Chapter 3

Case studies

3.1 Case descriptions

The method described in the previous chapter for estimating the inside temperature statistics was based on a well-verified deterministic method. It should therefore be applicable to all problems the deterministic method can be used for, provided the input data set is available. Still, different cases are needed to verify the Monte Carlo method.

For this reason the building selection was not considered critical. Input Data for several buildings used by Van Heerden (Van Heerden, E., 1997) and Ellis (Ellis, M.W., 1999) for verification studies was available. From this four buildings were chosen to test the method developed.

This ensures that the buildings used will be realistic. The details of the buildings are from the study of Ellis. To ease comparison with the work of Van Heerden and Ellis the designations they used for the buildings was kept. Detailed descriptions can be found in Appendix C.

Deciding on a ventilation rate to use for the building can also be tricky. Van Heerden gives values for the number of Air Changes per Hour (ACH) for a tight building as 0.5 ACH and for a very leaky building as 2 ACH. This can be taken to be a building with closed windows. When a building with open windows is considered, the ACH rates can be a lot higher. For this reason it was decided to use ventilation rates of 0, 1, 5, 10 and 50 ACH (Air Changes per Hour).

3.2 Input data

3.2.1 Time span and location

In order to find the statistics of the input variables, measured input data will have to be used. For the statistics to be reliable, this data will have to span some years. This must be the same type of data as used by Quick. Furthermore weather data is highly dependent on the site, as thus data from only one site is acceptable.

For the true nature of weather data to be clear, as much weather data as possible is needed. The South African Weather Bureau was able to supply data collected at the Irene weather station near Pretoria, since hourly data for temperature, humidity and global radiation was available for this site. (SAWB, 1999)

Although data for many of the months of 1993 were available, the data did not span the whole of that year. It was decided to stick to whole annual cycles, as this is one of the main periods of the data. (Hittle, D.C. and Pederson, C.O., 1981) Thus the five years of 1994-1998 was used. This data was made available in electronic format, making the subsequent analyzing and processing easier. Data files were of global radiation in mega joules, temperature in degrees Celsius and relative humidity as the fraction of the mass of water in the air divided by the mass the air can hold, expressed as a %. (SAWB, 1999)

Unfortunately diffuse radiation data are not measured at most weather stations, including Irene. For these locations ways have to be found to calculate the diffuse from the global values.

3.2.2 Calculation of Diffuse radiation

Several formulas exist for the calculation of diffuse radiation from the Global. Kimura (Kimura, K., 1977) gives an equation of Liu and Jordan (Liu, B.Y.H., and Jordan, R.C., 1960), Eq. 3.2.2-1. According to Lunde (Lunde, J.L., 1980) this is based too heavily on data from Blue Hill, Massachusetts. He then goes on to give a formula by Page, Eq 3.2.2-2 (Page, J.K., 1961)

$$\frac{I_{SH}}{I_O} = \sin\beta(0.2710 - 0.2913\frac{I_{DN}}{I_O}) \qquad \text{Eq. 3.2.2-1}$$

Where

I_{SH} = Diffuse solar radiation

I_O = Solar constant

β = The angle between the sun and the earth

I_{DN} = Direct normal solar radiation

$$\left(\frac{\overline{H_{Td}}}{\overline{H_T}}\right) = 1.00 - 1.13\overline{K_T} \qquad \text{Eq 3.2.2-2}$$

Where

$\overline{H_{Td}}$ = Monthly daily-average diffuse radiation on a horizontal surface

$\overline{H_T}$ = Monthly daily-average total global radiation on a horizontal surface

$\overline{K_T}$ = Clearness index, defined by $\overline{H_T}/\overline{H_{OT}}$, where

$\overline{H_{OT}}$ = Monthly daily-average extraterrestrial radiation on a horizontal surface

As with most methods, Page calculates the monthly Clearness Index, an indication of the fraction of extra terrestrial radiation that reaches the earth. This is then used in an linear relationship with the global radiation to give the diffuse.

It was decided to use the method of Page. According to Lunde it correlates well with Choudhury, (Choudhury, N.K.O., 1963) Stanhill (Stanhill, G., 1966) and Norris (Norris, D.J., 1966). It would be advisable to obtain new recent constants for South Africa, but none was available.

All these methods were set up to give the total amount of diffuse radiation per day, and use a clearness index to give it as a fraction of the global radiation for the entire day. But Quick uses hourly values of all its variables.

The problem is that although the total diffuse radiation for the day will still be correct, if the hourly value of global radiation is used to calculate the diffuse part, then the ratio of diffuse/global will stay constant during the day. It is well known that this is not the case, and that when the sun rises and sets the ratio is much larger than during the middle of the day, when it will be at a minimum.

At the moment this remains the best method available. It should be remembered that the global radiation would always be a lot more than the diffuse. Therefore this approach can be used for the moment. If and when a better method does come to the fore, or preferably measures values of diffuse radiation becomes available, it should be implemented without delay.

3.2.3 The reasoning behind and selection of periods of similar weather.

The reason to change to Monte Carlo simulations is to have available the statistics of the output variable of the problem. The simulation must calculate these statistics as completely as possible. Software should then interpret it in such a way that the user can extract all useable information without being confused.

The most comprehensive solution suitable for our needs will be where the full internal temperature PDF for any time is known for each and every day of the year. In this way it would be easy to find out exactly for what days cooling might be necessary, when it should heated, and for what times in the year there will be heating and cooling days. The maximum heating/cooling load will also be clear, as well as total power consumption.

From a full and true stochastic answer this can be found. However, for reasons as explained, we decided on a Monte Carlo method. To get this type of detail from a Monte Carlo method would entail a huge amount of data and very long simulation times. Weather data for many years will be needed in order to have a high enough certainty for the data of each day.

Being engineers, we have to make a working compromise between the limited data available, the amount of computing time necessary, and the extra accuracy obtained for the effort. It was thus decided to make a study to see in how many discrete periods of assumed constant weather the year can be divided.

The monthly average was calculated for temperature and radiation over the time period chosen. After this was presented graphically it was decided that for Irene four periods would define the problem sufficiently. See figure 3.2.3-1. These roughly concur with the seasons. Summer for Oct, Nov, Des, Jan, Feb and March. April and May for fall, June and July for winter, August and September for spring.

It must be made clear that this part of the analysis must be done for each new location. Hokoi et al divided the weather of Tokyo into winter and summer, although no indication is given of the reasoning behind this. (Hokoi, S. *et al*, 1990) Locations on the equator, for example, will have marked different periods of constant weather.

These weather data periods can now be treated as times of constant weather, and input statistics calculated for each of them. This would mean that with two variables chosen as stochastical, the whole Monte Carlo method would use 72 days to describe the weather statistics of 1826 days, 4% of the total.

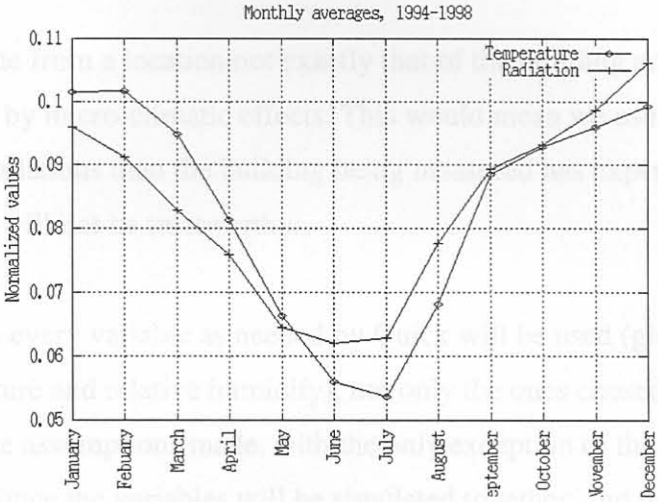

Figure 3.2.3-1

3.2.4 Data simulations for testing purposes.

As previously said, the reasoning behind this study is to develop a Monte Carlo method to give estimates of the output statistics with minimal effort. For this a deterministic tool will be utilized. Quick was chosen, in part because of its extensive verification. (Van Heerden, E., 1997)

In the end, the results as obtained by the Monte Carlo method developed in this study will have to be tested against measurements. However, since measurements are not available it was decided that it would be better to test against the results as obtained by simulating each day with QUICK. This would be taken as equivalent to a full 5 years of measured building internal temperatures.

Because of the verification done on the program, the results can be trusted. Furthermore, a full 5 years of real weather data will be used. It would be out of the time frame available for this study to measure a full 5 years of indoor temperature for a building. We will then also know that we have the exact corresponding external climate, and not the external climate for a location some distance away.

The external climate from a location not exactly that of the building under consideration may be influenced by micro-climatic effects. This would mean we use a different external climate for the simulations than the building being measured has experienced. In the end our measurements will not be trustworthy.

For this simulation every variable as needed by Quick will be used (global and diffuse radiation, temperature and relative humidity), not only the ones chosen as stochastical. This will test all the assumptions made, with the only exception of the calculation of the diffuse radiation. Since the variables will be simulated together, and no convolution will be done, cross-correlation's between different variables are inherently considered.

These simulations were done for the same ACH rates and houses used for the Monte Carlo simulations. After the simulations was done the PDF's for the inside temperature was obtained from the raw data, one for each hour of each of the periods of constant weather. These full simulations represent the true inside temperature statistics.

At the same time, the effect of the convolution done must be tested as well. Not only do we know there are cross-correlation's between the variables, but also we know for the convolution process to be correct the variables have to be independent. For this reason a second full simulation was done, this time simulating the temperature and radiation parts of the input as separate variables. The most important reason for this simulation is to see how big an error is made by assuming the variables are independent from one another, and if the error is acceptable. This was also done for the four houses, as well as the different ACH rates decided upon.

After simulating the separate variables, the PDF's was created for each season for each hour for each output variable. The output variables are inside temperature caused by outside temperature, and inside temperature caused by outside radiation. The combined effect was then found by convolving the PDF's, to obtain the statistics of the single output variable, inside temperature caused by outside weather.

These full convolutions represent the best possible result. They will be compared to the full simulations to see if the assumption that radiation and temperature can be taken as independent creates unacceptable errors.

3.3 Results

Input files were created with the method of minimum, mode and maximum. They are for the different seasons, for temperature with radiation, global and diffuse, and relative humidity taken as zero and for radiation, both global and diffuse, with temperature and relative humidity taken as zero. Simulations were then run for the four houses, for the different ACH rates, and from this PDF's were created with the method discussed.

Statistically the accepted way to test the result would be to use a Chi-square test. This would give an answer as the percentage chance that the two distributions were drawn from the same population. Lets look at Figure 3.3-1. The smooth curve is a PDF result from the Monte Carlo method, and the jagged curve a PDF from the full simulation.

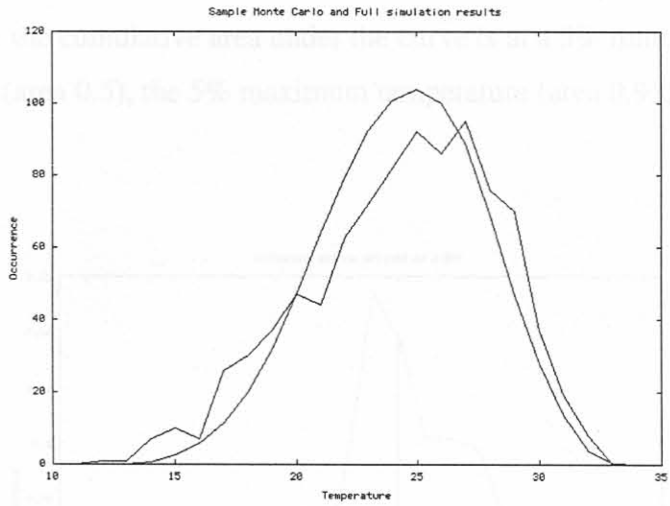

Figure 3.3-1

If we look at the distributions, we can see that they are not too different. The Chi-square statistic for two binned data sets is given by: $X^2 = \sum_i \frac{(R_i - S_i)^2}{R_i + S_i}$ (Press, W.H. et al, 1992). If this is calculated for these two curves, with the full simulation curve not normalized, and the area under the Monte Carlo curve made to be equal to that of the full simulation curve, we have a chi-square statistic value of 40. 53, and 22 degrees of freedom. See Appendix D for more detail.

We use the incomplete gamma function to find the percentage chance that the two distributions are from the same population (Press, W.H. et al, 1992) and we get an answer of 0.937%. From this we will decide that the distributions are not from the same population, and that the Monte Carlo method did fail. At the same time, we do not know far will the answer be out. The Chi-square does not give an indication of this. We knew we were not going to be 100% accurate. Therefore it was decided to find another way of presenting the results.

The most important question will be: if the Monte Carlo method predicts a temperature of 29 and higher for 5% of the time, how far will it be out? To answer these types of questions, five points on the PDF was defined, the minimum temperature expected, the temperature where the cumulative area under the curve is at a 5% minimum or 0.05, the mean temperature (area 0.5), the 5% maximum temperature (area 0.95) and the maximum temperature.

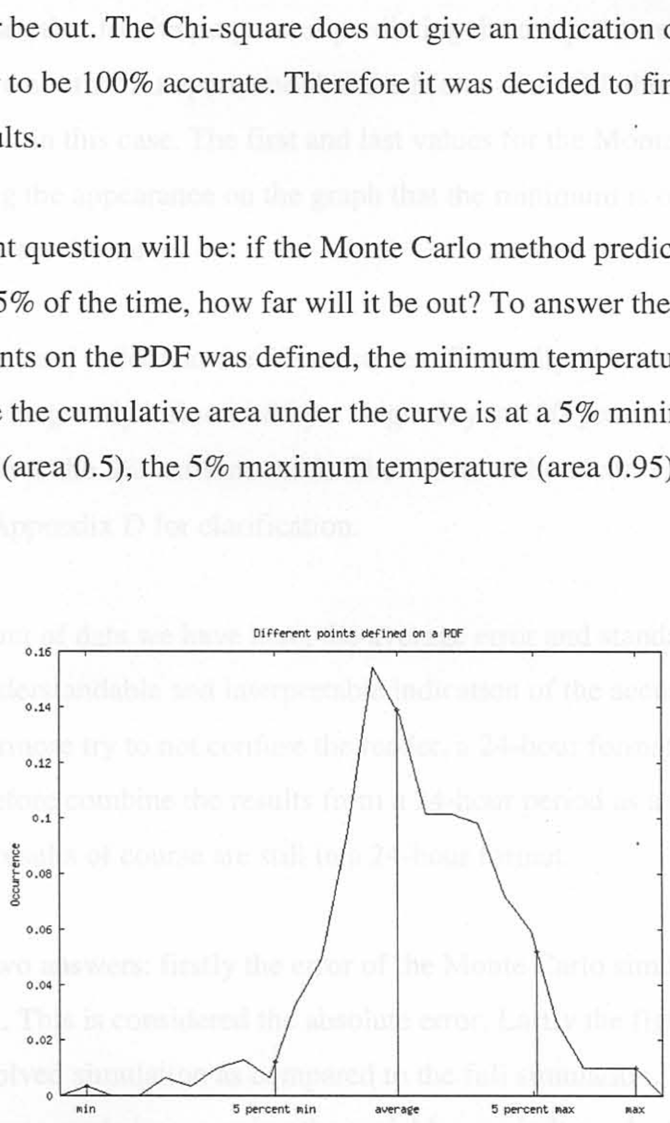

Figure 3.3-2

By then deducting the temperature predicted by the full simulations from that predicted by the Monte Carlo method at these points, the error made by the Monte Carlo method can be found. If we find these errors for the same PDF's in figure 3.3-1, we find that both show the minimum temperature as 12 degrees. The 5% minimum of the Monte Carlo is out by 1.4 degrees, the average by 0.31, the 5% maximum by 0.5 and the maximum by 2 degrees.

From this we can see that for the purpose of predicting the temperatures inside a building, these two PDF's are not that far apart, and that the Monte Carlo Method produced quite a good approximation in this case. The first and last values for the Monte Carlo method are very small, creating the appearance on the graph that the minimum is out by 2 degrees, and the maximums are the same.

This underlines the need to look at the 5% extremes. Generally, the maximum and minimum can also be greatly influenced by a single day in 100 years, but the effect will not be as noticeable at the 5% extreme mark. The values of both curves are given in tabular format in Appendix D for clarification.

For the large amount of data we have here, the average error and standard deviation of the error give a understandable and interpretable indication of the accuracy of the method. To furthermore try to not confuse the reader, a 24-hour format was not used. All figures given therefore combine the results from a 24-hour period as a single number. The Monte Carlo results of course are still in a 24-hour format.

The figures give two answers: firstly the error of the Monte Carlo simulation compared to the full simulation. This is considered the absolute error. Lastly the figures give the error made by the convolved simulation as compared to the full simulation. This will give an indication of the error made by assuming the variables are independent.

The first figure gives these two answers if all the data points are considered, i.e. all ACH's, houses, seasons and positions on the PDF are used. The rest of the graphs give the two answers split up according to the different variables, i.e. ACH's, houses, seasons and positions on the PDF used. In Appendix A the information of the figures are given in tabular format, and Appendix B gives the detailed results.

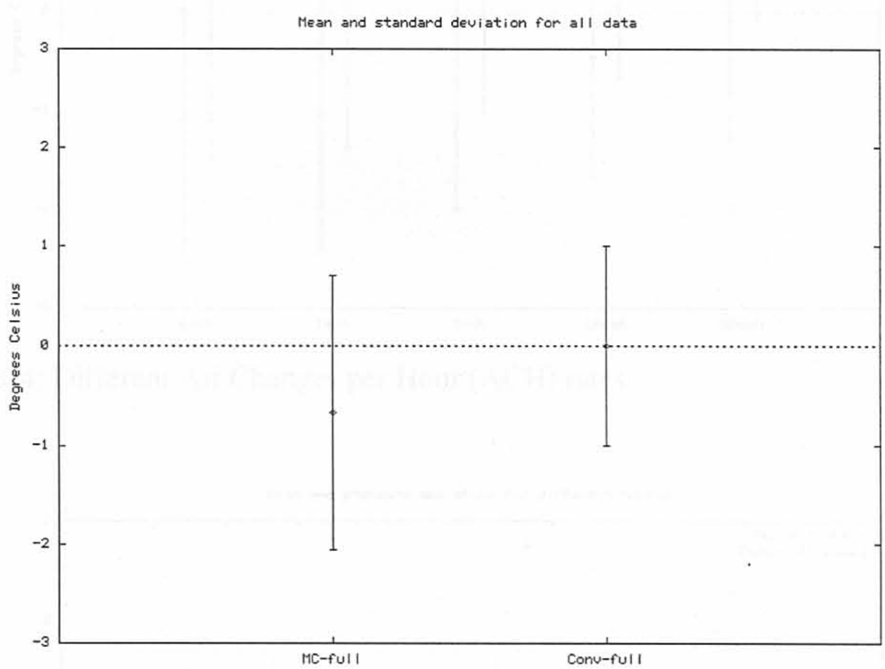

Figure 3.3-3 All data points

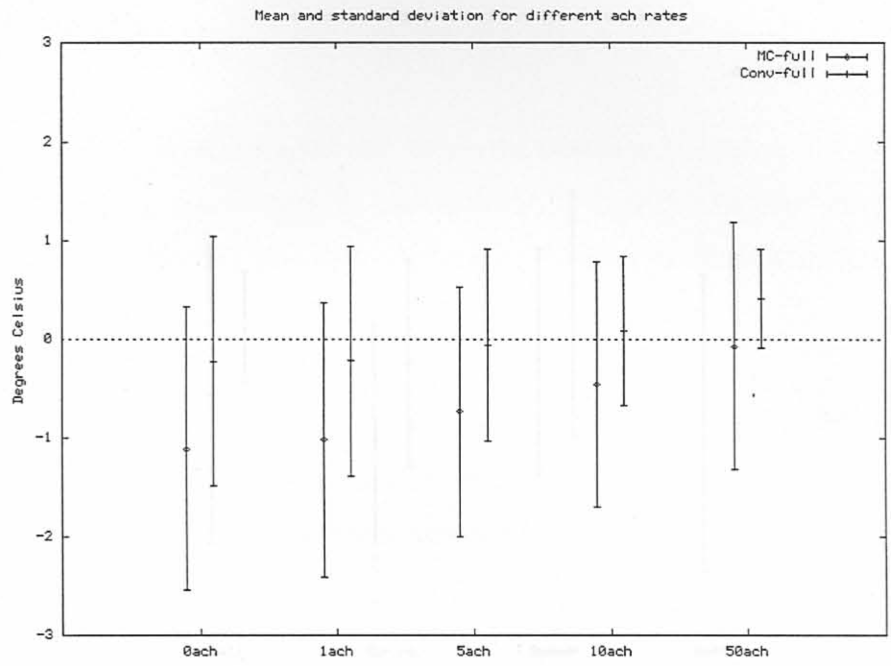

Figure 3.3-4: Different Air Changes per Hour (ACH) rates

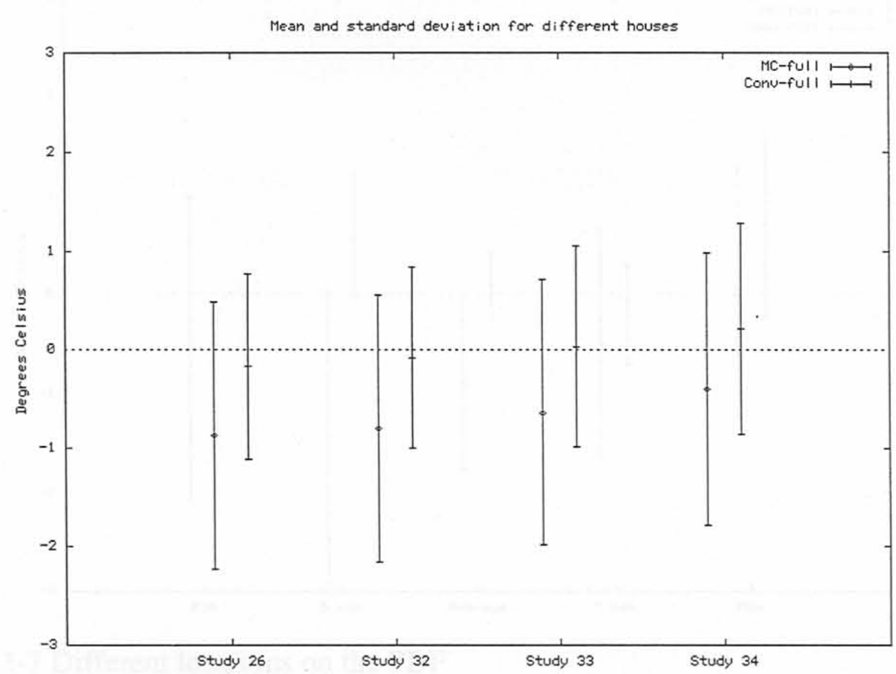

Figure 3.3-5 Different houses

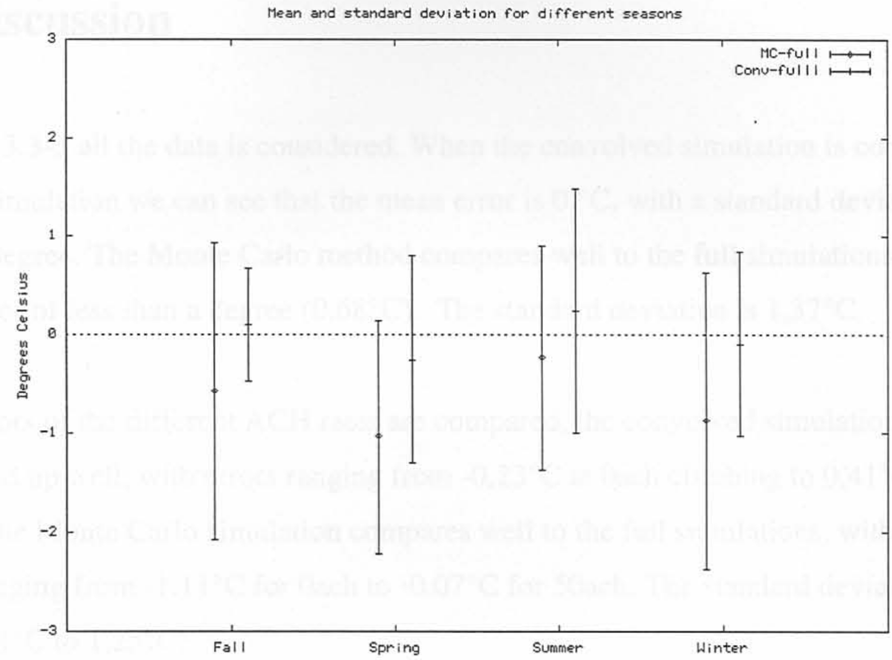

Figure 3.3-6 Different seasons

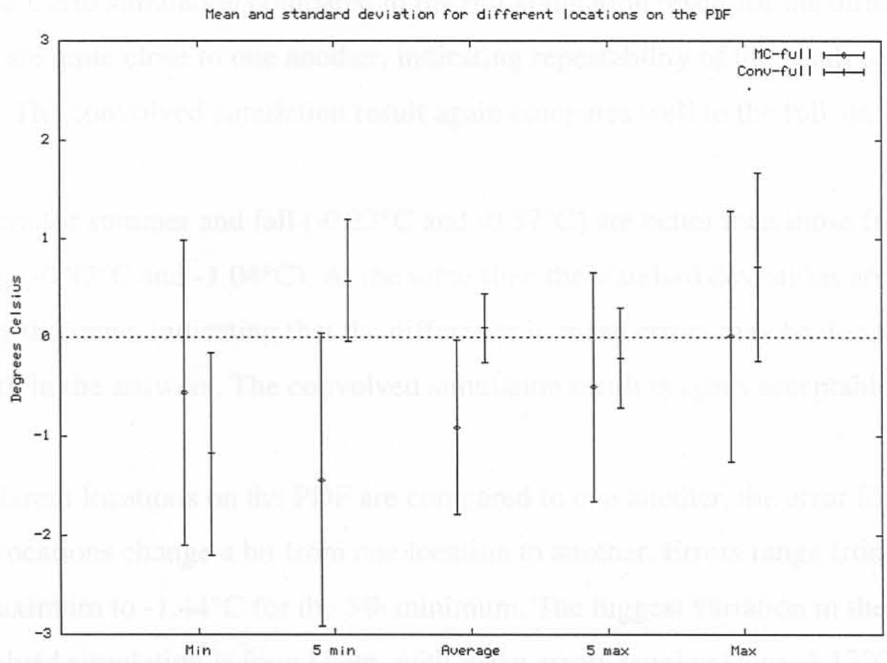

Figure 3.3-7 Different locations on the PDF

3.4 Discussion

In figure 3.3-3 all the data is considered. When the convolved simulation is compared to the full simulation we can see that the mean error is 0 °C, with a standard deviation of about 1 degree. The Monte Carlo method compares well to the full simulations, with a mean error of less than a degree (0.68°C). The standard deviation is 1,37°C.

If the errors of the different ACH rates are compared, the convolved simulation result again hold up well, with errors ranging from -0,23°C at 0ach climbing to 0,41°C at 50ach. The Monte Carlo simulation compares well to the full simulations, with mean errors ranging from -1.11°C for 0ach to -0.07°C for 50ach. The standard deviations range from 1,44°C to 1,25°C.

The Monte Carlo simulation compared to the full simulation result for the different buildings are quite close to one another, indicating repeatability of the result for different buildings. The convolved simulation result again compares well to the full simulation.

Mean errors for summer and fall (-0.23°C and -0.57°C) are better than those from winter and spring (-0.87°C and -1.04°C). At the same time the standard deviations are practically the same, indicating that the difference in mean errors may be due to the uncertainty in the answers. The convolved simulation result is again acceptable.

When different locations on the PDF are compared to one another, the error for the different locations change a bit from one location to another. Errors range from -0.02°C for the maximum to -1.44°C for the 5% minimum. The biggest variation in the result for the convolved simulation is found here, with mean errors ranging from -1.17°C to 0.71°C.

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