

DEVELOPMENT OF A DATABASE OF GRIDDED DAILY TEMPERATURES FOR SOUTHERN AFRICA

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

BACKGROUND AND OBJECTIVES

Temperature is a basic climatological parameter used frequently as an index of the energy status of the environment.

Because temperature measurement is a simple procedure and because long term temperature data are relatively abundant, it is not surprising that temperature parameters have been used as input variables in a wide range of climatological, hydrological and agricultural applications, from the estimation of solar radiation, relative humidity or potential evaporation to the concepts of heat and chill units or the delimitation of frost zones and agroclimatically optimum growth areas of crops.

In light of its importance, as highlighted above, temperature was selected as the one multiple-use hydroclimatic variable, other than rainfall, for detailed study in the Water Research Commission (WRC) Project K5/1156 titled

“Development of a Revised Spatial Database of Annual, Monthly and Daily Rainfall and Other Hydroclimatic Variables for South Africa”.

More specifically, this temperature related component of Project K5/1156, which is reported separately from the rainfall component, sought to

- develop procedures to infill missing daily maximum and minimum temperature values and extend temperature records to a pre-selected common 50 year base period (1950-1999) for stations qualifying on the strength of existing records, and to
- develop procedures to generate daily time series of temperature at any one of the 429 700 one arc minute of a degree grid points making up southern Africa, defined here as the RSA plus Lesotho and Swaziland.

In order to achieve these two objectives

- a database of temperature records in southern Africa first had to be collated and quality controlled (Chapter 2),
- temperature lapse rates had to be established for each month of the year for both maximum and minimum temperatures (T_{mx} , T_{mn}) for different lapse rate regions and sub-zones within southern Africa (Chapter 3),
- the temperature records at qualifying control stations then had to be infilled and extended to a common 50 year base period, and the procedures verified (Chapter 4), before
- techniques were developed for daily temperatures to be generated at any location (i.e. at any one of the 429 700 grid points) in southern Africa by making use of the extended/infilled control station values, lapse rates and methods to adjust for spatio-temporal lapse rate discontinuities (Chapter 5).

- Finally, conclusions were drawn and recommendations made for future research in this field (Chapter 6).

The specific objectives of this study relate clearly to *daily* temperature estimates. Why?

In a previous publication by the senior author (the "South African Atlas of Agrohydrology and -Climatology", WRC 1997), long term monthly means of temperature parameters were used in developing equations for computations of solar radiation, relative humidity, potential evaporation and crop yields. However, neither inter-annual nor intra-seasonal variabilities, nor probabilities of occurrence could be computed, neither could any trends over time be evaluated, because only long term monthly means were used as forcing functions. The generation of *daily* temperature time series at any location in southern Africa would, however, facilitate computation of all these higher order statistics.

METHODS AND RESULTS

For this research, daily temperature data were obtained to the end of year 2000 from three main sources, who are thanked for making their data available, *viz.*

- the South African Weather Service (SAWS) of the State Department of Environmental Affairs and Tourism, whose data included those from stations in Lesotho and Swaziland
- the Institute for Soil, Climate and Water (ISCW) of the Agricultural Research Council and
- the South African Sugar Association (SASEX).

The distribution of stations by length of record is shown in Figure ES1.

Only 23 stations in southern Africa have more than 50 years of daily data, of which 4 have record lengths in excess of 75 years. The station network is densest in KwaZulu-Natal (1 station per 433 km²), in Gauteng and the Western Cape and sparsest in the Northern Cape (1 station per 4263 km²) and Lesotho (1 station per 2867 km²).

Before any temperature related analyses were undertaken, stringent (and time-consuming) quality control of the daily temperature data was undertaken and any missing or doubtful values flagged for later infilling.

In this study on the estimation of daily maximum and minimum temperatures for a common base period at any location in southern Africa, that estimation is made using values from near-by control stations with 50 year daily temperature records (observed plus infilled and extended). Those temperatures are then adjusted up or down by a specified lapse rate which accounts for the difference in altitude between the control station and the location of interest. This specified lapse rate is, however, not constant.

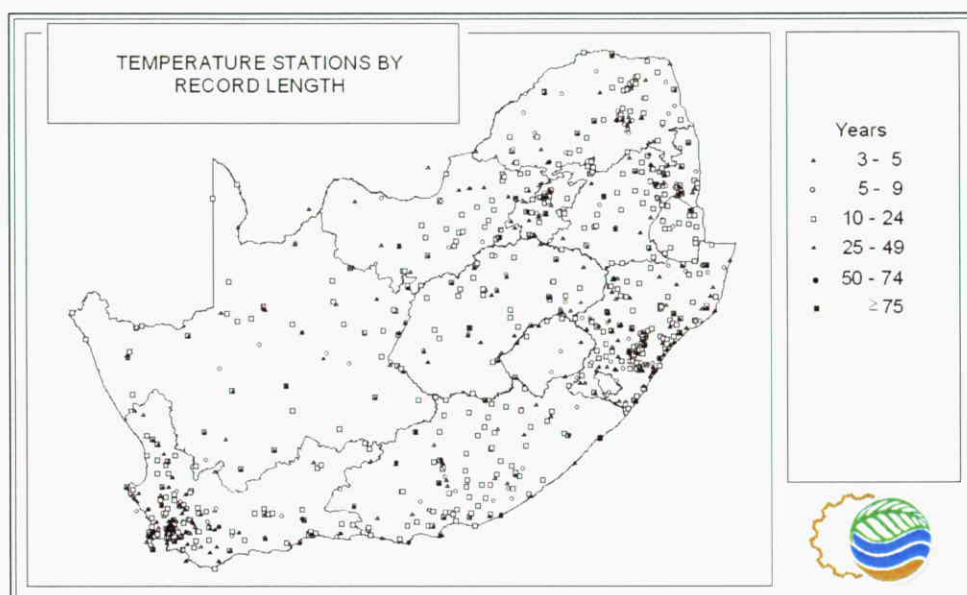


Figure ES1 Distribution of temperature stations in southern Africa by record length

Previous research had resulted in the delineation of southern Africa into 12 lapse rate regions (Figure ES2), later reduced to 11.

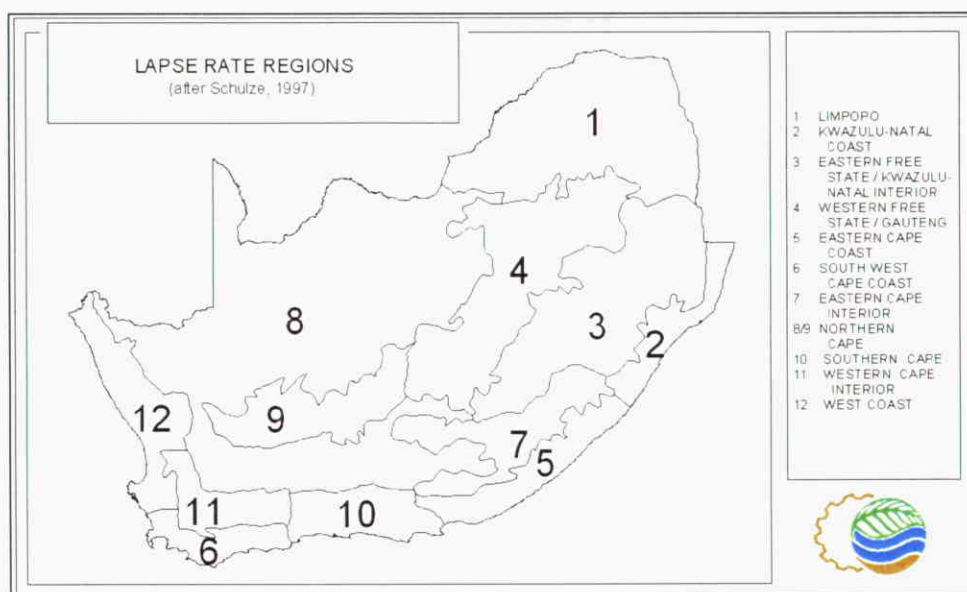


Figure ES2 Temperature lapse rate regions of southern Africa (after Schulze, 1997)

All qualifying temperature stations falling within the bounds of a lapse rate region and, in addition, all stations located within a 15 arc minute of a degree “grey zone” surrounding a specific region, were used in lapse rate computations.

Final (smoothed) monthly values of maximum and minimum temperature lapse rates are summarised in Table ES1 for the 11 lapse rate regions and, where applicable, their sub-zones, the latter being delineated on the basis of altitude (oceanic influences) and topographic position (cold air drainage into valleys in winter) within a region. What is immediately evident is that lapse rates vary considerably across southern Africa – by region, by sub-zone within a region, by season and between lapse rates of maximum and minimum temperatures.

The need for long station records over a common base period arises from temperature derived statistics (e.g. means, variances, extremes) and parameters (e.g. frost days, chill and heat units) requiring the same period of record in order to make valid comparisons, while any assessment of temperature trends (e.g. possible increases due to global warming) requires unbroken long duration temperature series. For the above reasons it was, therefore, necessary to select temperature stations with a minimum length of quality observed data (> 1500 days) to qualify as “control” stations and to test techniques to infill any missing data as well as extending the records to a desired common base period from “patching” stations.

From the available temperature database 973 stations qualified as potential control stations.

For each control station, 9 patching stations were selected. Two weighted selection criteria were used, viz. distance from the control station and altitude difference between the control and patching station.

In order to infill missing daily temperature values or to extend the record at a qualifying control station, two techniques were developed, viz. the Mean Temperature Difference Method (MTDM) and the Difference in Standard Deviation Method (DSDM). These two techniques were tested against observed data from a wide range of climatic conditions. An example of a visual verification is provided in Figure ES3.

The overall prognosis from statistical tests, however, was that neither of the two techniques gave inherently better results as a tool for daily temperature synthesis. Nevertheless, for all further analyses the Difference in Standard Deviation Method was selected as it is conceptually a sounder technique in accounting better for similarities in temperature variances between patching stations and the control.

Table ES1 Month-by-month lapse rates of maximum and minimum temperatures by region and sub-zone

REGION	LAPSE RATES (°C / 1000 m altitude)																									
	MAXIMUM TEMPERATURE												MINIMUM TEMPERATURE													
	ZONE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	ZONE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1. Limpopo	All	-5.0	-5.0	-5.2	-5.6	-6.0	-6.2	-5.9	-5.3	-4.4	-4.2	-4.7	-4.9	All	-5.0	-5.2	-5.4	-5.5	-5.6	-5.6	-5.5	-5.2	-4.9	-4.7	-4.7	-4.9
														TI < 100	-5.0	-5.2	-5.4	-5.5	-5.7	-5.7	-5.5	-5.3	-4.8	-4.7	-4.7	-4.9
														TI ≥ 100	-5.0	-5.2	-5.4	-5.5	-5.4	-5.3	-5.3	-5.2	-4.8	-4.7	-4.7	-4.9
2. KwaZulu-Natal Coast	All	-2.9	-3.0	-3.1	-3.3	-3.6	-3.9	-3.7	-2.9	-2.3	-2.2	-2.4	-2.6	All	-5.0	-5.1	-5.4	-5.7	-6.3	-6.6	-6.5	-6.1	-5.5	-5.2	-5.1	-5.0
														TI < 100	-5.0	-5.1	-5.4	-5.7	-6.3	-6.5	-6.5	-6.2	-5.5	-5.2	-5.1	-5.0
														TI ≥ 100	-5.0	-5.1	-5.4	-5.7	-6.4	-6.9	-6.6	-6.0	-5.5	-5.2	-5.1	-5.0
3. E. Free State/KZN Interior	All	-4.1	-4.2	-4.5	-5.0	-5.5	-5.9	-5.7	-5.0	-4.2	-3.9	-3.9	-4.0	All	-5.4	-5.4	-5.8	-6.2	-6.0	-5.6	-5.7	-6.0	-5.9	-5.5	-5.4	-5.4
	TI < 100	-4.3	-4.4	-4.6	-5.0	-5.5	-5.9	-5.7	-5.0	-4.2	-4.0	-4.0	-4.2	TI < 100	-5.4	-5.4	-5.8	-6.0	-5.9	-5.2	-5.3	-5.6	-5.6	-5.5	-5.4	-5.4
	TI ≥ 100	-2.1	-2.6	-3.5	-5.0	-5.5	-5.9	-5.7	-5.0	-4.0	-3.1	-2.5	-2.2	TI ≥ 100	-5.4	-5.4	-5.8	-7.3	-8.9	-9.6	-9.6	-9.3	-7.4	-5.5	-5.4	-5.4
4. W. Free St/ Gauteng	All	-10.2	-9.5	-8.8	-7.8	-6.7	-6.0	-5.9	-6.0	-6.8	-8.2	-9.2	-9.7	All	-7.5	-7.4	-6.6	-6.0	-5.6	-5.0	-4.7	-4.1	-4.6	-6.0	-6.8	-7.2
5. Eastern Cape Coast	Alt < Thr	+10.2 ¹	+10.2 ¹	+6.3 ¹	+8.0 ²	+16.0 ³	+25.0 ³	+27.0 ³	+24.0 ³	+13.0 ²	+6.0 ¹	+8.0 ¹	+9.0 ¹	All	-4.5	-4.7	-5.2	-5.9	-6.5	-7.0	-7.0	-6.0	-5.3	-5.0	-4.8	-4.7
	Alt ≥ Thr	-6.3	-6.5	-6.0	-3.9	-3.6	-3.9	-3.5	-2.5	-2.0	-3.5	-4.9	-5.5													
6. Southwest Cape Coast	Alt < 200m	+26.0	+18.0	+19.0	+22.2	+19.0	+17.0	+13.0	+11.0	+14.0	+19.0	+27.0	+33.3	All	-5.1	-5.0	-4.9	-4.8	-4.4	-4.1	-3.9	-4.0	-4.3	-4.7	-5.0	-5.2
	Alt ≥ 200m	-3.3	-3.5	-4.0	-4.6	-4.8	-4.8	-4.6	-4.3	-4.1	-3.9	-3.7	-3.5													
7. Eastern Cape Interior	All	-3.7	-4.1	-4.1	-3.6	-3.5	-3.7	-3.4	-2.8	-2.5	-2.6	-2.8	-3.3	All	-4.3	-4.5	-4.8	-5.5	-6.4	-6.0	-5.8	-5.5	-4.8	-4.2	-4.0	-3.8
8/9 Northern Cape	Alt < 800m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	All	-5.7	-5.4	-5.1	-4.8	-5.0	-5.1	-5.4	-5.0	-1.7	-1.4	-3.0	-4.2
	Alt ≥ 800m	-11.2	-9.8	-8.4	-6.3	-4.6	-3.7	-2.9	-2.8	-3.2	-6.0	-7.8	-9.9													
10. Southern Cape	Alt < 200m	+19.0	+18.0	+15.0	+10.5	+5.5	0.0	0.0	+6.5	+11.5	+14.5	+17.0	+19.0	All	-4.5	-4.2	-4.5	-5.3	-6.7	-7.5	-7.4	-6.8	-5.9	-5.2	-4.8	-4.6
	Alt ≥ 200m	-8.5	-7.0	-6.3	-6.3	-6.7	-6.0	-6.0	-7.0	-6.8	-5.4	-5.6	-6.9													
11. Western Cape Interior	All	-13.9	-14.4	-15.0	-15.0	-8.5	-6.5	-7.4	-9.2	-10.8	-12.2	-13.0	-13.4	All	-5.0	-4.7	-4.4	-4.5	-4.7	-4.8	-5.2	-5.4	-5.1	-4.8	-4.9	-5.1
														TI < 100	-5.0	-4.7	-4.5	-5.0	-6.5	-8.3	-8.8	-8.8	-7.5	-5.3	-4.9	-5.1
														TI ≥ 100	-5.0	-4.7	-4.4	-4.1	-3.5	-3.0	-3.4	-3.9	-4.5	-4.7	-4.9	-5.1
12. West Coast	Alt < 200m	+26.0	+26.5	+25.0	+18.0	0.0	0.0	0.0	0.0	+3.0	+14.5	+21.5	+24.0	Alt < 150m	+14.0	+17.8	+16.0	+8.3	-3.0	-3.8	-3.9	-3.9	-3.5	-2.6	+6.0	+10.0
	Alt > 200m	-8.3	-8.7	-8.7	-8.6	-8.1	-7.4	-6.2	-7.5	-8.9	-10.0	-9.5	-8.2	Alt ≥ 150m	-3.6	-3.4	-3.1	-3.0	-3.3	-3.8	-3.9	-3.9	-3.5	-3.2	-4.3	-4.5

TI = Topographic Index
Alt = Altitude (m)
Thr = Threshold altitude (m)
1 : Threshold = 400 m
2 : Threshold = 250 m
3 : Threshold = 100 m

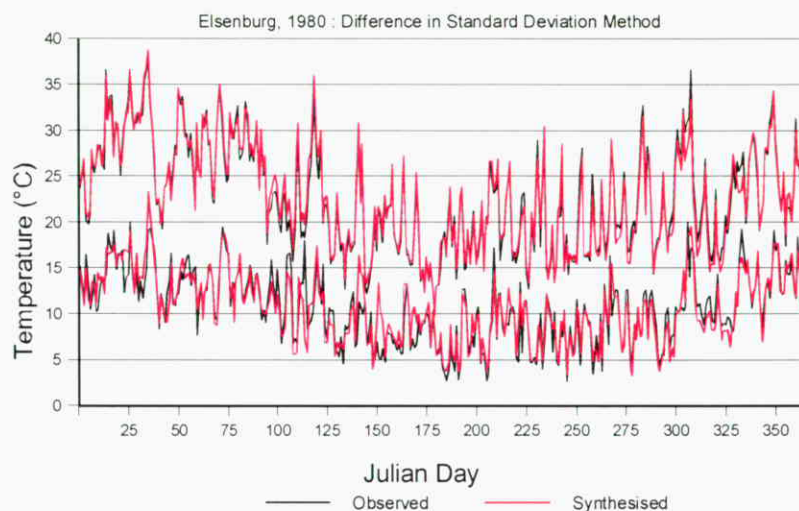


Figure ES3 Example of a visual verification of the Difference in Standard Deviation Method for synthesising daily maximum and minimum temperature values

With this project's aim being to generate daily T_{mx} and T_{mn} at any location in southern Africa to a one arc minute spatial resolution (~ 1.6 km), a 50 year base period from 1950 to 1999 was selected, as it represented a period in which the temperature station network was at its densest, it includes "current" data and is a period for which potential of global warming impacts could be assessed.

From the 973 temperature stations which qualified to have their missing daily data infilled and their records extended to the 50 year common base period 1950-1999, the overall conclusion was that, while many data gaps occur, over most of southern Africa the daily temperature information base generated in this project could be considered comprehensive enough for the estimation of temperature related variables at levels of detail far in excess of those used in any known previous temperature related analyses in southern Africa, to date.

Temperature is a continuously occurring variable, unlike rainfall which consists of discrete events. On any one day temperature will, therefore, be dependent on prevailing synoptic conditions which vary seasonally (hence monthly lapse rates), macro-location (hence temperature/lapse rate regions each with altitude dependent lapse rates) and on meso-location (hence altitude dependent sub-zones of regions as in Table ES1). These determinants were all factored into the methodologies used to generate a daily temperature series for any selected period (e.g. 1950-1999) at any location in southern Africa. "Any location" in the context of this report implies any grid (raster) point in the Republic of South Africa, Lesotho and Swaziland with a one arc minute of a degree latitude and longitude spatial resolution, i.e. at ~ 1.6 km spacing, to which an altitude has been assigned. This raster is made up of 429 700 point values in the study area.

The broad procedures for temperature estimation at any location consisted of

- selection of the “best” control station(s) for that location
- application of the regional and/or sub-zonal and monthly lapse rate to account for the change in temperature caused by the altitude difference between the point of interest and its control station(s)
- computation of an initial daily time series of T_{mx} and T_{mn} at any point of interest and
- determination of final daily temperature values following logic checks and those which account for spatial and temporal discontinuities of temperature values resulting from inter-monthly “jumps” in lapse rates and discrete lapse rate differences at the boundaries between lapse rate regions and sub-zones.

Once daily temperature time series had been generated from observed, infilled and extended temperature records at control stations, and adjusted for regional/zonal/monthly lapse rates at any given point, as well as adjusted for temporal/spatial lapse rate discontinuities, the final daily check involved the daily temperature range. On any day at any location the difference between T_{mx} and T_{mn} , if less than 1.5°C, was “forced” to be 1.5° by equally proportionate adjustments to both the maximum and minimum temperature values. This check was not only a logic check, but became necessary because of the several “smoothing” procedures the initial quality controlled observed temperature had undergone en route to a final set of temperature values for any given day at any specific location.

OUTCOMES OF THE RESEARCH

The tangible outcomes of this research have, to date, been

- a CD-ROM with a time series of daily maximum and minimum temperature values at 973 qualifying temperature stations, with missing values infilled and the record of each extended (where necessary) to cover a common 50 year base period 1950-1999;
- development of techniques to generate a 50 year time series of daily T_{mx} and T_{mn} values at any unmonitored location in southern Africa (i.e. at any one of the 429 700 one arc minute points) using the daily control station values from the 973 qualifying temperature stations together with regional/intra-seasonal lapse rates and with space/time adjustments for lapse rate discontinuities;
- application of this technique of generating daily temperature time series in recent scientific publications, for example, on climate change impacts on water resources in southern Africa (Perks *et al.*, 2000; Schulze and Perks, 2000), sugarcane water use (Schulze *et al.*, 2000) and afforestation water use (Gush *et al.*, 2002); and
- including the technique as an option for inputting daily temperature values in a national Quaternary Catchments database for use with the *ACRU* model throughout southern Africa.

In light of these outcomes, the objectives of this component of project K5/1156 have, clearly, been met.

POTENTIAL APPLICATIONS

Appropriately long daily time series of T_{mx} and T_{mn} can now be applied in climatic and hydrological computations, yielding from first order products to fourth order products.

- *First order* products include direct and revised computations of monthly means and temperature ranges, as well as cold spell and heat wave occurrences;
- *Second order* products include standard deviations of daily temperatures, month-by-month, probabilities of temperature thresholds being exceeded, computations of extremes and of any time trends;
- *Third order* output includes those of frost occurrences, heat units and chill units as well as higher order statistics thereof; while
- *Fourth order* applications are those in which temperature parameters are used as surrogates in computations of vapour pressure, relative humidity, solar radiation and reference potential evaporation – those hydrological applications for which this research was undertaken in the first instance.

RECOMMENDATIONS FOR FUTURE RESEARCH

This project has shown that it would be worthwhile expanding research efforts in future in, *inter alia*,

- temperature data rescue, as evidenced by the retrogression of the temperature recording network in southern Africa over the past decade and the possibility of many data not yet having been computerised (Chapter 2)
- updating the daily temperature database presently held in the School of Bioresources Engineering and Environmental Hydrology at the University of Natal to always be as current as possible
- re-visiting, and possibly re-delineating the temperature lapse rate regions in light of many temporal and spatial discontinuities that exist (Chapters 3; 4)
- re-looking the topographic valley index concept for its incorporation in temperature estimations and
- re-assessing methods of infilling the large numbers of missing daily temperatures which patching stations cannot provide.

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CHAPTER 1

BACKGROUND AND OBJECTIVES

1.1 THE IMPORTANCE OF TEMPERATURE

Temperature is a basic climatological parameter used frequently as an index of the energy status of the environment.

It has a direct effect on all forms of life on earth, affecting a wide range of processes and activities ranging from human comfort and consequent energy supply and demand for heating and cooling, to crop and domestic animal responses, the incidence of pests and diseases as well as rates of evaporation (Schulze, 1997).

Consequently, temperature parameters such as daily and seasonal means, maxima and minima, optimal and diurnal ranges of temperature are vital controls by which nature limits, for example, the distribution of crops or evaporative demand.

Because temperature measurement is a simple procedure and because long term temperature data are relatively abundant, it is not surprising that temperature parameters have been used as input variables in a wide range of climatological, hydrological and agricultural applications, from the estimation of solar radiation, relative humidity or potential evaporation to the concepts of heat and chill units or the delimitation of frost zones and agroclimatically optimum growth areas of crops (Schulze, 1997).

By the term temperature, the *air temperature* at Stevenson screen height is usually inferred, and this is taken as being representative of the surrounding area. However, air temperature may differ substantially from ground temperature and leaf temperature (Schulze, 1997). Air temperature is, furthermore, closely related to its main causative factor, viz. solar radiation, and it is often difficult to distinguish the effects of these two variables.

While many activities are defined or described by mean temperatures, the so-called *critical temperature* indices are generally of more significance to both natural plant and agricultural crop distributions.

- All plants have *upper* and *lower temperature* limits above or below which their growth/development processes cease (the plant may be killed or sustain damage). Between these limits there is an *optimum temperature*, which assures the most rapid growth for a particular species.
- These *cardinal temperatures* (lower, optimum, upper) differ from species to species, and even within a given species from one stage of the life-cycle to the next (Akin, 1991).

Additionally, temperature parameters constitute important, and in some cases the sole, drivers of

- *photosynthesis* (a daytime biochemical process influenced markedly by maximum temperatures),
- *vernalization* (a period of accumulated minimum temperatures below a threshold), which is often expressed through
- *chill units*, as well as
- *heat units* (accumulated temperature above a threshold),
- *thermoperiodism* (plant responses to diurnal temperature ranges),
- *frost* (its occurrence, distribution and variability),
- *saturated vapour pressure* (and hence vapour pressure deficit if used in conjunction with relative humidity) and
- *evaporation* (from water surfaces, intercepted water, the soil surface and through transpiration; through the capacity of air to take up more water vapour at higher temperatures and the amount of energy available for latent heat to be used in the process of evaporation).

1.2 OBJECTIVES OF THIS STUDY

It is in light of the importance of temperature, as highlighted above, aided by the fact that it is an easily measurable climatic variable and that it is often used as a surrogate in the estimation of more complex hydroclimatic variables such as humidity indices, solar radiation and reference potential evaporation that it was selected as the one multipurpose hydroclimatic variable (other than rainfall) for detailed study in the Water Research Commission (WRC) project K5/1156 titled

“Development of a Revised Spatial Database of Annual, Monthly and Daily Rainfall and Other Hydroclimatic Variables for South Africa”.

The study area, in fact, extends beyond South Africa *per se*, and includes Lesotho and Swaziland in what is hereafter referred to in the text as “southern Africa”. More specifically, this temperature related component of Project K5/1156 seeks to

- develop procedures to infill missing daily maximum and minimum temperature values and extend temperature records to a pre-selected common base period (1950-1999) for stations qualifying on the strength of existing records, and to
- develop procedures to generate daily time series of temperature for the base period at any location within southern Africa, where “any location” can be any one of the 429 700 one arc minute of a degree grid points making up the region.

In order to achieve these two objectives

- a database of temperature records in southern Africa first had to be collated and quality controlled (Chapter 2),
- temperature lapse rates had to be established for each month of the year for both maximum and minimum temperatures for different lapse rate regions and sub-zones within southern Africa (Chapter 3),
- the temperature records at qualifying control stations then had to be infilled and extended to a common 50 year base period, and the procedures verified (Chapter 4), before
- techniques were developed for daily temperatures to be generated at any location in southern Africa by making use of the extended/infilled control station values, lapse rates and methods to adjust for spatio-temporal lapse rate discontinuities (Chapter 5).
- Finally, conclusions were drawn and recommendations made for future research in this field (Chapter 6).

1.3 WHY DAILY TEMPERATURE VALUES?

The specific objectives of this study relate clearly to *daily* temperature estimates. Why?

The "South African Atlas of Agrohydrology and -Climatology (Schulze, 1997) published by the WRC used sub-region specific multiple regression equations to derive averaged temperature parameters, at monthly level for mapping, *inter alia*, the *monthly* means of daily maximum and minimum temperatures (T_{mx} , T_{mn}), *monthly* solar radiation, heat units, frost indicators, chill units, relative humidity and reference potential evaporation, as well as mean annual yields of pastures, agricultural and horticultural crops and timber production, all derived from averaged monthly temperature input as one of the driving variables (Schulze, 1997).

However, because long term monthly means of the temperature parameters were used in the equations developed for the variables mentioned above, neither inter-annual nor intra-seasonal variabilities, nor probabilities of occurrence could be computed, neither could any trends over time be evaluated. The generation of *daily* temperature time series at any location in southern Africa facilitates not only

- *first order* temperature parameters such as means and daily ranges to be re-evaluated and remapped, or the durations and severities of heat waves or cold spells to be assessed, but also
- *second order* statistics, such as intra-monthly and inter-annual variabilities to be computed, as well as extremes and probabilities of exceedance of threshold temperatures related to frost occurrence and trends over time. Furthermore,
- *third order* calculations can be undertaken, for example on heat and chill units, and
- *fourth order* derivatives of temperature can be calculated where these imply the use of temperature as a simplifying surrogate in estimations of vapour pressure, solar

radiation and potential evaporation, the latter in the form of the Penman-Monteith equation as a reference.

1.4 FACTORS AFFECTING TEMPERATURE

To round off this introductory chapter, and before embarking on the technical details of the research project in Chapters 2 to 5, readers are reminded of the main factors which affect the spatial and temporal distribution of temperature, and which were considered either directly or indirectly in subsequent chapters.

1.4.1 Factors Used in Previous Studies in Southern Africa

Since isotherms of temperature maps are constructed using estimates of temperature parameters at locations where temperature is not measured, these estimates have to be derived from variables which physically and intuitively account for the main factors affecting the distribution of temperature. In previous studies in southern Africa, Schumann and Le Roux (1940) had shown that altitude, total monthly rainfall and latitude all had a significant influence on mean monthly temperatures, while Schulze (1979; 1982; 1983) also used altitude and latitude, and in addition longitude, in the development of multiple regression equations for temperature in KwaZulu-Natal.

In probably the most detailed temperature study to date in southern Africa, Schulze (1997) applied stepwise multiple regression to develop individual monthly equations to estimate monthly means of daily maximum temperatures from altitude, latitude, longitude and the shortest distance from the ocean for 12 defined temperature regions. For monthly means of daily minimum temperatures a topographic valley index was added to the equation variables. Altitude was the only variable which was forced into each of the monthly and regional equations, since it was considered the dominant forcing factor (Hormann, 1994).

1.4.2 Factors Considered in the Present Project

The factors affecting temperature which were considered, either explicitly or implicitly, in this study are discussed below:

- *Temperature Region:* It stands to reason that southern Africa will consist of a series of regions in which different dominant factors will determine temperature regimes in different seasons of the year, with different interactions between the factors. This is so because southern Africa is flanked by a warm ocean along the east and south coasts and a cold ocean along its west coast, a narrow coastal strip rising rapidly to over 3 000 m altitude in places, often within 150 km of the coast, and a vast interior plateau – and all of this within a critical 12° latitudinal range (22°S to 34°S) which is characterised by seasonally variable air masses/synoptic conditions (Schulze, 1997). It is for these reasons that appropriately delineated *temperature regions* are considered a major prerequisite in explaining the temperature characteristics at a

given location. Twelve regions were originally delimited by Clemence (1986). These were subsequently modified by physiographic considerations (Schulze and Maharaj, 1991) and later reduced to 11 regions (Schulze, 1995).

- *Altitude*: Generally the higher the altitude, the lower the temperature. However, when considering altitude as a factor, the rate of decrease of temperature with altitude, i.e. the so-called *lapse rate*, is not constant, but varies with season, region, proximity to oceans, with altitude and between maximum and minimum temperatures (cf. Chapter 3).
- *Latitude*: South Africa extends from 22° - 34°S and it is hypothesised that with increasing latitude polewards, temperatures would decrease, independent of other factors. Latitudinal influences were factored in implicitly through the delimitation of temperature regions (Chapter 3).
- *Continentality* (i.e. Distance from Ocean): Oceans have a moderating influence on temperature, with relatively smaller variations near marine locations giving way rapidly to increases in daytime and decreases in night-time temperatures inland, where less humid conditions favour strong daytime solar radiation and night-time outgoing radiation. Especially for temperature maxima, the further inland the hotter it is likely to be. Continentality was expressed indirectly via the delineation of temperature regions (Chapter 3).
- *Topographic Index*: Night-time cold air drainage into valley bottoms, caused by radiative cooling of uplands and valley slopes under clear sky conditions, is well documented in southern Africa. Occurring most commonly during the cooler months, cold air drainage assumes importance in hilly inland areas (Tyson, Preston-Whyte and Schulze, 1976) and is expressed through a topographic index (Chapter 3). Because of the manner in which the topographic index is calculated (Chapter 3), valleys are assigned smaller values and uplands/spurs larger values.

* * * * *

Following upon this introduction, Chapter 2 evaluates the temperature database which was collated and used in this research.

CHAPTER 2

THE SOUTHERN AFRICAN DAILY TEMPERATURE DATABASE

2.1 SOURCES OF DAILY TEMPERATURE DATA

For this research, daily temperature data were obtained to the end of year 2000 from three main sources, who are thanked for making their data available, viz.

- the South African Weather Service (SAWS) of the State Department of Environmental Affairs and Tourism, whose data included those from stations in Lesotho and Swaziland
- the Institute for Climate, Soil and Water (ISCW) of the Agricultural Research Council and
- the South African Sugar Association (SASEX).

Data from a small number of other stations, derived mainly from a public appeal for climatological information in the 1980s (Dent, Lynch and Schulze, 1988), were also used. Only records from stations with 3 or more years of daily temperature data were considered in any of the analyses which follow.

2.2 DAILY TEMPERATURE DATA: TEMPORAL PERSPECTIVES

The development of southern Africa's daily temperature station network over time is shown graphically in Figure 2.1 and in tabular form in Table 2.1.

Table 2.1 Number of temperature stations for which ≥ 3 years daily data were available in southern Africa, at decadal intervals

Year	No. of Stations, According to Source of Data				Total
	SAWS	ISCW	SASEX	PUBLIC	
1900	4	2	0	0	6
1910	6	4	0	0	10
1920	12	18	0	0	30
1930	22	36	1	0	59
1940	26	75	1	1	103
1950	29	87	1	1	118
1960	212	91	1	0	304
1970	231	104	29	2	366
1980	168	241	37	1	447
1990	252	286	41	3	582
2000	134	144	20	1	299

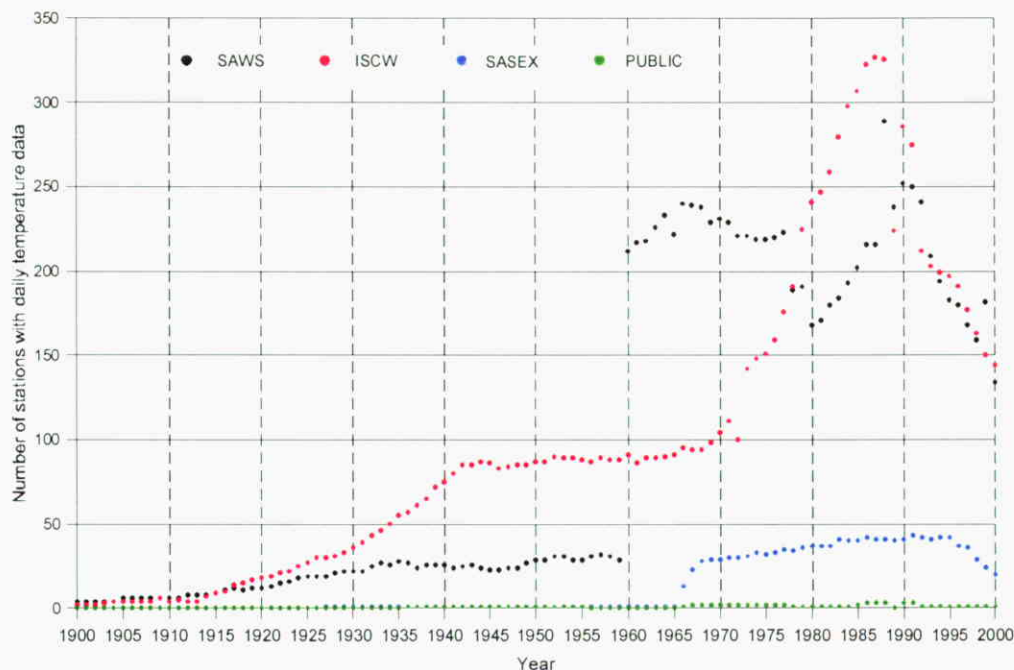


Figure 2.1 Development of the southern African daily temperature station network over time (1900-2000). Only stations with ≥ 3 years' daily temperature data were considered

The following are highlighted from Figure 2.1 and Table 2.1:

- SAWS daily temperature stations show a gradual increase over time, with a major jump in station numbers in 1960, followed by a decline in the late 1970s and an increase again in the 1980s, peaking in 1988, whereafter another decline sets in until that reverses again in the late 1990s.
- This pattern reflects what are probably policy changes on network expansion or rationalisation at various times.
- The sudden jump of SAWS temperature stations in 1960 appears to indicate also that many pre-1960 temperature data may in fact exist, but are not readily available because they may not yet have been computerised.
- The ISCW station network displays a gradual increase up to the early 1940s, whereafter the network of around 88 stations is maintained up until 1969. This is followed by an increase in station numbers up to a peak in 1987/88, whereafter a network rationalisation appears to have taken place.
- The SASEX temperature station network in the sugarcane growing areas of southern Africa commenced in 1966 and soon reached a plateau at approximately 35 stations, before declining from 1996 onwards.
- The three major temperature network organisations, viz. SAWS, ISCW and SASEX, operate collaboratively and many temperature stations report their data to more than one of the three organisations.

- At some stage or other between 1900 and 2000 a total of 1021 stations in the RSA, Lesotho and Swaziland had ≥ 3 years of daily temperature data.
- The total network peaked in 1988, when 693 temperature stations reported data to their respective organisations.
- Since 1988 a marked decline in the overall network is evident. This retrogression of climate networks is a world-wide phenomenon.

2.3 DAILY TEMPERATURE DATA: SPATIAL PERSPECTIVES

The spatial distribution, according to the source of the data, of the 1021 stations each with ≥ 3 years of daily temperature data at some time during the 20th century, is given in Figure 2.2. As “national custodian” of climate data, the SAWS stations are spread most evenly throughout the area. The ISCW temperature station network, thereagainst, is markedly more dense in the more intensive commercial agriculture areas, especially in clusters within the Western Cape, KwaZulu-Natal and Mpumalanga provinces, while the SASEX stations are, understandably, concentrated along the coast of KwaZulu-Natal and Swaziland.

Not only the spatial distribution, but also the length of the temperature records, is important. Long station records of temperature are valuable as they act as a “control” from which temperature values from stations with shorter records may be extrapolated/extended to a desired common base period for further analyses. Furthermore, trends of temperature over time (e.g. increases, which may signify global warming) can only be evaluated from long records. The distribution of stations by length of record is, therefore, shown in Figure 2.3 and in Table 2.2.

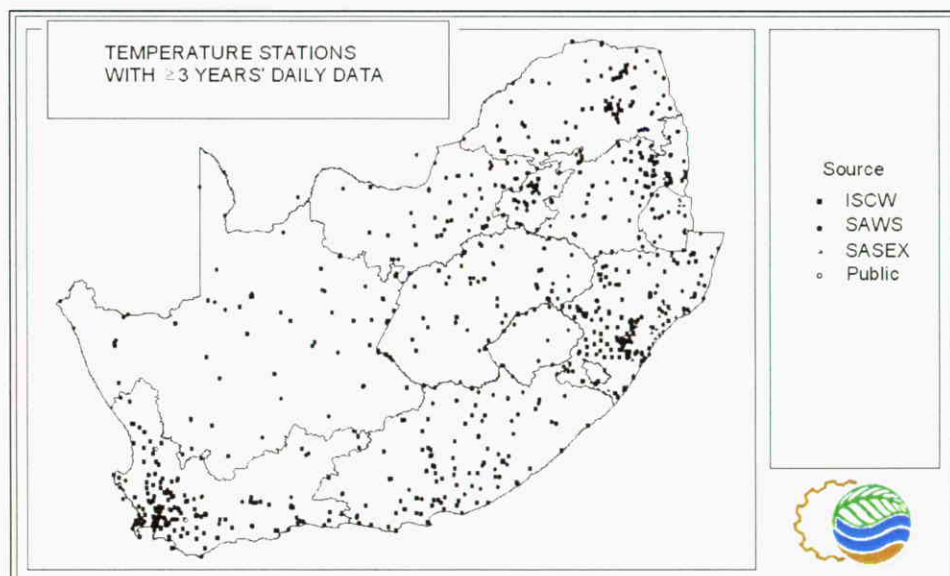


Figure 2.2 Distribution of temperature stations in southern Africa with ≥ 3 years daily data, by source of data

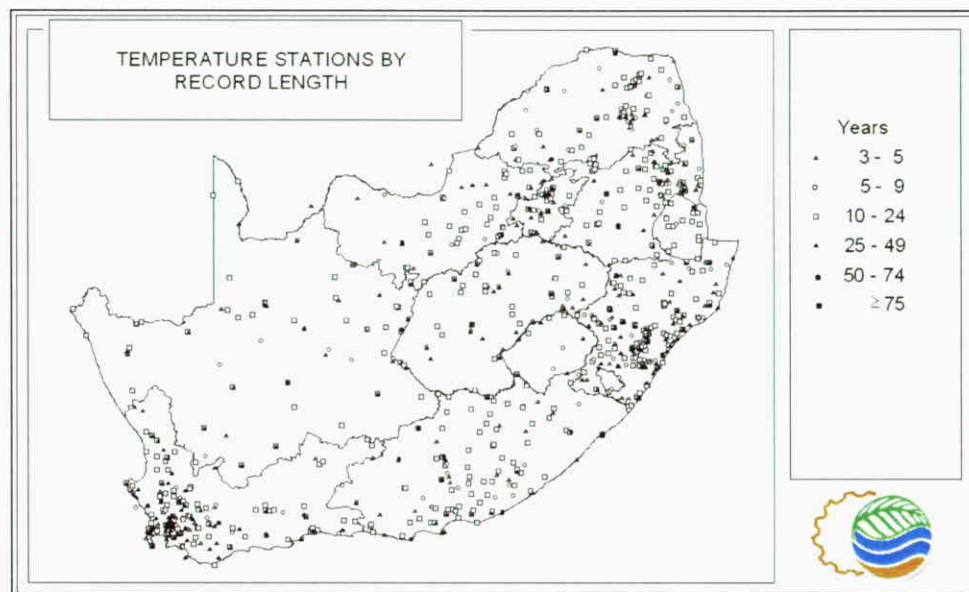


Figure 2.3 Distribution of temperature stations in southern Africa by record length

Only 23 stations in southern Africa have more than 50 years of daily data (Table 2.2), of which 4 have record lengths in excess of 75 years. The station network is densest in KwaZulu-Natal (1 station per 433 km²), in Gauteng and the Western Cape and sparsest in the Northern Cape (1 station per 4263 km²) and Lesotho (1 station per 2687 km²).

Table 2.2 Distribution of temperature stations by record length in the various provinces and countries of the study area, and network density

Province/ Country	Number of Stations by Categories of Record Length (years)						Total	Density/km ²
	3-5	5-9	10-24	25-49	50-75	> 75		
Limpopo	19	24	45	12	2	0	102	1200
North-West	10	8	33	11	0	2	64	1814
Gauteng	7	7	15	9	1	0	39	477
Mpumalanga	16	18	53	11	3	0	101	775
Swaziland	0	3	14	1	0	0	18	967
Northern Cape	13	18	37	17	0	0	85	4263
Free State	10	9	30	15	1	0	65	1997
Lesotho	0	2	4	5	0	0	11	2687
KwaZulu-Natal	27	40	88	55	2	1	213	433
Western Cape	35	28	79	47	4	0	193	671
Eastern Cape	22	20	66	15	6	1	130	1371
Totals	159	177	464	198	19	4	1021	1242

2.4 DATA QUALITY CONTROLS

Before any temperature related analyses were undertaken, stringent (and time-consuming) quality control of the daily temperature data was undertaken. Listed and discussed below are some of the problems encountered:

- Five stations were found to still have their temperature data given in degree Fahrenheit, either for part of, or for the entire record, without this having been indicated. These records were identified by logical checks and then converted to °C.
- In total 946 errors were encountered where daily temperature maxima, T_{mxd} , were smaller than the minimum temperature, T_{mnd} , for the same day. These records were then flagged as errors and subsequently synthesised by methods described in subsequent chapters.
- Where daily maximum temperatures exceeded 45°C, these were flagged and checked against same-day temperatures of surrounding stations. Where found to be anomalous, these records were flagged as errors and later infilled synthetically.
- In the initial quality control the range between T_{mxd} and T_{mnd} on a given day was checked to be $\geq 1^\circ\text{C}$. In over 13 000 cases the daily range, T_{dra} , was found to be $< 1^\circ\text{C}$. On the assumption that a low temperature range was indicative of moist atmospheric conditions at low temperatures, days with $T_{\text{dra}} < 1^\circ\text{C}$ were flagged as errors if both T_{mxd} and T_{mnd} were $\geq 20^\circ\text{C}$. When both T_{mxd} and T_{mnd} were $< 20^\circ\text{C}$, surrounding stations were checked for low T_{dra} before deciding whether or not the data were flagged as errors.
- It is highly unlikely that the identical temperature (i.e. to 0.1°C) occurs on more than 2 consecutive days. When identical T_{mxd} or T_{mnd} values were recorded for 3 or more consecutive days, those records were flagged as errors and later infilled synthetically from surrounding station values. Over 8 000 such errors were found.
- A further time consuming quality control involved checking the exact location, i.e. latitude, longitude and altitude, of all the temperature stations on 1:50 000 topographic sheets. The “exact” locations are crucial in computations of lapse rates and for determination of topographic indices. Many station altitudes (in particular) were found to be out by several hundred metres.

* * * * *

Following this brief overview of the status of daily temperatures in southern Africa, the following chapter describes the determination of regional and intra-annual lapse rates of maximum and minimum temperatures.

CHAPTER 3

DETERMINATION OF REGIONAL AND INTRA-ANNUAL LAPSE RATES OF MAXIMUM AND MINIMUM TEMPERATURES

3.1 TEMPERATURE LAPSE RATES: BACKGROUND

3.1.1 What are Temperature Lapse Rates?

Generally, the higher the altitude of a location, the lower the temperature. The rate of decrease of temperature with altitude is termed the *lapse rate*.

3.1.2 Why Apply Lapse Rates?

In this particular study on the estimation of daily maximum and minimum temperatures for a common base period at any location in southern Africa, that estimation is made using values from a near-by control station with a 50 year daily temperature record and adjusting those temperatures up or down by a specified lapse rate which accounts for the difference in altitude between the control station and the location of interest. This specified lapse rate is, however, not expected to be a constant or "standard" value (Schulze, 1997).

3.1.3 A Brief Review on Temperature Lapse Rates

While an average lapse rate of -6.5°C per 1000 m altitude rise is often regarded as a "standard", it has been widely documented that lapse rates vary with location, season, maximum vs minimum temperature, prevailing topography or the degree of cloudiness. Thus Torrance (1973) reports a maximum temperature (T_{mx}) lapse rate of $-9^{\circ}\text{C}/1000$ m altitude in the dry season in the highlands of eastern Zimbabwe, decreasing with cloudiness in the rainy season and when T_{mn} are considered. Parry *et al.* (1988) report a lapse rate of $-4.6^{\circ}\text{C}/1000$ m altitude in Ecuador, but distinguish between lapse rates on flatter areas vs those on mountain slopes, while Lennon and Turner (1995) report only a small seasonal variation in the UK. In southern Africa, the Weather Bureau (1965) distinguished between summer and winter lapse rates in six regions, viz. an interior region flanked by five regions on the seaward side of the Great Escarpment.

In a subsequent study in southern Africa, Schulze (1995) published monthly lapse rates for both maximum and minimum temperatures for 12 defined regions (Figure 3.1). These lapse rates were used mainly for extrapolations of monthly temperature estimates by multiple regression at altitudes above and below those of the highest/lowest stations in a region (Schulze, 1997). From that research the lowest lapse rate (LR) of maximum temperature was found to be $-0.6^{\circ}\text{C}/1000$ m (Region 5, September) and the highest to be $-9.9^{\circ}\text{C}/1000$ m (Region 2, May). In addition to regional and monthly differences in LRs, they found, when lumping results from all

regions/months, that in southern Africa minimum temperatures had lower LR_s than maxima and that summer season LR_s tended to be lower than those of winter months.

3.2 PROCEDURES FOR DETERMINING REGIONAL AND INTRA-SEASONAL TEMPERATURE LAPSE RATES IN SOUTHERN AFRICA

3.2.1 Step 1: Determination of Temperature Lapse Rate Regions

Research by Clemence (1986) resulted in the delineation of southern Africa (i.e. by definition for this study the RSA plus Lesotho and Swaziland) into 12 regions in each of which the factors influencing temperature and potential evaporation (e.g. latitude, altitude, proximity to oceans, seasonally varying synoptic and rainfall conditions) had similar influences. These temperature regions were subsequently modified into lapse rate regions by Schulze and Maharaj (1991) to take account of major physiographic features with respect to terrain morphology (Figure 3.1). Schulze (1995) later showed Regions 8 and 9 to be indistinguishable from one another in regard to their lapse rates. These two regions were therefore combined into a Region 8/9 (Schulze, 1995; 1997).

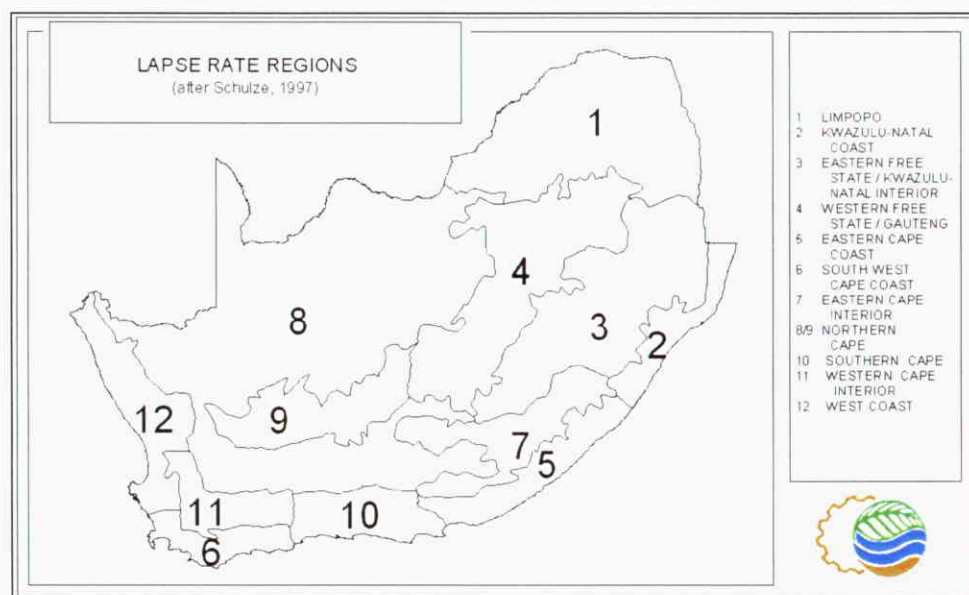


Figure 3.1 Temperature lapse rate regions of southern Africa (after Schulze, 1997)

In order to appreciate the respective roles of altitude, seasonality of rainfall and terrain morphology in the general descriptions of the temperature lapse rate regions which follow in Section 3.3, maps thereof are presented below. Additional background on the derivation of the maps of altitude (Figure 3.2), seasonality of rainfall (Figure 3.3) and

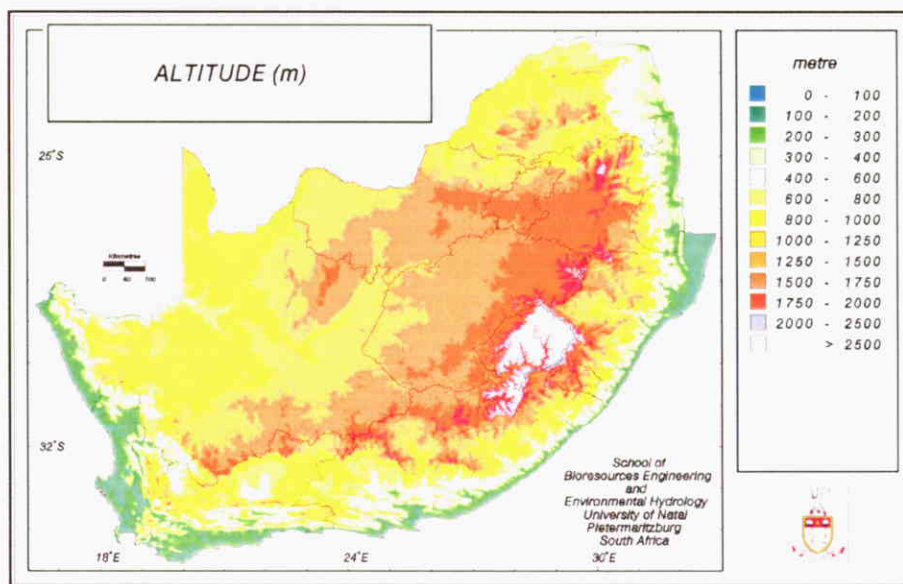


Figure 3.2 Altitude (m) zones of southern Africa (from Schulze, 1997)

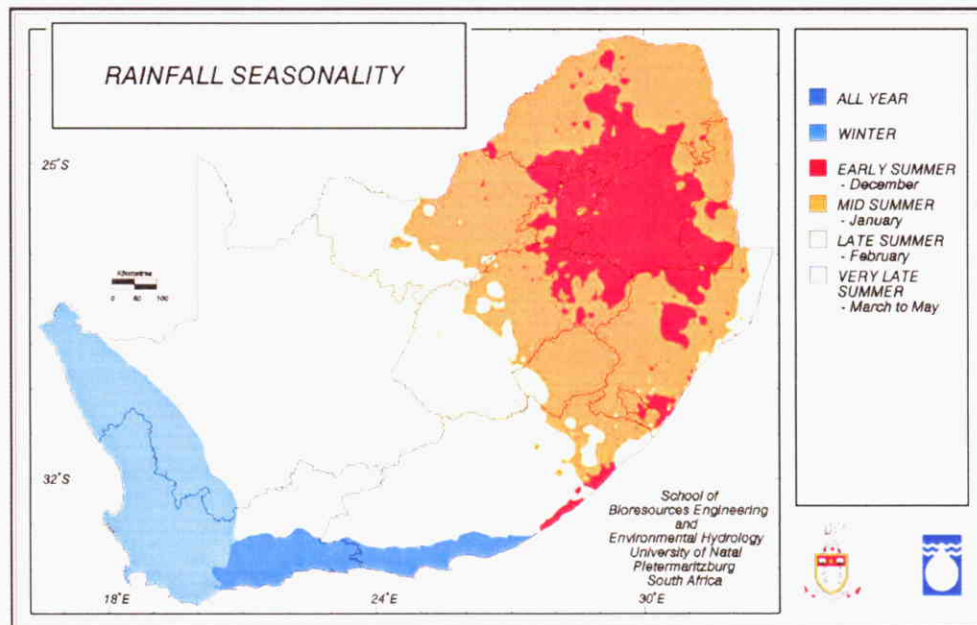


Figure 3.3 Rainfall seasonality zones of southern Africa (Schulze, 1997)

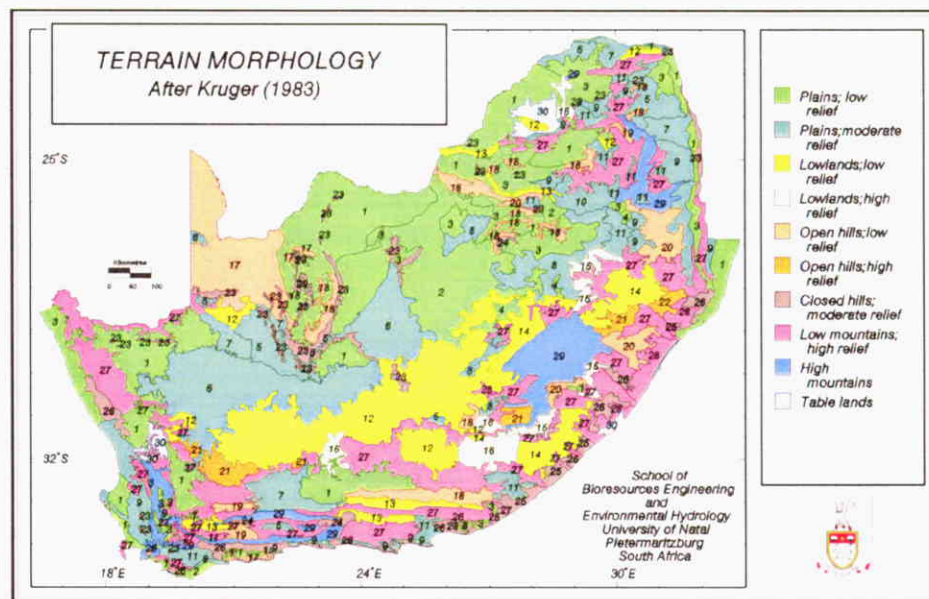


Figure 3.4 Terrain morphological zones of southern Africa (after Kruger, 1983)

terrain morphology (Figure 3.4) is given in the “South African Atlas of Agrohydrology and –Climatology” (Schulze, 1997).

3.2.2 Step 2: Determination of the “Grey Zone” Around Lapse Rate Regions

While temperature lapse rate regions are delimited by “fixed” lines on a map (cf. Figure 3.1), they generally merge into one another in their natural environment, with a transition zone between regions. In order to account for these overlapping transitional areas, the so-called distance related “grey zone” concept between regions was introduced. The grey zone was defined in this and previous temperature studies (e.g. Schulze, 1997) as a 15 arc minute of a degree digitised zone on either side of the fixed temperature region boundary, and in which transitions of influences and attributes between adjacent regions are considered. These distance related grey zones are used in temperature station selection for lapse rate determinations and are depicted for the 11 temperature lapse rate regions in Figure 3.5. It may be deduced from Figure 3.5 that certain areas may be totally “uninfluenced” by any grey zone, or be “influenced” by the grey zones of either 1 or 2 or 3 or even 4 adjacent regions.

3.2.3 Step 3: Temperature Station Selection

All temperature stations with records ≥ 3 years falling within the bounds of a lapse rate region qualified for selection for that region. In addition, all stations located within the 15 arc minute of a degree grey zone surrounding a specific region were also included.

Using 15 arc minutes for the grey zone was found to work well with larger LR regions of the interior of southern Africa, but not necessarily with the smaller regions in which grey

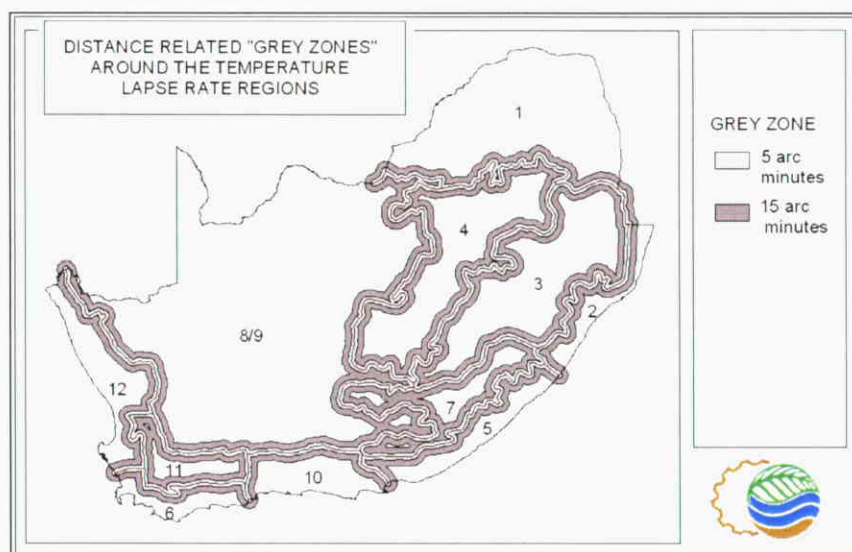


Figure 3.5 Distance related "grey zones" around the temperature lapse rate regions in southern Africa

zone stations could dominate and create different "populations" of LRs within a region. Cognisance was taken of this in later analyses.

3.2.4 Step 4: Plotting Temperature: Altitude Relationships

Long term monthly means of both daily maximum and minimum of all qualifying stations in a LR region were plotted against altitude for each month of the year. The month was chosen as a convenient length of time to capture transient intra-annual changes in LRs as a result of typical prevailing synoptic situations which change between and within seasons in a given LR region.

In the temperature:altitude plots a further distinction was made between stations located in valleys, and thus prone to cold air drainage and consequently a possible increase in temperature with altitude, and those which were topographically exposed on, for example, ridges. This distinction is expressed through an adaptation of Myburgh's (1974) topographic index (TI), which is described in Schulze (1997), and where a low TI designates a valley location and a high TI a topographically exposed location.

3.2.5 Step 5: Determination of Initial Computed Lapse Rates

In order to eliminate undue influences of "outliers", in temperature:altitude relationships, particularly for stations at the extremities of altitudes (both high and low), as well as taking cognisance of the influence of grey zone stations, those stations for a specific region and month which constituted the highest 10% of altitudes were clustered and their mean altitude and temperature were determined. The same procedure was

adopted for the stations and their temperatures of the lowest 10% of station altitudes. The computed slope joining altitude:temperature “point” representing the upper 10% cluster and the lower 10% cluster was then taken to represent the “initial computed lapse rate”.

3.2.6 Step 6: Assigning Confidence Ratings to Lapse Rates

Each lapse rate plot was assigned a confidence rating to one of three categories by subjective judgement. The three categories were

- *high*, when a tight and distinctly linear association between temperature and altitude was evident, and no further adjustment/revision to LRs was deemed necessary;
- *medium*, when there was still a clearly discernible linear relationship between temperature and altitude, but the relationship was more diffuse, frequently caused by different plots of those stations with high vs low TIs, which would then result in a re-evaluation of the LRs; and
- *low*, when no distinct overall linear pattern was evident in the scatter plot, for example, because of different dominant LRs due to different TIs, or because a “dog-leg” of the temperature:altitude relationship occurred, indicating two distinct “populations” of LRs which needed to be dis-aggregated by a sub-zonation of the region and a subsequent revision of computed lapse rates.

Typical examples of high, medium and low confidence ratings of lapse rates are illustrated in Figure 3.6.

3.2.7 Step 7: Determination of Revised Computed Lapse Rates

Lapse rates plots with medium or low confidence ratings were revisited and, where there was clear visual evidence, lapse rate computations were revised on the basis of further sub-zonation of a region according to

- the *topographic index*, TI, in which case separate lapse rates were computed for $TI < 100$, i.e. topographically “enclosed” (or valley) stations, vs $TI \geq 100$, i.e. topographically “exposed” stations (Figure 3.7), or
- *altitude*, where in coastal regions the oceanic influence sometimes resulted in a “dog-leg” lapse rate, with temperatures initially increasing up to a threshold altitude and thereafter decreasing once the threshold altitude was exceeded (Figure 3.8).

The topographic valley index expresses the ease with which cold air drainage is possible, depending on

- the steepness of the gradient and
- the surrounding topography.

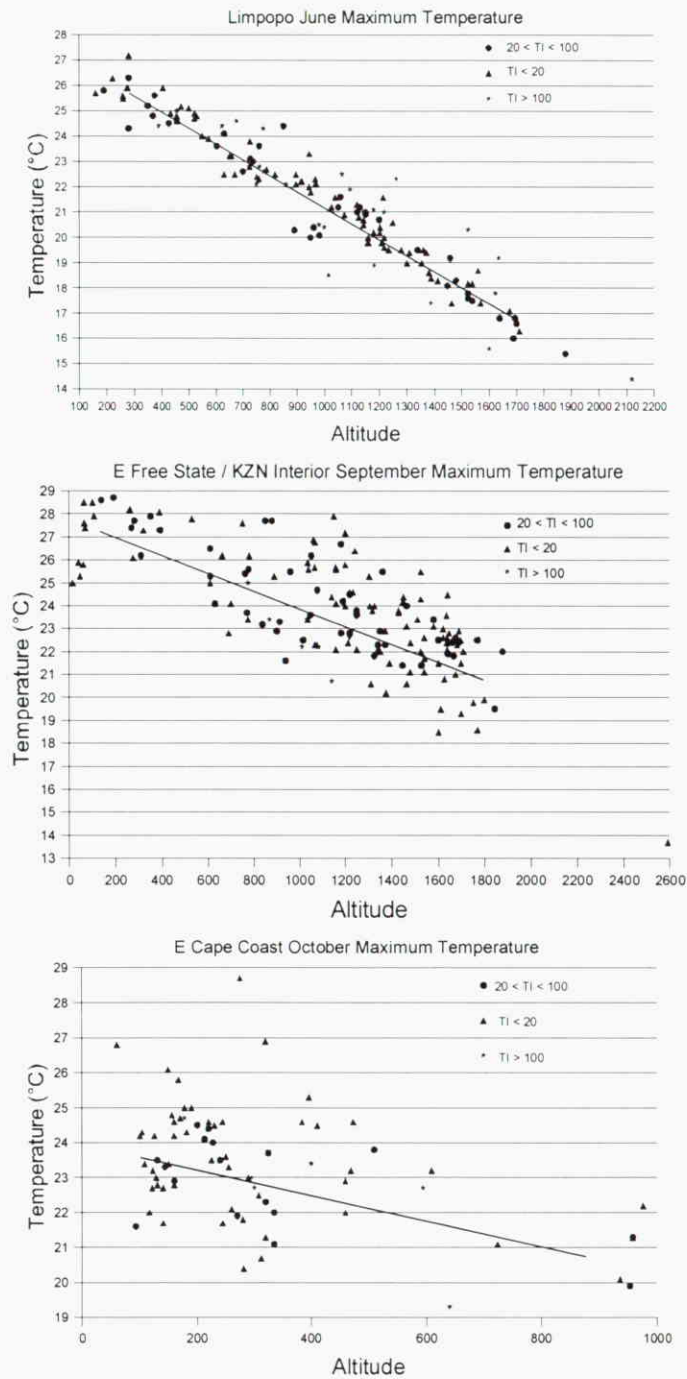


Figure 3.6 Examples of initial lapse rates with high (top graph), medium and low (bottom graph) confidence ratings

The TI at a point, illustrated in more detail with examples in Schulze (1997), is an adaptation of Myburgh's (1974) index and is expressed as

$$TI = (Z_x - Z_{sng}) N_{sa} / 8$$

where

- TI = topographic valley index
- Z_x = altitude (m) of the point in question
- Z_{sng} = altitude (m) of the lowest neighbouring grid point of those surrounding the point in question
- N_{sa} = number of surrounding points with altitudes lower than that of the point in question and
- 8 = number of surrounding points considered.

Based on the one arc minute raster of altitudes, Figure 3.7 shows up which areas in southern Africa have TIs less than or exceeding 100.

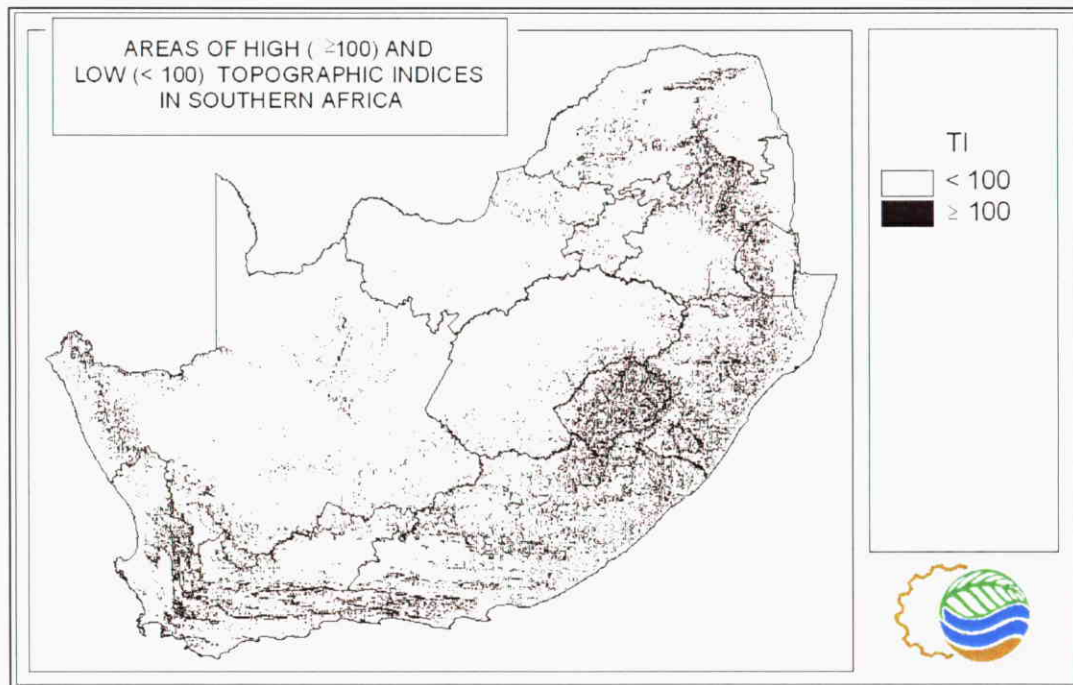


Figure 3.7 Areas of high (≥ 100) and low (< 100) topographic indices in southern Africa, where a low TI designates topographically enclosed (valley) and/or flat locations and a high TI implies a topographically open (exposed) location (e.g. hills, ridges)

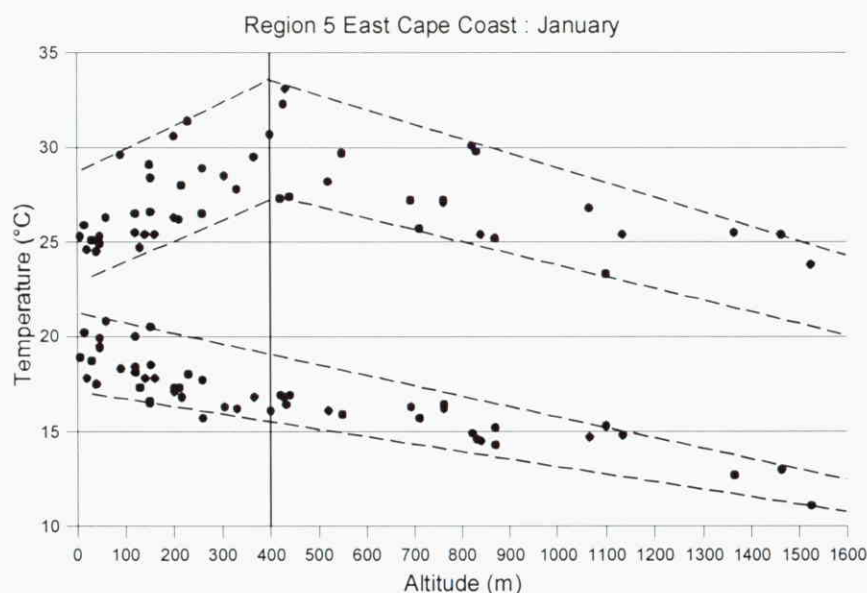


Figure 3.8 Example of a “dog-legged” lapse rate of maximum temperature found in certain coastal regions

3.2.8 Step 8: Final (Smoothed) Lapse Rates per Region and Month

As a final step the values of the monthly lapse rates (either initial or revised, where applicable) were “smoothed” manually to produce more realistic transitions from month to month.

3.3 LAPSE RATES IN REGION 1: LIMPOPO

3.3.1 Initial Basic Information for Region 1

Variable	Value
No. of temperature stations	140
Altitude (m) of highest station	2118
Altitude (m) of lowest station	160
Mean altitude (m) of highest 10% of stations	1688
Mean altitude (m) of lowest 10% of stations	282

3.3.2 General Description: Region 1

- The Limpopo LR Region (Figure 3.1) is located in the early to mid-summer rainfall zone (Figure 3.3) with MAPs ranging from < 400 mm in the north to > 1200 mm on higher lying Drakensberg mountains, but mainly in the ranges 400-600 mm.
- Altitudes vary from < 200 m, but mainly around 600 m in the east to over 1500 m in the north-south trending Drakensberg (Figure 3.2).

- Terrain morphologically, Region 1 consists largely of plains of low and medium relief, but bisected by the low Drakensberg mountains of high relief and containing also some table lands (Figure 3.4).

3.3.3 Maximum Temperature Lapse Rates for Region 1

3.3.3.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 1

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-5.0	-5.0	-5.2	-5.6	-6.0	-6.2	-5.9	-5.3	-4.4	-4.2	-4.7	-4.9
Confidence Rating	M	M	M	H	H	H	H	H	H	M	M	M

3.3.3.2 Observations on Lapse Rates of Maximum Temperatures: Region 1

- Lapse rate plots were assigned high confidence ratings in winter months (April to September) and medium confidence ratings in summer (October to March).
- Points plotted according to high and low topographic indices (TIs) of station locations showed no distinctly different patterns from month to month.
- No further adjustments, other than smoothing, were thus deemed necessary.

3.3.3.3 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 1

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-5.0	-5.0	-5.2	-5.6	-6.0	-6.2	-5.9	-5.3	-4.4	-4.2	-4.7	-4.9

3.3.4 Minimum Temperature Lapse Rates for Region 1

3.3.4.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 1

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-5.0	-5.2	-5.4	-5.5	-5.6	-5.6	-5.5	-5.3	-4.8	-4.7	-4.8	-4.9
Confidence Rating	H	H	H	H/M	M	M	M	M	H	H	H	H

3.3.4.2 Observations on Lapse Rates of Minimum Temperatures: Region 1

- Lapse rate plots were assigned high confidence ratings from September through March/April and medium confidence ratings in the winter months April/May to August.
- In most months from May to August stations located in areas of low topographic index ($TI < 100$) showed distinctly different slopes to those with $TI \geq 100$.
- For those four months separate LRs were thus computed according to $100 > TI \geq 100$.

3.3.4.3 Revised Basic Information for Separate Minimum Temperature Lapse Rates in Region 1 According to Topographic Index

Variable	TI < 100	TI ≥ 100
No. of temperature stations	114	26
Altitude (m) of highest station	1878	2118
Altitude (m) of lowest station	160	380
Mean altitude (m) of highest 10% of stations	1654	1792
Mean altitude (m) of lowest 10% of stations	257	409

3.3.4.4 Revised Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 1

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR (TI<100)					-5.7	-5.3	-5.6	-5.5				
LR (TI≥100)					-5.1	-5.3	-5.3	-5.3				

3.3.4.5 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 1

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
a) Without TI distinction												
Lapse Rate	-5.0	-5.2	-5.4	-5.5	-5.6	-5.6	-5.5	-5.2	-4.9	-4.7	-4.7	-4.9
b) With TI distinction												
LR (TI<100)	-5.0	-5.2	-5.4	-5.5	-5.7	-5.7	-5.5	-5.3	-4.9	-4.7	-4.7	-4.9
LP (TI≥100)	-5.0	-5.2	-5.4	-5.5	-5.4	-5.3	-5.3	-5.2	-4.9	-4.7	-4.7	-4.9

3.4 LAPSE RATES IN REGION 2: KWAZULU-NATAL COAST

3.4.1 Initial Basic Information for Region 2

Variable	Value
No. of temperature stations	75
Altitude (m) of highest station	1700
Altitude (m) of lowest station	15
Mean altitude (m) of highest 10% of stations	1469
Mean altitude (m) of lowest 10% of stations	35

3.4.2 General Description: Region 2

- The KwaZulu-Natal Coast Region stretches inland from the Indian Ocean to 50-80 km (Figure 3.1).
- Altitudes are mainly < 100 m in the north, but increase to 800 m further south (Figure 3.2).
- This is a mid to late-summer rainfall zone (Figure 3.3) with MAPs mainly in the 800-1000 mm range.
- Its terrain morphology (Figure 3.4) consists of plains of low relief in the northern third and low mountains of high relief in the southern two thirds of the region.

3.4.3 Maximum Temperature Lapse Rates for Region 2

3.4.3.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 2

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-2.9	-3.0	-3.3	-3.3	-3.6	-4.0	-3.7	-2.9	-2.0	-2.3	-2.4	-2.6
Confidence Rating	M	M	M	M	H	H	H	H/M	M	M/L	M	M/L

3.4.3.2 Observations on Lapse Rates of Maximum Temperatures : Region 2

- Lapse rate plots, with the exception of those for May-July, were of medium confidence ratings only.
- No marked differences in LR's for either different altitudes or TIs were distinguishable.
- No further adjustments, other than smoothing, were thus deemed necessary.

3.4.3.3 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 2

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-2.9	-3.0	-3.1	-3.3	-3.6	-3.9	-3.7	-2.9	-2.3	-2.2	-2.4	-2.6

3.4.4 Minimum Temperature Lapse Rates for Region 2

3.4.4.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 2

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-5.0	-5.1	-5.4	-5.7	-6.3	-6.6	-6.5	-6.2	-5.5	-5.3	-5.1	-5.1
Confidence Rating	H	H	H	H/M	M	M	M	M/H	H	H	H	H

3.4.4.2 Observations on Lapse Rates of Minimum Temperatures: Region 2

- Lapse rate plots are given high confidence ratings in the summer months September to March and medium ratings in the winter months.
- From May to August those stations located in areas of low TI generally display different lapse rates to those of high TI (i.e. $TI \geq 100$).
- For those four months separate LR's were, therefore, computed according to $100 > TI \geq 100$.

3.4.4.3 Revised Basic Information for Separate Minimum Temperature Lapse Rates in Region 2 According to Topographic Index

Variable	TI < 100	TI ≥ 100
No. of temperature stations	60	15
Altitude (m) of highest station	1700	1340
Altitude (m) of lowest station	15	152
Mean altitude (m) of highest 10% of stations	1506	1264
Mean altitude (m) of lowest 10% of stations	28	209

3.4.4.4 Revised Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 2

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR (TI<100)					-6.3	-6.5	-6.5	-6.2				
LP (TI≥100)					-6.4	-6.9	-6.5	-6.0				

3.4.4.5 Final (Smoothed) Lapse Rates (°C/1000 m) for Minimum Temperatures in Region 2

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
a) Without TI distinction												
Lapse Rate	-5.0	-5.1	-5.4	-5.7	-6.3	-6.6	-6.5	-6.1	-5.5	-5.2	-5.1	-5.0
b) With TI distinction												
LR (TI<100)	-5.0	-5.1	-5.4	-5.7	-6.3	-6.5	-6.5	-6.2	-5.5	-5.2	-5.1	-5.0
LP (TI≥100)	-5.0	-5.1	-5.4	-5.7	-6.4	-6.9	-6.6	-6.0	-5.5	-5.2	-5.1	-5.0

3.5 LAPSE RATES IN REGION 3: EASTERN FREE STATE/KWAZULU-NATAL INTERIOR

3.5.1 Initial Basic Information for Region 3

Variable	Value
No. of temperature stations	150
Altitude (m) of highest station	2590
Altitude (m) of lowest station	15
Mean altitude (m) of highest 10% of stations	1796
Mean altitude (m) of lowest 10% of stations	131

3.5.2 General Description: Region 3

- Region 3 (Figure 3.1) is a very diverse lapse rate region within the early to mid-summer rainfall zone (Figure 3.3) and with MAPs varying from < 600 mm to > 1200 mm
- With altitudes ranging from < 600 m in the east to > 2500 m (up to 3400 m) in the Drakensberg-Maluti mountains (Figure 3.2), a varied terrain morphology is expected.
- This is, indeed so, for it contains plains of moderate relief, lowlands of low and high relief open hills as well as low and high mountains (Figure 3.4).

3.5.3 Maximum Temperature Lapse Rates for Region 3

3.5.3.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 3

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-4.1	-4.2	-4.7	-5.0	-5.4	-5.9	-5.7	-5.1	-3.9	-3.9	-3.9	-4.0
Confidence Rating	M	M	M/H	H	H	H	H	H	H/M	M	M	M

3.5.3.2 Observations on Lapse Rates of Maximum Temperatures: Region 3

- While LRs for monthly means of daily maximum temperatures were given a high confidence rating in the winter months, they were only of medium confidence in the summer months.
- A partial explanation for this was that in summer months a visual distinction, even if not always convincing, would be made between temperature vs altitude relationships of stations with low vs high TIs (i.e. < 100 vs ≥ 100)
- Separate TI-dependent LRs were, therefore, computed for the months October through March.

3.5.3.3 Revised Basic Information for Separate Maximum Temperature Lapse Rates in Region 3 According to Topographic Index

Variable	TI < 100	TI ≥ 100
No. of temperature stations	130	20
Altitude (m) of highest station	2590	1676
Altitude (m) of lowest station	15	267
Mean altitude (m) of highest 10% of stations	1815	1671
Mean altitude (m) of lowest 10% of stations	109	328

3.5.3.4 Revised Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 3

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR (TI<100)	-4.3	-4.4	-4.8							-4.0	-4.0	-4.2
LP (TI≥100)	-2.0	-2.7	-3.3							-3.3	-2.3	-2.4

3.5.3.5 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 3

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
a) Without TI distinction												
Lapse Rate	-4.1	-4.2	-4.5	-5.0	-5.5	-5.9	-5.7	-5.0	-4.2	-3.9	-3.9	-4.0
b) With TI distinction												
LR (TI<100)	-4.3	-4.4	-4.6	-5.0	-5.5	-5.9	-5.7	-5.0	-4.2	-4.0	-4.0	-4.2
LP (TI≥100)	-2.1	-2.6	-3.5	-5.0	-5.5	-5.9	-5.7	-5.0	-4.0	-3.1	-2.5	-2.2

3.5.4 Minimum Temperature Lapse Rates for Region 3

3.5.4.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 3

Attitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-5.3	-5.4	-5.8	-6.2	-6.1	-5.5	-5.8	-6.0	-5.8	-5.5	-5.4	-5.4
Confidence Rating	H	H	H	H	M	M	M	M	H/M	H	H	H

3.5.4.2 Observations on Lapse Rates of Minimum Temperatures: Region 3

- Distinct LRs with high levels of confidence are evident in all but the mid-winter months May to August.
- As expected in an interior zone with hilly topography, cold air drainage influences minimum temperature patterns. This is evident from the TI plots from May to August.
- Separate LRs for T_{mn} were, therefore, computed for these four months plus a month on either side.

3.5.4.3 Revised Basic Information for Separate Minimum Temperature Lapse Rates in Region 3 According to Topographic Index

This information is the same as for maximum temperatures in Region 3.

3.5.4.4 Revised Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 3

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR (TI<100)				-6.0	-5.9	-5.2	-5.4	-5.6	-5.6			
LR (TI≥100)				-7.3	-8.9	-9.7	-9.6	-9.3	-7.4			

3.5.4.5 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 3

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
a) Without TI distinction												
Lapse Rate	-5.4	-5.4	-5.8	-6.2	-6.0	-5.6	-5.7	-6.0	-5.9	-5.5	-5.4	-5.4
b) With TI distinction												
LR (TI<100)	-5.4	-5.4	-5.8	-6.0	-5.9	-5.2	-5.3	-5.6	-5.6	-5.5	-5.4	-5.4
LP (TI≥100)	-5.4	-5.4	-5.8	-7.3	-8.9	-9.6	-9.6	-9.3	-7.4	-5.5	-5.4	-5.4

3.6 LAPSE RATES IN REGION 4: WESTERN FREE STATE/GAUTENG

3.6.1 Initial Basic Information for Region 4

Variable	Value
No. of temperature stations	114
Altitude (m) of highest station	1878
Altitude (m) of lowest station	967
Mean altitude (m) of highest 10% of stations	1736
Mean altitude (m) of lowest 10% of stations	1142

3.6.2 General Description: Region 4

An interior region (Figure 3.1) covering most of the western Free State, the southern two thirds of Gauteng as well as much of western portions of Mpumalanga provinces, this region consists in the main of the "highveld" plains of low and moderate relief (Figure 3.4) at general altitudes between 1250 and 1750 m (Figure 3.2).

3.6.3 Maximum Temperature Lapse Rates for Region 4

3.6.3.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 4

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-10.2	-9.5	-8.8	-7.8	-6.7	-6.2	-6.1	-6.2	-6.3	-8.2	-9.2	-9.7
Confidence Rating	M/H	H	H	H	M/H	M/H	H	H	M/H	H	H	M/H

3.6.3.2 Observations on Lapse Rates of Maximum Temperatures : Region 4

- This is a region of very high maximum temperature lapse rates, especially in summer (> 8.0 °C/1000 m).
- Lapse rates plots are given medium/high to high confidence ratings.
- No LR differences were observed between stations with high vs low topographic indices and, therefore, no further adjustments were deemed necessary, other than smoothing.

3.6.3.3 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 4

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-10.2	-9.5	-8.8	-7.8	-6.7	-6.0	-5.9	-6.0	-6.8	-8.2	-9.2	-9.7

3.6.4 Minimum Temperature Lapse Rates for Region 4

3.6.4.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 4

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-7.5	-7.4	-6.6	-5.8	-4.1	-2.8	-2.4	-3.0	-4.0	-6.0	-6.8	-7.2
Confidence Rating	H	H	H	H/M	M	M	M	M	M/H	H	H	H

3.6.4.2 Observations on Lapse Rates of Minimum Temperatures : Region 4

- Minimum temperature LRs display distinct summer maximum and winter minimum values.
- Similarly, confidence ratings are high in summer, but become moderate in winter when local topographic influences become influential.
- Stations with low TI (< 100) show up different LR trends to those with high TIs (≥ 100), especially in the winter months April to September. Separate TI-related LRs were, therefore, computed for those months.

3.6.4.3 Revised Basic Information for Separate Minimum Temperature Lapse Rates in Region 4 According to Topographic Index

Variable	TI < 100	TI ≥ 100
No. of temperature stations	109	5
Altitude (m) of highest station	1878	1689
Altitude (m) of lowest station	967	1371
Mean altitude (m) of highest 10% of stations	1735	1698
Mean altitude (m) of lowest 10% of stations	1142	1371

3.6.4.4 Revised Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 4

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(TI<100)	-7.8	-7.6	-6.9	-6.1	-4.6	-3.2	-2.8	-3.5	-4.4	-6.3	-7.2	-7.5
LR(TI≥100)	-1.5	-0.6	+1.5	+7.0	+12.8	+11.0	+11.0	+14.1	+12.5	+7.6	+5.2	+1.5

3.6.4.5 Conclusions on Revised Minimum Temperature Lapse Rates in Region 4

- In light of there being only 5 stations with TI ≥ 100 in this essentially non-hilly region, and apparently anomalous results (positive lapse rates) emanating from those 5 stations in this vast area, it was decided not to distinguish between LRs according to TI.
- The plots of minimum temperature vs altitude were, however, revisited and final (smoothed) values are given in the table below.

3.6.4.6 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 4

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-7.5	-7.3	-6.6	-6.0	-5.5	-5.0	-4.7	-4.1	-4.6	-6.0	-6.8	-7.2

3.7 LAPSE RATES IN REGION 5: EASTERN CAPE COAST

3.7.1 Initial Basic Information: Region 5

Variable	Value
No. of temperature stations	60
Altitude (m) of highest station	1463
Altitude (m) of lowest station	6
Mean altitude (m) of highest 10% of stations	1247
Mean altitude (m) of lowest 10% of stations	19

3.7.2 General Description: Region 5

- This “coastal” region (Figure 3.1) stretches from the KwaZulu-Natal/Eastern Cape province border to Port Elizabeth and from the coast inland to approximately 80 km, where general altitudes are around 1000 m (Figure 3.2).
- In regard to its terrain morphology this region is a “mixed bag”, containing plains of moderate relief, lowlands of low relief, open hills of low relief, closed hills of moderate relief, low mountains of high relief and table lands (Figure 3.4).

3.7.3 Maximum Temperature Lapse Rates for Region 5

3.7.3.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 5

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(Alt<400 m)	+10.7	+10.6	+7.6							+5.9	+7.3	+9.2
LR(Alt<250 m)				+5.0					+13.0			
LR(Alt<100 m)					+16.0	+28.0	+27.0	+22.0				
Confidence Rating	M	M	M	M	M/L	L	L	L	M	M	M	M
LR(Alt>Thresld)	-6.1	-5.8	-5.9	-3.4	-3.3	-4.1	-3.8	-2.4	-2.2	-4.8	-5.2	-5.6
Confidence Rating	M	M	M/H	M/H	H/M	M	M	M/H	M/H	M	M	M

3.7.3.2 Observations on Lapse Rates of Maximum Temperatures: Region 5

- Maximum temperature lapse rates are clearly “dog-legged”, i.e. with temperatures initially *increasing* with altitude from the coast inwards, up to a threshold altitude which was observed to be 400 m in the summer months and decreasing to only 100 m in winter.
- This phenomenon results from the moderating influence on temperatures of the Indian Ocean.

- The “dog-leg” pattern all but vanishes in the cooler winter months, and in some months (June to August) it was debatable whether or not to include it.
- While clearly observable, the coastal (positive) leg of the LR is plotted with moderate confidence, but reduces to low confidence in mid-winter months.
- The inland (negative) leg of the LR is plotted with moderate confidence, but tends to more confident plots in the transitional months (March to May; August and September).
- Because this region covers a range of physiographic conditions, lapse rates were re-computed, omitting outlier and “grey zone” stations.

3.7.3.3 Revised Computed Lapse Rates (°C/1000 m) for Maximum Temperatures in Region 5

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(Alt<400 m)	+9.7	+9.8	+4.9							+4.1	+10.3	+7.5
LR(Alt<250 m)				+11.7					+14.4			
LR(Alt<100 m)					+17.0	+7.7	+15.0	+21.0				
LR(Alt≥Threshold)	-6.5	-7.3	-6.8	-4.0	-3.9	-4.0	-3.0	-2.7	-1.6	-2.7	-4.6	-5.5

3.7.3.4 Final (Smoothed) Lapse Rates (°C/1000 m) for Maximum Temperatures in Region 5

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(Alt<400 m)	+10.2	+10.2	+6.3							+6.0	+8.0	+9.0
LR(Alt<250 m)				+8.0					+13.0			
LR(Alt<100 m)					+16.0	+25.0	+27.0	+24.0				
LR(Alt≥Threshold)	-6.3	-6.5	-6.0	-3.9	-3.6	-3.9	-3.5	-2.5	-2.0	-3.5	-4.9	-5.5

3.7.4 Minimum Temperature Lapse Rates for Region 5

3.7.4.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 5

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-4.5	-4.7	-5.2	-5.9	-6.5	-7.1	-7.0	-5.9	-5.3	-5.1	-4.8	-4.7
Confidence Rating	H/M	H/M	H/M	M	M	M	M	M	M/H	H/M	H/M	H/M

3.7.4.2 Observations on Lapse Rates of Minimum Temperatures: Region 5

- Lapse rates of minimum temperatures peak in winter months.
- They are of high/medium confidence in summer months, reducing to medium confidence ratings in winter months.
- No further adjustments, other than smoothing, were deemed necessary.

3.7.4.3 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 5

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-4.5	-4.7	-5.2	-5.9	-6.5	-7.0	-7.0	-6.0	-5.3	-5.0	-4.8	-4.7

3.8 LAPSE RATES IN REGION 6: SOUTHWEST CAPE COAST

3.8.1 Initial Basic Information: Region 6

Variable	Value
No. of temperature stations	72
Altitude (m) of highest station	975
Altitude (m) of lowest station	60
Mean altitude (m) of highest 10% of stations	877
Mean altitude (m) of lowest 10% of stations	104

3.8.2 General Description: Region 6

- The Southwest Cape Coast Region (Figure 3.1) extends 50-80 km inland from the coast from just west of George, around Cape Agulhas, to 50 km north of Cape Town.
- It contains varied terrain (Figures 3.2; 3.4) ranging from plains of low relief to those of moderate relief, open hills of low relief, closed hills of moderate relief, low mountains of high relief and high mountains – the last three being part of the Cape fold mountain belt.
- Region 6 is in the winter rainfall region (Figure 3.3) and at the interface of the cold Benguella current of the Atlantic Ocean on the west coast and the warm Agulhas current of the Indian Ocean along the south coast.

3.8.3 Maximum Temperature Lapse Rates for Region 6

3.8.3.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 6

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-3.3	-3.5	-3.9	-4.7	-4.7	-4.9	-4.4	-4.3	-4.1	-4.0	-3.7	-3.8
Confidence Rating	M	M	M	M/H	M/H	H	H	M/H	M	M	M	M

3.8.3.2 Observations on Lapse Rates of Maximum Temperatures: Region 6

- Maximum temperature LRs plot with moderate confidence in summer months, increasing to high confidence plots in mid-winter.
- Lapse rates of moderate values (-3.3 to -4.9 °C/1000 m altitude) peak in winter, in phase with the rainfall season.
- Maximum temperature vs altitude plots display a “dog-leg” at around 200 m in altitude. Further adjustments were therefore made for positive lapse rates up to 200 m altitude.

3.8.3.3 Revised Computed Lapse Rates (°C/1000 m) for Maximum Temperatures in Region 6 According to Altitude

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(Alt<200 m)	+26.5	+14.9	+20.0	+22.4	+12.2	+22.0	+13.2	+10.6	+15.0	+16.7	+27.7	+34.3
LR(Alt≥200 m)	- 3.3	- 3.5	- 3.9	- 4.7	- 4.7	-4.9	- 4.4	- 4.3	- 4.1	- 4.0	- 3.7	- 3.8

3.8.3.4 Comments on Revised Lapse Rates of Maximum Temperatures: Region 6

- The distinction between LRs at altitudes above and below 200 m did not affect the temperature:altitude slope markedly at altitudes ≥ 200 m. Initial values were therefore not adjusted.
- The positive lapse rates at altitudes < 200 m show some intra-seasonal inconsistencies, but with values tending to be highest in mid-summer and lowest in late winter. Marked smoothing was necessary.

3.8.3.5 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 6

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(Alt<200 m)	+26.0	+18.0	+19.0	+22.0	+19.0	+17.0	+13.0	+11.0	+14.0	+19.0	+27.0	+33.0
LR(Alt≥200 m)	- 3.3	- 3.5	- 4.0	- 4.6	- 4.8	-4.8	- 4.6	- 4.3	- 4.1	- 3.9	- 3.7	- 3.5

3.8.4 Minimum Temperature Lapse Rates for Region 6

3.8.4.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 6

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-5.1	-4.9	-5.0	-5.0	-4.3	-4.2	-3.9	-4.0	-4.3	-4.8	-5.0	-5.2
Confidence Rating	H	H	H	H	M	M	M	M	H	H	H	H

3.8.4.2 Observations on Lapse Rates of Minimum Temperatures: Region 6

- Minimum temperature LRs plot at high confidence in most months, except in the four winter months May to August, when the scatter of plots becomes more dispersed.
- Lapse rates have a low range, from -3.9 °C/1000 m in July to -5.2 °C/1000 m in December.
- With neither distinct TI trends nor the “dog-leg” of maximum temperature LRs evident, no further adjustments (except smoothing) were considered.

3.8.4.3 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 6

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-5.1	-5.0	-4.9	-4.8	-4.4	-4.1	-3.9	-4.0	-4.3	-4.7	-5.0	-5.2

3.9 LAPSE RATES IN REGION 7: EASTERN CAPE INTERIOR

3.9.1 Initial Basic Information for Region 7

Variable	Value
No. of temperature stations	65
Altitude (m) of highest station	1770
Altitude (m) of lowest station	249
Mean altitude (m) of highest 10% of stations	1669
Mean altitude (m) of lowest 10% of stations	377

3.9.2 General Description: Region 7

- The Eastern Cape Interior region (Figure 3.1) includes a small part of the southeastern corner of the Northern Cape province.
- Altitudes range predominantly from 400 to 1650 m (Figure 3.2).
- Physiographically, Region 7 includes lowlands of low and of high relief, open hills of low and high relief as well as low mountains of high relief (Figure 3.4).

3.9.3 Maximum Temperature Lapse Rates For Region 7

3.9.3.1 Initial Computed Lapse Rates (°C/1000 m) for Maximum Temperatures in Region 7

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-3.7	-4.1	-4.1	-3.6	-3.5	-3.7	-3.4	-2.8	-2.5	-2.6	-3.4	-2.8
Confidence Rating	M	M	M	M/H	H	H	H	H	H	M/H	M	M

3.9.3.2 Observations on Lapse Rates of Maximum Temperatures: Region 7

- This region displays a low inter-monthly range of LR (-2.5 to -4.1 °C/1000 m), with plots of temperature vs altitude given a medium confidence rating in summer months and a high rating in winter months.
- With no stations located where the TI $\geq$ 100, no further adjustments were deemed necessary, other than smoothing.

3.9.3.3 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 7

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-3.7	-4.1	-4.1	-3.6	-3.5	-3.7	-3.4	-2.8	-2.5	-2.6	-2.8	-3.3

3.9.4 Minimum Temperature Lapse Rates for Region 7

3.9.4.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures for Region 7

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-4.3	-4.5	-4.8	-5.5	-6.4	-6.0	-5.7	-5.7	-4.8	-4.1	-4.0	-3.7
Confidence Rating	H	H	H	H	H	H/M	M	M	M/H	H	H	H

3.9.4.2 Observations on Lapse Rates of Minimum Temperatures: Region 6

With very tight associations between temperature and altitude in summer and plots of a medium confidence rating in winter, no further adjustments, other than smoothing, were necessary.

3.9.4.3 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Minimum Temperatures for Region 7

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-4.3	-4.5	-4.8	-5.5	-6.3	-6.1	-5.8	-5.5	-4.8	-4.2	-4.0	-3.8

3.10 LAPSE RATES IN REGION 8/9: NORTHERN CAPE

3.10.1 Initial Basic Information for Region 8/9

Variable	Value
No. of temperature stations	159
Altitude (m) of highest station	1580
Altitude (m) of lowest station	61
Mean altitude (m) of highest 10% of stations	1497
Mean altitude (m) of lowest 10% of stations	317

3.10.2 General Description of Region 8/9

- This vast region (Figure 3.1) is made up of the bulk of the Northern Cape province plus northwestern parts of the Western Cape province, small parts of the Eastern Cape and the western Free State and the entire western half of North-West province.
- With the exception of small parts of the lower Orange River valley, the region lies at altitudes above 800 m (Figure 3.2).
- While containing diverse terrain morphology, the major tracts of the landscape consist of plains of low and moderate relief (central and north), lowlands of low relief (south central) and open hills of low relief (Kalahari desert). However, low mountains of high relief occur in the south and in scattered areas in the central parts of Region 8/9 (Figure 3.4).

- The central Karroo was originally identified as a separate region (Region 9; Clemence, 1986), but was later combined with the original Region 8 to form this region (Schulze, 1997).

3.10.3 Maximum Temperature Lapse Rates for Region 8/9

3.10.3.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 8/9

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-0.5	-1.1	-1.2	-1.5	-1.7	-2.2	-1.6	-0.2	+1.4	+1.4	+0.7	+0.2
Confidence Rating	L	L	L	L/M	L/M	M	M	L	L	L	L	L

3.10.3.2 Observations on Lapse Rates of Maximum Temperatures: Region 8/9

- Perusal of scatter plots of maximum temperatures vs altitude showed that viewing Region 8/9 as an entity in regard to LR's was not meaningful. Clearly, in a region as large and diverse as this, there were numerous different "populations" of LR's in evidence.
- A natural break in lapse rate patterns appeared to occur around 1000 m altitude, above which LR's plotted with high to medium confidence ratings, whereas below 500 m there was a suggestion of "inverse" lapse rates occurring in some months (i.e. temperature increase with altitude), while between 500 and 1000 m altitude no LR patterns at all were discernible.
- Separate LR's for maximum temperatures were then computed for altitudes < 500 m, 500-1000 m (LR = 0) and ≥ 1000 m.
- However, further analysis, plus the fact that a large part of Region 8/9 was between 800 and 1000 m and many of the stations below 800 m were either in relatively isolated major valleys such as that of the Orange River, or from "grey zone" areas of other temperature regions, the decision was made to have a two-fold split of maximum temperature LR's, viz. < 800 m, where LR's were largely indeterminate (LR ≡ 0) and ≥ 800 m, where LR trends were clearly discernible for a certain population of temperature stations.

3.10.3.3 Revised Basic Information for Separate Maximum Temperature Lapse Rates in Region 8/9 According to Altitude

Variable	Alt < 800 m	Alt ≥ 800 m
No. of temperature stations	27	132
Altitude (m) of highest station	790	1580
Altitude (m) of lowest station	61	805
Mean altitude (m) of highest 10% of stations	777	1518
Mean altitude (m) of lowest 10% of stations	137	833

3.10.3.4 Revised Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 8/9

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(Alt<800 m)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Confidence Rating	L	L	L	M	M	M/H	M/H	M	L	L	L	L
LR(Alt≥800 m)	-11.2	-9.8	-8.4	-6.3	-4.4	-3.7	-2.9	-2.9	-2.9	-6.0	-7.8	-9.9
Confidence Rating	M/H	H/M	H/M	H	M	M	M/H	M	M/L	M	M/H	M/H

3.10.3.5 Comments on Lapse Rates of Maximum Temperatures: Region 8/9

- An element of subjective judgement had to be applied in LR computations in this region.
- Certainly for those parts of Region 8/9 where altitudes are in excess of 1000 m, the LRs in the table above are considered to be very representative. Between 800 and 1000 m the LRs are generally less representative, but more so in winter than in summer.

3.10.3.6 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 8/9

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(Alt<800 m)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LR(Alt≥800 m)	-11.2	-9.8	-8.4	-6.3	-4.6	-3.7	-2.9	-2.8	-3.4	-6.0	-7.8	-9.9

3.10.4 Minimum Temperature Lapse Rates for Region 8/9

3.10.4.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 8/9

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-1.2	-1.8	-2.1	-3.1	-4.1	-4.8	-4.6	-3.3	-1.6	-0.9	-0.9	-1.0
Confidence Rating	L	L	L	M	M	M	M	M	M	M	L	L

3.10.4.2 Observations on Lapse Rates of Minimum Temperatures: Region 8/9

- Once again, visual analysis of plots of T_{mn} vs altitude shows up a number of different "populations" of LRs, which are evident particularly in summer months.
- Various ways of disaggregating the data were considered. In light of the altitude of Region 8/9 being predominantly ≥ 800 m, it was decided to re-calculate LRs for stations only above 800 m and consider those lapse rates to be representative for the entire region, including those areas at altitudes < 800 m.

3.10.4.3 Revised Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 8 / 9 Considering only Stations at Altitudes > 800 m

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-6.2	-5.0	-5.4	-4.4	-5.2	-4.7	-5.7	-5.0	-1.6	-1.4	-3.0	-4.0

3.10.4.4 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 8/9

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-5.7	-5.4	-5.1	-4.8	-5.0	-5.1	-5.4	-4.8	-1.7	-1.4	-3.0	-4.2

3.11 LAPSE RATES IN REGION 10: SOUTHERN CAPE

3.11.1 Initial Basic Information for Region 10

Variable	Value
No. of temperature stations	34
Altitude (m) of highest station	880
Altitude (m) of lowest station	5
Mean altitude (m) of highest 10% of stations	844
Mean altitude (m) of lowest 10% of stations	15

3.11.2 General Description of Region 10

- Covering the southwestern parts of the Eastern Cape and southeastern parts of the Western Cape provinces, Region 10 (Figure 3.1) lies predominantly in the all-year rainfall zone of South Africa (Figure 3.3).
- Morphologically this region covers the west-east trending Cape fold mountain belt and consists largely of low mountains of high relief, some high mountains and some lowlands of low relief with a zone of plains of moderate relief around Port Elizabeth (Figure 3.4).
- Being a region in which MAP varies from < 200 mm to > 1000 mm and in which the crests and vales of the fold mountains play a dominant role in local climates, this is a region in which some complex lapse rate patterns are expected, and found.

3.11.3 Maximum Temperature Lapse Rates for Region 10

3.11.3.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 10

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	+4.4	+4.3	+2.9	+0.9	-1.7	-4.5	-3.9	-1.4	+1.1	+2.2	+3.7	+4.2
Confidence Rating	L/M	L	L	L/M	L/M	M/H	M/H	M	L	L/M	L	L/M

3.11.3.2 Observations on Lapse Rates of Maximum Temperatures: Region 10

- The combination of complex topography and, particularly, the coastal influence results in a “dog-leg” of lapse rates (i.e. with initial increases of temperature with altitude) being observed in all months but June and July, up to approximately 200 m altitude.
- At altitudes > ~200 m coastal influences are evident at some stations, but a dominant negative lapse rate is shown by the scatter plots of station maximum temperature vs altitude.
- Using 200 m as a threshold altitude, separate lapse rates were therefore calculated for lower vs higher altitudes for the 10 months (August to May) in which the “dog-leg” was clearly discernible.
- Because of the relatively small number of stations (34) in this region, some subjective judgement was applied in eliminating the anomalously plotting stations from the “grey zones” of adjacent regions before LRs were re-computed.

3.11.3.3 Revised Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 10

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(Alt<200 m)	+23.8	+16.3	+14.5	+12.3	+5.5	0.0	0.0	+8.0	+18.0	+10.0	+9.0	+14.7
LR(Alt≥200 m)	- 9.3	- 6.8	- 6.3	- 6.3	- 7.6	-5.9	-6.0	- 7.8	- 6.8	- 5.3	-5.6	- 6.9

3.11.3.4 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 10

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(Alt<200 m)	+19.0	+18.0	+15.0	+10.5	+5.5	0.0	0.0	+6.5	+11.5	+14.5	+17.0	+19.0
LR(Alt≥200 m)	- 8.5	- 7.0	- 6.3	- 6.3	- 6.7	-6.0	-6.0	- 7.0	- 6.8	- 5.4	-5.6	- 6.9

3.11.4 Minimum Temperature Lapse Rates for Region 10

3.11.4.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 10

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-4.5	-4.1	-4.7	-5.1	-6.7	-7.5	-7.4	-6.8	-5.9	-5.2	-4.8	-4.7
Confidence Rating	H	H	H	H	H/M	M	M	M	H	H	H	H

3.11.4.2 Observations on Lapse Rates of Minimum Temperatures: Region 10

- Minimum temperature lapse rates plotted with a high confidence rating from September through April, deteriorating to plots of medium confidence ratings in the winter months May to August.
- With neither altitude nor TI threshold breaks discernible, no further adjustments, other than smoothing, were applied.

3.11.4.3 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 10

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-4.5	-4.2	-4.5	-5.3	-6.7	-7.5	-7.4	-6.8	-5.9	-5.2	-4.8	-4.6

3.12 LAPSE RATES IN REGION 11: WESTERN CAPE INTERIOR

3.12.1 Initial Basic Information for Region 11

Variable	Value
No. of temperature stations	82
Altitude (m) of highest station	1040
Altitude (m) of lowest station	8
Mean altitude (m) of highest 10% of stations	566
Mean altitude (m) of lowest 10% of stations	32

3.12.2 General Description of Region 11

- Located inland of Regions 6 and 12, the Western Cape Interior (Figure 3.1) covers a range of altitudes (~ 300 m to ~ 1700 m, mainly 600-1250 m; Figure 3.2) and rainfalls (MAP 400 to > 1200 mm; winter rainfall region; Figure 3.3).
- Terrain morphologically it covers plains of low relief to high mountains of the Cape fold belt, but includes also lowlands of low relief and low mountains of high relief (Figure 3.4).
- The many low altitude stations below 150 m (36), which cause a “dog-leg” of LR_s, are from adjacent coastal Regions 6 and 12.

3.12.3 Maximum Temperature Lapse Rates for Region 11

3.12.3.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 11

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	+0.3	-0.1	-0.4	-1.9	-3.2	-3.8	-4.0	-3.5	-2.2	-1.7	-1.1	-0.3
Confidence Rating	L	L	L/M	L/M	L/M	M/H	M/H	M/H	M	L	L	L

3.12.3.2 Observations on Lapse Rates of Maximum Temperatures: Region 11

- The low confidence rating in especially the summer months is entirely due to a “dog-leg” of lapse rates, which is the result of inclusion of 36 stations at altitudes < 150 m from the “grey zones” of coastal regions (6 and 12).
- By delineation Region 11 is dominantly at altitudes > 200 m. Therefore, LR_s for maximum temperatures were re-calculated using stations only at altitudes ≥ 200 m.

3.12.3.3 Revised Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 11

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-11.6	-14.8	-13.2	-17.3	-8.5	-6.5	-9.2	-9.2	-9.5	-12.2	-13.2	-13.3
Confidence Rating	M	M	M	M	M	H	H/M	H/M	H/M	M	M/H	M/H

3.12.3.4 Comments on Revised Lapse Rates of Maximum Temperature: Region 11

- A very different, more realistic, picture of LR_s and their seasonal distribution, emerges, with an increase also in the confidence rating of the LR_s.
- LR_s are higher in the non-rainy summer months compared to those of the winter months.
- LR_s are generally very high in this region.
- Considerable smoothing was necessary for LR_s of maximum temperatures in Region 11.

3.12.3.5 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 11

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-13.9	-14.4	-15.0	-14.5	-8.5	-6.5	-7.4	-9.2	-10.8	-12.2	-13.0	-13.4

3.12.4 Minimum Temperature Lapse Rates for Region 11

3.12.4.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 11

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-5.0	-4.6	-4.4	-4.5	-4.9	-3.5	-5.2	-5.4	-5.4	-4.7	-4.9	-5.1
Confidence Rating	H/M	H/M	H/M	M/H	M	M	M	M	M/H	M/H	H/M	H

3.12.4.2 Observations on Lapse Rates of Minimum Temperatures: Region 11

- Minimum temperature LR_s in Region 11 plot with high/medium confidence, especially in the dry summer months.
- What is visually discernible is that exposed stations with a TI ≥ 100 clearly have lower lapse rates in winter months (April to September inclusive) than less exposed stations. However, this pattern does not show up clearly in summer.
- For the months April to September a distinction in LR_s is, therefore, made according to $100 > \text{TI} \geq 100$, but with final values assigned by smoothing.

3.12.4.3 Revised Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 11

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(TI<100 m)	-5.0	-4.6	-4.4	-4.8	-8.1	-6.3	-8.8	-9.3	-7.5	-4.7	-4.9	-5.1
LR(TI≥100 m)	-5.0	-4.6	-4.4	-4.4	-3.5	-2.3	-3.7	-3.7	-4.5	-4.7	-4.9	-5.1

3.12.4.4 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 11

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
a) Without TI distinction												
Lapse Rate	-5.0	-4.7	-4.4	-4.5	-4.7	-4.8	-5.2	-5.4	-5.1	-4.8	-4.9	-5.1
b) With TI distinction												
LR (TI<100)	-5.0	-4.7	-4.5	-5.0	-6.5	-8.3	-8.8	-8.8	-7.5	-5.3	-4.9	-5.1
LP (TI≥100)	-5.0	-4.7	-4.4	-4.1	-3.5	-3.0	-3.4	-3.9	-4.5	-4.7	-4.9	-5.1

3.13 LAPSE RATES IN REGION 12: WEST COAST

3.13.1 Initial Basic Information for Region 12

Variable	Value
No. of temperature stations	50
Altitude (m) of highest station	985
Altitude (m) of lowest station	5
Mean altitude (m) of highest 10% of stations	959
Mean altitude (m) of lowest 10% of stations	24

3.13.2 General Description of Region 12

- The West Coast Region extends 70-150 km inland from the Atlantic ocean north of 33½°S (Figure 3.1).
- It consists largely of plains of low to moderate relief bounded in the east by low mountains of high relief, with some high mountains in the south and table lands in the central east (Figures 3.2; 3.4).
- The region falls entirely into the winter rainfall belt (Figure 3.3), but rainfalls are generally low, with over 60% of the region receiving < 200 mm MAP.
- The juxtapositioning of warm land mass and cold ocean current causes frequent coastal fogs, which impact on LRs near the ocean.

3.13.3 Maximum Temperature Lapse Rates for Region 12

3.13.3.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 12

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	+3.8	+3.4	+2.2	-0.8	-2.7	-4.0	-3.7	-2.5	-0.5	+0.6	+2.5	+3.1
Confidence Rating	M	L	L	L	L	M/H	M/H	M	M	L	L	L

3.13.3.2 Observations on Lapse Rates of Maximum Temperatures: Region 12

- The generally low confidence ratings of LR plots is due entirely to a very distinct “dog-leg” in the maximum temperature:altitude plots, with a clear break at 200 m altitude.
- For T_{mx} lapse rates, Region 12 was therefore split into two sub-zones, viz. < 200 m altitude and ≥ 200 m altitude, for each of which LRs were computed separately.
- For the altitude sub-zone ≥ 200 m temperature stations at altitudes > 900 m were omitted from LR computations because those were “grey zone” stations from adjacent regions from a distinctly different “population” of lapse rates.

3.13.3.3 Revised Computed Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 12 According to Altitude Differences

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(Alt<200 m)	+28.0	+26.5	+25.0	+19.0	0.0	0.0	0.0	0.0	0.0	+14.5	+25.9	+20.0
LR(Alt $\geq$ 200 m)	- 8.3	- 8.9	- 8.4	- 8.6	-8.6	-6.7	-5.6	-8.6	-7.4	-10.7	- 9.9	- 8.1

3.13.3.4 Comments on Revised Lapse Rates of Maximum Temperatures: Region 12

- A much clearer set of LR patterns emerges, with coastal LRs for altitudes <200 m both positive (i.e. coastal zone maximum temperatures initially increase with altitude) and high for all months but May to September, when no LR pattern is identifiable.
- LR estimates for altitudes ≥ 200 m range between 5.6 and 10.7 with lowest values in mid-winter months.

3.13.3.5 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Maximum Temperatures in Region 12

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(Alt<200 m)	+26.0	+26.5	+25.0	+18.0	0.0	0.0	0.0	0.0	+3.0	+14.5	+21.5	+24.0
LR(Alt $\geq$ 200 m)	- 8.3	- 8.7	- 8.7	- 8.6	-8.1	-7.4	-6.2	-7.5	-8.9	-10.0	- 9.5	- 8.2

3.13.4 Minimum Temperature Lapse Rates for Region 12

3.13.4.1 Initial Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 12

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lapse Rate	-1.2	-0.9	-1.4	-2.7	-3.3	-3.8	-3.9	-4.0	-3.5	-2.8	-2.0	-1.5
Confidence Rating	M/H	M	M/L	M/L	M	M	M	M	M/H	M/H	M/H	M/H

3.13.4.2 Observations on Lapse Rates of Minimum Temperatures: Region 12

- As with T_{mx} lapse rates, there is a clear altitude “break” for T_{mn} LRs. At this “break” the positive LRs of the coastal belt “flip” to become negative LRs. The lapse rate point of inflection for minimum temperatures is distinctly at 150 m (rather than at 200 m as for T_{mx}).
- Consequently LRs for T_{mn} were recalculated for $150 > \text{Alt} \geq 150$ m for those months in which a “dog-leg” was clearly discernible, viz. November to April.

3.13.4.3 Revised Computed Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 12

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(Alt<150 m)	+12.0	+20.0	+16.7	+8.3	-3.3	-3.8	-3.9	-4.0	-3.5	-3.0	+7.0	+10.5
LR(Alt≥150 m)	- 3.2	- 4.2	- 3.2	-3.1	-3.3	-3.8	-3.9	-4.0	-3.5	-3.0	- 4.3	- 4.5

3.13.4.4 Comments on Revised Lapse Rates of Minimum Temperatures: Region 12

- The coastal influence on positive LRs peaks in late summer.
- At higher altitudes LRs are both relatively low and display a small intra-seasonal range only (-3.0 to -4.5°C/1000 m), with a low amplitude double peak in autumn and spring.

3.13.4.5 Final (Smoothed) Lapse Rates (°C/1000 m altitude) for Minimum Temperatures in Region 12

Attribute	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LR(Alt<150 m)	+14.0	+17.8	+16.0	+8.3	-3.0	-3.8	-3.9	-3.9	-3.5	-2.6	+6.0	+10.0
LR(Alt≥150 m)	- 3.6	- 3.4	- 3.1	-3.0	-3.3	-3.8	-3.9	-3.9	-3.5	-3.2	- 4.3	- 4.5

3.14 DISCUSSION OF RESULTS

Final (smoothed) monthly values of maximum and minimum temperature lapse rates are summarised in Table 3.1 and in Figure 3.9 for the 11 lapse rate regions and, where applicable, their sub-zones. What is immediately evident is that lapse rates vary considerably across southern Africa – by region, by sub-zone within a region, by season and between LRs of maximum and minimum temperatures. With the more detailed

Table 3.1 Month-by-month lapse rates of maximum and minimum temperatures by region and sub-zone

REGION	LAPSE RATES (°C / 1000 m altitude)																									
	MAXIMUM TEMPERATURE												MINIMUM TEMPERATURE													
	ZONE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	ZONE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1. Limpopo	All	-5.0	-5.0	-5.2	-5.6	-6.0	-6.2	-5.9	-5.3	-4.4	-4.2	-4.7	-4.9	All	-5.0	-5.2	-5.4	-5.5	-5.6	-5.5	-5.2	-4.9	-4.7	-4.7	-4.9	
														TI < 100	-5.0	-5.2	-5.4	-5.5	-5.7	-5.5	-5.3	-4.8	-4.7	-4.7	-4.9	
														TI ≥ 100	-5.0	-5.2	-5.4	-5.5	-5.4	-5.3	-5.2	-4.8	-4.7	-4.7	-4.9	
2. KwaZulu-Natal Coast	All	-2.9	-3.0	-3.1	-3.3	-3.6	-3.9	-3.7	-2.9	-2.3	-2.2	-2.4	-2.6	All	-5.0	-5.1	-5.4	-5.7	-6.3	-6.6	-6.5	-6.1	-5.5	-5.2	-5.1	-5.0
														TI < 100	-5.0	-5.1	-5.4	-5.7	-6.3	-6.5	-6.5	-6.2	-5.5	-5.2	-5.1	-5.0
														TI ≥ 100	-5.0	-5.1	-5.4	-5.7	-6.4	-6.9	-6.6	-6.0	-5.5	-5.2	-5.1	-5.0
3. E. Free State/KZN Interior	All	-4.1	-4.2	-4.5	-5.0	-5.5	-5.9	-5.7	-5.0	-4.2	-3.9	-3.9	-4.0	All	-5.4	-5.4	-5.8	-6.2	-6.0	-5.6	-5.7	-6.0	-5.9	-5.5	-5.4	-5.4
	TI < 100	-4.3	-4.4	-4.6	-5.0	-5.5	-5.9	-5.7	-5.0	-4.2	-4.0	-4.0	-4.2	TI < 100	-5.4	-5.4	-5.8	-6.0	-5.9	-5.2	-5.3	-5.6	-5.6	-5.5	-5.4	-5.4
	TI ≥ 100	-2.1	-2.6	-3.5	-5.0	-5.5	-5.9	-5.7	-5.0	-4.0	-3.1	-2.5	-2.2	TI ≥ 100	-5.4	-5.4	-5.8	-7.3	-8.9	-9.6	-9.6	-9.3	-7.4	-5.5	-5.4	-5.4
4. W. Free St/ Gauteng	All	-10.2	-9.5	-8.8	-7.8	-6.7	-6.0	-5.9	-6.0	-6.8	-8.2	-9.2	-9.7	All	-7.5	-7.4	-6.6	-6.0	-5.6	-5.0	-4.7	-4.1	-4.6	-6.0	-6.8	-7.2
5. Eastern Cape Coast	Alt < Thr	+10.2 ¹	+10.2 ¹	+6.3 ¹	+8.0 ²	+16.0 ³	+25.0 ³	+27.0 ³	+24.0 ³	+13.0 ²	+6.0 ¹	+8.0 ¹	+9.0 ¹	All	-4.5	-4.7	-5.2	-5.9	-6.5	-7.0	-7.0	-6.0	-5.3	-5.0	-4.8	-4.7
	Alt ≥ Thr	-6.3	-6.5	-6.0	-3.9	-3.6	-3.9	-3.5	-2.5	-2.0	-3.5	-4.9	-5.5													
6. Southwest Cape Coast	Alt < 200m	+26.0	+18.0	+19.0	+22.2	+19.0	+17.0	+13.0	+11.0	+14.0	+19.0	+27.0	+33.3	All	-5.1	-5.0	-4.9	-4.8	-4.4	-4.1	-3.9	-4.0	-4.3	-4.7	-5.0	-5.2
	Alt ≥ 200m	-3.3	-3.5	-4.0	-4.6	-4.8	-4.8	-4.6	-4.3	-4.1	-3.9	-3.7	-3.5													
7. Eastern Cape Interior	All	-3.7	-4.1	-4.1	-3.6	-3.5	-3.7	-3.4	-2.8	-2.5	-2.6	-2.8	-3.3	All	-4.3	-4.5	-4.8	-5.5	-6.4	-6.0	-5.8	-5.5	-4.8	-4.2	-4.0	-3.8
8/9 Northern Cape	Alt < 800m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	All	-5.7	-5.4	-5.1	-4.8	-5.0	-5.1	-5.4	-5.0	-1.7	-1.4	-3.0	-4.2
	Alt ≥ 800m	-11.2	-9.8	-8.4	-6.3	-4.6	-3.7	-2.9	-2.8	-3.2	-6.0	-7.8	-9.9													
10. Southern Cape	Alt < 200m	+19.0	+18.0	+15.0	+10.5	+5.5	0.0	0.0	+6.5	+11.5	+14.5	+17.0	+19.0	All	-4.5	-4.2	-4.5	-5.3	-6.7	-7.5	-7.4	-6.8	-5.9	-5.2	-4.8	-4.6
	Alt ≥ 200m	-8.5	-7.0	-6.3	-6.3	-6.7	-6.0	-6.0	-7.0	-6.8	-5.4	-5.6	-6.9													
11. Western Cape Interior	All	-13.9	-14.4	-15.0	-15.0	-8.5	-6.5	-7.4	-9.2	-10.8	-12.2	-13.0	-13.4	All	-5.0	-4.7	-4.4	-4.5	-4.7	-4.8	-5.2	-5.4	-5.1	-4.8	-4.9	-5.1
														TI < 100	-5.0	-4.7	-4.5	-5.0	-6.5	-8.3	-8.8	-8.8	-7.5	-5.3	-4.9	-5.1
														TI ≥ 100	-5.0	-4.7	-4.4	-4.1	-3.5	-3.0	-3.4	-3.9	-4.5	-4.7	-4.9	-5.1
12. West Coast	Alt < 200m	+26.0	+26.5	+25.0	+18.0	0.0	0.0	0.0	0.0	+3.0	+14.5	+21.5	+24.0	Alt < 150m	+14.0	+17.8	+16.0	+8.3	-3.0	-3.8	-3.9	-3.9	-3.5	-2.6	+6.0	+10.0
	Alt ≥ 200m	-8.3	-8.7	-8.7	-8.6	-8.1	-7.4	-6.2	-7.5	-8.9	-10.0	-9.5	-8.2	Alt ≥ 150m	-3.6	-3.4	-3.1	-3.0	-3.3	-3.8	-3.9	-3.9	-3.5	-3.2	-4.3	-4.5

TI = Topographic Index
 Alt = Altitude (m)
 Thr = Threshold altitude (m)
 1 Threshold = 400 m
 2 Threshold = 250 m
 3 Threshold = 100 m

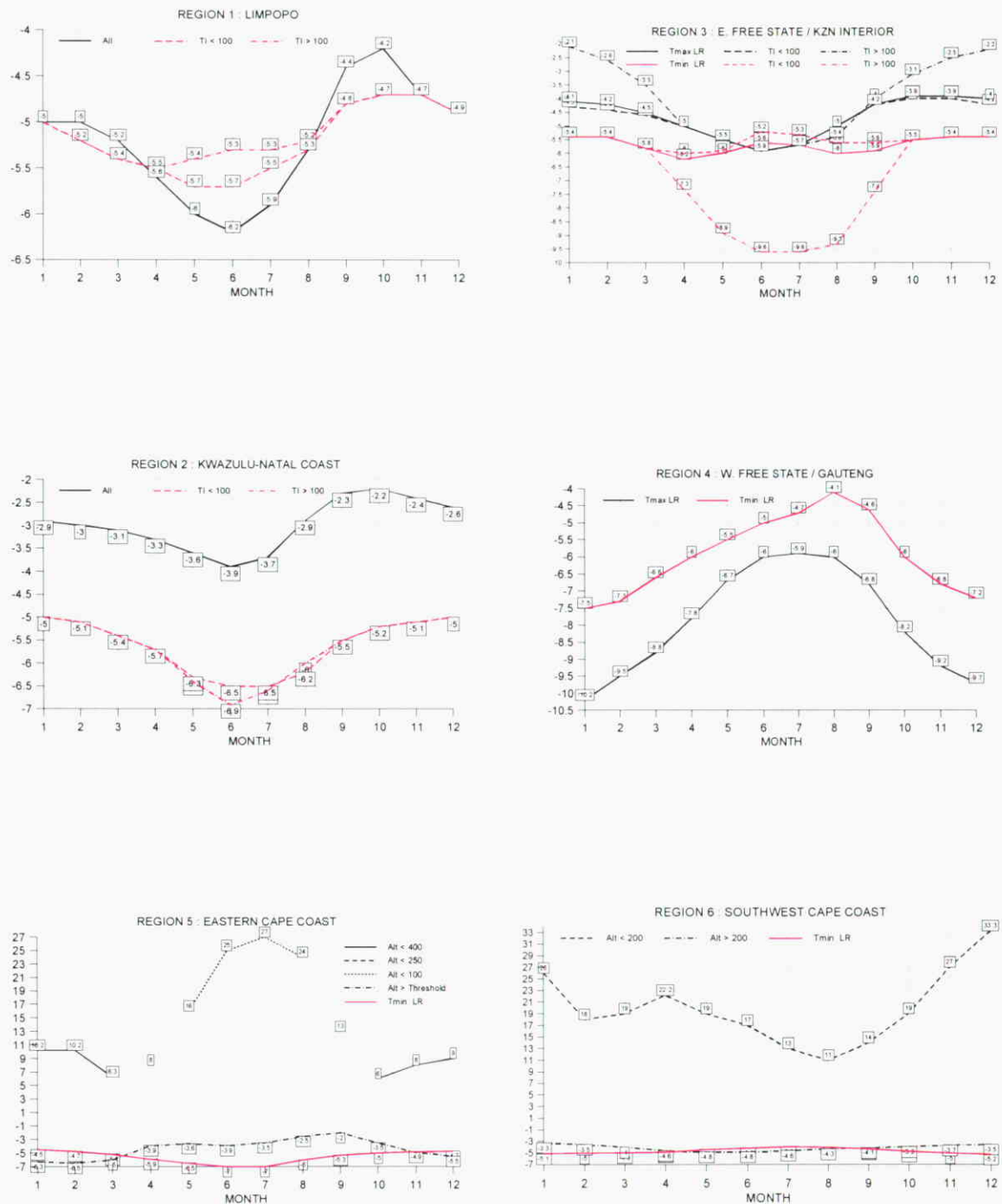


Figure 3.9 Smoothed monthly values of maximum and minimum temperature lapse rates for regions and sub-zones of regions

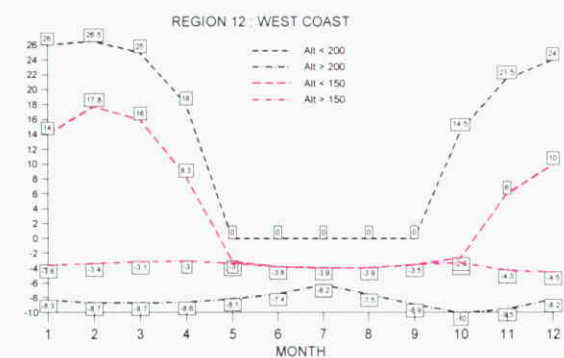
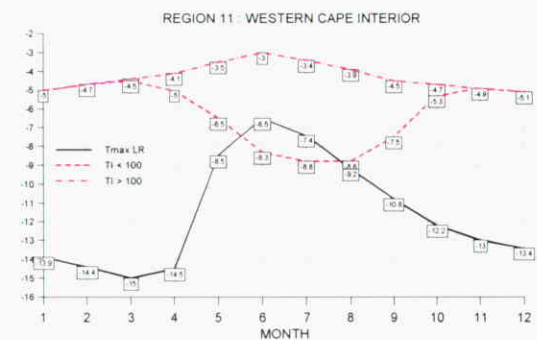
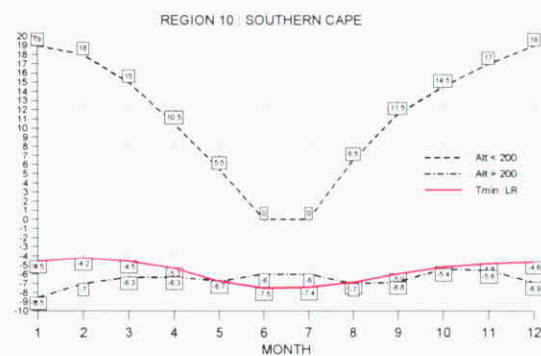
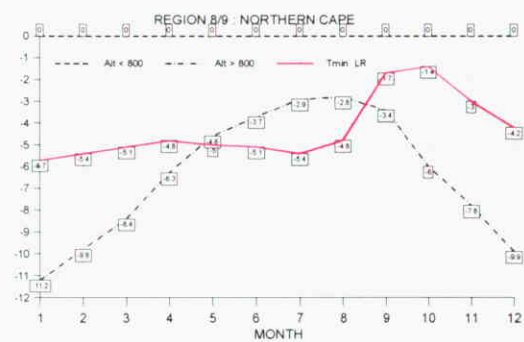
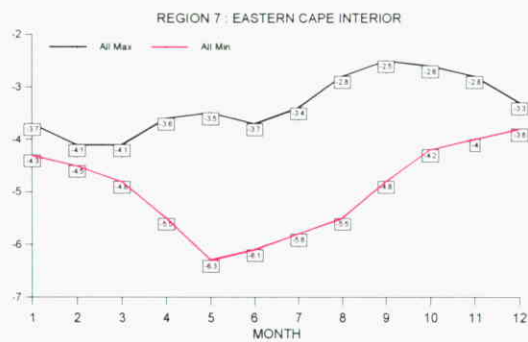


Figure 3.9 (continued) Smoothed monthly values of maximum and minimum temperature lapse rates for regions and sub-zones of regions

approach adopted in this study, differences in LRs are more marked than those of other recent studies in southern Africa (cf. Schulze and Maharaj, 1991; Schulze, 1995; Schulze, 1997).

Spatial differences in lapse rate characteristics are illustrated in Figures 3.10 to 3.13. In regard to the sub-zonation of regions, for example, it may be seen that the topographic index generally takes on significance in the hillier eastern third of southern Africa, i.e. in Regions 1 to 4, and in the hilly Western Cape Interior (Region 11). Sub-zonation by altitude, on the other hand, is predominantly a coastal feature (Regions 5, 6, 10-12) where the ocean/land interface reverses normal negative lapse rates from the coast into the inland up to a certain threshold altitude. The altitude sub-delineation of Region 8/9, however, is caused by the lower altitudes (< 800 m) of the Orange River valley within a region of higher altitudes.

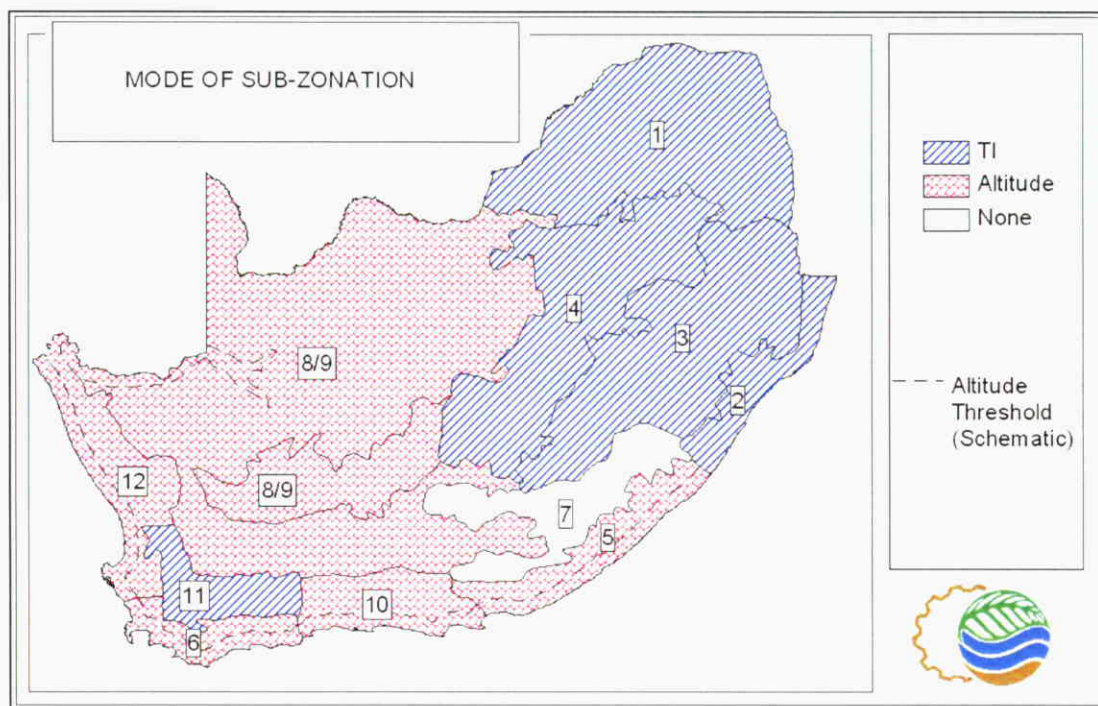


Figure 3.10 Sub-zonation of temperature lapse rate regions (schematic)

The season of highest lapse rates of maximum temperature (Figure 3.11, top) generally occur in the winter months (April-September) in the eastern third of the study area (Regions 1-3, the coastal sub-zone of 5 and the higher altitude sub-zone of Region 6). With the exception of Region 7, the lower altitude sub-zone of Region 8/9 and the higher altitudes of Region 12, which display no distinct seasonality of maximum LRs, the western two-thirds of southern Africa have their highest LRs in summer (October-March). Highest lapse rates of minimum temperatures occur in winter in the southeast

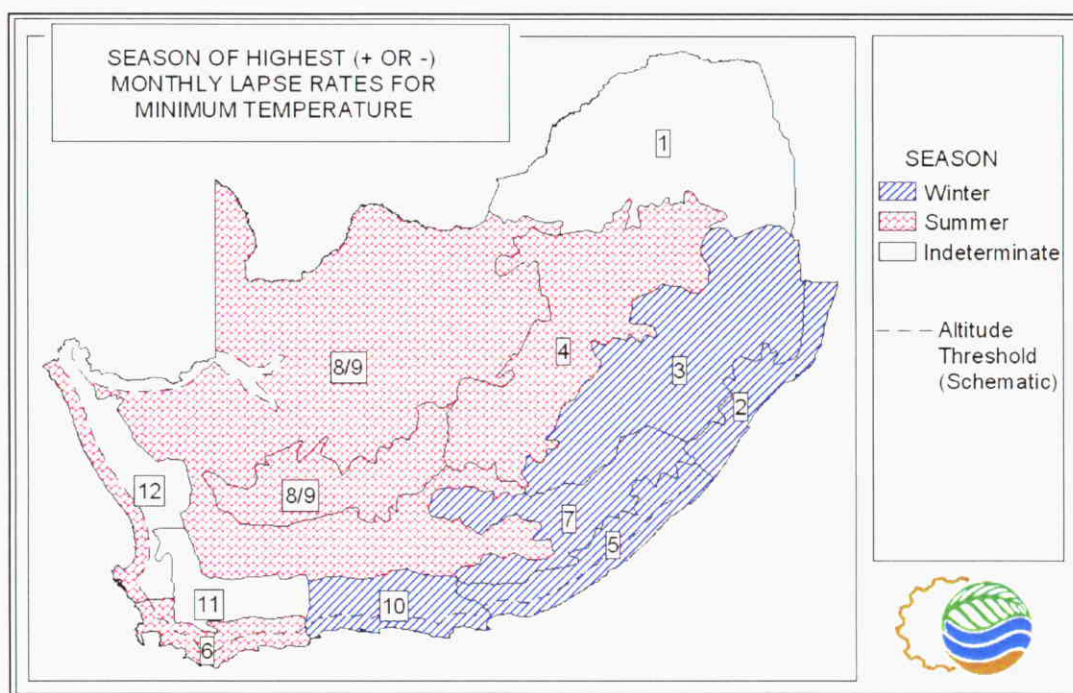
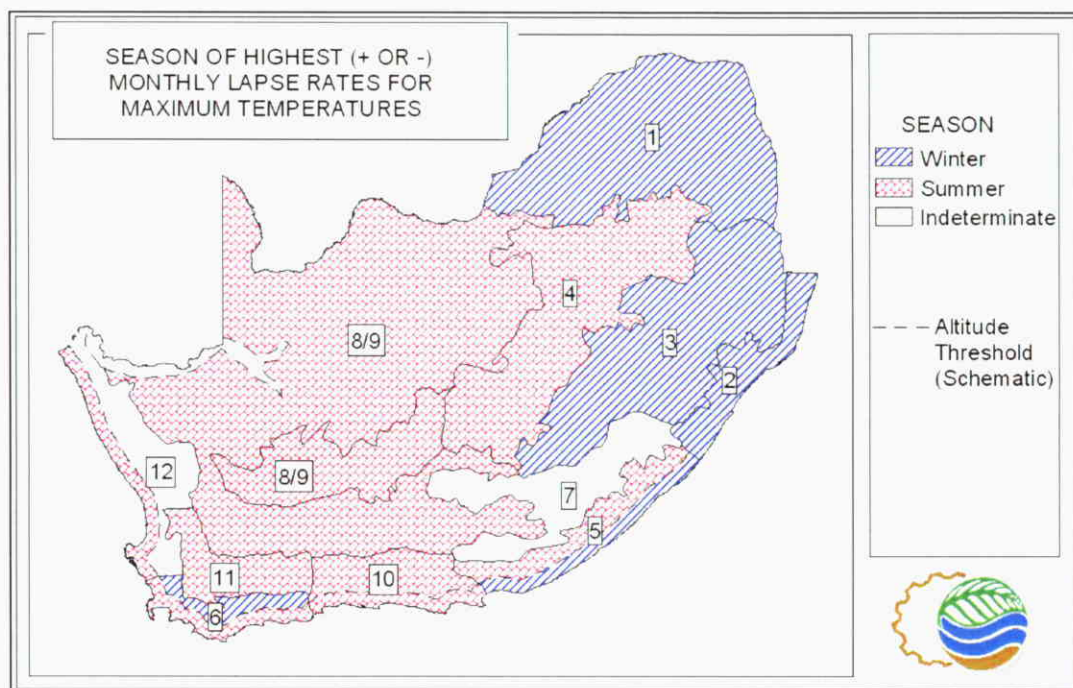


Figure 3.11 Seasons in which highest maximum (top) and minimum (bottom) temperature lapse rates occur

(Regions 2-3, 5, 7 and 10) with indeterminate seasonality in Regions 1, 8/9 (low altitude sub-zone), 11 and 12 (high altitude sub-zone).

The highest 3-month values of T_{mx} lapse rates (Figure 3.12, top) occur in the low altitude belts of coastal regions where positive “dog-leg” values are found ($LR > 20^{\circ}\text{C}/1000\text{ m}$ in coastal sub-zones of Regions 5, 6 and 12); otherwise also in the west/central parts of southern Africa (Regions 8/9, 10 low altitude and 11 have highest 3-months LR values $> -10^{\circ}\text{C}/1000\text{ m}$). Three-month highs of T_{mn} lapse rates are considerably lower than those of T_{mx} .

Intra-annual amplitudes of LRs (i.e. the difference between the highest and lowest monthly LR values in a Region or sub-zone) are generally much higher for maximum than for minimum temperatures (Figure 3.13). T_{mx} amplitudes exceed $20^{\circ}\text{C}/1000\text{ m}$, for example, in the coastal sub-zones of Regions 5, 6 and 12 and $5^{\circ}\text{C}/1000\text{ m}$ in Regions 8/9 and 11. Amplitudes of T_{mn} lapse rates, on the other hand, exceed $10^{\circ}\text{C}/1000\text{ m}$ only in Region 12 (low altitude sub-zone).

* * * * *

Temperature lapse rates in southern Africa and their characteristics having been discussed in this Chapter, the following chapter focuses on procedures for synthesising missing values and extending records at qualifying control temperature stations.

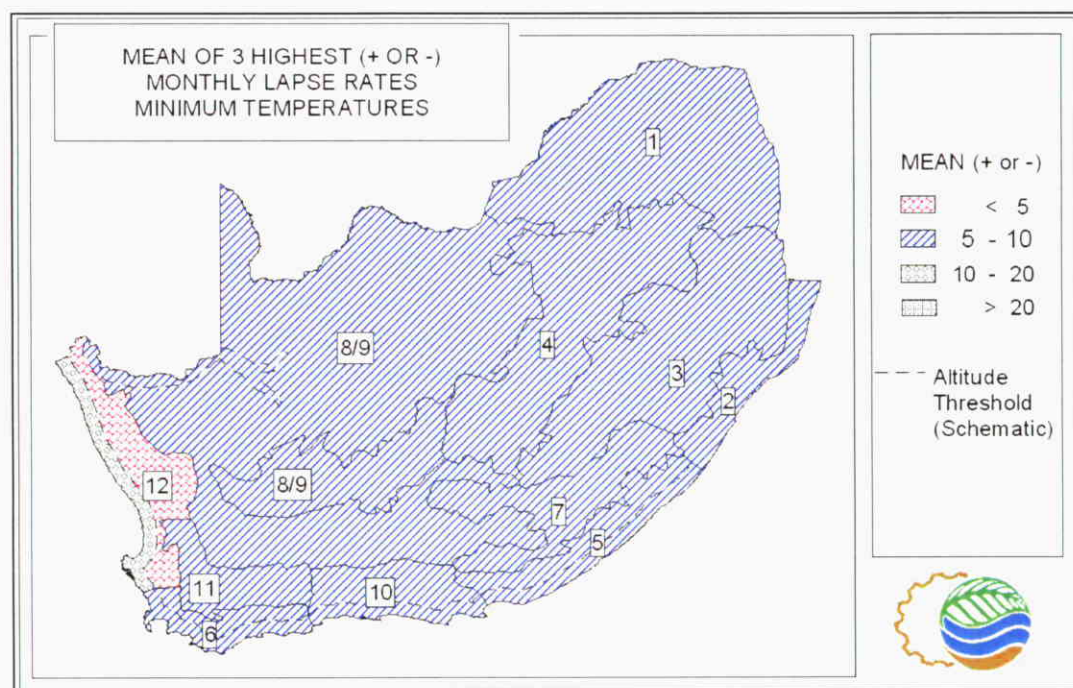
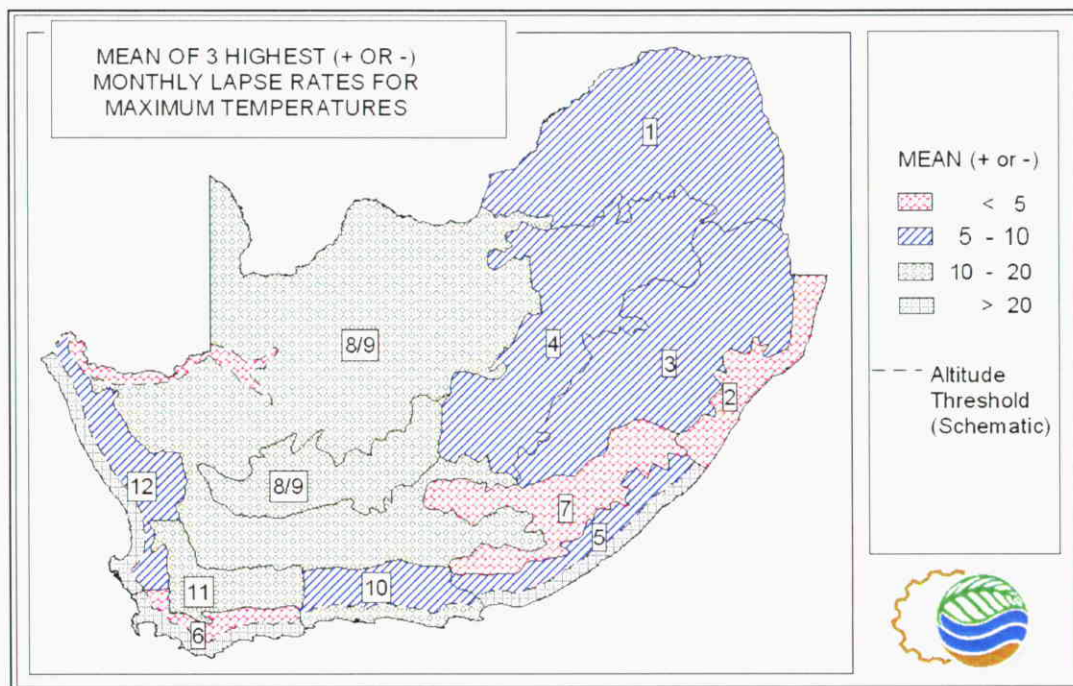


Figure 3.12 Means of three highest (+ or -) monthly lapse rates for maximum (top) and minimum (bottom) temperatures

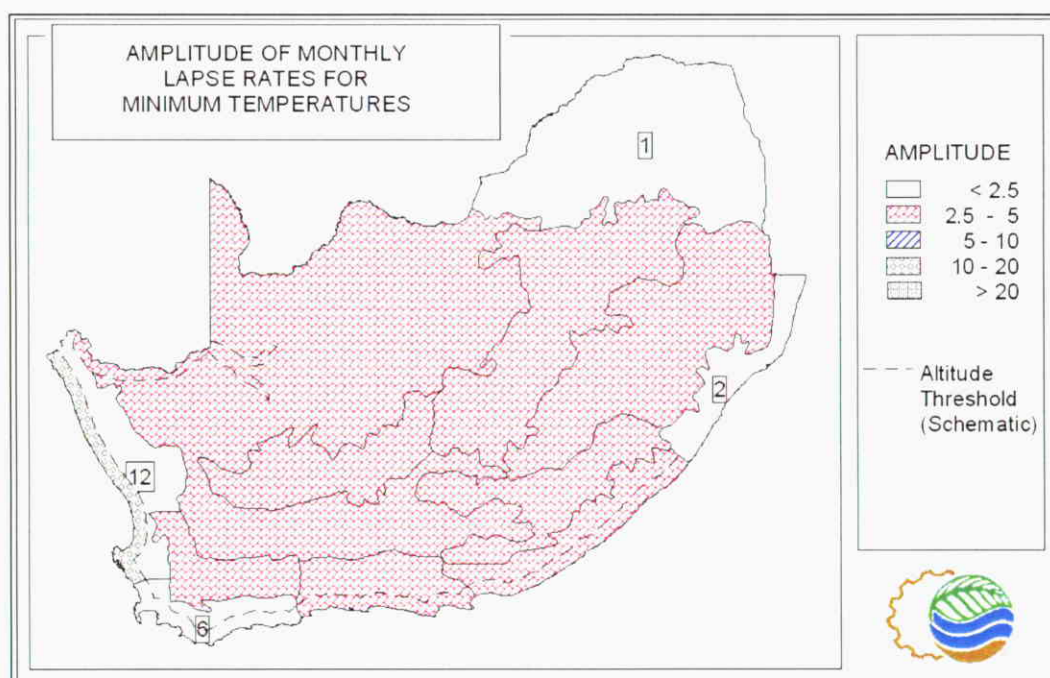
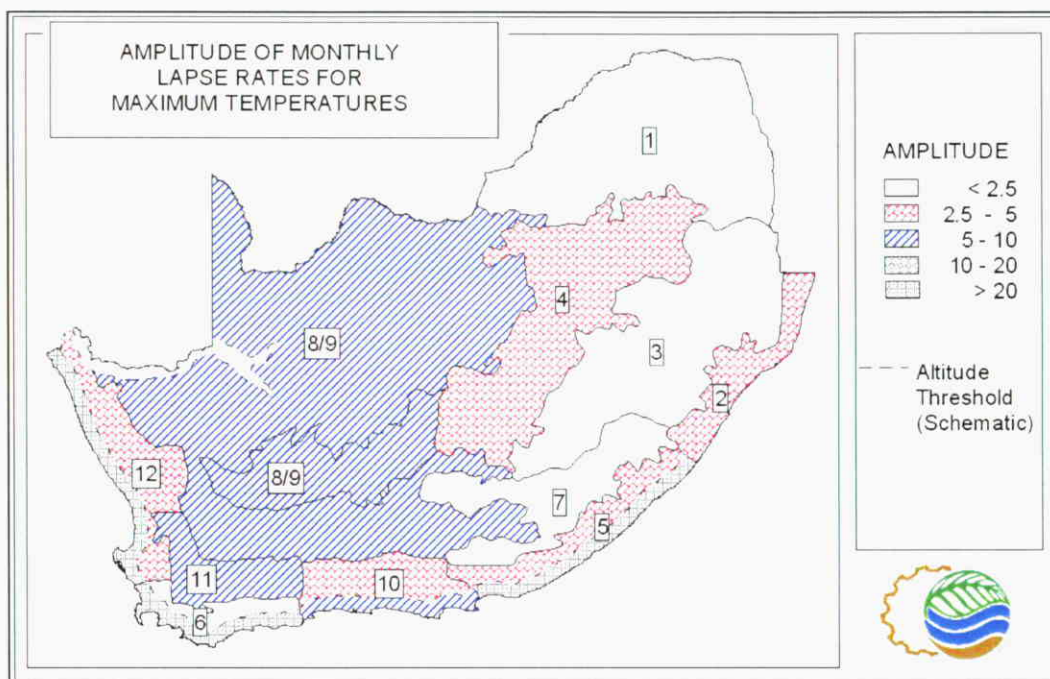


Figure 3.13 Intra-annual amplitudes of monthly lapse rates for maximum (top) and minimum (bottom) temperatures

CHAPTER 4

PROCEDURES FOR SYNTHESISING TEMPERATURE VALUES AT RECORDING STATIONS

4.1 THE NEED FOR SYNTHESISING TEMPERATURE VALUES TO INFILL AND EXTEND RECORDS

There are relatively few temperature stations in southern Africa with long records and these stations are not distributed evenly (Chapter 2). Those stations with longish records are, furthermore, not operated over common time periods, e.g. a 20-year record at one station may be from 1960-1979 while at another from 1981-2000. Added to the above is that temperature records usually have occasional missing data either for individual days or longer periods and also that many stations have closed since the early 1990s (Chapter 2).

The need for long station records over a common base period arises from temperature derived statistics (e.g. means, variances, extremes) and parameters (e.g. frost days, chill and heat units) requiring the same period of record in order to make valid comparisons, while any assessment of temperature trends (e.g. possible increases due to global warming) requires unbroken long duration temperature series. For the above reasons it was, therefore, necessary to select temperature stations with a minimum length of quality observed data to qualify as "control" (or test) stations and to test techniques to infill any missing data as well as extending the records to a desired common base period from "target" (or patching) stations.

This chapter therefore

- describes the selection procedure of qualifying control stations and their "target" stations with which to infill and extend temperature values
- presents two techniques for synthesising temperature values
- compares and evaluates these two techniques
- outlines procedures for infilling and extending temperature values from target station data
- describes the procedure for synthesising any remaining temperature values required by Fourier Analysis before it
- evaluates the outcomes of the analysis.

4.2 SELECTION OF STATIONS QUALIFYING AS CONTROL AND TARGET STATIONS FOR SYNTHESISING OF TEMPERATURE VALUES

4.2.1 Selection of Temperature Stations Qualifying for Analysis

Precipitation, which consists of discrete events of uneven magnitude and spacing, and which displays high inter-annual variability, requires long records (15 to 40 years) to estimate means and variances with confidence. Temperature, on the other hand, is a continuous climatological variable, which is both temporally and spatially relatively conservative, i.e. if it is cold or hot at one location it will also be cold or hot at surrounding locations for that period of time. Temperature therefore requires a considerably shorter period of time with which to evaluate most statistics with confidence.

In order for stations to be used as control and/or target stations for extension of records, a minimum period of 1500 days at which both maximum and minimum quality controlled temperature observations were available, was set as the qualifying criterion. From the available temperature database 973 stations qualified as potential control stations. Each temperature station's given co-ordinates and altitude were checked manually from 1:50 000 topographic sheets and corrected. Many originally given altitudes, especially, were found to be incorrect.

4.2.2 Selection of Target (i.e. "Patching") Stations Qualifying for Each Control (i.e. "Test") Station

4.2.2.1 Terminology

Terminology used in this report is that

- the station the record of which is to be infilled (i.e. where there are missing days of data) or extended (i.e. beyond its length of observation to the desired common base period) is termed the "control" (or "test") station, whereas
- stations the records of which are used for infilling or extension (because they include observation periods which the control station did not have) are termed the "target" (or "patching") stations.

Each of the 973 qualifying stations became, in turn, a control station.

4.2.2.2 Method for Selecting Patching Stations

For each control station, 9 patching stations were selected. Two selection criteria were used, viz.

- distance from the control station and
- altitude difference between the control and patching station.

Following a number of tests the two criteria were weighted as follows:

- the distance weighting, W_D , was

$$W_D = (1 - D) * 0.9 + 0.1$$
 where D = distance of the patching station from the control station, in degrees latitude/longitude and fractions thereof, and if $D > 1$, $W_D = 0.1$
- and the altitude difference weighting, W_A , was

$$W_A = [(500 - \Delta A)/500] * 0.9 + 0.1$$
 where ΔA = difference in altitude between the control and patching stations, in m, and if $\Delta A > 500$, $W_A = 0.1$.

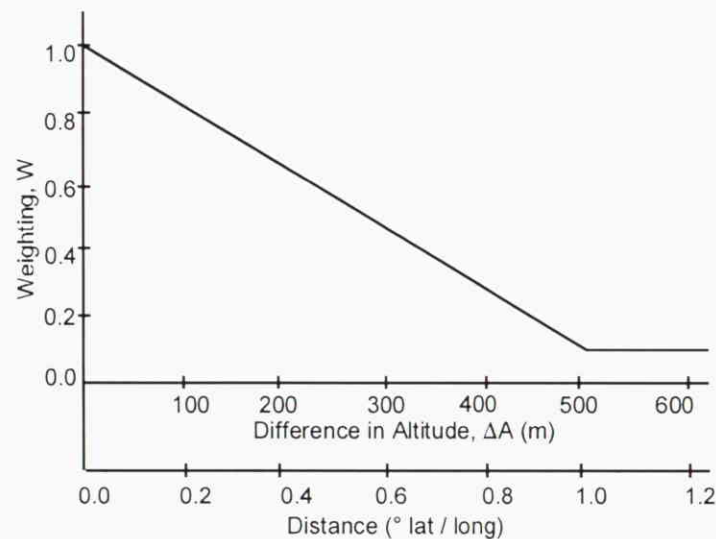


Figure 4.1 Weighting for selection of target (i.e. patching) stations

From the illustration on the weighting of the two criteria (Figure 4.1) it may be seen that the weighting decayed linearly from unity up to a threshold distance (1° latitude/longitude) and altitude difference (500 m), which were set at a weighting of 0.1, at which value the weighting remained if target stations were only found beyond the threshold distance and altitude difference.

The two weightings were summed, e.g. if a target station was 10 arc minutes of a degree (i.e. $1/6^\circ$) distant, its weighting of 0.85 would be added to the altitude difference weighting which, if 150 m, would be 0.73, giving a combined weighting of 1.58.

For each control station the 9 best target (patching) stations were selected by this procedure. An example is given in Table 4.1.

Table 4.1 Example of selection and ranking of 9 target stations for a control station

Stations	SAWS No.	Station Name	Latitude (°)	Longitude (°)	Altitude (m)
Control	0001517 A	Danger Point Vrt	34.62	19.30	14
Target 1	0006413 A	Braemar	34.38	19.23	79
2	0006411 A	Oude Hemel en Aarde	34.35	19.23	192
3	0007019 A	Dunghye Park	34.32	19.52	104
4	0006612 A	Boontjieskraal	34.20	19.35	160
5	0007346 A	Hoogeleë	34.27	19.68	285
6	0006039 A	Grabouw Bos	34.15	19.03	290
7	0007008 A	Dwaalhoek	34.15	19.57	363
8	0006038 A	Elgin (NIVV)	34.13	19.03	322
9	0006273 A	Longdown	34.05	19.17	265

4.3 DEVELOPMENT AND VERIFICATION OF TWO TECHNIQUES FOR SYNTHESISING DAILY TEMPERATURE VALUES

In order to infill missing daily temperature values or to extend the record at a qualifying control station, two techniques were developed, viz. the Mean Temperature Difference Method (MTDM) and the Difference in Standard Deviation Method (DSDM). These are described below, followed by an evaluation of the two techniques.

4.3.1 The Mean Temperature Difference Method

For each month of the year the differences of the monthly mean values of daily maxima and minima from the 9 target stations and the control station were calculated. These differences were then ranked for the 9 target (i.e. patching) stations, from the lowest absolute difference (i.e. the "best" station for that month) to the highest absolute difference (Table 4.2). The hypothesis of this technique is that the lower the absolute difference between control and qualifying target station, the more appropriate it is to use that target station's data for infilling and extending daily records at the control station. For synthesising daily temperature values from a target station's record at the control station, the control station's infilled/extended daily values were adjusted by the mean difference for that month. By implication

- a different target station may be used as most appropriate for patching in different months of the year (cf. Table 4.2)
- for a given month different patching stations may be selected for maximum vs minimum temperatures and
- it is assumed that an averaged monthly difference may be applied to daily values.

The MTDM technique is conceptually simple. However, it does not reflect any differences in deviations from mean values which may occur between stations for various reasons, including exposure. For that reason the second technique was devised.

Table 4.2 Examples for January to June of target station rankings for maximum temperatures using the Mean Temperature Difference Method for infilling/extending daily temperature values. The control station is 0001517A

Target Stations	Differences in Monthly Means of T_{mx} (Control-Target, °C) and Ranking ()					
	Jan	Feb	Mar	Apr	May	Jun
1. 0006413 A	2.88 (2)	3.91 (3)	3.48 (3)	3.47 (4)	2.51 (7)	1.11 (8)
2. 0006411 A	2.61 (1)	3.35 (1)	2.67 (1)	2.27 (2)	0.84 (3)	0.03 (3)
3. 0007019 A	5.24 (7)	5.97 (6)	5.35 (8)	4.42 (8)	2.62 (8)	0.92 (7)
4. 0006612 A	6.13 (9)	7.03 (9)	6.00 (9)	5.11 (9)	2.56 (9)	1.49 (9)
5. 0007346 A	4.82 (5)	5.95 (5)	4.22 (5)	3.64 (6)	0.42 (2)	-0.01 (1)
6. 0006039 A	3.11 (3)	3.71 (2)	2.72 (2)	1.15 (1)	-0.20 (1)	-0.69 (5)
7. 0007008 A	6.10 (8)	6.54 (8)	5.28 (7)	4.21 (7)	1.63 (6)	0.69 (6)
8. 0006038 A	3.34 (4)	4.18 (4)	3.76 (4)	2.77 (3)	0.94 (5)	-0.01 (2)
9. 0006273 A	5.05 (6)	6.08 (7)	4.98 (6)	3.63 (5)	0.84 (4)	-0.05 (4)

4.3.2 The Difference in Standard Deviation Method

Based on the hypothesis that any infilled, or extended, values at a qualifying control station should reflect the daily temperature variability at the control station, from both regional and local perspectives, the standard deviations of daily T_{mx} and T_{mn} were computed for each month of the year for data from the control and its 9 target stations. In the DSDM the differences in standard deviations between the control and patching stations were therefore ranked from the lowest difference (the "best" patching station for that month) to the highest difference (Table 4.3). The same three implications named for the MTDM in Section 4.3.1 above hold for this technique.

Table 4.3 Examples for January to June of target station rankings for maximum temperatures using the Difference in Standard Deviation Method for infilling/extending daily temperature values. The control station 0001517A

Target Stations	Differences in Monthly Means of T_{mx} (control-Target, °C) and Ranking ()					
	Jan	Feb	Mar	Apr	May	Jun
1. 0006413 A	1.75 (1)	2.17 (1)	2.13 (1)	2.93 (7)	2.14 (5)	0.94 (4)
2. 0006411 A	2.04 (4)	2.28 (2)	2.27 (3)	2.72 (2)	2.29 (8)	1.11 (7)
3. 0007019 A	1.94 (2)	2.33 (3)	2.20 (2)	2.81 (4)	1.97 (1)	0.40 (1)
4. 0006612 A	2.04 (3)	2.46 (4)	2.37 (4)	2.76 (3)	1.98 (2)	0.74 (2)
5. 0007346 A	2.21 (6)	2.89 (9)	2.78 (8)	2.62 (1)	2.00 (3)	1.04 (5)
6. 0006039 A	2.67 (9)	2.62 (5)	2.80 (9)	2.83 (5)	2.05 (4)	1.29 (9)
7. 0007008 A	2.18 (5)	2.78 (7)	2.44 (5)	2.86 (6)	2.18 (6)	0.91 (2)
8. 0006038 A	2.39 (7)	2.69 (6)	2.73 (6)	2.96 (8)	2.25 (7)	1.04 (5)
9. 0006273 A	2.55 (8)	2.79 (8)	2.74 (7)	3.02 (9)	2.32 (9)	1.23 (8)

For synthesising daily temperature values from a target station's record at the control stations using the DSDM, the control station's infilled/extended daily values were once again adjusted by the mean difference in temperature for that month (cf. Section 4.3.1 on the MTDM), but the sequence of target stations used was determined by the ranking according to the DSDM.

Because the DSDM is conceptually sounder than the MTDM as an infilling/extension technique, it was felt intuitively that it would be the better of the two in verification tests. These are carried out in the following section.

4.4 IS EITHER METHOD BETTER THAN THE OTHER? A VERIFICATION STUDY

In order to test whether

- the two techniques possessed the ability to synthesise daily temperature values adequately, and to evaluate
- whether one technique was consistently better than the other,

temperature stations at 7 locations from widely varying climatic regimes were selected for their daily temperature records to be used in verification studies. The 7 stations and their attributes are given in Table 4.4.

Table 4.4 Locational and climatic information at the 7 locations selected for verification studies

Location	Latitude (°,')	Longitude (°,')	Altitude (m)	Mean Annual Precipitation (mm)	Climate Description
Eisenburg	33°51'	18°50'	180	610	Winter rainfall
Outeniqua	33°55'	22°28'	259	692	All year rainfall
Mt Edgecombe	29°42'	31°02'	96	958	Summer rain – coast
Cedara	29°31'	30°17'	1067	879	Summer rain – hinterland
Roodeplaat	25°55'	28°21'	1170	655	Summer rain – interior
Mara	23°09'	29°33'	899	438	Subtropical sub-humid
Upington	28°27'	21°25'	800	181	Arid

For the verification study one year in which all 7 stations had as close as possible to a complete set of observed daily maximum and minimum temperature was selected. The year was 1980.

The 366 days' daily T_{mx} and T_{mn} values for 1980 were then synthesised at the 7 locations by both the MTDM and the DSDM *using only target station data, i.e. assuming all observed data at the 7 locations to be missing*. The 366 synthesised T_{mx} and T_{mn} values were then compared with the actually observed values at the 7 locations. For one station, Mara, no target stations were assumed to qualify.

Graphs of observed and simulated values for 1980 are presented in Figure 4.2 for the two techniques of synthesising daily temperature for selected locations. Visually, both techniques mimic daily T_{mx} as well as T_{mn} excellently, with neither technique appearing to give intrinsically better results than the other, irrespective of climatic regime. At Mara, where no target stations were assumed to qualify, the 366 temperature values were synthesised by Fourier Analysis, hence the smoothed curve for simulated values. This procedure is described in Section 4.5.

A statistical comparison of the results for 1980 was then undertaken. The outcome is summarised in Table 4.5. Five statistics were considered as objective functions, viz.

- r^2 , as a measure of the strength of the linear relationship between synthesised and observed values, with the simulation aim of attaining a value as close to unity as possible
- slope of the least-squared line, as an index of bias in the relationship, with the aim of attaining a value as close as possible to unity
- base constant (i.e. intercept) as a further measure of bias, with the aim of attaining a zero constant in the least-squared line
- skewness coefficient as an index of symmetry (i.e. normality) of the values, aiming at a zero skew, and then assessing the difference in skewness between observed and simulated, and
- kurtosis coefficient, which measures the peakedness of the distribution relative to a normal distribution, with the aim of minimising the kurtosis coefficient to zero and, once more, evaluating the difference in kurtosis between observed and simulated.

With very few exceptions (one being the low r^2 at Mara where temperature synthesis was by Fourier Analysis only), all five statistical indices for both T_{mx} and T_{mn} were highly impressive for the MTDM as well as the DSDM. To try to distinguish which technique gave better results overall, corresponding statistics for the two methods (e.g. r^2 for Elsenburg's T_{mx} by MTDM vs DSDM) were compared by assigning a '+' if one method gave a better statistic, a '-' if it was worse than the other method and an '=' if the statistics were approximately equal. The MTDM yielded 28+, 31- and 11=, essentially no different to the DSDM's 33+, 27- and 10=. Similar comparisons were made for T_{mx} statistics only vs T_{mn} statistics for the two techniques.

The overall prognosis from the statistical tests, however, was that neither of the two techniques gave inherently better results as a tool for daily temperature synthesis. Nevertheless, for all further analyses the Difference in Standard Deviation Method was selected as it is conceptually a sounder technique in accounting better for similarities in temperature variances between target stations and the control.

4.5 PROCEDURES FOR INFILLING AND EXTENDING DAILY TEMPERATURE VALUES AT CONTROL STATIONS FROM TARGET STATION DATA

4.5.1 Step 1: Select a Base Period for Analysis

The base period can be of any length, up to 100 years. With this project's aim being to generate daily T_{mx} and T_{mn} at any location in southern Africa to a one arc minute of a degree spatial resolution (~ 1.6 km), a 50 year base period from 1950 to 1999 was selected, as it represented a period in which the temperature station network was at its densest, it includes 'current' data and is a period for which potential of global warming impacts could be assessed.

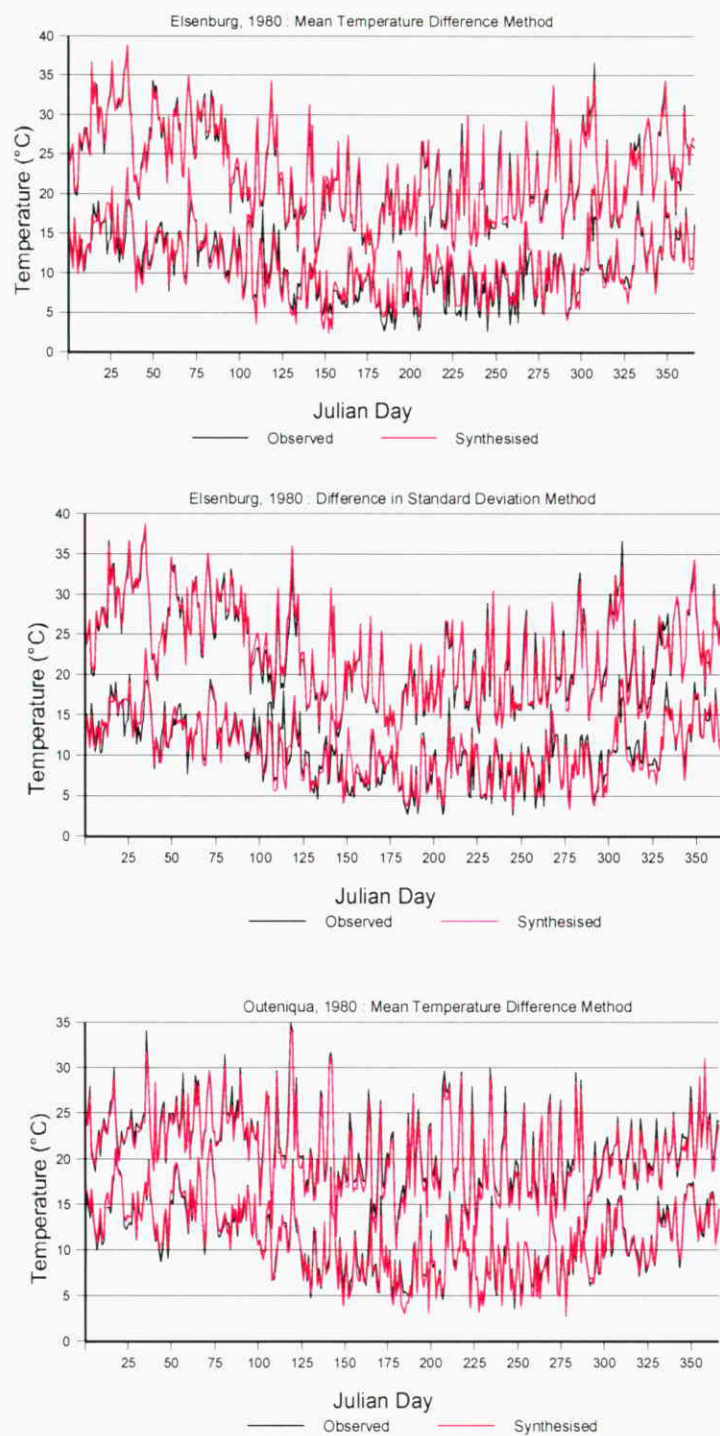


Figure 4.2 Plots of synthesised and observed daily maximum and minimum temperatures for 1980 at selected locations in southern Africa

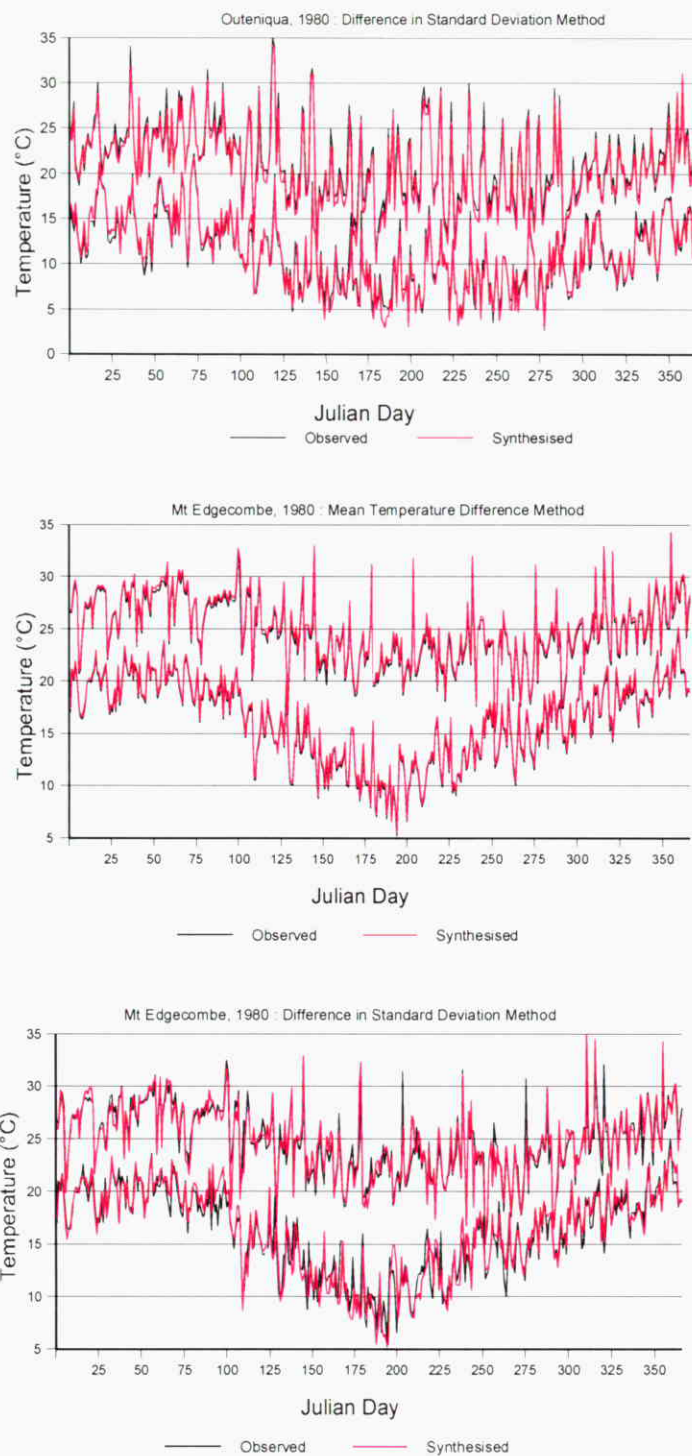


Figure 4.2 (continued) Plots of synthesised and observed daily maximum and minimum temperatures for 1980 at selected locations in southern Africa

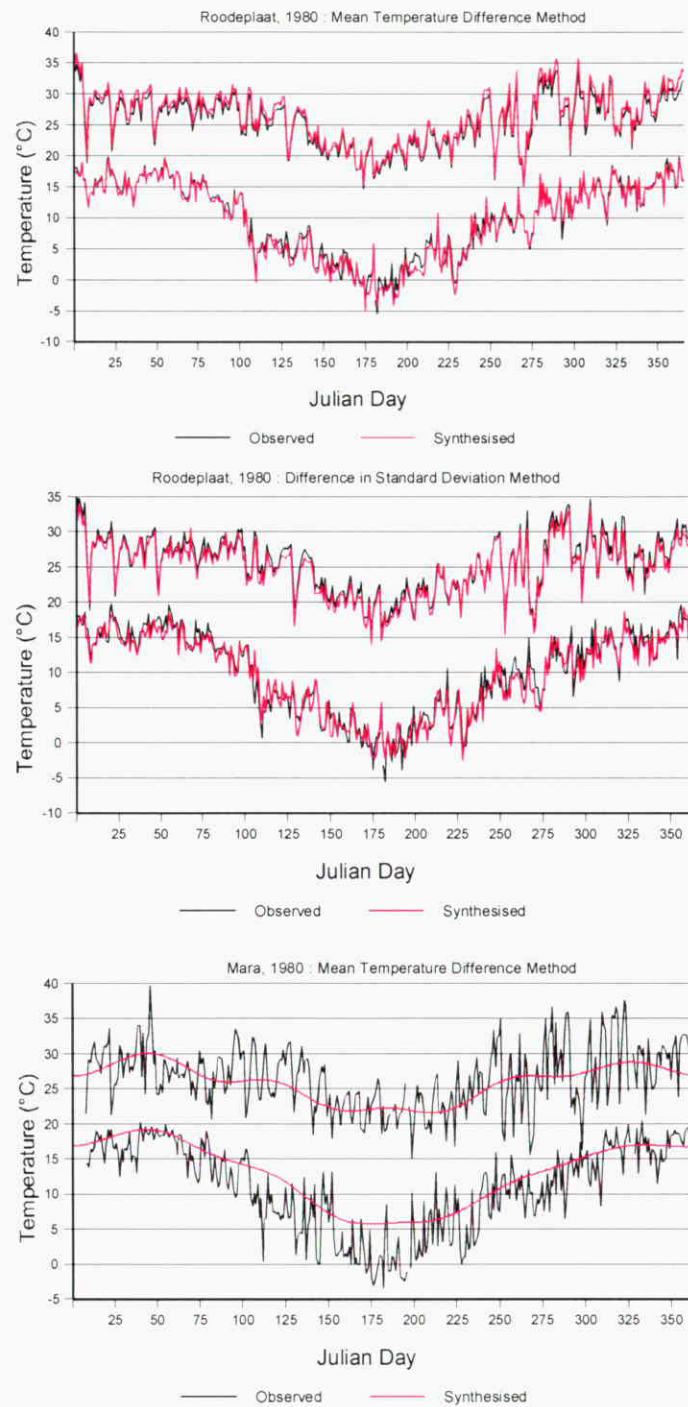


Figure 4.2 (continued) Plots of synthesised and observed daily maximum and minimum temperatures for 1980 at selected locations in southern Africa

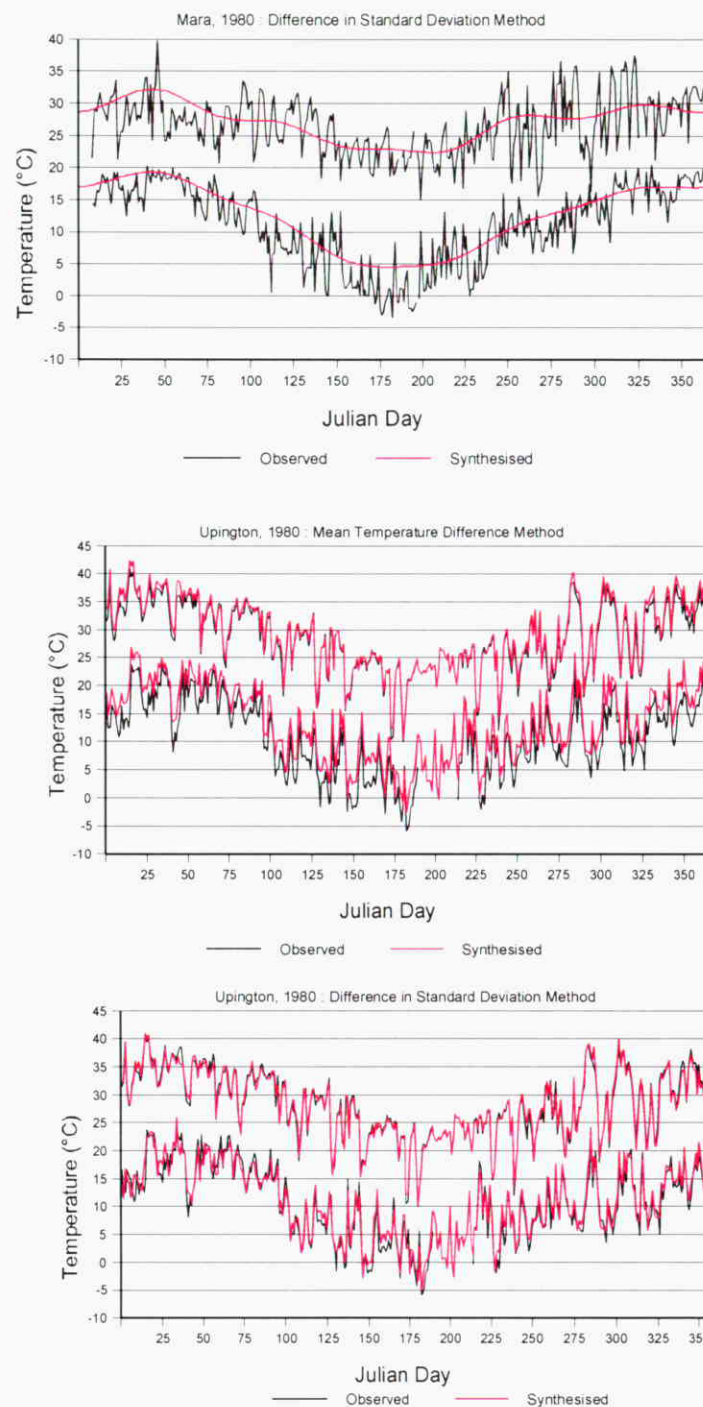


Figure 4.2 (continued) Plots of synthesised and observed daily maximum and minimum temperatures for 1980 at selected locations in southern Africa

Table 4.5 Comparative statistics at 7 locations for 1980 for observed vs simulated daily temperatures, with the latter generated by the MTDM and the DSDM

MEAN TEMPERATURE DIFFERENCE METHOD						
Station	Variable	R ²	Slope	Intercept	Δ Skewness	Δ Kurtosis
Elsenburg	T _{mx}	0.978 +	1.010 =	-0.338 -	0.263 -	-0.738 =
	T _{mn}	0.812 -	0.885 -	0.997 +	0.265 -	-0.320 +
Outeniqua	T _{mx}	0.974 +	0.977 +	1.179 +	0.293 -	-0.127 +
	T _{mn}	0.964 +	0.933 -	0.789 -	0.197 +	-0.590 -
Mt Edgecombe	T _{mx}	0.999 +	1.003 +	-0.417 +	-0.037 =	-0.347 -
	T _{mn}	0.999 +	1.002 +	-0.297 +	-0.297 +	-0.755 -
Cedara	T _{mx}	0.902 -	0.801 -	4.940 -	-0.257 -	-0.434 -
	T _{mn}	0.814 -	1.095 +	-0.290 -	-0.376 +	-0.649 +
Roodeplaat	T _{mx}	0.993 +	0.941 -	0.731 -	-0.224 +	-0.552 -
	T _{mn}	0.978 +	0.949 -	0.872 -	-0.376 -	-1.052 =
Mara	T _{mx}	0.278 =	0.963 +	1.783 +	0.214 -	0.346 -
	T _{mn}	0.759 =	1.225 -	-4.753 -	-0.609 -	-0.540 +
Upington	T _{mx}	0.987 +	0.949 -	0.702 -	-0.415 +	-0.325 -
	T _{mn}	0.940 =	1.012 =	-2.973 -	-0.210 +	-0.653 =

MEAN TEMPERATURE DIFFERENCE METHOD						
Station	Variable	R ²	Slope	Intercept	Δ Skewness	Δ Kurtosis
Elsenburg	T _{mx}	0.966 -	0.991 =	0.085 +	0.252 +	-0.759 =
	T _{mn}	0.815 =	0.930 +	0.695 -	0.190 +	-0.514 -
Outeniqua	T _{mx}	0.925 -	0.938 -	1.236 -	0.267 +	-0.165 -
	T _{mn}	0.943 -	0.976 +	0.455 +	0.253 -	-0.529 +
Mt Edgecombe	T _{mx}	0.860 -	0.913 -	2.108 -	-0.053 =	-0.216 +
	T _{mn}	0.871 -	0.876 -	1.936 -	-0.358 -	-0.737 +
Cedara	T _{mx}	0.929 +	0.975 +	0.366 +	-0.215 +	-0.346 +
	T _{mn}	0.873 +	0.892 -	0.860 +	-0.390 -	-0.796 -
Roodeplaat	T _{mx}	0.970 -	1.022 +	0.187 +	-0.287 -	-0.491 +
	T _{mn}	0.933 -	1.011 +	0.273 +	-0.364 +	-1.063 -
Mara	T _{mx}	0.271 =	0.856 -	3.459 -	-0.042 +	0.031 +
	T _{mn}	0.766 =	1.117 +	-2.771 +	-0.517 +	-0.763 -
Upington	T _{mx}	0.977 -	1.005 +	-0.066 +	-0.461 +	0.233 +
	T _{mn}	0.935 =	1.026 =	-0.766 +	-0.217 -	-0.683 =

4.5.2 Step 2: Commence Analysis at a Control Station

For a selected qualifying control station all T_{mx} and T_{mn} data were first extracted.

4.5.3 Step 3: Infill Missing Data and Extend the Record from Target Station Observations

For the selected base period, any missing daily values from the control station data (be they odd missing days within the period of observations or extensions of the record) were synthesised from target station data as follows:

- Using the DSDM, the best (i.e. lowest ranked) target station was selected for a given month and temperature variable, i.e. either T_{mx} and T_{mn} (Example: Table 4.3).

- Any missing daily temperature values from the control station which were available from Target Station # 1's data were extracted and adjusted according to that month's mean temperature difference between the two stations (Example: Table 4.2).
- This step was repeated for Target Station # 2 and up to Target Station # 9, or until the entire base period at the control station was "patched" with daily T_{mx} and T_{mn} values.
- All temperature values were flagged according to whether they were from the control station or a target station, and if the latter, from which target station.

4.5.4 Step 4: Synthesise Remaining Values (if any) by Fourier Analysis

If, after utilising the available data from all 9 qualifying target stations to infill/extend the control station's missing values, any record extension was still required to complete the selected base period, the remaining values were synthesised by Fourier Analysis, as follows:

- A six-harmonic Fourier Analysis was applied to the 12 monthly mean values of daily T_{mx} and T_{mn} from the control station. The first harmonic generated an equation from the 12 values, the second harmonic generated an equation from the residuals of the first harmonic which was added to that of the first harmonic's equation, and so on for six harmonics.
- The final equation was then used to generate 365 daily estimates of T_{mx} and T_{mn} , as illustrated in Figure 4.2 for Mara.
- Values generated by Fourier Analysis were flagged as such.

By this method the smoothed generated daily values of T_{mx} and T_{mn} infilled any remaining missing values of the control station. The advantage of this approach is that a base period record is completed by a statistically sound technique; the disadvantage is that all values generated for a given day of the year by Fourier Analysis have the same value for all years.

4.5.5 Step 5: Repeat Procedure at All Other Qualifying Temperature Stations

Steps 1-4 were repeated for both T_{mx} and T_{mn} for all qualifying temperature stations in southern Africa.

4.6 EVALUATION OF OUTCOMES

Of the 973 temperature stations which qualified to have missing daily data infilled and their records extended to the 50 year common base period 1950-1999, the observed daily temperature at the control station, i.e. "own" values, made up

- ≥90% of the daily 50 year record at 8 stations (i.e. at 0.82% of stations)
- 75-90% of the record at a further 29 stations (2.98%)

- 50-75% of the record at another 133 stations (13.67%) and
- < 50% of the record at the remaining 803 stations (i.e. at 82.53% of stations).

The distribution of stations with "own" data for the 50 year base period is shown in Table 4.6 and Figure 4.3. The two stations with the best daily temperature records for the period 1950-1999 were 0437134_A Potchefstroom (Agricultural Research Station) with 99.7% own data and 0241042_S Mt Edgecombe (SASA Experiment Station) with 99.0% own data. Not a single station, therefore, had a "perfect" dataset of maximum and minimum temperatures for the entire base period 1950-1999.

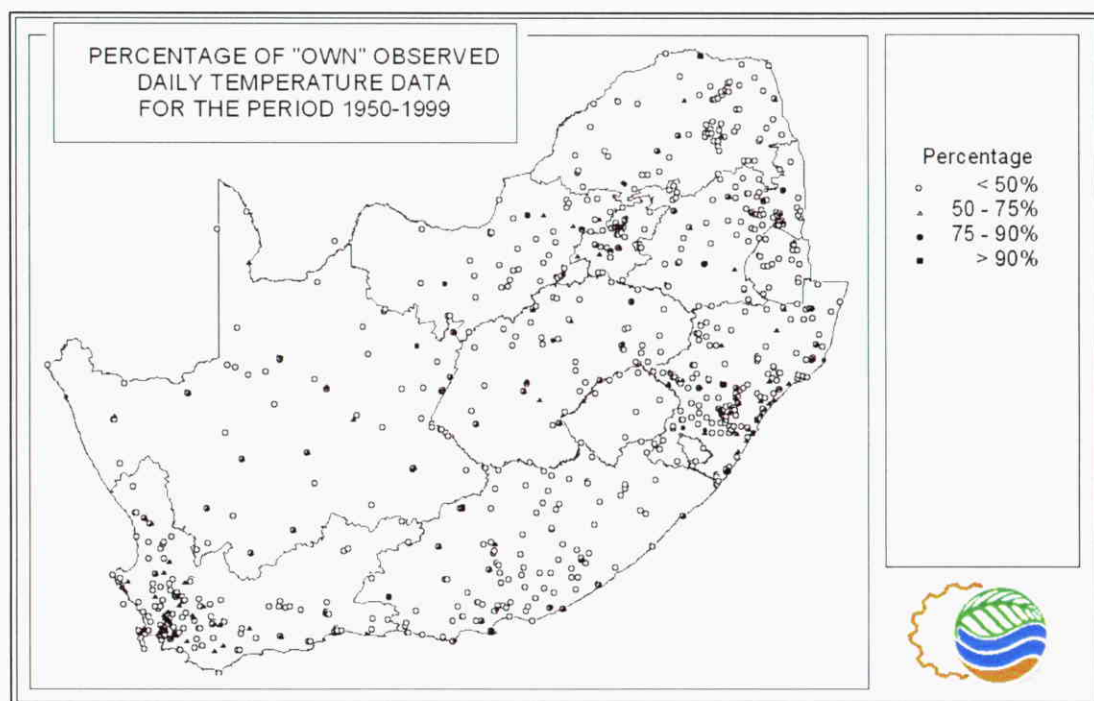


Figure 4.3 Percentages of "own" observed daily temperature data at qualifying stations for the common base period 1950-1999

In the 50 years of daily temperature record the number of target (patching) stations which were interrogated to synthesise missing values at each of the 973 qualifying stations was:

- 1-2 patching stations at 6 locations (i.e. 0.62%)
- 3-5 patching stations at 83 locations (i.e. 8.53%) and
- 6-9 patching stations at 884 locations (i.e. 90.85%).

Table 4.6 Number of temperature stations with “own” observed daily temperature data in different percentage classes, by province/country

Province/ Country	Number of Stations in Each Percentage Class			
	< 50% own data	50-75% own data	75-90% own data	≥ 90% own data
Limpopo	68	6	3	0
North-West	53	5	1	2
Gauteng	31	6	3	0
Mpumalanga	84	8	2	1
Swaziland	21	1	0	0
Northern Cape	61	13	5	1
Free State	52	9	3	0
Lesotho	11	1	0	0
KwaZulu-Natal	160	38	5	2
Western Cape	141	35	3	1
Eastern Cape	121	11	4	1
Totals	803	133	29	8

The distribution of target (patching) stations at each qualifying temperature station is given in Figure 4.4.

It should be noted that when the Rank 1 patching station was interrogated to infill missing data, it did not necessarily have any of the data missing from the control station, and frequently it was only the Rank 6 or 7 patching station that came out as the “best” and could supply the missing values.

Where neither the control nor any of its 9 target stations had any observations for the period 1950-1999, Fourier Analysis (Section 4.5.4) was used to estimate daily temperature values. As illustrated for Mara in Figure 4.2, once this technique has to be resorted to there is a strong deterioration in the estimates of individual daily temperature values, and hence the variance of the values, which are important in, for example, estimates of days with frost. The Fourier Analysis had to supply

- no values whatsoever in the 50 year base period at only 31 stations (i.e. 3.19%)
- < 10% at 649 stations (66.70%)
- 10-25% at 213 stations (21.89%) and
- 25-50% at 80 stations (8.22%).

At no single station of the 973 did the Fourier Analysis make up more than 50% of the values between 1950 and 1999. The distribution of stations with various percentages of application of the Fourier Analysis in the 50 year base period is given in Figure 4.5.

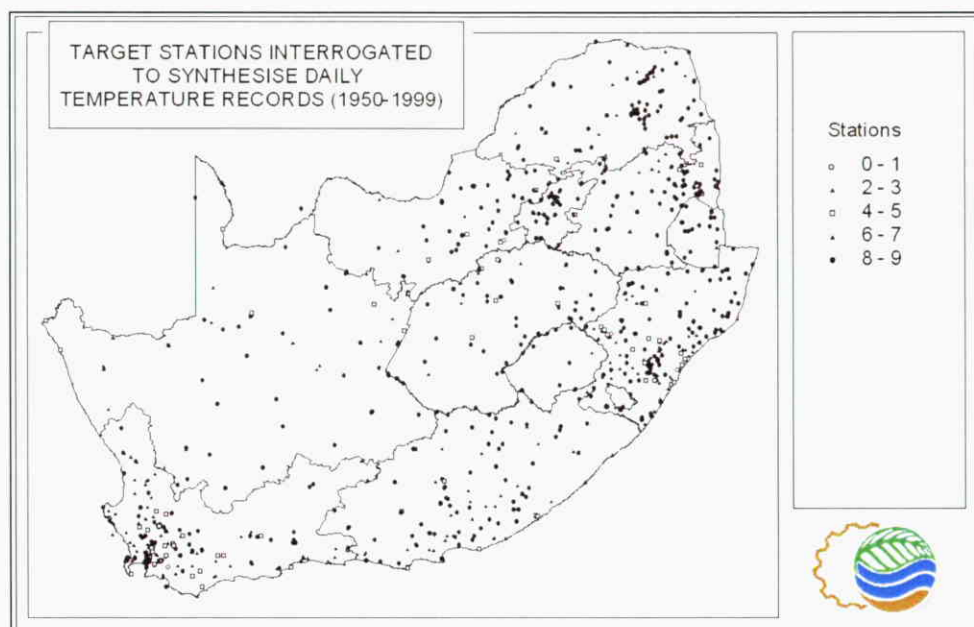


Figure 4.4 Number of target (i.e. "patching") stations interrogated to provide synthesised daily temperature records at qualifying stations for the common base period 1950-1999

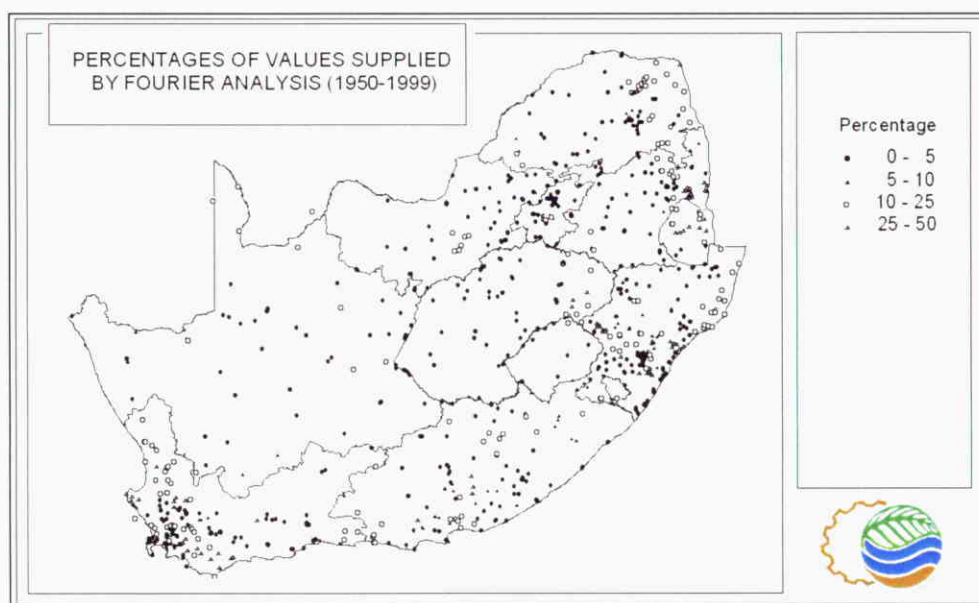


Figure 4.5 Percentages of values having to be provided by the Fourier Analysis in the estimation of daily temperature values for the common base period 1950-1999

The overall conclusion of the above analysis is that, while many data gaps occur, over most of southern Africa the daily temperature information base generated in this project is considered comprehensive enough for the estimation of temperature related variables at levels of detail far in excess of those used in the "South African Atlas of Agrohydrology and –Climatology" (Schulze, 1997) and in any known temperature related analyses in southern Africa, to date.

* * * * *

The next chapter describes how this information base can be used to estimate a 50 year series of daily maximum and minimum values at any location in the study area of South Africa, Lesotho and Swaziland.

CHAPTER 5

GENERATION OF DAILY TEMPERATURE TIME SERIES AT ANY LOCATION IN SOUTHERN AFRICA ON A ONE ARC MINUTE RASTER

5.1 INTRODUCTION

Temperature is a continuous variable, unlike rainfall which consists of discrete events. On any one day temperature will, therefore, be dependent on prevailing synoptic conditions which vary seasonally (hence monthly lapse rates), macro-location (hence temperature/lapse rate regions each with altitude dependent lapse rates), meso-location (hence altitude dependent sub-zones of regions) and micro-location (e.g. local topography induced cold air drainage; hence introduction of the topographic index). These determinants are all factored into the methodologies used to generate a daily temperature series for any selected period (e.g. 1950-1999) at any location in southern Africa. "Any location" in the context of this report implies any grid point (raster) in the Republic of South Africa, Lesotho and Swaziland with a one arc minute of a degree latitude and longitude spatial resolution, i.e. at ~ 1.6 km spacing, to which an altitude has been assigned. This raster is made up of 429 700 point values in the study area. The altitude at each co-ordinate was originally determined from, *inter alia*, 1:50 000 topographic sheets, and checked/corrected against a digital elevation model at 200 and 400 m resolution from the Department of Survey and Mapping as well as the 800 m DEM from the United States Geological Survey, as described in detail in Lynch (2003).

The broad procedures for temperature estimation at any location consist of

- selection of the "best" control station(s) for that location
- application of the regional and/or sub-zonal and monthly lapse rate to account for the altitude difference between the point of interest and its control station(s)
- computation of an initial daily time series of T_{mx} and T_{mn} at any point of interest and
- determination of final daily temperature values following logic checks and those which account for spatial and temporal discontinuities of temperature values resulting from inter-monthly "jumps" in lapse rates and discrete lapse rate differences at the boundaries between lapse rate regions and sub-zones.

5.2 SELECTION OF "BEST" CONTROL STATIONS FOR ESTIMATION OF DAILY TEMPERATURE AT AN UNMONITORED POINT

5.2.1 Selection of Best Stations in Sub-Zones of those Regions which are Delimited by Threshold Altitudes, at Altitudes Below the Threshold

In Chapter 3 sub-zones of lapse rate regions were delimited by altitude in Regions 5, 6, 8/9, 10 and 12 (Table 5.1) and, with exception of Region 8/9, these were coastal

regions in which oceanic influences resulted in strong inverse lapse rates up to clearly discernible altitude thresholds, i.e. the “dog-leg” effect. These sub-zones required a different control station selection because of the relatively invariate sub-zone delimitation by altitude.

Table 5.1 Summary of altitude thresholds for the delimitation of lapse rate regions into sub-zones

Region Number and Name	Altitude Threshold (m)			
	T _{mx} and Period		T _{mn} and Period	
5 Eastern Cape Coast	< 400 m	Oct – Mar	N/A	
	< 250 m	Apr, Sep	N/A	
	< 100 m	May – Aug	N/A	
6 Southwest Cape Coast	< 200 m	All months	N/A	
8/9 Northern Cape	< 800 m	All months	N/A	
10 Southern Cape	< 200 m	All months	N/A	
12 West Coast	< 200 m	All months	< 150 m	All months

In order to simplify computational procedures, the different threshold altitude for the coastal lapse rate regions (Regions 5, 6, 10 and 12) were all set at 200 m for all months and for both maximum temperature (all four regions) as well as minimum temperature (Region 12).

The procedure for control station selection for a grid point located below 200 m altitude in coastal Regions 5, 6, 10 and 12 was as follows:

- Within the lapse rate region, scan for candidate temperature stations which have altitudes below the threshold 200 m, *plus* an altitudinal “grey zone” of 50 m, i.e. scan for control stations with altitudes < 250 m.
- Weight each qualifying control temperature station for suitability using

$$W_x = D_x * \Delta A_x$$

where W_x = weighting for control station ‘x’ being tested
 D_x = distance (km) between point and the control station ‘x’ being tested and
 ΔA_x = altitude difference (m) between the point and control station ‘x’.

- This simple weighting factor was arrived at following much experimentation with higher order weighting combinations.
- By this procedure identify the “best” (lowest weighting) control station, c1, and the second best, c2. For example, the best may be at $D_{c1} = 10$ km and $\Delta A_{c1} = 20$ m, $\therefore W_{c1} = 10 \times 20 = 200$; the second best may be at $D_{c2} = 8$ km and $\Delta A_{c2} = 40$ m, $\therefore W_{c2} = 8 \times 40 = 320$.
- Because of the very strong inverse lapse rates in most months in many of these sub-zones an element of caution needs to be built into daily temperature estimates; hence the selection of 2 control stations from which estimates are to be made, from which a single value is then calculated by weighting the 2 temperature estimates for a given day by an inverse distance weighting (IDW), as follows:

$$W_{c1,IDW} = \frac{W_{c2}}{W_{c1} + W_{c2}}$$

$$W_{c2,IDW} = 1 - W_{c1,IDW}$$

where $W_{c1,IDW}$ = the temperature weighting for the best station and
 $W_{c2,IDW}$ = the temperature weighting for the second best station.

- In the case of the inland Region 8/9 where the threshold altitude is 800 m, the same 50 m additional altitudinal grey zone was applied. Control station scanning for a grid point at altitudes < 800 m was, therefore, from any station within Region 8/9 with an altitude < 850 m.

5.2.2 Selection of Best Stations in Sub-Zones of those Regions which are Delimited by Threshold Altitudes, but at Altitudes Above the Threshold

- Select temperature stations within the applicable coastal region (i.e. 5, 6, 10, 12) at altitudes above the 200 m threshold, minus a 50 m grey zone at lower altitudes, i.e. stations above 150 m would qualify.
- No grey zone stations from other adjacent regions are considered.
- For Region 8/9 the selection would be from control temperature stations with altitudes > 750 m.
- Weight the stations as described in Section 5.2.1, in order to select the best and second best stations from which a point's initial weighted temperatures are to be calculated.
- Compute the inverse distance weighting for the best and second best control stations at the point by the procedures described in the previous section (Section 5.2.1).

5.2.3 Selection of Best Stations in Other Temperature Regions

- Within the other regions, viz. 1-4, 7 and 11, the best and second best control stations for a point are selected by using the weighting procedures outlined in Section 5.2.1.
- The inverse distance weighting is applied to the best and second best stations, again as outlined in Section 5.2.1.
- Once again, no stations outside the defined temperature region's boundary are considered.

5.2.4 Summary of Procedures for Selecting Best Control Temperature Stations

The procedures for selecting the best two temperature control stations at each point of interest, as described in Sections 5.2.1 to 5.2.3, are summarised in Figure 5.1.

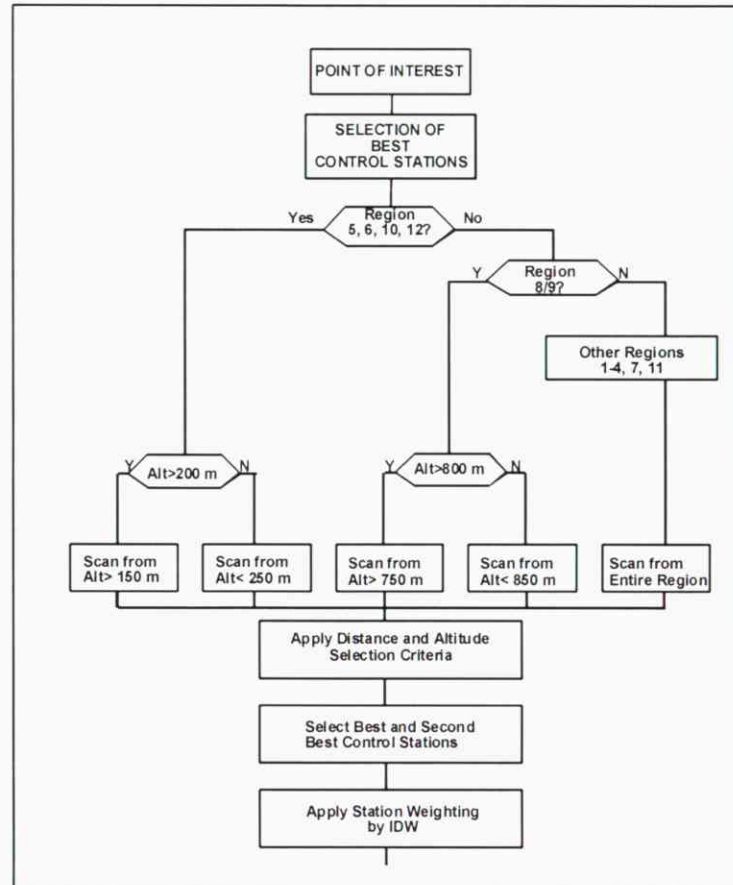


Figure 5.1 Summary of procedures for selecting best control temperature stations

5.3 COMPUTATION OF AN INITIAL (UNADJUSTED) TIME SERIES OF DAILY TEMPERATURES

Compute a point's initial temperature for a given day by adjusting the best and second best control station's temperature values for that day by the product of the relevant lapse rate for the region/month and the difference in altitude between control station and the point, and then finding the weighted value of the two temperatures, as follows:

$$T_{p,d} = \left[T_{c1,d} + L_{R,m} (A_p - A_{c1}) \right] \times W_{c1,IDW} + \left[T_{c2,d} + L_{R,m} (A_p - A_{c2}) \right] \times W_{c2,IDW}$$

where

- $T_{p,d}$ = weighted temperature at point 'p' for day 'd'
- $T_{c1,d}$ = temperature at the best control stations, 'c1', for day 'd'
- $T_{c2,d}$ = temperature at the second best control station, 'c2', for day 'd'

- $L_{R,m}$ = lapse rate (in °C/1000 m) for region 'R' and month 'm' in which day 'd' falls
- A_p = altitude (m) at point 'p'
- A_{c1} = altitude (m) at the best control station, 'c1'
- A_{c2} = altitude (m) at the second best control station, 'c2'
- $W_{c1,IDW}$ = inverse distance weighting for the best control station, 'c1'
- $W_{c2,IDW}$ = inverse distance weighting for the second best control station, 'c2'.

- Repeat the above procedure for both maximum and minimum temperatures at the point, then repeat at that point for the entire time series (e.g. 1950-1999).
- Thereafter repeat for every point in that region, followed by repeating for all points in all other regions.

5.4 COMPUTATION OF FINAL VALUES OF TIME SERIES OF DAILY TEMPERATURES

5.4.1 Temporal and Spatial Lapse Rate and Temperature Discontinuities

Despite “smoothing” of lapse rates of specific regions (cf. Chapter 3) there exist discontinuities of lapse rates from month to month within a region, as well as discontinuities of a given month's lapse rate and that of the same month at the boundary between adjacent lapse rate regions (cf. Table 3.1). In order to adjust for these abrupt breaks in lapse rates and, consequently, in temperature values in a daily time series within a year and also temperature values at adjacent points which may be in different regions, a series of adjustments are necessary to the initial temperature values computed from procedures described in Sections 5.2 and 5.3.

5.4.2 Accounting for Lapse Rate Discontinuities Between Months

- If a region's lapse rate “jumps” from one month to the next, the given point's temperature between the last day of a month and first day of the next month may also exhibit a discontinuity, for that reason alone.
- For example, if January's and February's maximum temperature LRs are, respectively, -4.0 and -6.0 °C/1000 m, the difference in altitude between the control station and the point is 300 m (with the point at a lower altitude in this example) and daily maximum temperature for both 31 January and 1 February is 20 °C at the control station, then LR adjusted temperatures for the two days would be:

$$31\text{January: } 20^\circ - \frac{300}{1000} (-4.0) = 21.2^\circ \text{C}$$

$$01\text{February: } 20^\circ - \frac{300}{1000} (-6.0) = 21.8^\circ \text{C}$$

i.e. the inter-monthly LR difference by itself would result in a temperature difference of 0.6° for identical initial temperatures.

- In order to account for such inter-monthly "jumps" of lapse rates, a Fourier Analysis (cf. Section 4.5.4) was applied to monthly lapse rate values, resulting in smoothed daily values of lapse rates at each control station.

5.4.3 Accounting for Lapse Rate Discontinuities Between Adjacent Regions and Sub-Zones, for a Given Month

Two options were considered in order to adjust initial daily temperatures at those points close enough to boundaries of lapse rate regions and/or sub-zones and which could be affected by lapse rate discontinuities.

5.4.3.1 The Grey Zone Grading Option for Weighting Initial Temperatures

In this option the following steps were undertaken:

- Compute daily temperatures for a given month at all grid points within a specific region (e.g. Region X) with the respective lapse rate for that region.
- Additionally, compute temperatures at those points within grey zones of other regions which are adjacent to Region X, but using Region X's lapse rates.
- Within a grey zone assume the degree of influence of an adjacent region on a point to be graded, depending on the point's location within the grey zone and its distance from the boundary between adjacent regions.
- This grading is undertaken by further delimiting, within the 15 arc minute grey zone, a 5 arc minute grey zone, as shown in Figure 5.2.
- Weighting of a point's daily temperature would be as in the example which follows, with reference to Figure 5.2:
 - Point #1 is entirely within the sphere of influence of Region X and would retain its temperature value (i.e. 1.0 times Region X weighting).
 - Point #2, which lies between 15 and 5 arc minutes from a region boundary line, would have its temperature weighted by 0.75 Region X plus 0.25 Region Y.
 - Points #3 and #4, both within 5 arc minutes of a boundary line, would be given 0.50 : 0.50 weightings from each of Regions X and Y.
 - Point #5 would have temperatures weighted 0.25 Region X plus 0.75 Region Y.
 - Point #6 would retain its temperature value.

This is a relatively simple weighting procedure to follow when the grey zone is one which is between only 2 adjacent lapse rate regions. However, it becomes complicated when the grey zone applies to 3 or 4 adjacent lapse rate regions, or when some regions have adjacent altitudinally defined sub-zones and others not, or when taking cognisance of the abrupt discontinuities around the threshold altitude used in sub-zone delimitation, and also when sub-zones below the altitude threshold overlap into the standard 15 arc minute grey zone regions. For these reasons a second option was considered.

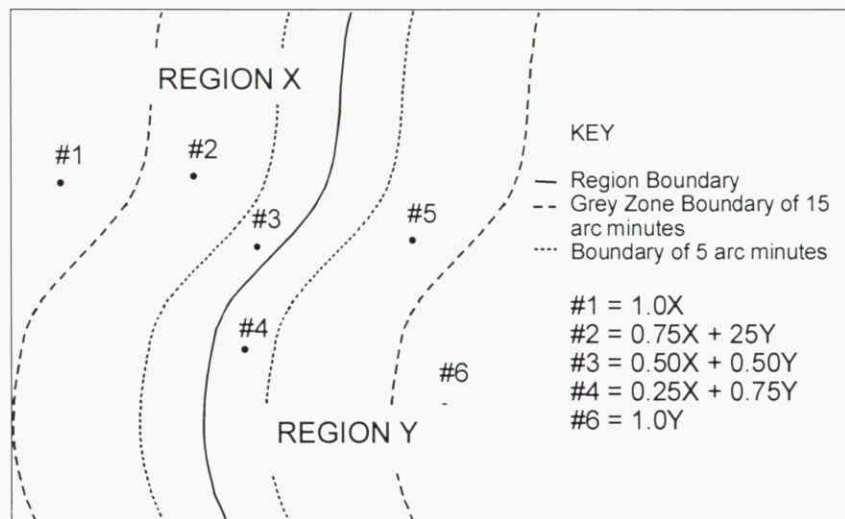


Figure 5.2 Weighting of temperature values within lapse rate regions and their distance related "grey zones"

5.4.3.2 The Surrounding Grid Points Option for Weighting Initial Temperatures

This option assumes that the transitional zone for temperature discontinuities between lapse rate regions does not extend beyond a distance of ~ 6.5 km, i.e. 4 arc minutes, or 2 raster points on either side of the point under consideration. The following steps are then undertaken:

- For a given point, scan for points within 2.85 arc minutes on either side of the point (hypotenuse of a 2 arc minute right angled triangle is $(2^2 + 2^2)^{0.5} = 2.828$).
- This yields a 5 x 5 arc minute grid, given the point in question plus 24 surrounding raster points (cf. Figure 5.3).
- If all 25 points fall within the same region or sub-zone, no weighting is applied to the temperature at the grid point of interest (Figure 5.3, Point #1).
- If one or more of the 24 surrounding points falls within one or more lapse rate regions/sub-zones, then the mean of the temperature at the point in question, plus the temperatures of the 24 surrounding points, is computed. That mean represents the value for that point (e.g. as in Figure 5.3, Points #2 and #3).

The advantage of this method is that temperature is weighted in a simple, but objective, manner between either 2, 3 or 4 lapse rate regions and also within a region which contains sub-zones. This method was, therefore, adopted to account for lapse rate discontinuities between regions and sub-zones.

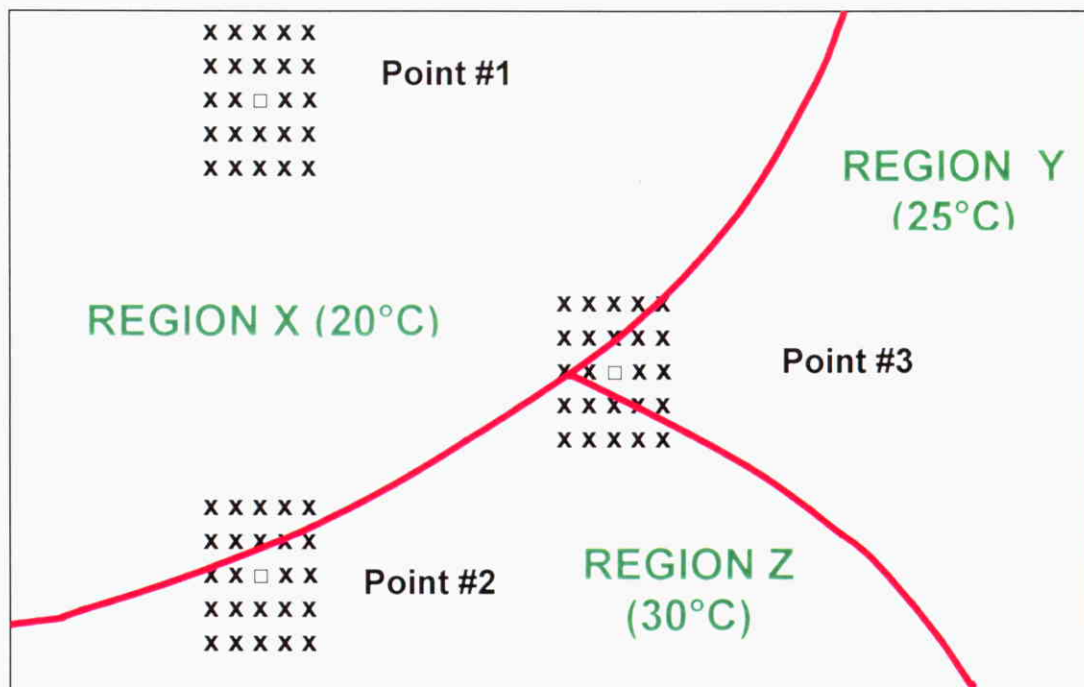


Figure 5.3 Example of the gridded temperature weighting method

- By way of example, if in Figure 5.3 all computed point temperatures in Region X were 20°C, all in Region Y were 25°C and all in Region Z were 30°C, then
 - Point #1 would have an unadjusted temperature remaining at 20°C
 - Point #2, with 17 of the 25 points in Region Z and 8 in Region X, would have its temperature of 30°C adjusted to 26.8°C $[(17 \times 30) + (8 \times 20)] / 25$
 - Point #3, with 7 of the points in Region X, 10 in Region Y and 8 in Region Z, would have its temperature of 25°C adjusted to 25.2°C $[(7 \times 20) + (10 \times 25) + (8 \times 30)] / 25$.

5.4.4 Accounting for Temperature Adjustments for Local Topographic Influences: Revisiting a Concept

In Chapter 3, different lapse rates were computed in Regions 1-3 and 11 for those stations which were exposed (i.e. with a Topographic Index ≥ 100) vs those which were more enclosed in valleys (and with a TI < 100). This was done in an attempt to account for any local topographic influences on temperature, especially for nocturnal cold air drainage in winter months. The distinction in lapse rates for TI ≥ 100 vs TI < 100 was not always very high (cf. Table 3.1). In trying to adjust temperatures by the TI was,

however, found in retrospect not to represent cross-sectional cold air drainage from crest to valley bottom (the short arrows in Figure 5.4), but rather longitudinal cold air

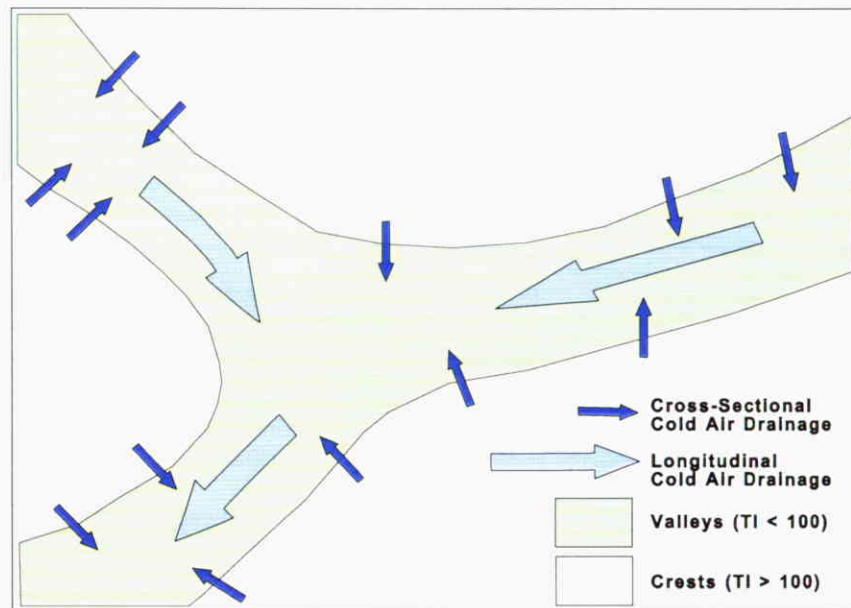


Figure 5.4 Schematic of longitudinal and cross-sectional cold air drainage, illustrating local topographic influences on temperature

drainage within a valley, i.e. from higher altitudes of the upper valley to the lower altitudes of the lower valley (the longer arrows in Figure 5.4).

Because there were, overall, not enough valley stations within a single valley system in a region to solve the more complex dynamics of longitudinal air drainage, the lapse rate adjustment by TI has not been used in this study. In those regions where the TI was found to be an important variable in lapse rate estimations (Regions 1-3, 11), the final lapse rates designated by "Without TI distinction" in Sections 3.3.4.5, 3.4.4.5, 3.5.4.5 and 3.12.4.4 were thus used in this research.

5.4.5 Daily Temperature Range Checks

Daily temperature time series having been generated from observed, infilled and extended temperature records at control stations, adjusted for regional/zonal/monthly lapse rates at any given point and adjusted for temporal/spatial lapse rate discontinuities, the final daily check involved the daily temperature range. On any day at any location the difference between T_{mx} and T_{mn} , if less than 1.5°C , was "forced" to be 1.5° by equally proportionate adjustments to both the maximum and minimum temperature values. This check was not only a logic check, but became necessary

because of several “smoothing” procedures the initial quality controlled observed temperature had undergone en route to a final set of temperature values for any given day at any specific location.

5.5 SUMMARY OF PROCEDURES

Using an inverse distance weighting at the “best” two control temperature stations for a point location in question, which were determined by different criteria depending on sub-zonation of lapse rate regions, an initial daily temperature was computed at the point with due consideration to the LR applicable to the region and the month. This initial temperature was first adjusted within a region for discontinuities in lapse rates between months, and then for discontinuities (for days in the same month) which occurred between adjacent regions/sub-zones because they may have had different LRs. No further adjustments for local topographic influences were applied. By these procedures a 50 year time series of daily maximum and minimum temperatures could be generated at a specific point, thereafter for all points within a lapse rate region and, finally, for all points covering the RSA, Lesotho and Swaziland.

CHAPTER 6

SUMMARY, PRODUCTS, POTENTIAL APPLICATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 SUMMARY

The research reported in this document set out to produce daily time series of maximum and minimum temperatures from as many qualifying temperature stations as possible in southern Africa (in this context RSA, Lesotho and Swaziland) for a common base period (1950-1999) and to use this database, together with techniques developed, to enable the generation of a 50 year daily time series of T_{mx} and T_{mn} at any unmonitored point in southern Africa.

This was achieved by

- gathering, quality controlling and evaluating a database, from qualifying temperature stations, of suitable daily temperature records in southern Africa (Chapter 2)
- determining regional and sub-zonal lapse rates of T_{mx} and T_{mn} at monthly time steps, by starting with simple procedures, progressing to more complex approaches and then simplifying once more (Chapter 3)
- developing and evaluating procedures to infill missing data and extend temperature records at the qualifying 973 control temperature stations to a common 50 year base period from 1950-1999 (Chapter 4)
- and then, utilising the above 50 year daily T_{mx} and T_{mn} database, together with the lapse rate information, to develop techniques to generate a 50 year daily time series at any location within southern Africa, with appropriate space/time checks for temperature discontinuities.

6.2 PRODUCTS

The tangible outcomes of this research have, to date, been

- a CD-ROM with a time series of daily maximum and minimum temperature values at 973 qualifying temperature stations, with missing values infilled and the record of each extended (where necessary) to cover a common 50 year base period 1950-1999;
- development of techniques to generate a 50 year time series of daily T_{mx} and T_{mn} values at any unmonitored location in southern Africa (i.e. at any one of the 429 700 one arc minute points) using the daily control station values from the 973 qualifying temperature stations together with regional/intra-seasonal lapse rates and with space/time adjustments for lapse rate discontinuities;

- application of this technique of generating daily temperature time series in recent scientific publications, for example, on climate change impacts on water resources in southern Africa (Perks *et al.*, 2000; Schulze and Perks, 2000), sugarcane water use (Schulze *et al.*, 2000) and afforestation water use (Gush *et al.*, 2002); and
- including the technique as an option for inputting daily temperature values in a national Quaternary Catchments database for use with the *ACRU* model throughout southern Africa.

6.3 POTENTIAL APPLICATIONS

Appropriately long daily time series of T_{mx} and T_{mn} can now be applied in climatic and hydrological computations, yielding from first order products to fourth order products.

- *First order* products include direct and revised computations of monthly means and temperature ranges, as well as cold spell and heat wave occurrences;
- *Second order* products include standard deviations of daily temperatures, month-by-month, probabilities of temperature thresholds being exceeded, computations of extremes and of any time trends;
- *Third order* output includes those of frost occurrences, heat units and chill units as well as higher order statistics thereof; while
- *Fourth order* applications are those in which temperature parameters are used as surrogates in computations of vapour pressure, relative humidity, solar radiation and reference potential evaporation – those hydrological applications for which this research was undertaken in the first instance.

6.4 RECOMMENDATIONS FOR FUTURE RESEARCH

This project has shown that it would be worthwhile expanding research efforts in future in, *inter alia*,

- temperature data rescue, as evidenced by the retrogression of the temperature recording network in southern Africa over the past decade and the possibility of many data not yet having been computerised (Chapter 2)
- updating the daily temperature database presently held in the School of Bioresources Engineering and Environmental Hydrology at the University of Natal to always be as current as possible
- re-visiting, and possibly re-delineating the temperature lapse rate regions in light of many temporal and spatial discontinuities that exist (Chapters 3; 4)
- re-looking the topographic valley index concept for incorporation of a TI in temperature estimations and
- re-assessing the Fourier Analysis as a method of infilling the large numbers of missing daily temperatures.

6.5 A FINAL REQUEST

It is envisaged that the control temperature station database with 973 stations' records extended to a common base period of 50 years, and the gridded temperature values which can be generated at any location within southern Africa, will find wide application. To this end it is hoped that users will feed back any problems they experience and suggestions they have to the authors for possible rectification.

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