THE CREATION OF COOLING DEGREE (CDD) AND HEATING DEGREE DAY (HDD) CLIMATIC MAPS FOR SOUTH AFRICA

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Abstract

The current six climatic regions map used in the SANS 204 (2011) South African National Building Standards does not optimally support quantified design decisions within the built environment. It also does not give an indication of the amount of cooling and heating energy that would be required within a particular climatic region.

To address this, the application of Standard Effective Temperature (SET) was assessed during the course of 2014 in an attempt to provide a rational and more accurate replacement for the current SANS 204, six zone climate map of South Africa. The intention was to create maps based on a set of factors that determine human comfort, such as relative humidity and dry-bulb temperature. The intention was also to create a system that could better support adaptive building design decisions in creating comfortable thermal environments.

Over the last 100 years, many different heat strain indices have been proposed to indicate comparative thermal comfort levels. After reviewing these standards the team concluded that Standard Effective Temperature (SET), as proposed by Gagge, might be the best index as it considers the effect of humidity in the experience of thermal comfort. SET maps were produced using the same data as had been used to produce the Köppen-Geiger map. Verification of the SET maps showed weak to poor correlations between SET and the expected building heating and cooling energy demands.

As a result of the poor correlation, the decision was made to create a set of maps based on interpreted degree days in order to establish if such an index would give a better correlation to building energy demand. A very large dataset of 21 years of hourly data, which assumes an A2 climate change scenario at a 50 km resolution, was used in the process. An algorithm was used to resample the source data from 50 km to 5 km. This 5 km grid dataset was used to produce heating and cooling degree day maps. An excellent correlation between degrees days and modelled building energy demand was found.

This paper describes the data processing, creation of the degree day map and the subsequent verification processes in detail.

1. Introduction

An analysis of the current SANS 204 (2011) six zone map highlighted that the map does not optimally support quantified design decisions within the built environment. This was because the map could not be related to actual energy usage, nor could it be used to support passive design strategies such as solar heating, thermal mass and natural ventilation. In addition the poor resolution of the map may have exacerbated the problem.

The first quantitative classification of world climate was created by the German scientist Wladimir Köppen (1846-1940) in 1900. It has been updated by Rudolf Geiger (1894-1981). The Köppen-Geiger climatic map became the international de-facto standard (Kottek *et al.*, 2006).

As a first step the CSIR created a detailed Köppen-Geiger map to quantify the current climatic conditions as accurately as possible in South Africa using a well-known international climate map standard (Figure 1) (Conradie et al., 2012). The Köppen-Geiger climatic classification uses a concatenation of a maximum of three alphabetic characters that describe the main climatic category, amount of precipitation and temperature characteristics. This is based on a set of empirical formulas detailed in Tables 1 and 2. A detailed historic dataset of 20 years of temperature and precipitation spanning 1985 to 2005, based on a 1 km x 1 km grid, was obtained from the South African Agricultural Research Council (Agrometeorology staff, 2001). ArcMap Geographic Information System (GIS) was used to compile a climatic map using the algorithms as described by Kottek (2006) (Figure 1).

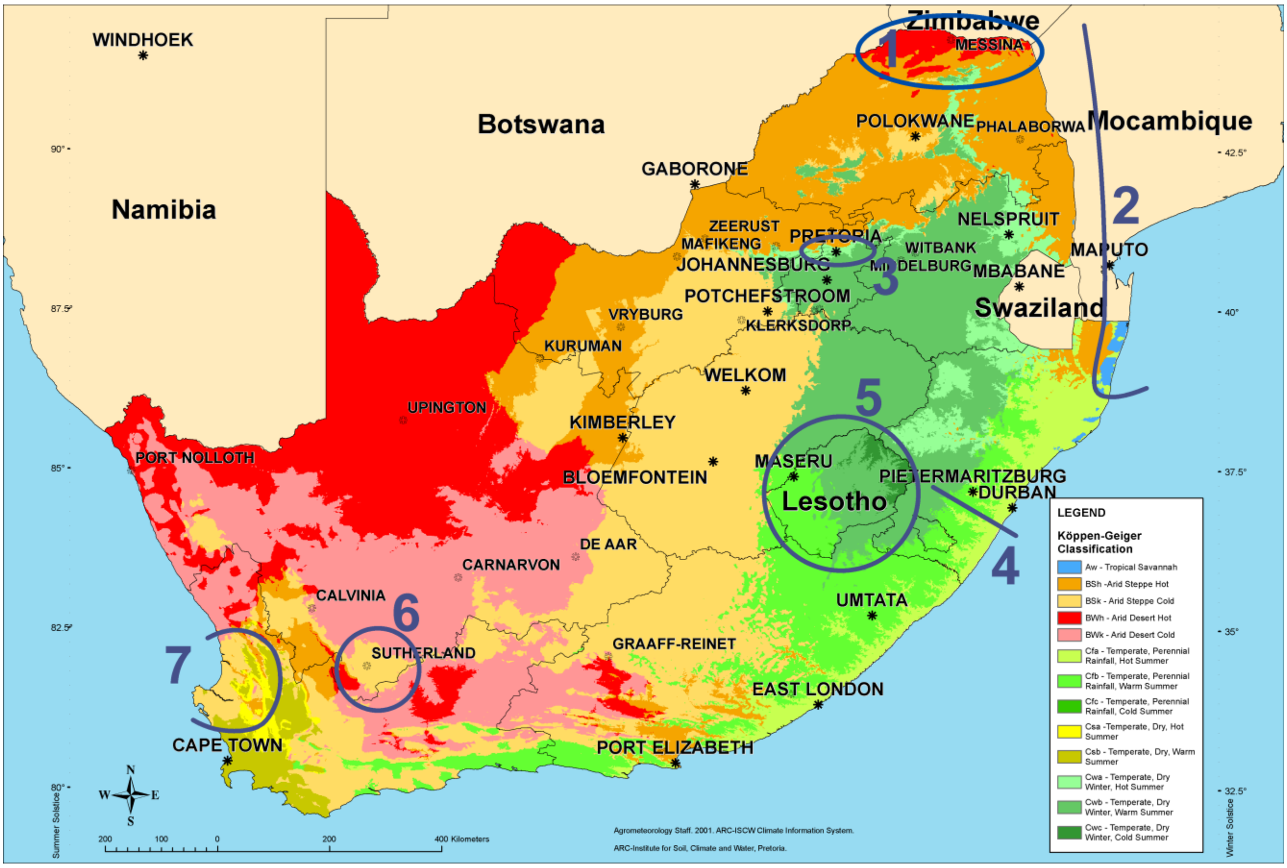

Figure 1 CSIR Köppen-Geiger map based on 1985 to 2005 Agricultural Research Council data on a very fine 1 km x 1 km grid (authors)

Table 1 lists the formulae that were used to derive the first two letters of the classification. The annual mean temperature is denoted by T_{ann} and the monthly mean temperature of the warmest and coldest months by T_{max} and T_{min}, respectively. P_{ann} is the accumulated annual precipitation and P_{min} is the precipitation of the driest month. The values P_{smin}, P_{smax}, P_{wmin} and P_{wmax} are defined as the lowest and highest monthly precipitation values for the summer and winter half-years for the particular hemisphere considered. All temperatures are calculated in °C and monthly precipitation in mm/ month and P_{ann} in mm/ year.

In addition to the temperature and precipitation values, a dryness threshold P_{th} in mm is introduced for the arid climates (B), which depends on $\{T_{ann}\}$, the absolute measure of the annual mean temperature in °C and on the annual cycle of precipitation.

$$P_{th} = \begin{cases} 2\{T_{ann}\} & \text{if at least 2/3 of the annual precipitation occurs in winter,} \\ 2\{T_{ann}\} + 28 & \text{if at least 2/3 of the annual precipitation occurs in summer,} \\ 2\{T_{ann}\} + 14 & \text{in all other cases.} \end{cases}$$

Table 1 Key to calculating the first two letters of Köppen-Geiger

Type	Description	Criterion
A	**Equatorial climates**	$T_{min} \geq +18$ °C
Af	Equatorial rainforest, fully humid	$P_{min} \geq 60$ mm
Am	Equatorial monsoon	$P_{ann} \geq 25(100-P_{min})$
As	Equatorial savannah with dry summer	$P_{min} < 60$ mm in summer
Aw	Equatorial savannah with dry winter	$P_{min} < 60$ mm in winter
B	**Arid climates**	$P_{ann} < 10\ P_{th}$
BS	Steppe climate	$P_{ann} > 5\ P_{th}$
BW	Desert climate	$P_{ann} \leq 5\ P_{th}$
C	**Warm temperate climates**	-3 °C $< T_{min} < +18$ °C
Cs	Warm temperate climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm
Cw	Warm temperate climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
Cf	Warm temperate climate, fully humid	Neither Cs nor Cw
D	**Snow climates**	$T_{min} \leq -3$ °C
Ds	Snow climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm
Dw	Snow climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
Df	Snow climate, fully humid	Neither Ds nor Dw
E	**Polar climates**	$T_{max} < +10$ °C
ET	Tundra climate	0 °C $\leq T_{max} < +10$ °C
EF	Frost climate	$T_{max} < 0$ °C

Table 2 indicates how the additional temperature conditions, i.e. the third letter, was determined for arid climates (B) as well as for warm temperate (C) and snow climates (D). In this table T_{mon} is the mean monthly temperature in °C.

Table 2 Key to calculating the third-letter temperature classification

Type	Description	Criteria
h	Hot steppe/desert	$T_{ann} \geq +18$ °C
k	Cold steppe/desert	$T_{ann} < +18$ °C
a	Hot summer	$T_{max} \geq +22$ °C
b	Warm summer	not (a) and at least 4 $T_{mon} \geq +10$ °C
c	Cool summer and cold winter	not (b) and $T_{min} > -38$ °C
d	Extremely continental	like (c) but $T_{min} \leq -38$ °C

The Köppen-Geiger climatic map clearly highlighted the different climatic regions that proved valuable in the subsequent creation and verification of the Standard Effective Temperature (SET) and Cooling and Heating Degree maps. It also indicated that the maps would need to be of sufficient resolution so that important climatic variation and detail do not meld. A resolution of 5 km x 5 km cells was chosen.

Some notable South African climatic characteristics are indicated by numbers on the map in Figure 1:

1) Very hot Limpopo river valley, classification BWh.
2) A tropical descender into the northern parts of the Kwa-Zulu province of South Africa, classification Aw.
3) Pretoria has three climatic zones, i.e. BSh, Cwa and Cwb.
4) The climatic staircase effect starting from humid Durban, moving into the Natal midlands and eventually the Drakensberg mountains corresponding to classifications Cfa, Cfb and Cwb respectively.
5) The very cold Lesotho highlands, classification Cfb, Cwb and Cwc. The latter is very nearly a snow climate.
6) The cold high lying area around Sutherland with a classification of BSk.
7) The arid climatic region lying north of Cape Town starting at Yzerfontein with a classification of BSk.

2. Some International precedents

Further analysis of the Köppen-Geiger map indicated that it would not be suitable to support energy efficient building design directly, because human comfort in a particular climatic region is determined by the environmental factors of air temperature (dry bulb), radiant temperature, air speed and humidity. (ASHRAE 55, 2004) The Köppen-Geiger functions are based on air temperature and precipitation. Furthermore it is also not suitable to estimate the anticipated amount of cooling and heating energy, because it is not taking account of the substantial diurnal variations in temperature normally experienced in South Africa. Other international energy map precedents were therefore studied.

2.1 Global Building Performance Network (GBPN)

The GBPN (GBPN, 2015) climate classification divides the world into 11 key regions such as Western Europe, Eastern Europe, Middle East and Sub-Saharan Africa. Within each region the different climate zones are considered in order to capture the difference in building energy use, caused by climate variations. The differentiation among different climate zones is based on several climatic factors in terms of their influence on building energy demand for space heating, cooling and dehumidification, namely:

- Heating Degree Days (HDD)
- Cooling Degree Days (CDD)
- Relative Humidity of the warmest month (RH)
- Average Temperature of the warmest month (Tdb)

Abovementioned parameters were processed by means of the *ArcMap*™ Geographic Information System (GIS) software. The GIS analysis facilitated the combination of the parameters, according to a certain set of empirical criteria for each climate zone. Each selected geographical area corresponds to a certain climate zone categorized by energy needs for space heating, cooling and dehumidification.

In this system there are a total of 17 climate zones. Each of them is characterized in terms of heating and/or cooling demand, which varies from “low” to “very high” depending on the amount of average annual HDD and CDD in each area. The need for dehumidification is determined on the basis of the combination of values for relative humidity and average temperature of the warmest month. It is assumed that if relative humidity of the warmest month is higher than 50% and average temperature of the warmest month is higher or equals 23°C, then dehumidification in buildings is needed. Such a climate split gives the opportunity to capture variation in energy needs for heating, cooling and dehumidification in different geographical locations.

2.2 USA International Energy Conservation Code (IECC) and Building America climatic regions

Prior to 2004, there was no single, agreed upon climate zone map for the United States for use with building codes. Four different methods for specifying climate-dependent requirements were used by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the International Energy Conservation Code (IECC) for their residential and commercial building standards. ASHRAE used 38 climate groupings identified for 240 cities, while the IECC used 33 different climate zones based on county boundaries. In most cases, the climate data needed to determine which requirements apply were not included in the standard or code documents.

In the early 2000s, researchers at the U.S. Department of Energy's Pacific Northwest National Laboratory (PNNL) created a simplified map of U.S. climate zones. The map was based on analysis of the 4 775 U.S.A. weather sites identified by the National Oceanic and Atmospheric Administration (NOAA) as well as widely accepted classifications of world climates that have been applied in a variety of different disciplines. This PNNL developed map divided the United States into eight temperature-oriented climate zones. These zones are further divided into three moisture regimes designated A, B, and C. The IECC map allows for up to 24 potential climate designations. The new climate zones were set along county boundaries, making it easier for builders to determine what climate zone applied to a specific building. The 2004 IECC Supplement was the first model energy code to adopt this new climate zone map. It first appeared in ASHRAE 90.1 (ASHRAE 90.1, 2004). The climate zone map was also adopted by ENERGY STAR for Homes in 2006. In 2003, with direction from the Building America teams, in particular Building Science Corporation, researchers at the Department of Energy National Renewable Energy Laboratory (NREL) further simplified the new IECC map for purposes of the Building America Program. They divided the map into eight climate zones based on temperature, precipitation, and heating and cooling degree days. The zones are hot-humid, hot-dry, mixed-dry, mixed-humid, marine, cold, very cold, and subarctic. Building America prepared a guide that includes detailed definitions of each climate zone and a listing of all U.S. counties by state, indicating the climate region in which each county is located.

2.3 Standard Effective Temperature (SET)

Victor Olgyay initiated the concept of bioclimatic design in 1963 (Olgyay, 1963). He was a leading researcher in the investigation on the relation between architecture and energy. Other researchers such as Givoni developed the concept further by changing the original square bioclimatic chart to overlays on a regular psychrometric chart (Givoni, 1969). Watson and Labs refined the principles further (Watson *et al*., 1993).

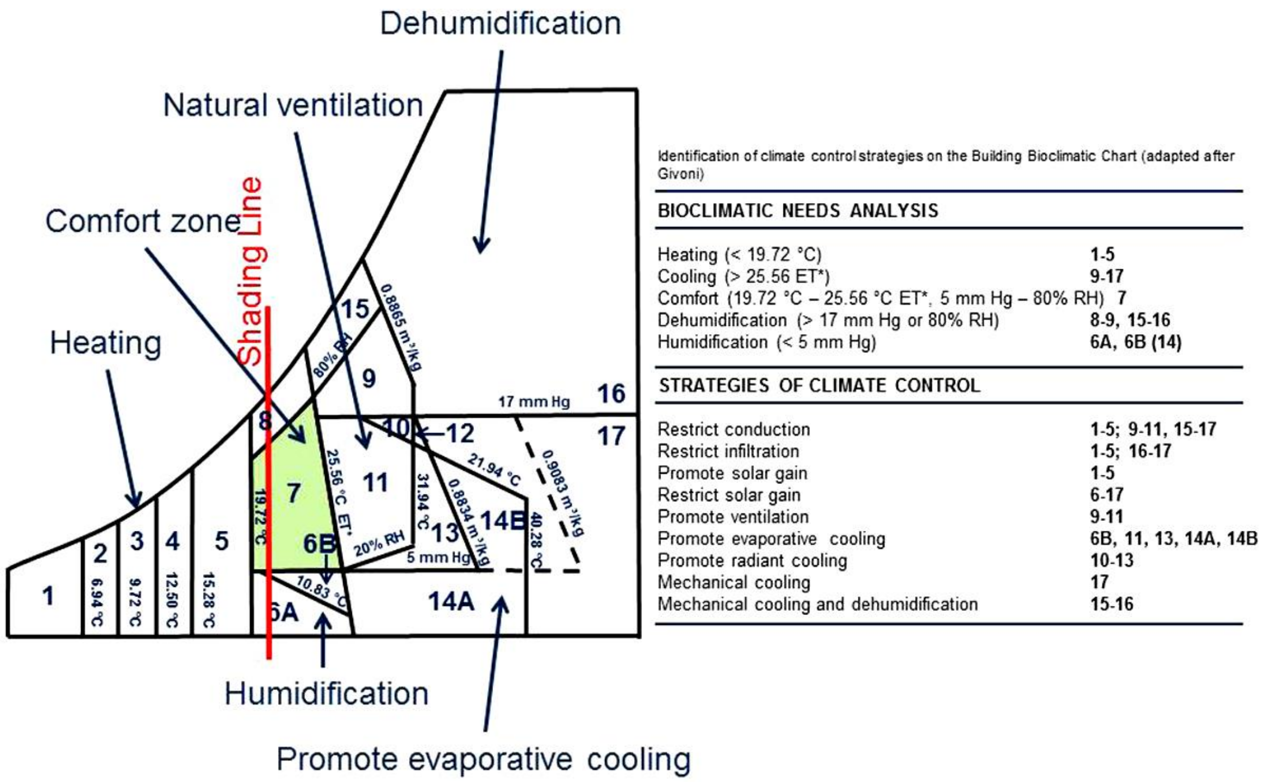

Figure 2 Strategies of climate control overlaid on a psychrometric chart (After Watson and Labs).

The work of the bioclimatic researchers and Gonzalez (Gonzalez *et al*., 1974) indicated that Standard Effective Temperature (SET) is a very good heat strain index or indication of human comfort. SET is closely related to the New Effective Temperature (ET*) that has been used in the Watson and Labs climate strategies (Figure 2).

The Authors used downscaled data from the conformal cubic atmospheric model (CCAM) of the National Centres for Environmental Prediction (NCEP) (Engelbrecht *et al*., 2011) to produce SET maps covering South Africa for winter and summer using a simplified method described by Sarhan (2012). This simplified method utilized the following algorithms:

$$P_{vs} = 0.133322 \times \exp\left[18.6686 - \left(\frac{(4030.183)}{(T+235)}\right)\right] \tag{1}$$

$$SH = 622 \times \frac{P_{VS}}{(101.325 - P_{VS})} \tag{2}$$

$$AH = RH \times SH \tag{3}$$

$$T_{LS} = T_L + 0.023(T_L - 14)AH \tag{4}$$

Where:

P_{vs}	is the saturation vapour pressure
T	is the dry bulb temperature
SH	is the saturation humidity
AH	is absolute humidity
RH	is relative humidity

Correlations between SET and expected building heating and cooling energy demands were found to be weak to poor. As a result of the poor correlations, the decision was made to create a set of maps based on interpreted degree days in order to establish if such an index would give a better correlation to building energy demand.

2.4 Degree days

The Degree-days method has its origins in agricultural research where knowledge of the cumulative variation in outdoor air temperature is important. This concept is readily transferable to buildings and can be used in the analysis and assessment of weather related energy consumption in buildings. Degree-days are essentially a summation of the differences between the outdoor temperature and a base temperature over a specified time period. A key issue in the application of degree-days is the definition of this base temperature, which, in buildings, relates to the energy balance of the building and systems. This applies to both heating and cooling systems, which leads to the dual concepts of Cooling Degree Days (CDD) and Heating Degree Days (HDD). (CIBSE TM41, 2006).

The most rigorous and precise method of calculating degree-days is to sum hourly temperature differences to the base temperature and divide these by 24. (CIBSE TM41, 2006). This method was adopted as it takes the often significant diurnal temperature variation in South Africa into account. Formula 5 was used for the calculation of heating degree days and formula 6 for cooling degree days.

$$D_d = \frac{\sum_{j=1}^{24} (\theta_{o,j} - \theta_b)_{((\theta_{o,j} - \theta_b) > 0)}}{24} \tag{5}$$

$$D_d = \frac{\sum_{j=1}^{24} (\theta_b - \theta_{o,j})_{((\theta_b - \theta_{o,j}) > 0)}}{24} \tag{6}$$

Where:

D_d	is the degree-days for one day
θ_b	is the base temperature
$\theta_{o,j}$	is the outdoor temperature in hour *j*

In both formulas the subscripts denote that only positive values are taken into account in the relevant calculation.

3. Methodology

3.1 Input data set and climate change

To ensure the long term applicability of the climate map, it was decided, that over and above the use of historic climatic data, climate-change should also be factored into the creation of the maps. An A2 climate-change scenario of the Special Report on Emission Scenarios (SRES) for the period 1961-2100 (Engelbrecht *et al*., 2011) was used. The A2 scenario is where technological change is more heterogeneous than in an A1 scenario. Regions with abundant energy and mineral resources evolve more resource-intensive economies, while those poor in resources place a very high priority on minimizing import dependence through technological innovation to improve resource efficiency and make use of substitute inputs. The fuel mix in different regions is determined primarily by resource availability. High-income but resource-poor regions shift toward advanced post-fossil technologies (renewables or nuclear), while low-income resource-rich regions generally rely on older fossil technologies.

Projections of future global climate change such as those described in Assessment Report Four (AR4) of the Inter-governmental Panel on Climate Change (IPCC), are based on coupled global climate models (CGCMs) that simulate the coupled ocean, atmosphere and land-surface processes. CGCMs are computationally very expensive and are typically run on super computers. When used to simulate climate over a period of a century these models are typically applied at horizontal resolutions of 100 – 200 km. However, more detailed simulations are required for regional climate-change impact studies and to drive application models such as required for energy use estimates to support passive design in the construction industry. Dynamic regional climate models (RCMs) are used to obtain such detailed projections. Present day computing power allows RCMs to be applied at resolutions of about 50 km. (Engelbrecht *et al*., 2011)

In the application described in this paper the CSIR Natural Resources and Environment unit (NRE) used a conformal cubic atmospheric model (CCAM) of the National Centres for Environmental Prediction (NCEP) with cells of approximately 250 km. The sea-ice and bias-corrected sea-surface temperature (SST) of six CGCMs (CSIRO Mk 3.5, GFDL2.1, GFDL2.0, HadCM2, ECHAM5 and Miroc-Medres) were used to produce a dataset with cells of approximately 50 km. (Engelbrecht *et al*., 2011)

3.2 Lapse rate resampling procedure

In order to prevent the melding of climatic zones, the 50 km data received from the NRE was resampled to a 5 km grid through a lapse rate adjustment. Lapse rate is defined as the rate at which atmospheric temperature decreases with an increase in altitude. The terminology arises from the word lapse in the sense of a decrease or decline (Figure 3).

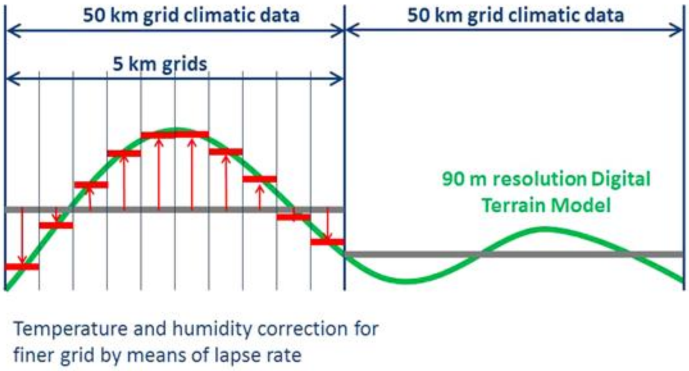

Figure 3 Lapse rate adjustment procedure to create 5 km resolution data

The 90 m resolution Shuttle Radar Topography Mission (SRTM) (Farr *et al.*, 2007) digital terrain model and the 50 km climatic data were spatially aligned. The SRTM was then resampled to both a 50 km and a 5 km resolution (Figure 3).

Data provided by NRE contained upper air temperature, surface air temperature and the height difference between these two points. This allowed the calculation of lapse rates for each month of each year for all 50 km cells using the following formula:

$$\frac{LR = (T_{Surface} - T_{Upper})}{H_{Delta}} \qquad (7)$$

Where:

LR	is the lapse rate
$T_{Surface}$	is the surface air temperature
T_{Upper}	is the upper air temperature
H_{Delta}	is the difference in altitude between the upper air and surface air

These calculated lapse rates were then used to adjust the dry bulb temperature as per the following formula:

$$T_{5km} = LR \times (Alt_{50km} - Alt_{5km}) + T_{50km} \qquad (8)$$

Where:

T_{5km}	is the lapse rate adjusted temperature for the 5 km grid cell

LR is the lapse rate
Alt_{5km} is the altitude for the 5 km grid cell
Alt_{50km} is the altitude for the 50 km grid cell
T_{50km} is the temperature for the 50 km grid cell

In this way a higher resolution 5 km data set was synthetically created for use in the creation of the SET and CDD/HDD maps.

3.3 Map production

Hourly data for relative humidity and dry-bulb temperature covering a 21 year period (10 years historic, the current year and 10 years predictive) was converted to a raster dataset using *ArcMap* GIS. This raster dataset was then resampled to a 5 km grid using the method and formulas outlined above. An average year was then calculated by taking the average for each hour of the year across the 21 years data. From this "average year" HDD and CDD were calculated using the method and formulas described above.

Two maps were produced, HDD and CDD, using 18 °C as the base temperature (Figure 4) with defined breaks of approximately 300 Degree Days used for delineating the map classes. These classes were then simplified further into Low, Medium and High (LMH) energy demand for both heating and cooling.

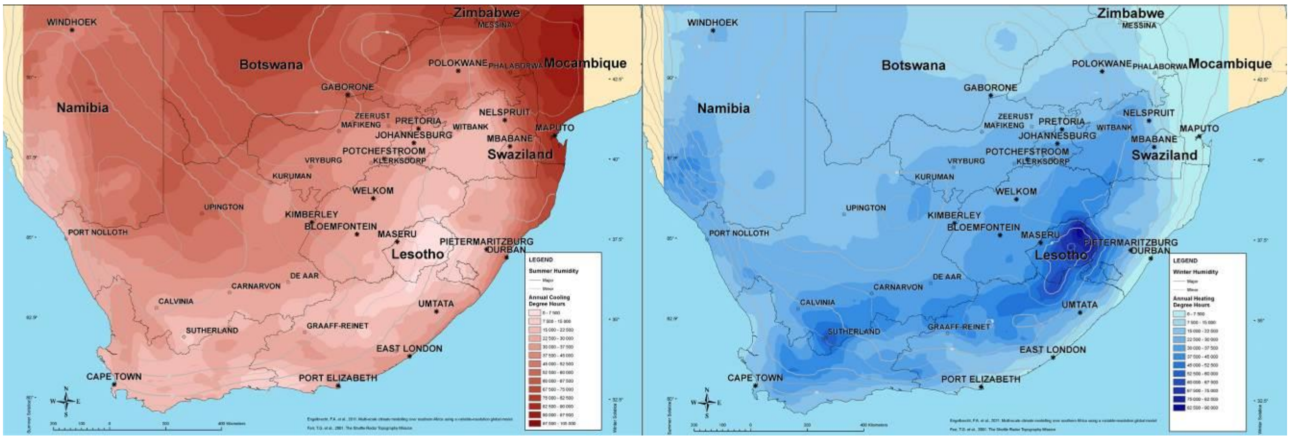

Figure 4 Separate Cooling and Heating degree maps before combination into a single map.

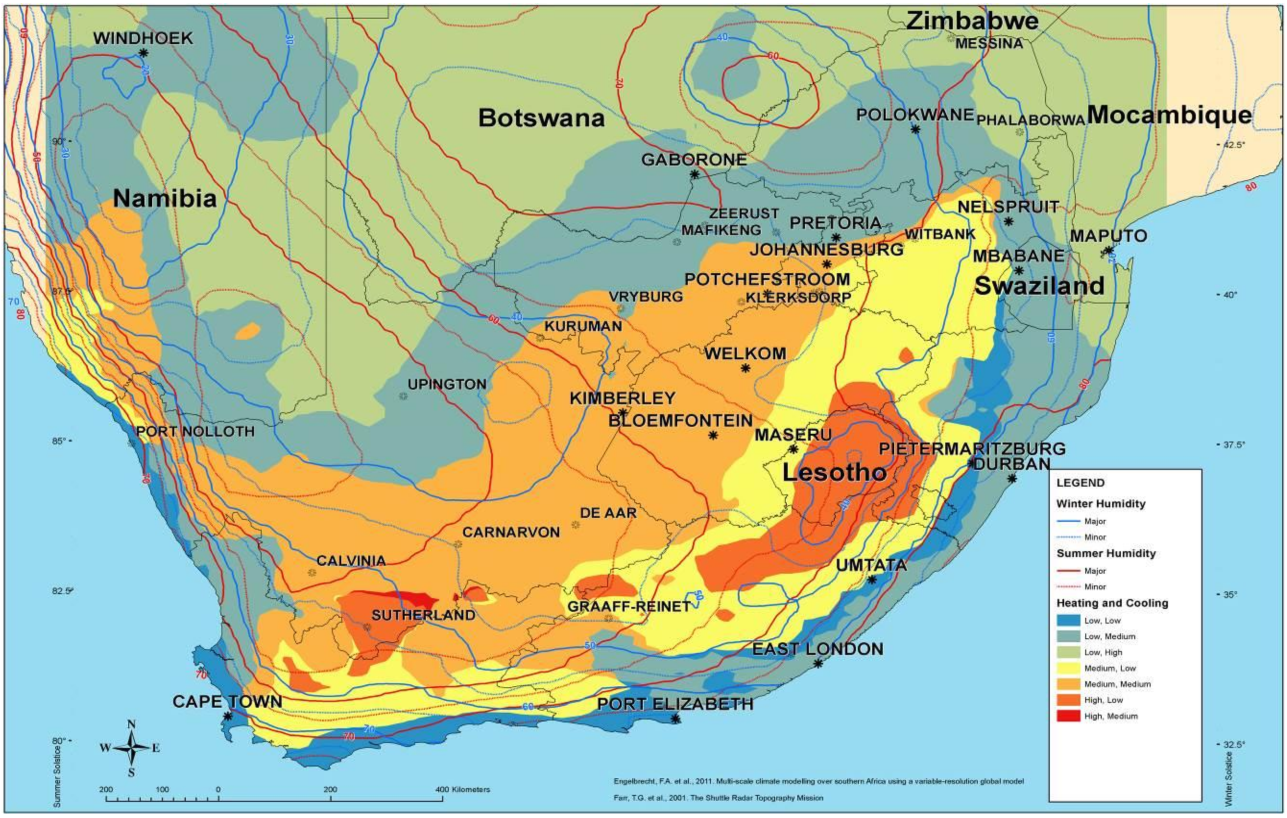

Figure 5 Heating and Cooling Degree maps combined into one map with summer and winter humidity lines.

The heating and cooling energy demand maps were then combined into a single total energy demand map (Figure 5) to make it more convenient to use in the National Standard. The combining of two different measures of LMH energy demand could possible result in nine different zones. In the South African context, however, only seven zones were realised.

4. Verification of HDD/ CDD map

After completion of the separate CDD and HDD maps (Figure 4) the results were verified to external climatic data sources and modelled building heating and cooling energy demand.

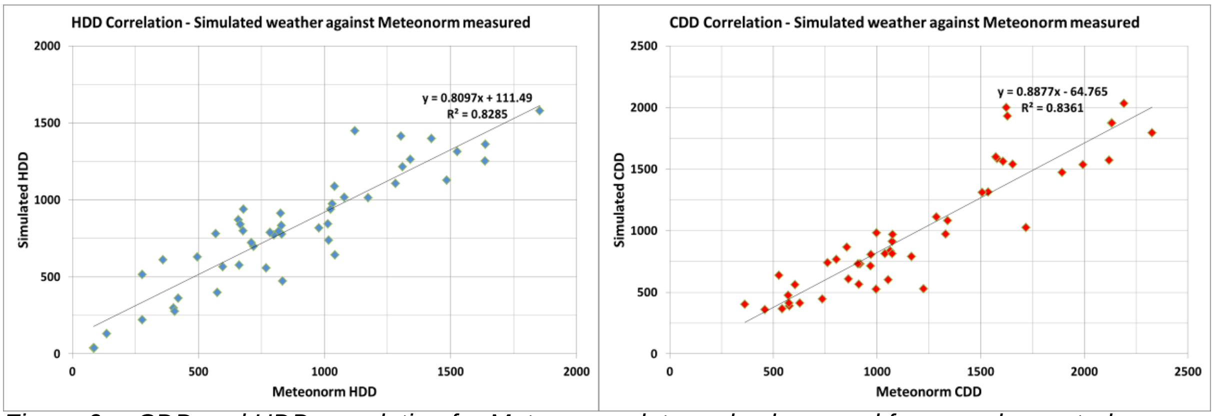

Figure 6 CDD and HDD correlation for Meteonorm data and values read from newly created maps.

Detailed weather files for 51 real weather station locations were extracted from *Meteonorm v*7, using temperature data for 2000 to 2009. HDD and CDD were calculated for these 51 locations by means of formulas (5) and (6) above. Using the geographic coordinates of each location, the HDD and CDD values were extracted from the maps illustrated in Figure 4.

The HDD and CDD values extracted from the maps were correlated against the values calculated from the *Meteonorm* data (Figure 6).

The HDD correlation was 83% and the CDD correlation was 84%. This was deemed acceptable as perfect correlation was not expected, since the *Meteonorm* data is purely historic (2000 to 2009) and the data used to produce the maps includes predictive values.

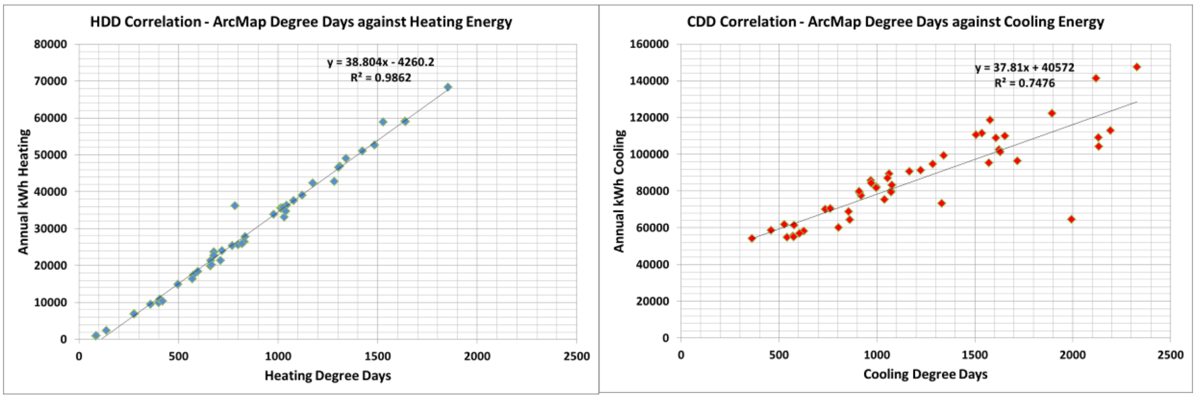

Figure 7 Correlation between CDD and HDD and building heating and cooling energy respectively

In order to correlate degree days to building heating and cooling demand, a notional building was modelled in *Ecotect*™. This model is validated to a real building for heating, cooling and indoor thermal conditions for Pretoria (Conradie *et al.,* 2012). Figure 7 displays the correlation between annual building heating and cooling demand using the same weather files of the 51 locations described above. As expected, a very strong correlation was found between the heating degree days and the modelled annual heating demand (99%). The correlation between the cooling degree days and the annual cooling demand was not as strong (75%), possibly owing to the omission of latent heat energy from the cooling degree day algorithm. In addition no direct allowance is made for the effect of solar radiation in the CDD values. The outlier on the CDD correlation above is noted as being Upington. The HDD calculated for Upington from *Meteonorm*™ also seems quite high considering climatically similar locations. Equivalent hot arid climates are represented in the data set by locations such as Springbok, Kimberley and Jwaneng without producing similar discrepancies. A data set excluding stations with an annual CDD above 1574 (Thohoyandou) resulted in a far better correlation of 84%. Coincidently this excludes many of the locations in South Africa's northern neighbours.

5. Conclusions and Further Research

Although the SET map uses functions of dry bulb and humidity and should theoretically give a good indication of human comfort and energy requirement, it failed to correlate well with annual building heating and cooling demand.

A number of analyses of heating and cooling energy demand and the HDD/ CDD proved that these correlate well if the calculation is based on hours. The inclusion of summer and winter solar angles and humidity lines give some support to passive design considerations.

Further work is envisioned to obtain adequate correlation between a heat strain index and building heating and cooling demand.

6. Acknowledgements

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