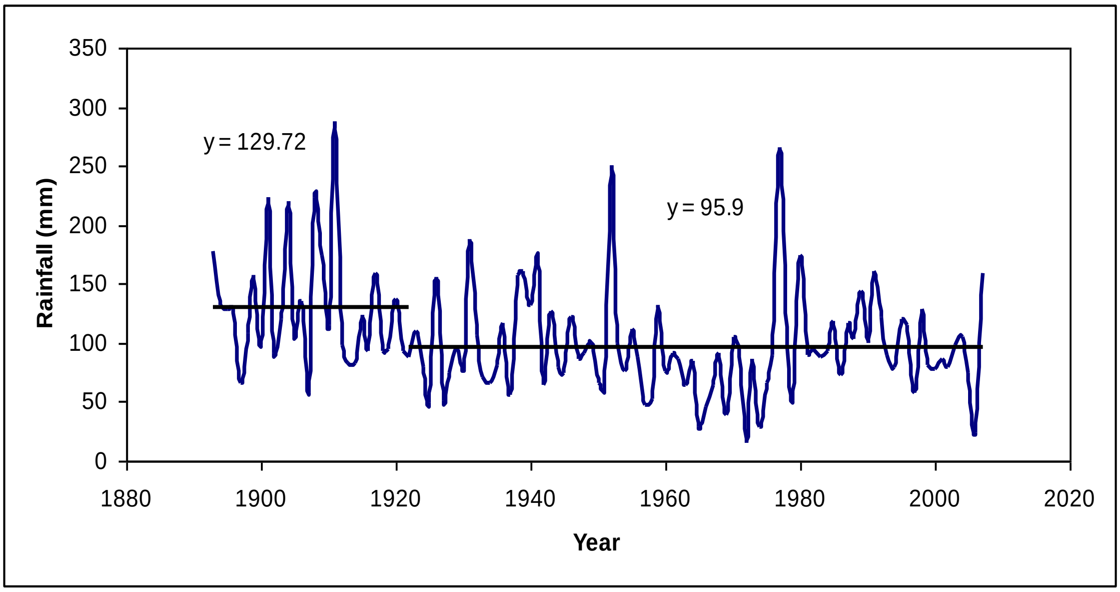


Figure A7 Monthly rainfall for June at Maroondah with a step change in 1922

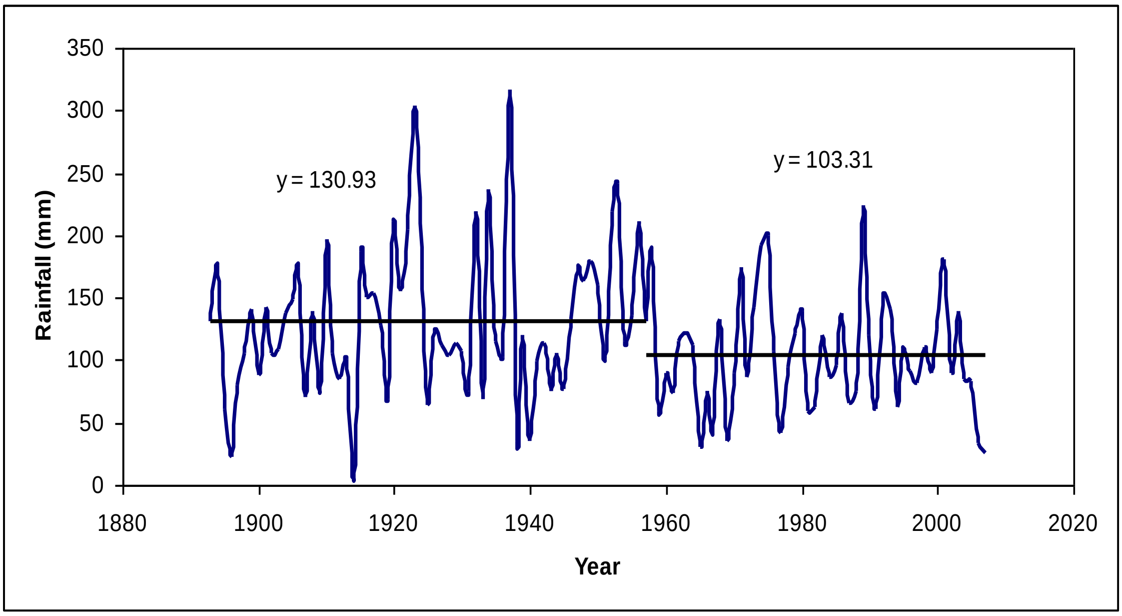


Figure A8 Monthly rainfall for October at Maroondah with a step change in 1957

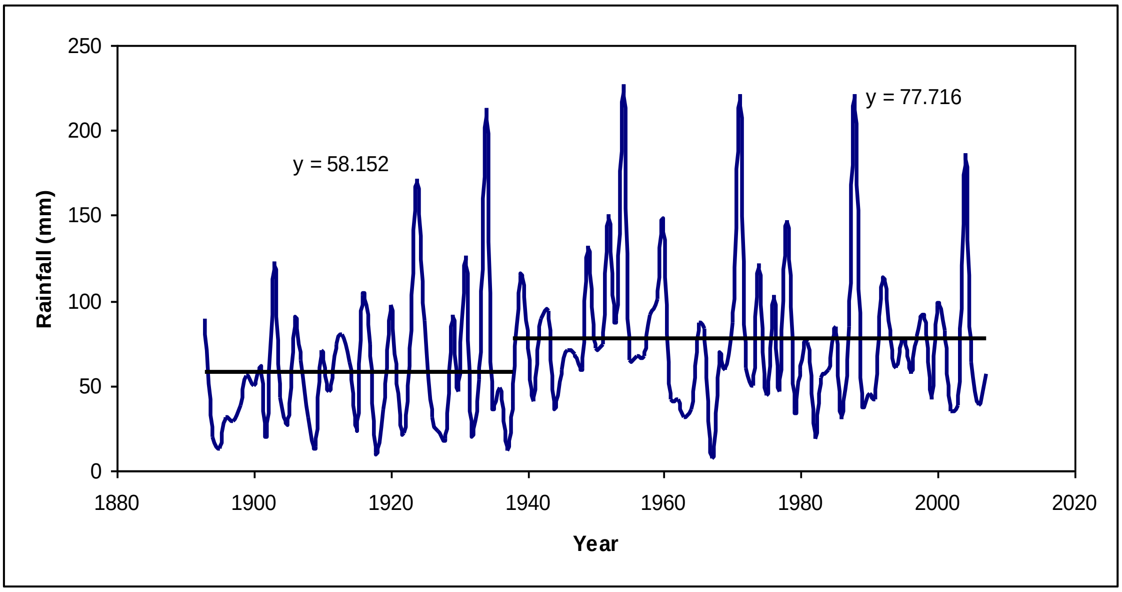


Figure A9 Monthly rainfall for November at Toorourrong with a step change in 1938

# Appendix B

## [*] Primary and secondary step change points for monthly rainfall

* Please refer to Section 4.1.2.2, Table 4.4

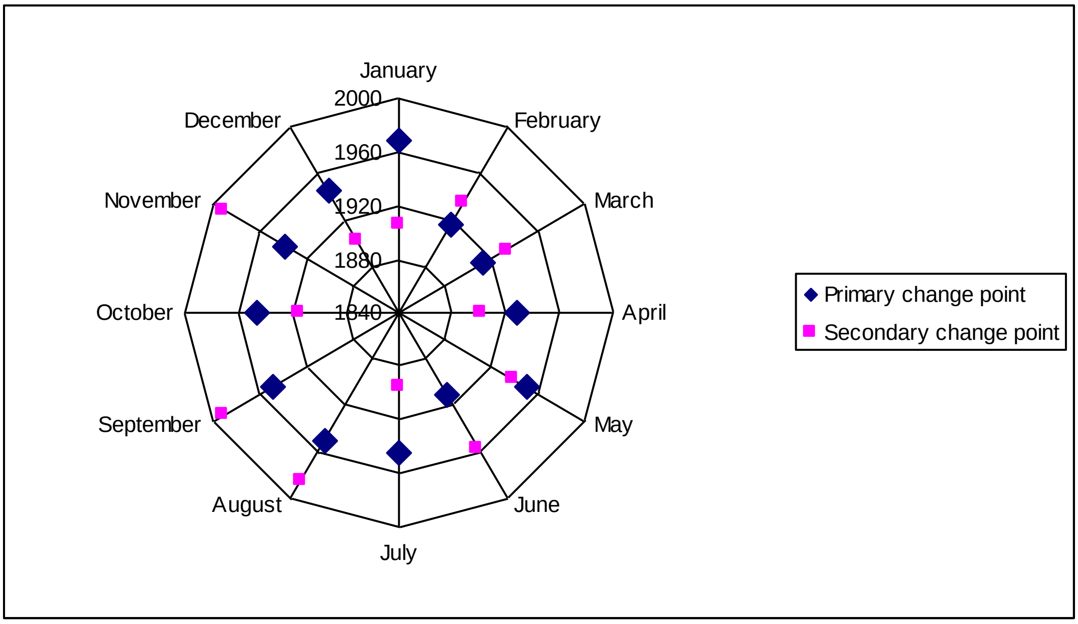


Figure B1 Primary and secondary step change points of monthly rainfall at Caulfield

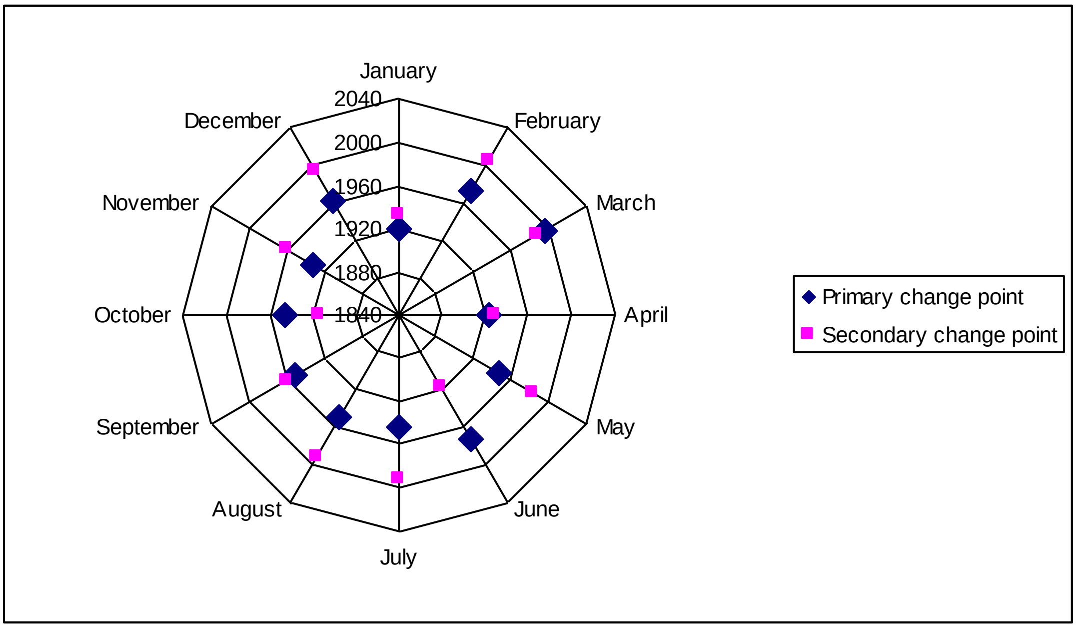


Figure B2 Primary and secondary step change points of monthly rainfall at Eltham

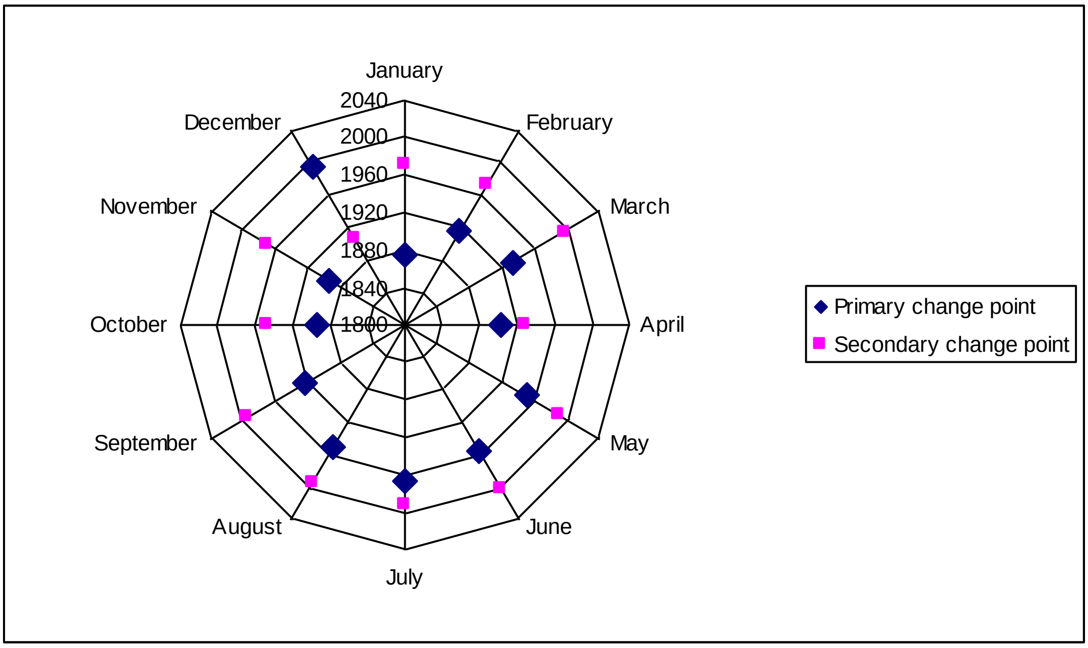


Figure B3 Primary and secondary step change points of monthly rainfall at MRO

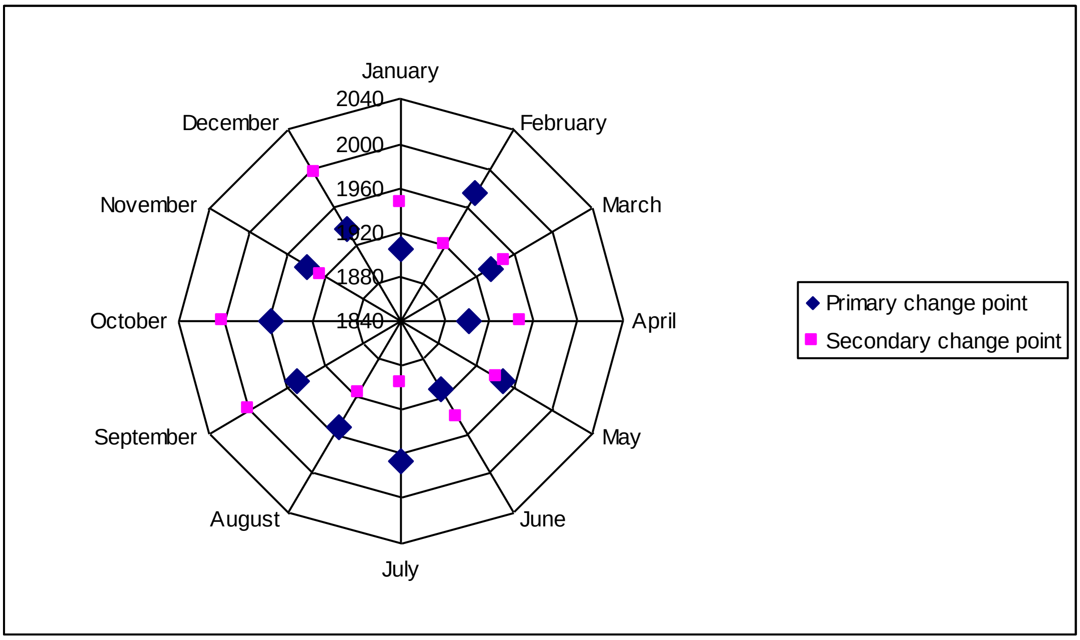


Figure B4 Primary and secondary step change points of monthly rainfall at Lilydale

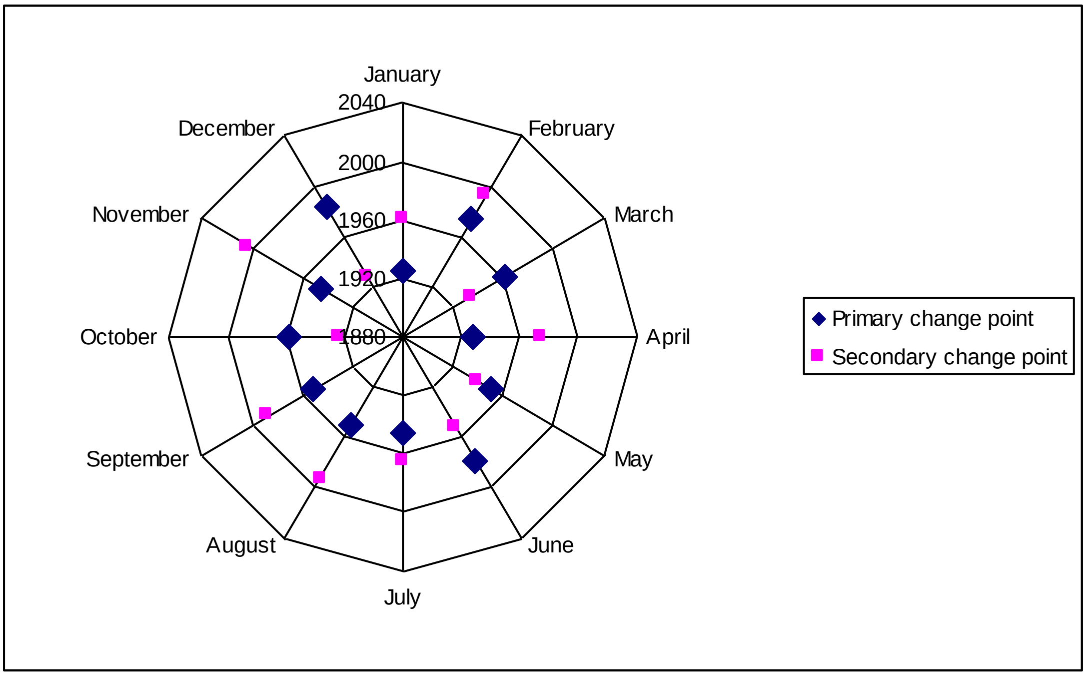


Figure B5 Primary and secondary step change points of monthly rainfall at Silvan

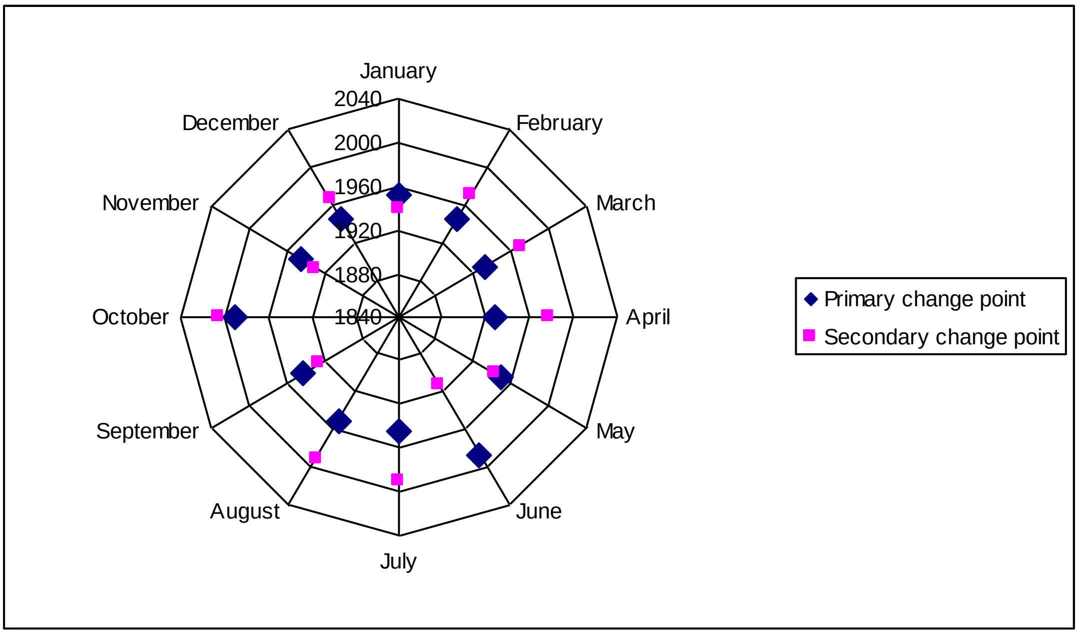


Figure B6 Primary and secondary step change points of monthly rainfall at Epping

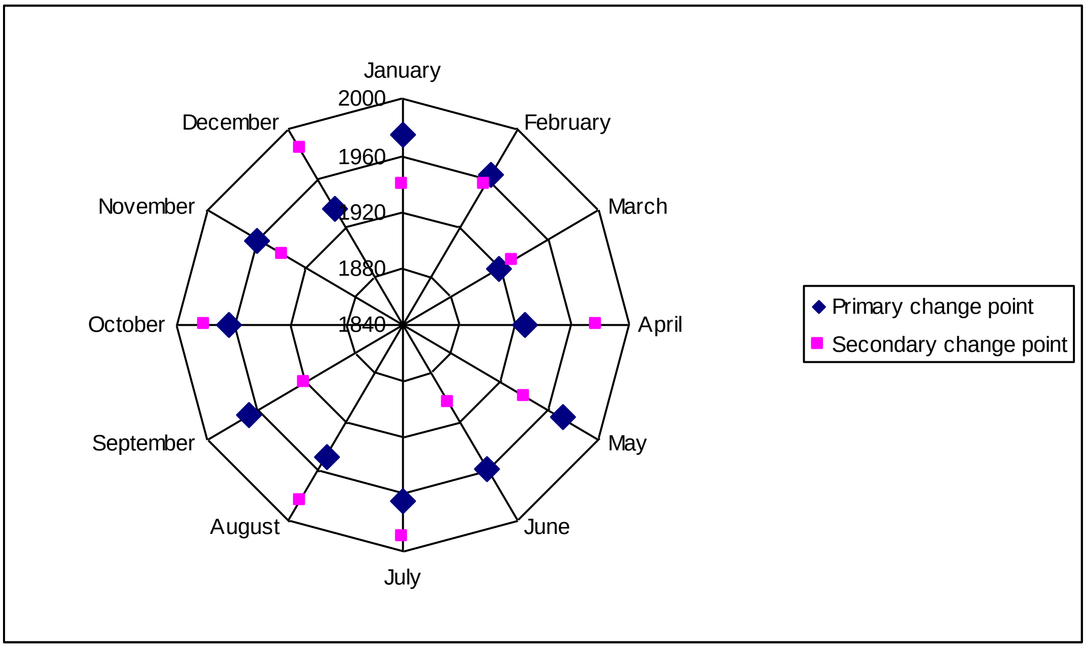


Figure B7 Primary and secondary step change points of monthly rainfall at Mickleham

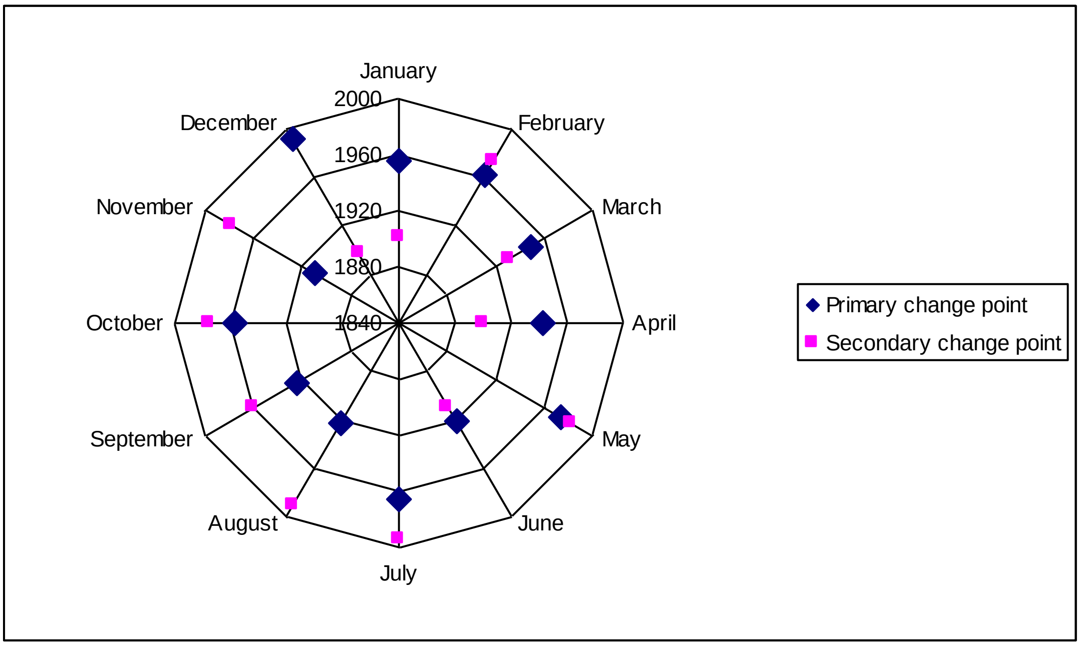


Figure B8 Primary and secondary step change points of monthly rainfall at Maroondah

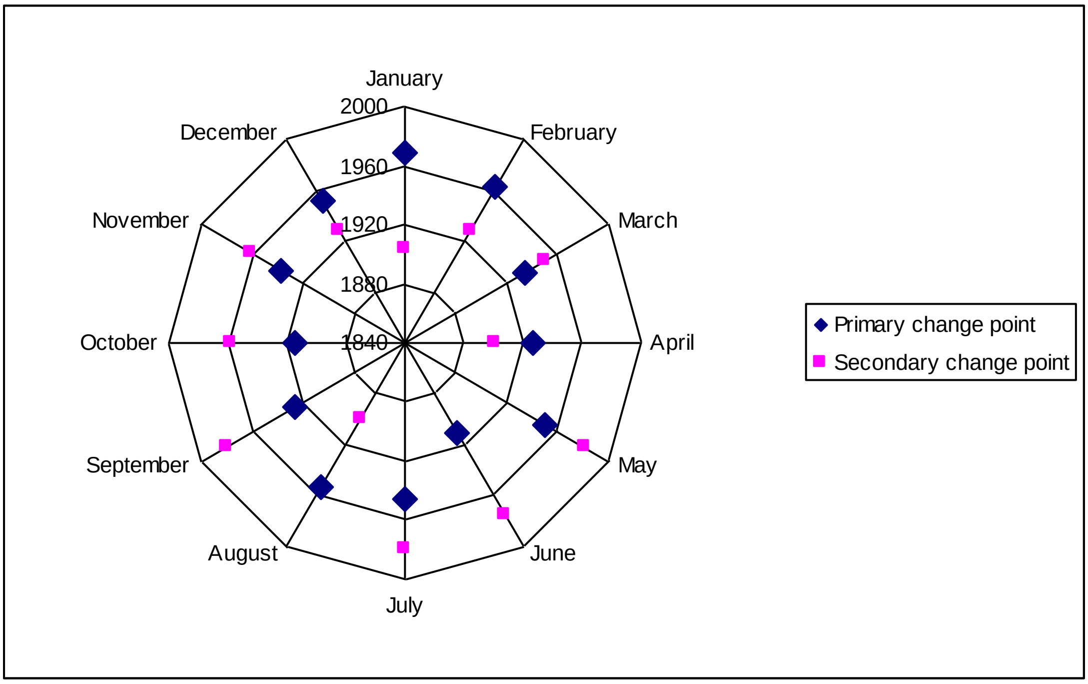


Figure B9 Primary and secondary step change points of monthly rainfall at Toorourrong

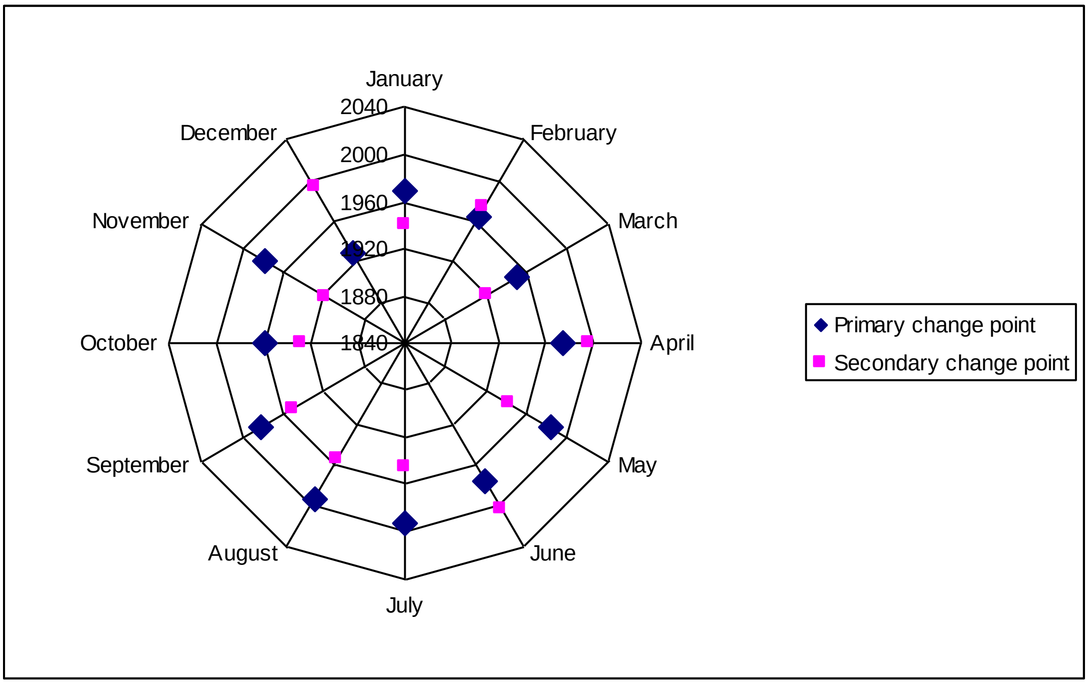


Figure B10 Primary and secondary step change points of monthly rainfall at Warburton

# Appendix C

## [*]Step change points for mean monthly maximum temperature

[*] Please refer to Section 5.1.2.3 and Table 5.7

## MRO:

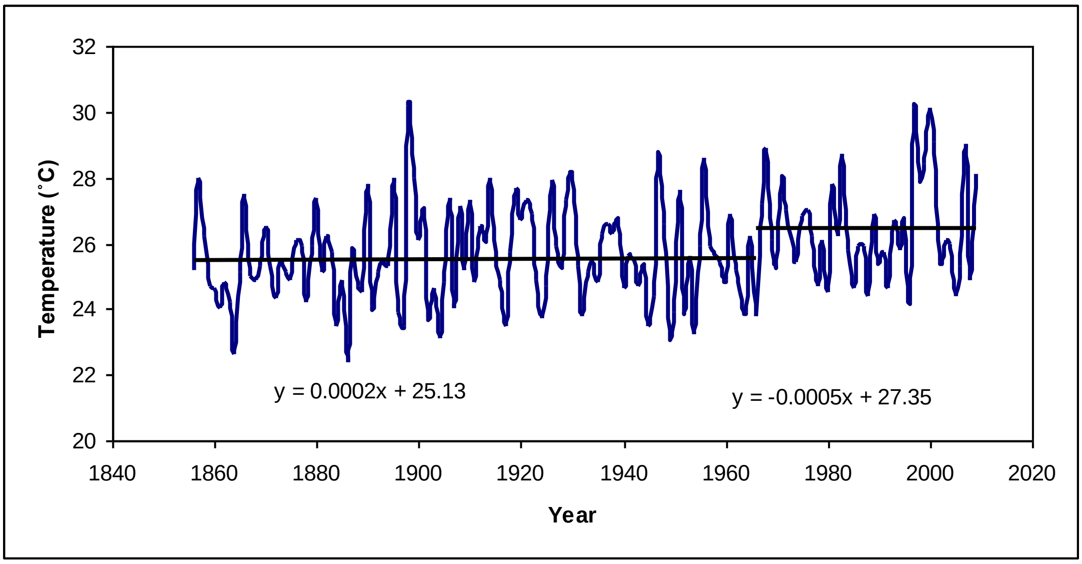


Figure C1 Mean monthly maximum temperature for February at MRO with step change in 1966

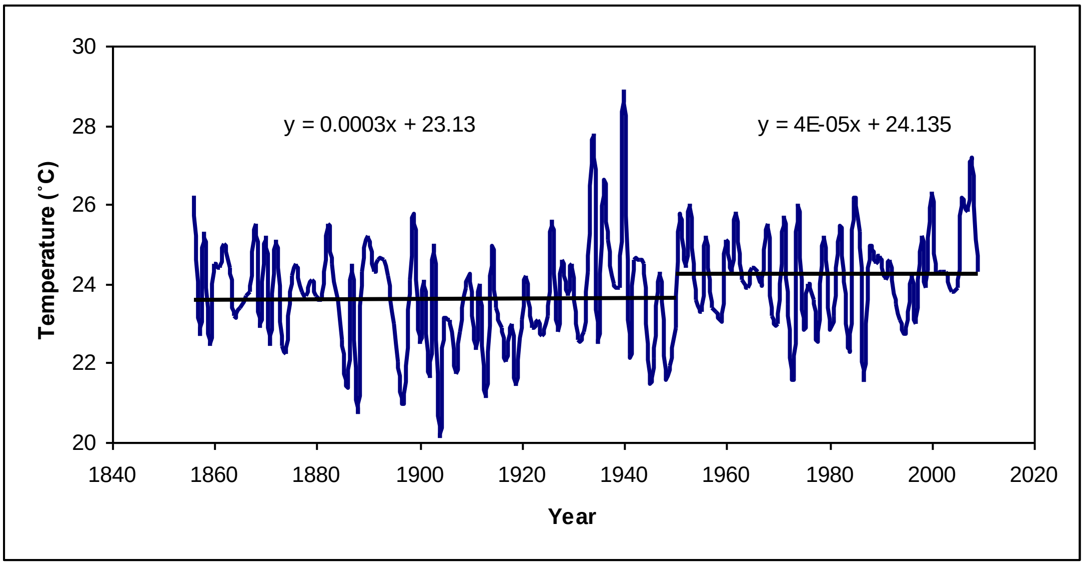


Figure C2 Mean monthly maximum temperature for March at MRO with step change in 1950

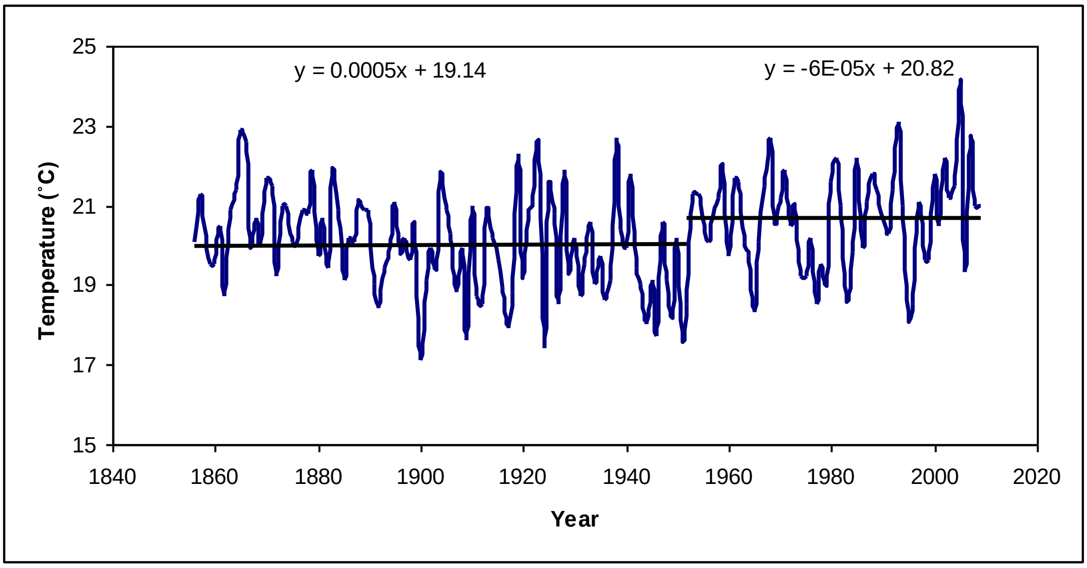


Figure C3 Mean monthly maximum temperature for April at MRO with step change in 1952

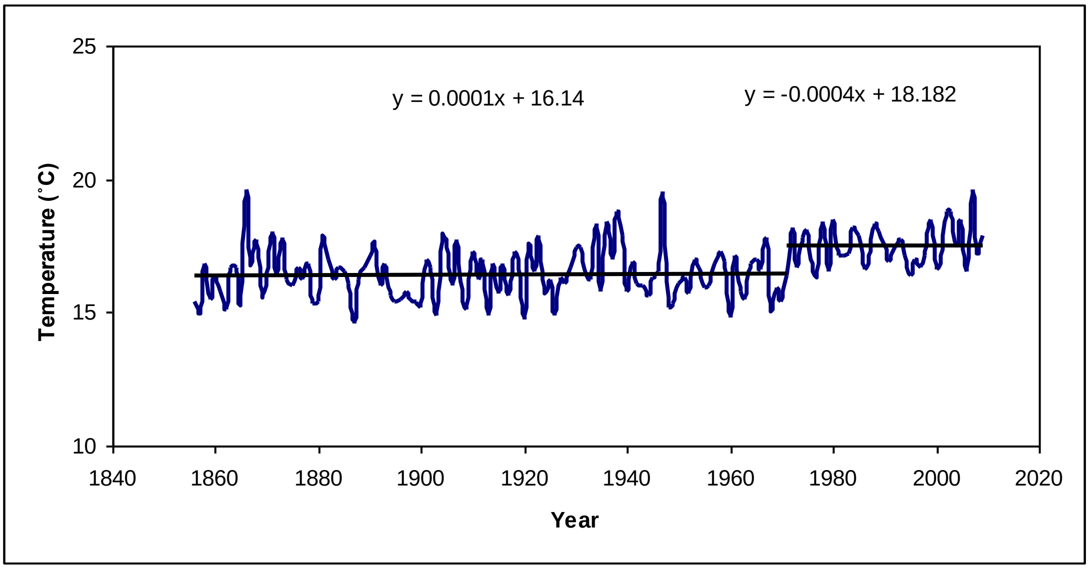


Figure C4 Mean monthly maximum temperature for May at MRO with step change in 1971

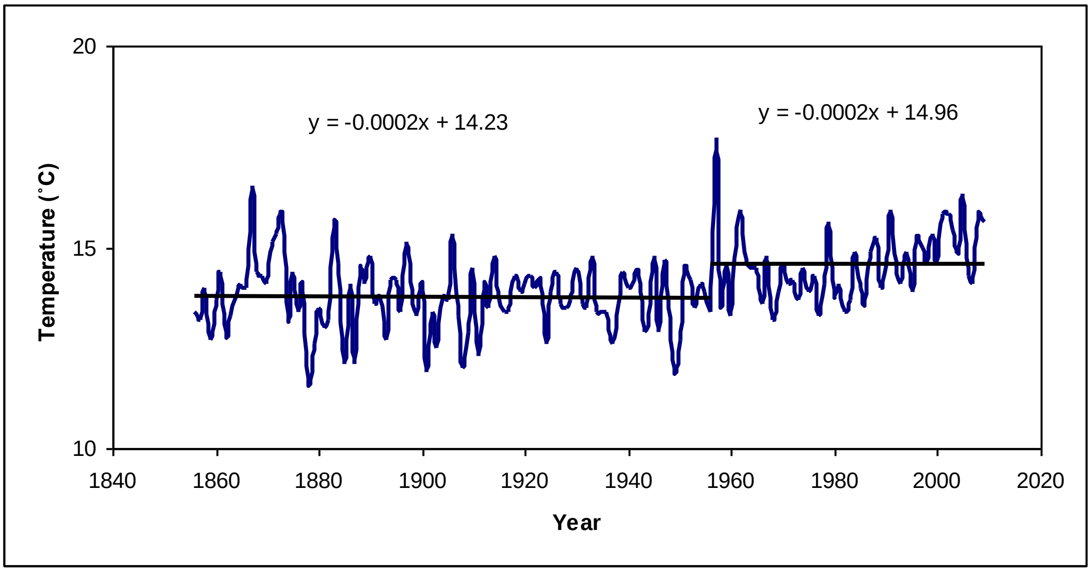


Figure C5 Mean monthly maximum temperature for June at MRO with step change in 1956

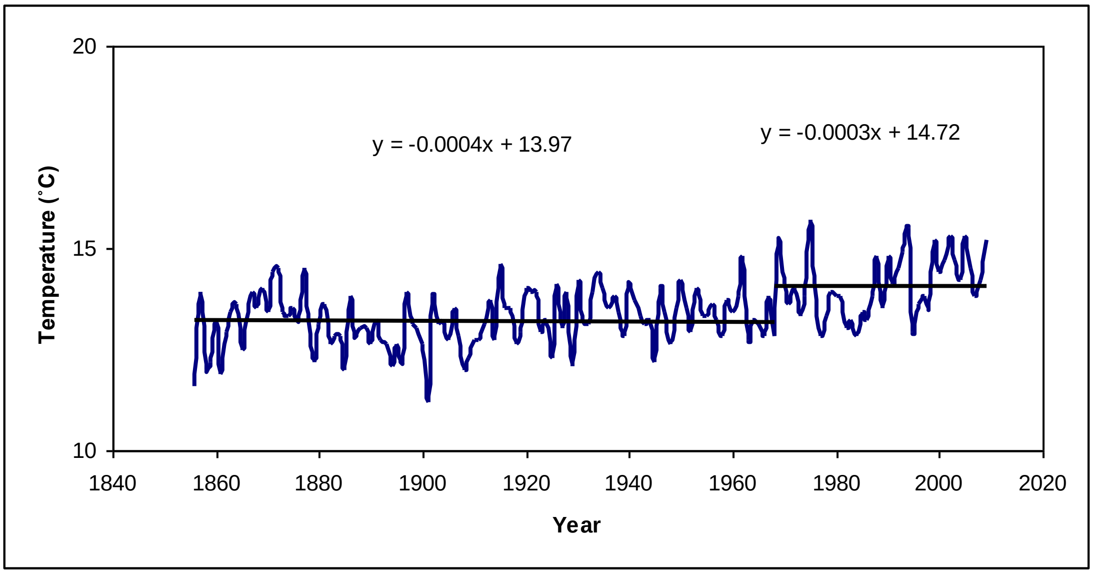


Figure C6 Mean monthly maximum temperature for July at MRO with step change in 1968

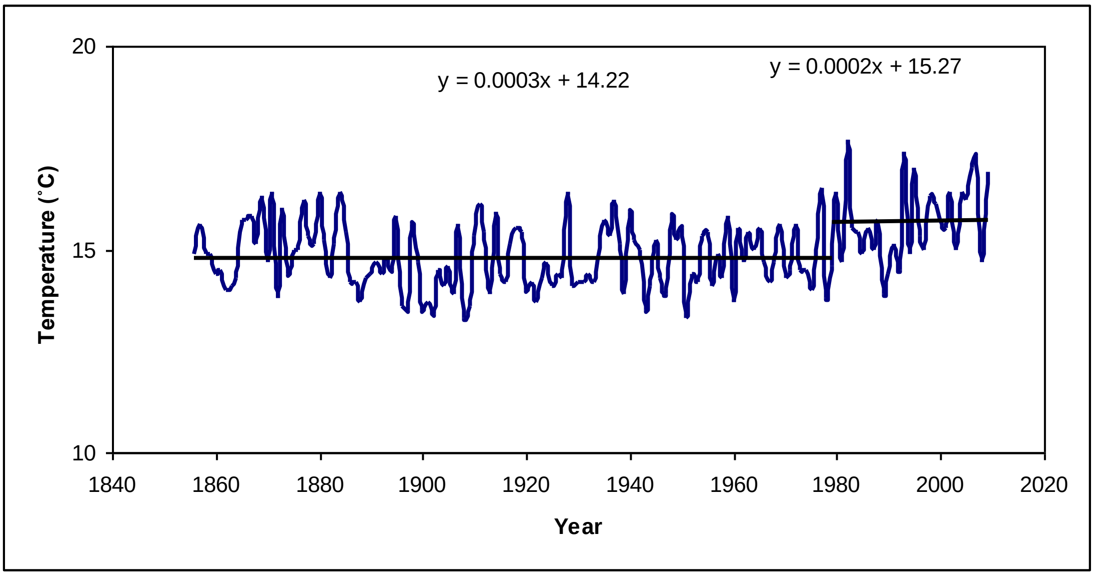


Figure C7 Mean monthly maximum temperature for August at MRO with step change in 1979

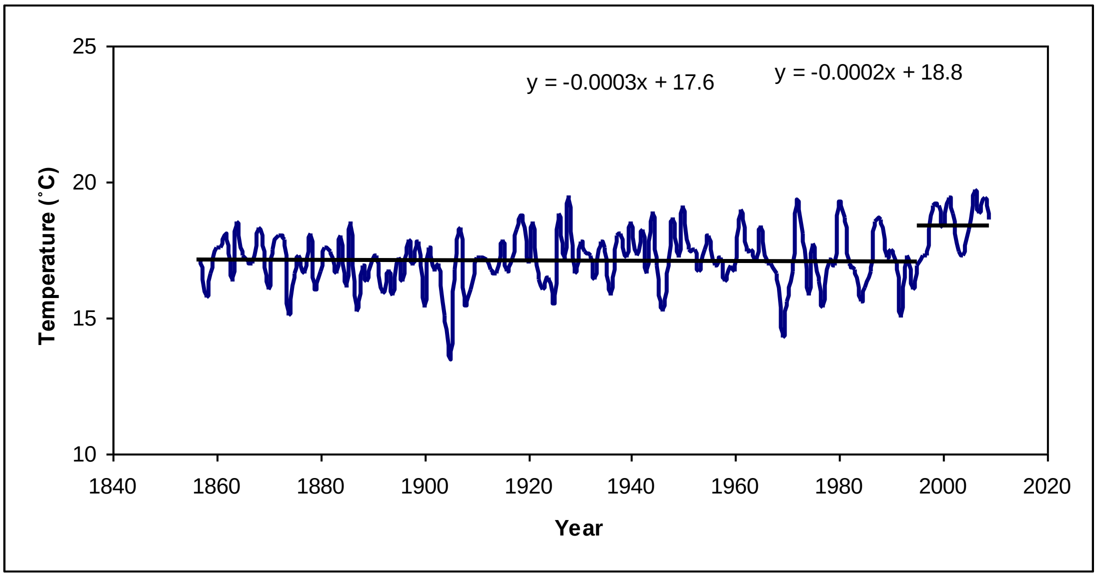


Figure C8 Mean monthly maximum temperature for September at MRO with step change in 1995

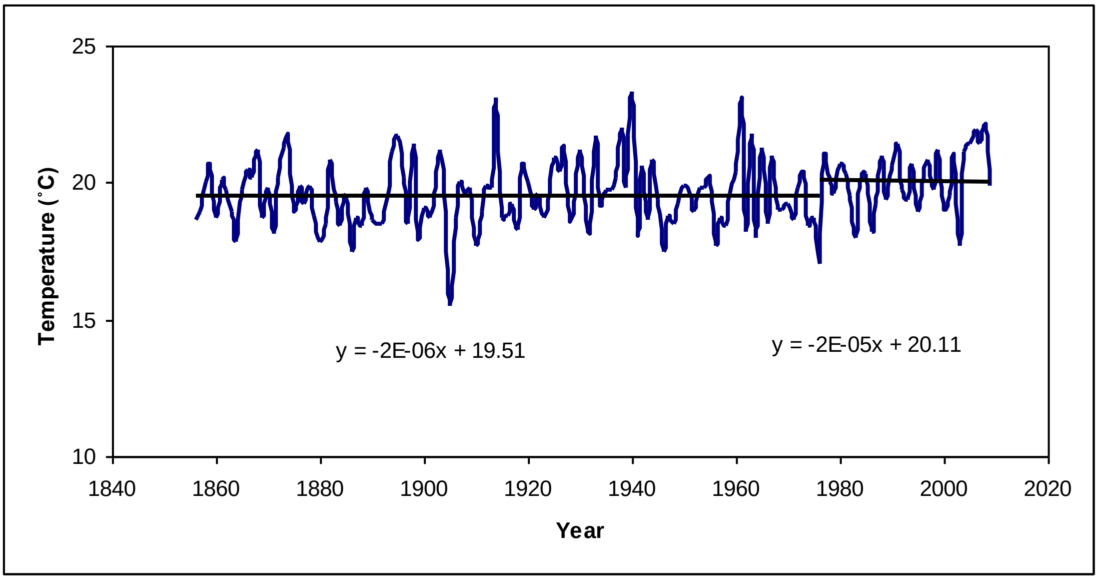


Figure C9 Mean monthly maximum temperature for October at MRO with step change in 1976

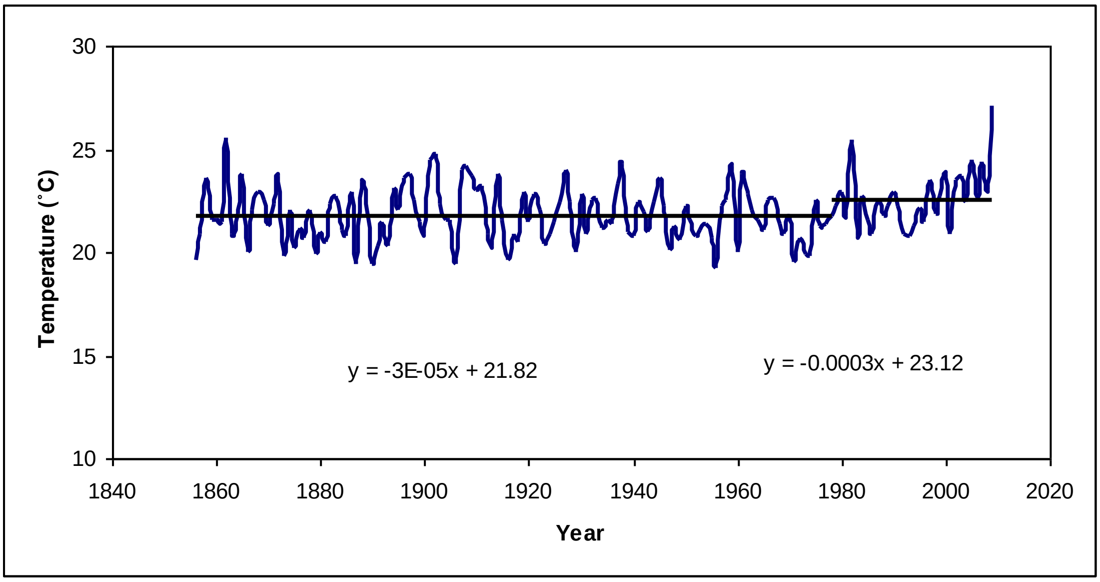


Figure C10 Mean monthly maximum temperature for November at MRO with step change in 1978

# Epping:

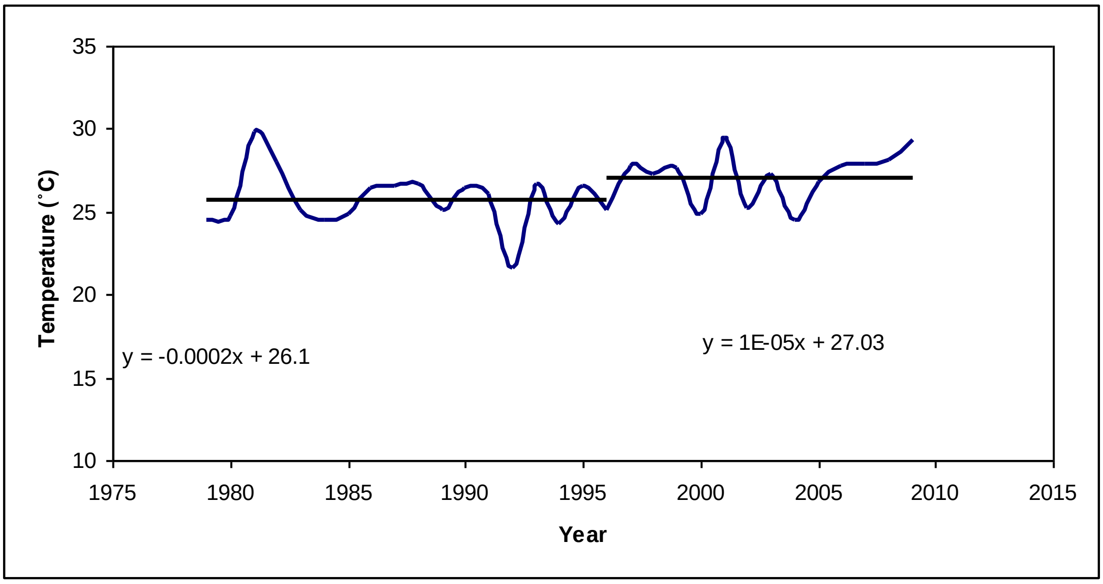


Figure C11 Mean monthly maximum temperature for January at Epping with step change in 1996

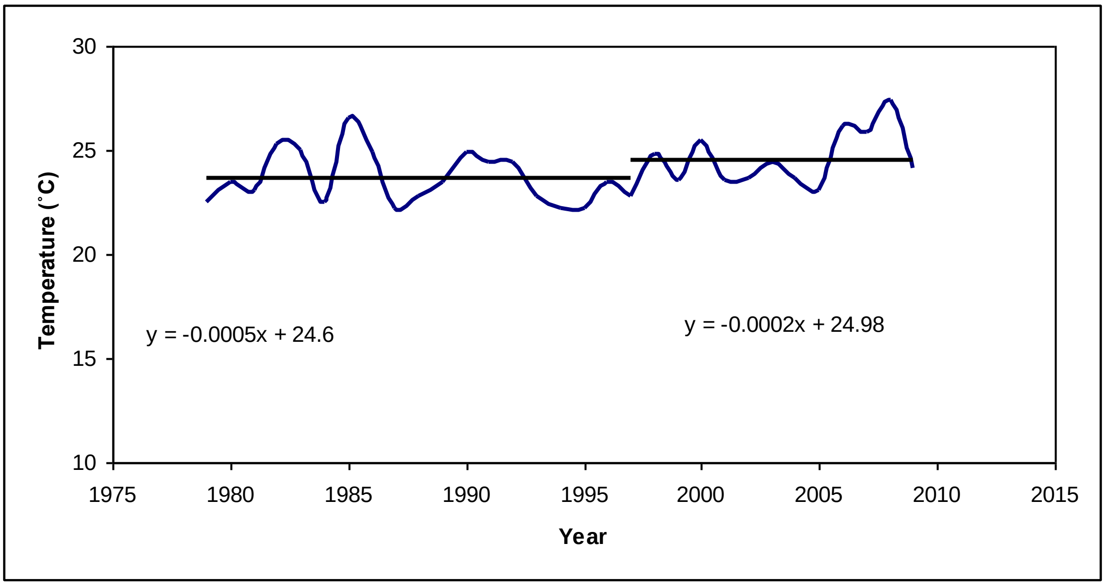


Figure C12 Mean monthly maximum temperature for March at Epping with step change in 1997

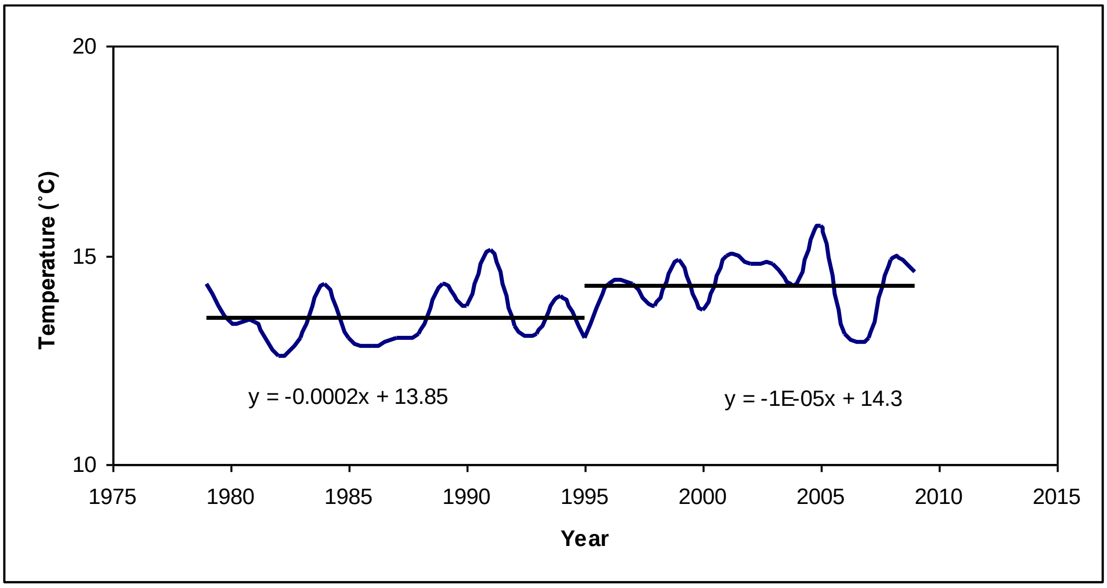


Figure C13 Mean monthly maximum temperature for June at Epping with step change in 1995

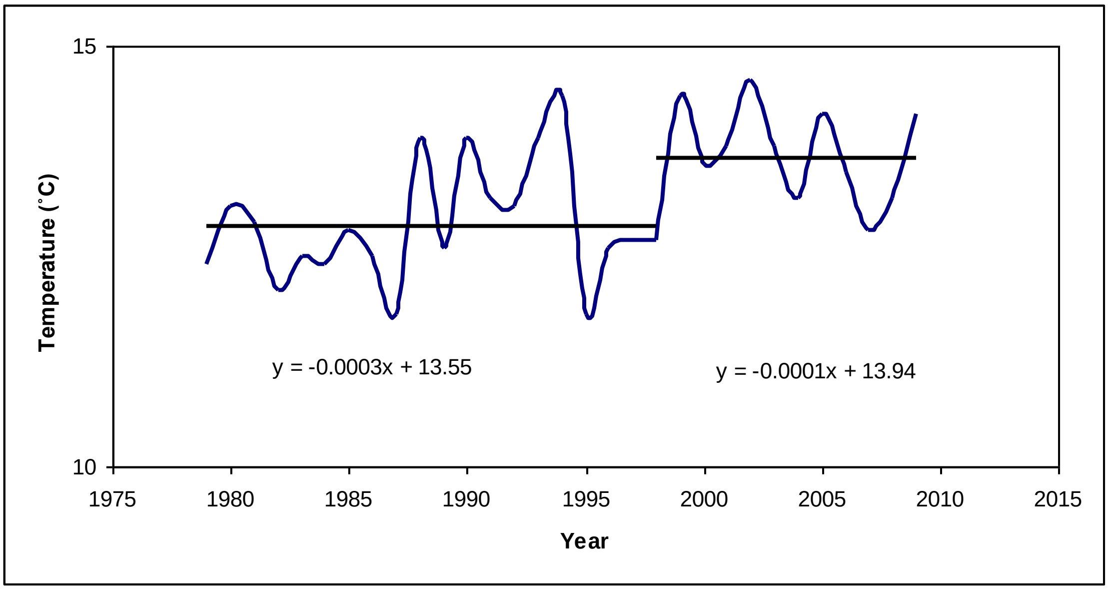


Figure C14 Mean monthly maximum temperature for July at Epping with step change in 1998

## Maroondah:

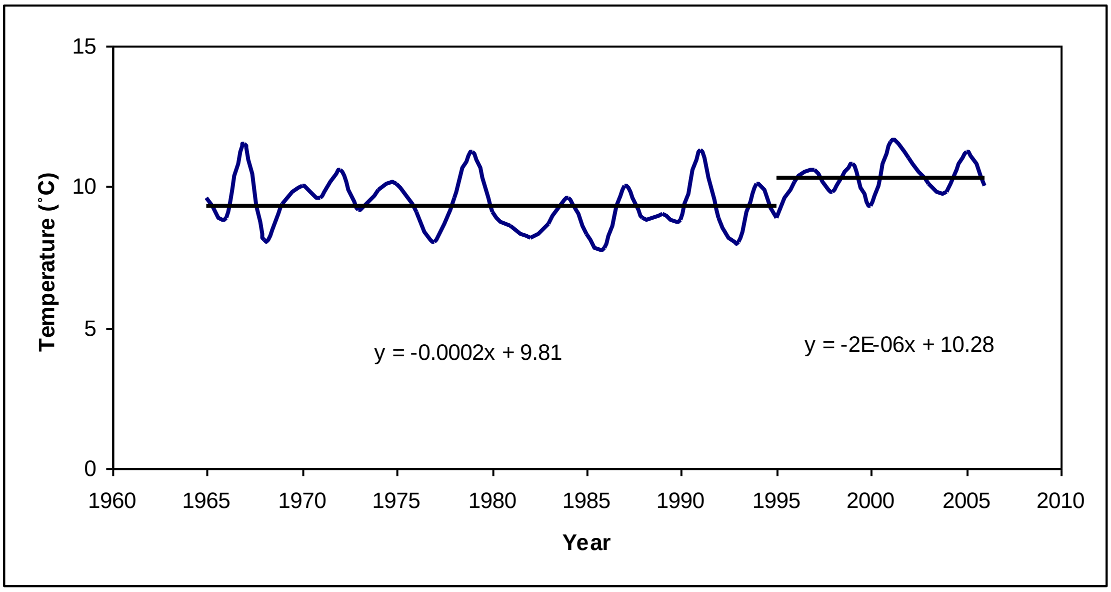


Figure C15 Mean monthly maximum temperature for June at Maroondah with step change in 1995

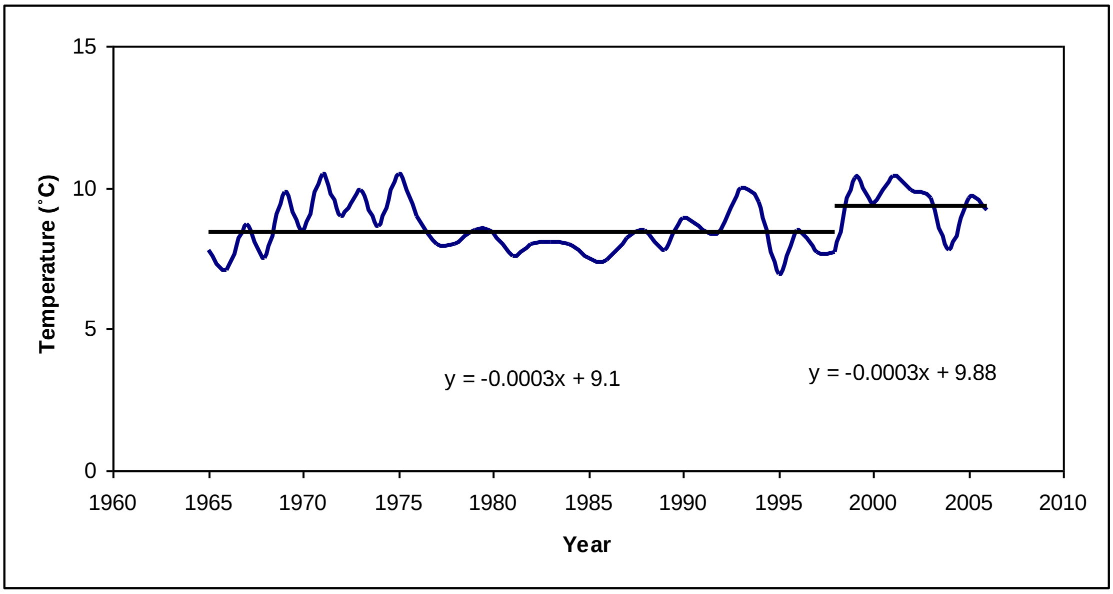


Figure C16 Mean monthly maximum temperature for July at Maroondah with step change in 1998

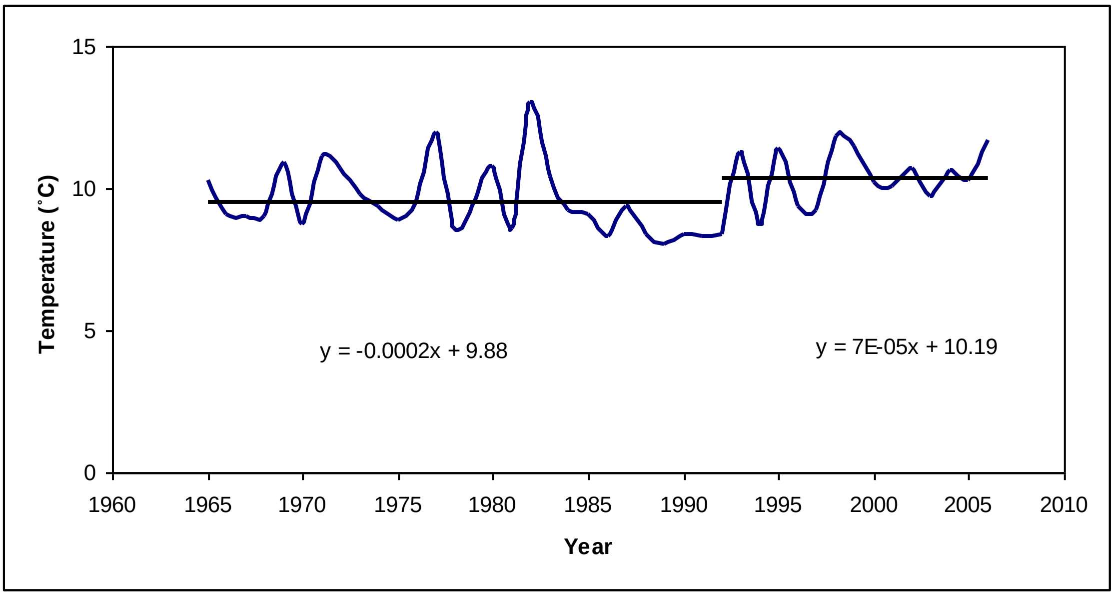


Figure C17 Mean monthly maximum temperature for August at Maroondah with step change in 1992

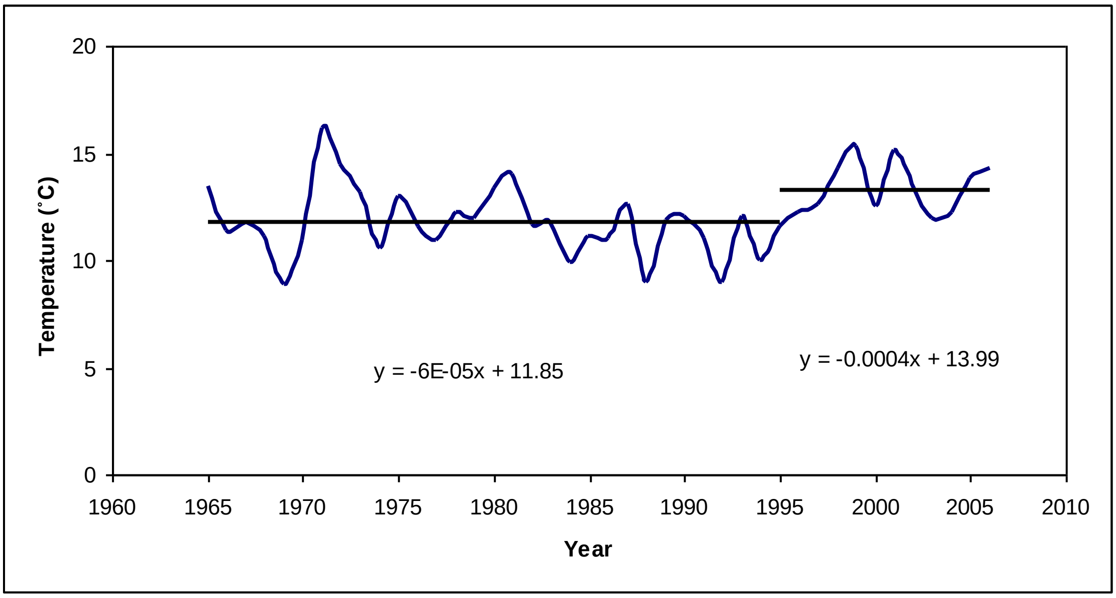


Figure C18 Mean monthly maximum temperature for September at Maroondah with step change in 1995

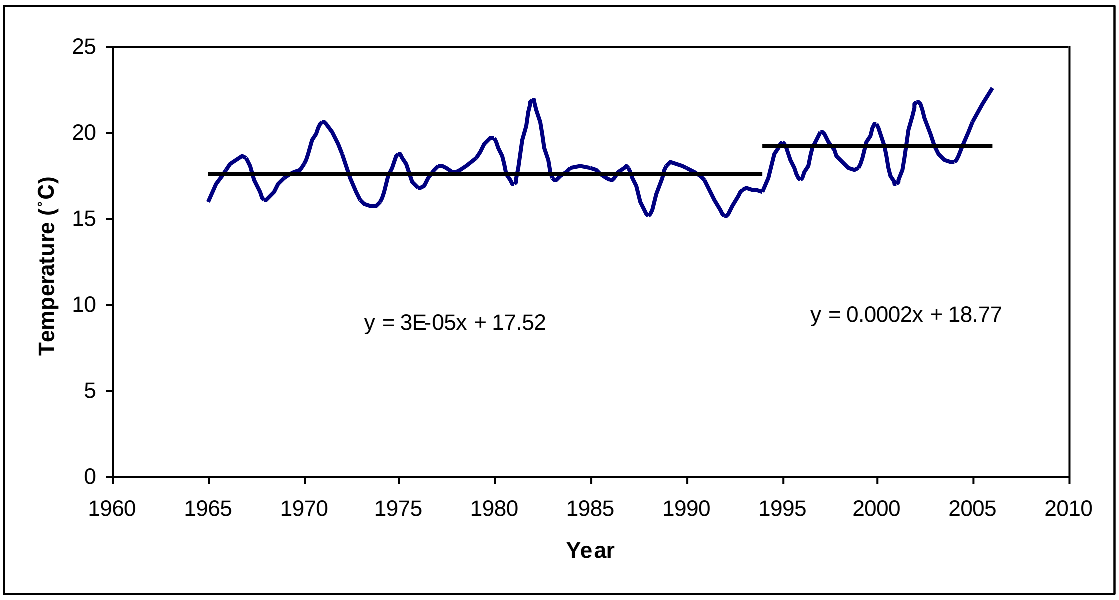


Figure C19 Mean monthly maximum temperature for November at Maroondah with step change in 1994

# Appendix D

## [*]Step change points for mean monthly minimum temperature

[*] Please refer to Section 5.1.2.4 and Table 5.8

# MRO:

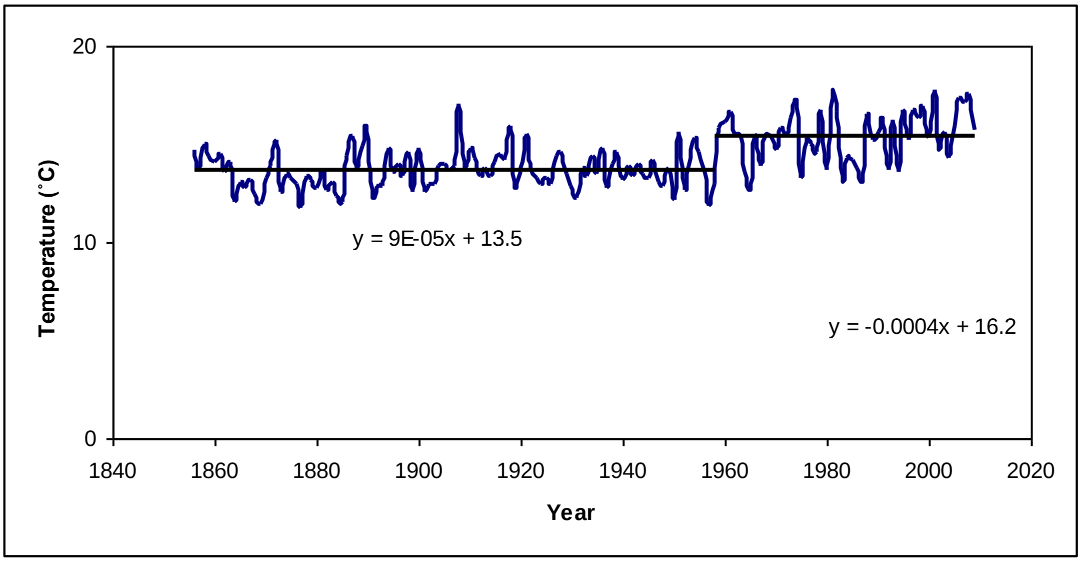


Figure D1 Mean monthly minimum temperature for January at MRO with step change in 1958

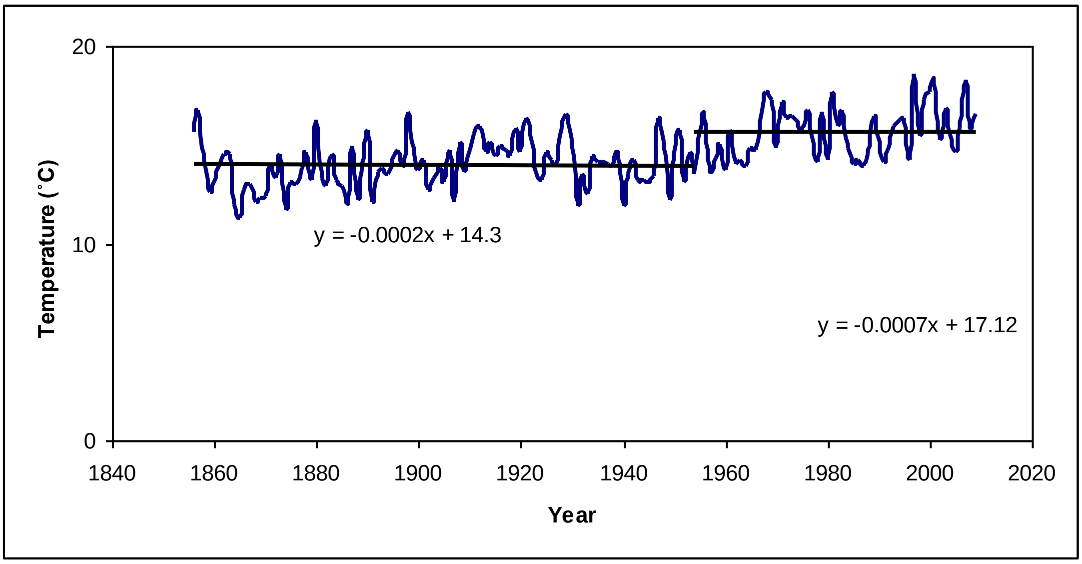


Figure D2 Mean monthly minimum temperature for February at MRO with step change in 1954

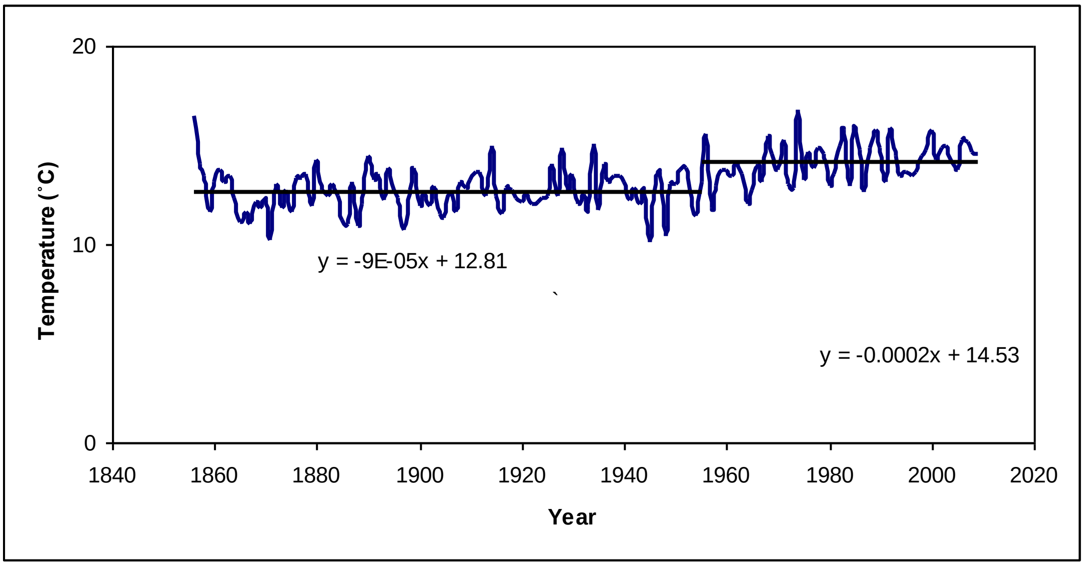


Figure D3 Mean monthly minimum temperature for March at MRO with step change in 1955

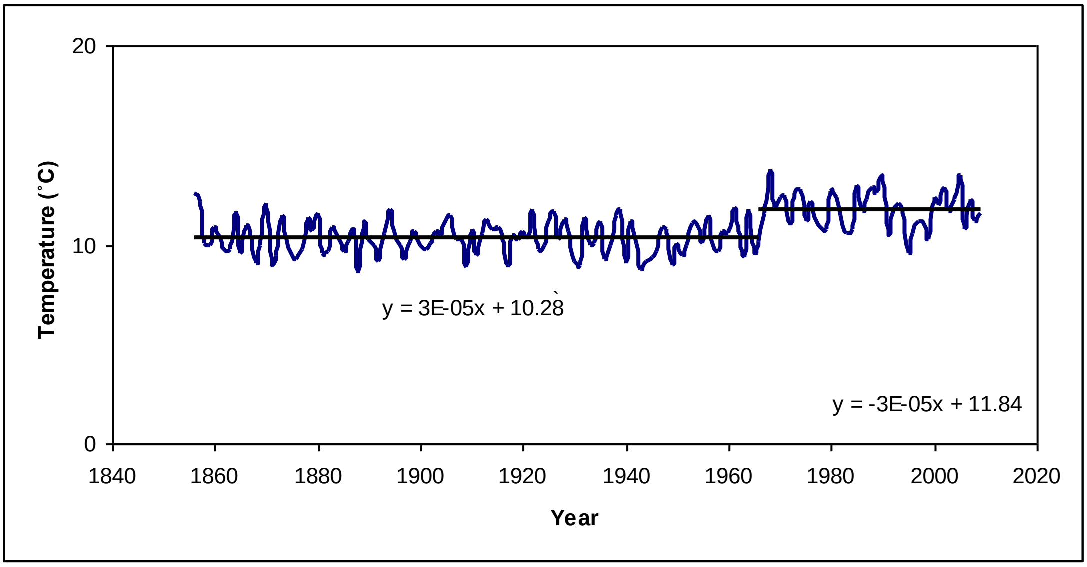


Figure D4 Mean monthly minimum temperature for April at MRO with step change in 1966

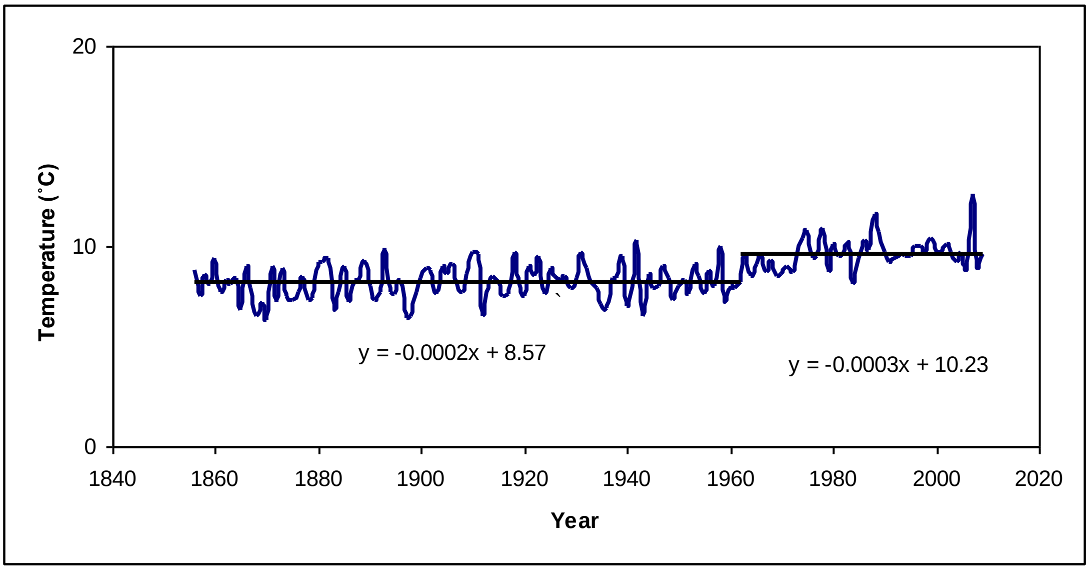


Figure D5 Mean monthly minimum temperature for May at MRO with step change in 1962

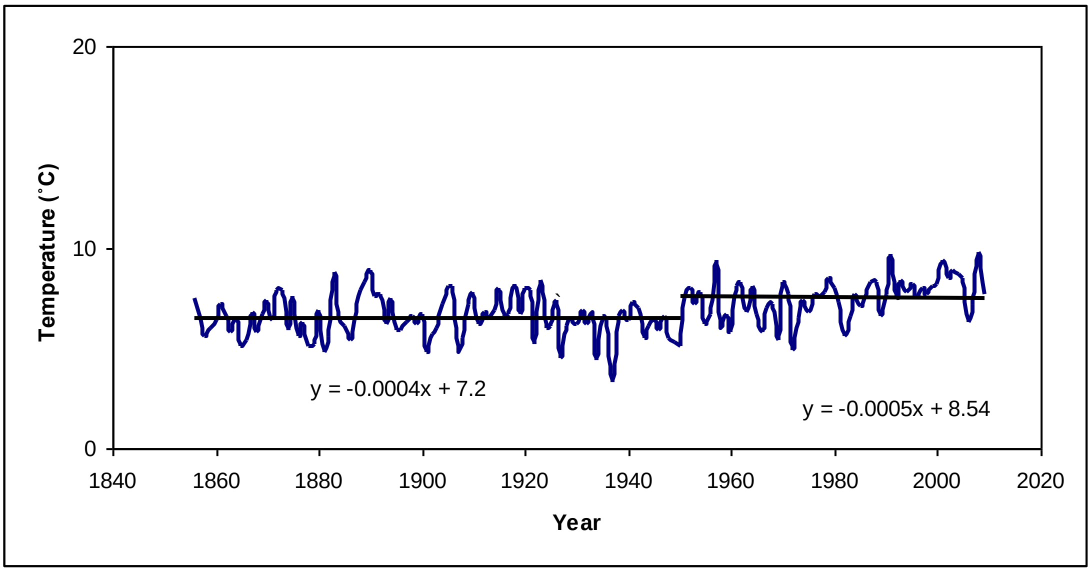


Figure D6 Mean monthly minimum temperature for June at MRO with step change in 1950

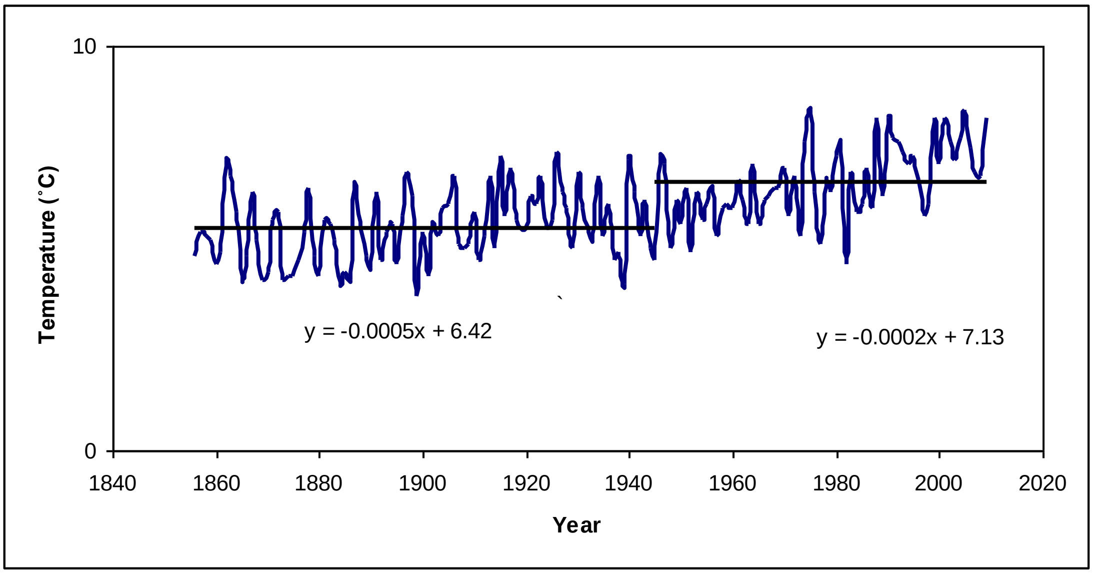


Figure D7 Mean monthly minimum temperature for July at MRO with step change in 1945

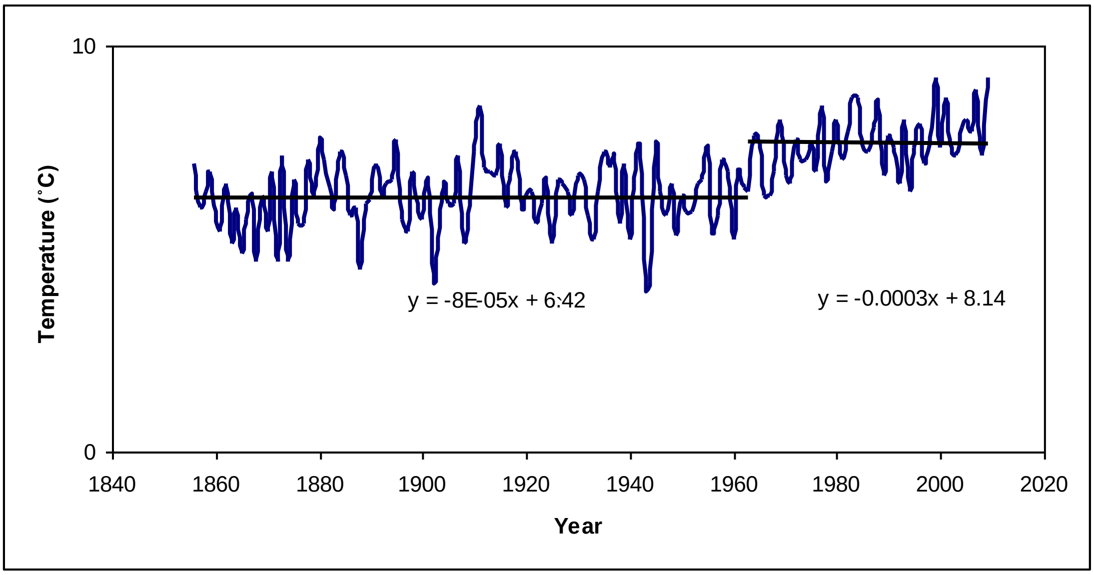


Figure D8 Mean monthly minimum temperature for August at MRO with step change in 1963

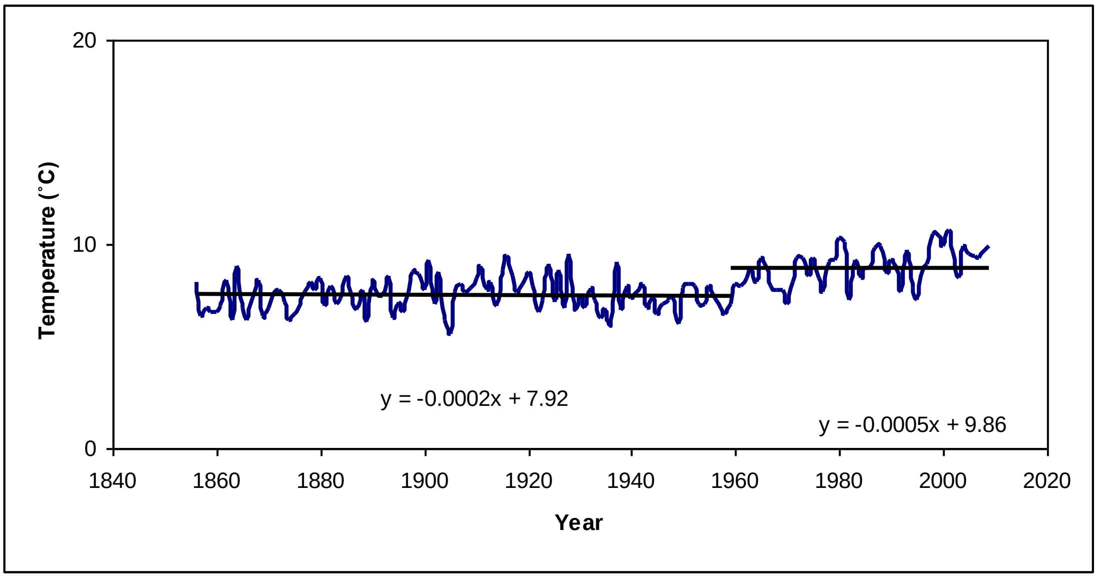


Figure D9 Mean monthly minimum temperature for September at MRO with step change in 1959

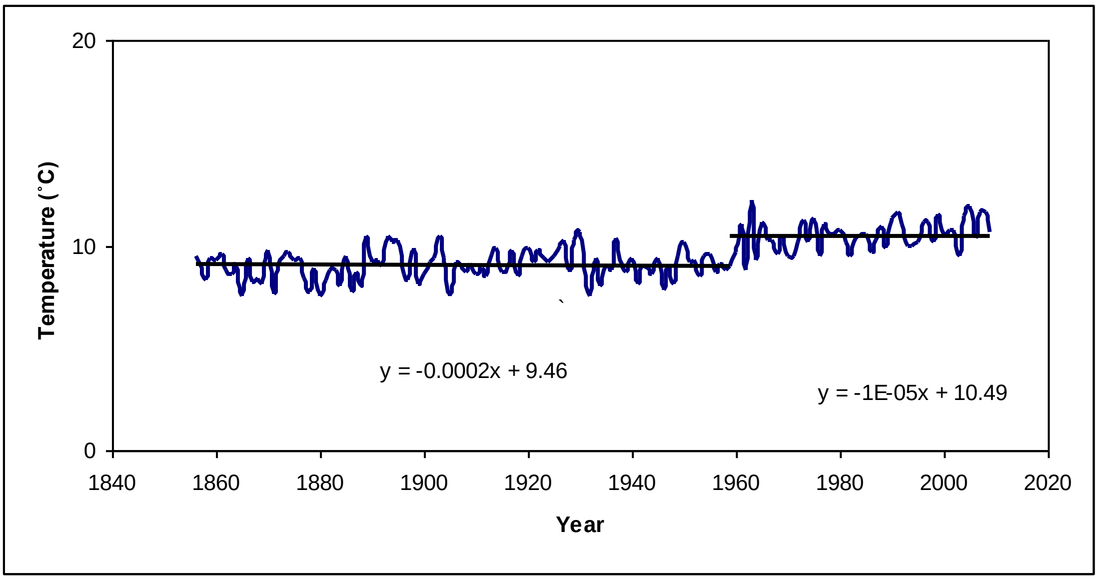


Figure D10 Mean monthly minimum temperature for October at MRO with step change in 1959

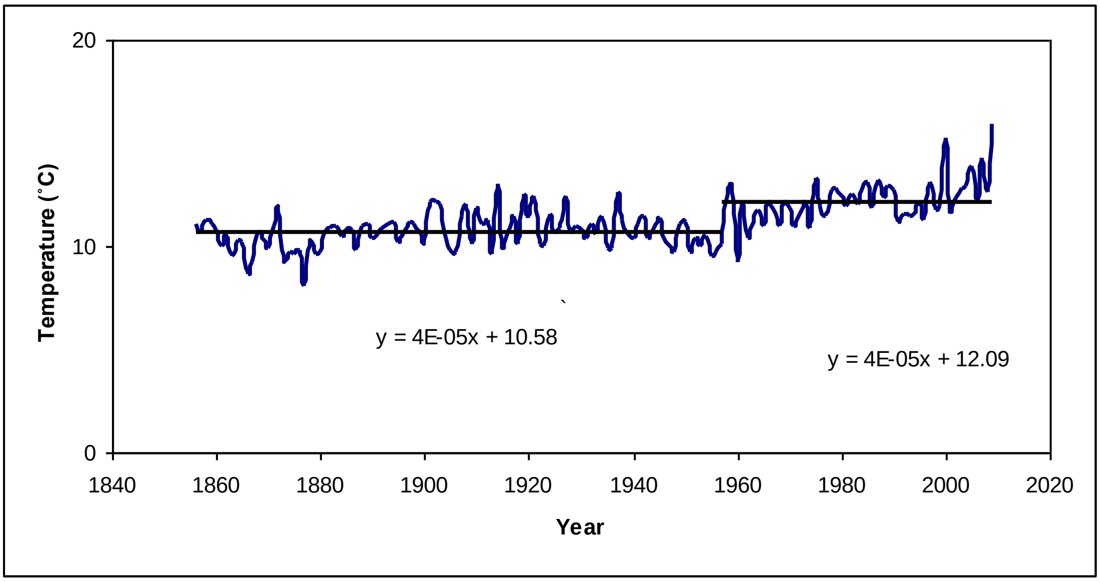


Figure D11 Mean monthly minimum temperature for November at MRO with step change in 1957

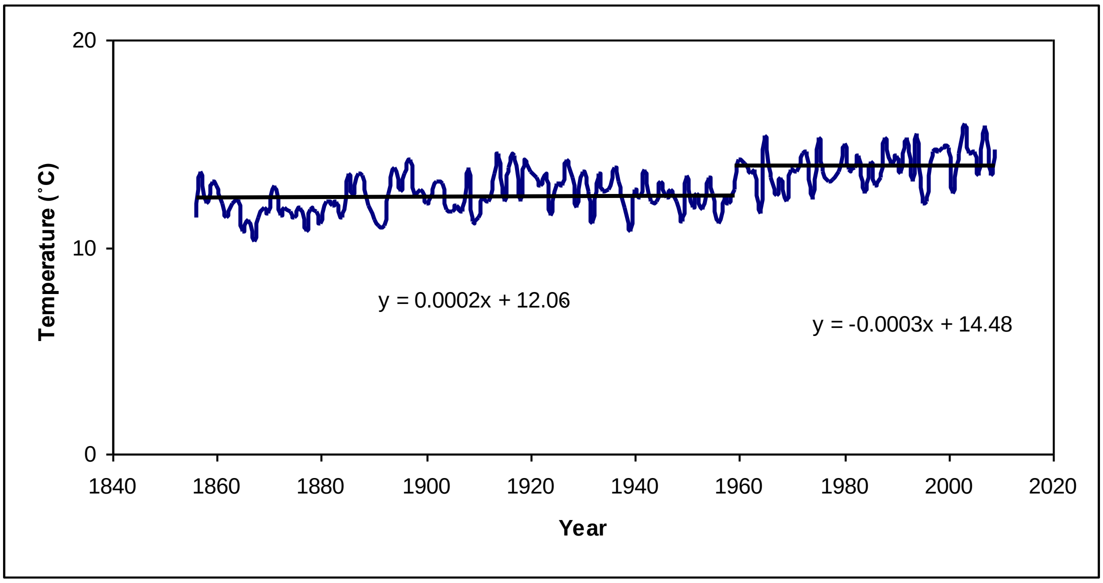


Figure D12 Mean monthly minimum temperature for December at MRO with step change in 1959

# Epping:

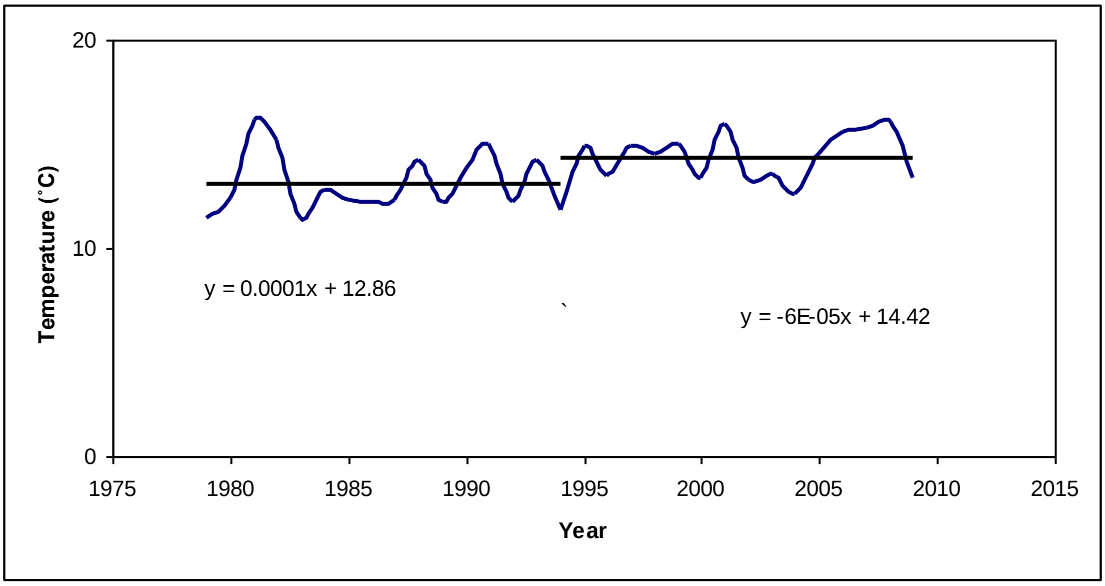


Figure D13 Mean monthly minimum temperature for January at Epping with step change in 1994

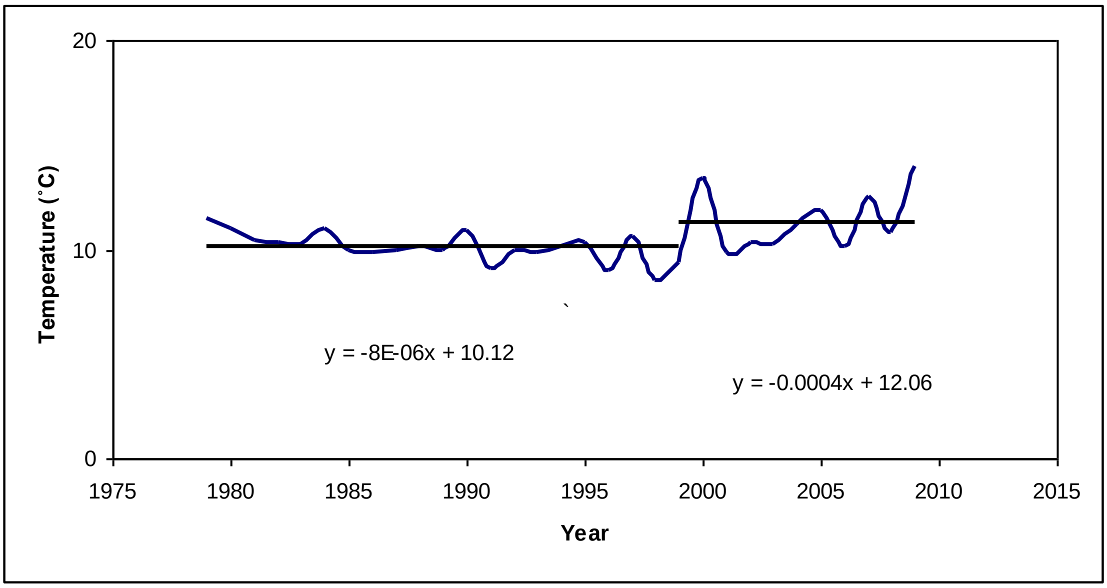


Figure D14 Mean monthly minimum temperature for November at Epping with step change in 1999

# Maroondah:

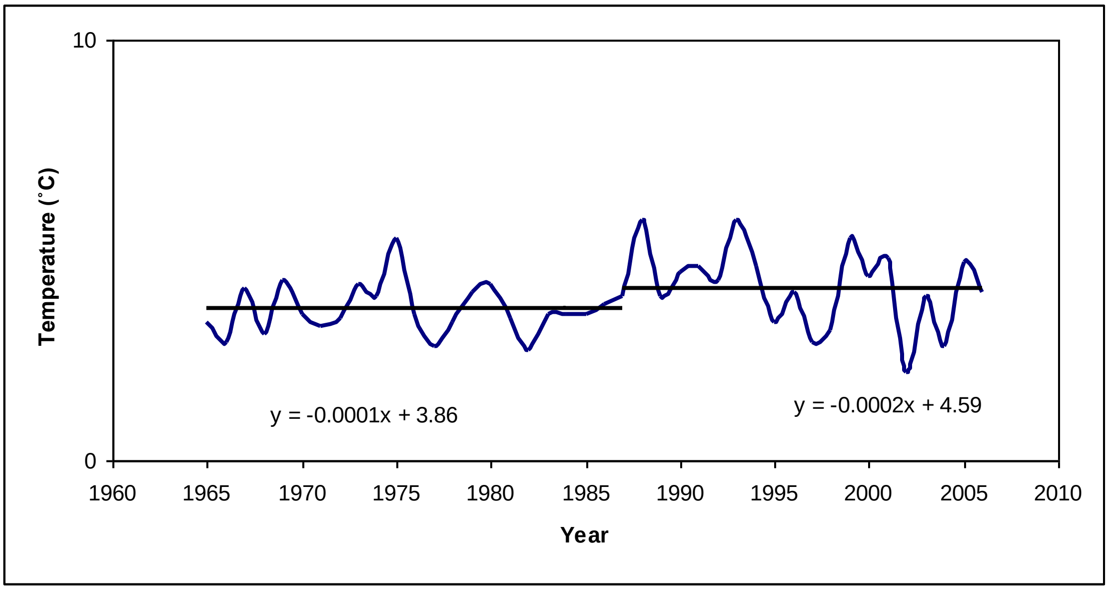


Figure D15 Mean monthly minimum temperature for July at Maroondah with step change in 1987