THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Hygrothermal Simulations of Buildings Concerning Uncertainties of the Future Climate

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Abstract

Global warming and its effects on climate are of great concern. Climate change can affect buildings in different ways, i.e. it can change the energy demand or the moisture durability of buildings in the future. In Sweden, most of the last 20 years have been mild and wet compared to the 1961-1990 climate reference period. Future needs and risks of the building sector depend on the future climate which can be simulated by climate models. It is possible to assess the future conditions of buildings using simulated climate data. Since climate models are not certain there exist different scenarios for the future climate.

Impact assessment of the climate change on buildings in Sweden has been performed in this study. The hygrothermal conditions of attics and the energy performance of buildings in Sweden were simulated. The study was mainly based on comparative analysis of different scenarios, buildings and periods. Four attic constructions, and the building stocks of four cities, were studied considering 12 climate scenarios for the period of 1961-2100 and one reference scenario for the period of 1961-2005.

Future climate data sets were generated by the global climate models (GCMs) which were downscaled using regional climate models (RCMs) at the Rossby Centre at the Swedish Meteorological Hydrological Institute (SMHI). Climate scenarios were selected in a way to assess climate data uncertainties caused by different GCMs, RCMs, emissions scenarios, initial conditions and spatial resolutions. With the help of different statistical methods, uncertainties of the climate data and their effects on the hygrothermal simulations were analysed in different time scales.

According to the results of this work, a reliable impact analysis of the climate change cannot be based on a few number of climate scenarios. Uncertainties of the climate data can affect the building simulation results considerably. Depending on the case, some uncertainty factors of the climate data might be neglected, however it depends on the building construction, the phenomenon and the season that are considered. Among the climate uncertainties which were studied in this work, the uncertainty caused by GCMs affected the hygrothermal simulations the most.

The Swedish building sector can gain or recede from changes in climate; the heating demand of buildings will decrease by having warmer climate but the moisture problems will increase by having more humid climate. Results point to an increment of the moisture problems in attics. The absolute safe case for preventing mould growth is using controlled mechanical ventilation in attics which consumes energy. The energy simulations of the building stocks showed that the heating demand and its variations will decrease in the future. Comparing the indoor temperature in buildings with and without mechanical cooling system showed that there is no substantial need for increased mechanical cooling in the future.

Keywords: climate change, climate uncertainties, hygrothermal simulation, mould growth, energy demand

Appended papers

I. Nik, Vahid M., Angela Sasic Kalagasidis, and Erik Kjellström. 2012. “Statistical Methods for Assessing and Analysing the Building Performance in Respect to the Future Climate.” Building and Environment 53 (July): 107–118. doi:10.1016/j.buildenv.2012.01.015.

II. Nik, Vahid M., Angela Sasic Kalagasidis, and Erik Kjellström. 2012. “Assessment of Hygrothermal Performance and Mould Growth Risk in Ventilated Attics in Respect to Possible Climate Changes in Sweden.” Building and Environment (2012), doi:10.1016/j.buildenv. 2012.01.024.

III. Nik, Vahid M., Angela Sasic Kalagasidis, “Impact study of the Climate Change on the Energy Performance of the Building Stock in Stockholm Considering Four Climate Uncertainties.” Submitted to the Journal of Building and Environment

IV. Nik, Vahid. 2011. “Mould Growth Inside an Attic Concerning Four Different Future Climate Scenarios.” In 9th Nordic Symposium on Building Physics - NSB 2011, 2:841–848. Tampare, Finland: Department of Civil Engineering, Tampare University of Technology.

Other publications

I. M. Nik, V., Sasic Kalagasidis, A., "Long term simulation of the hygro-thermal response of buildings Results and questions", *Proceedings of Building Physics Symposium*, Leuven, October 29-31 2008.

II. Sasic Kalagasidis A., Nik V., Kjellström E., Nielsen A. (2009), "Hygro-thermal response of a ventilated attic to the future climate load in Sweden", *Proceedings of the fourth International Building Physics Conference*, Istanbul, Turkey, pp. 519-526.

III. Nik, V., Sasic Kalagasidis, A., "Statistical methods for assessment of long-term hygrothermal performance of buildings", *International Conference on Building Envelope Systems and Technologies, ICBEST 2010*, Vancouver, Canada, June 27-30, 2010.

IV. Nik, V., Sasic Kalagasidis, A., "Influence of the uncertainties in the future climate scenarios on the hygrothermal simulation of an attic", *International Conference on Building Envelope Systems and Technologies,* ICBEST 2010, Vancouver, Canada, June 27-30, 2010.

V. Nik, V., "The uncertainties in simulating the future hygro-thermal performance of an attic related to global climate models", *10th REHVA World Congress, Clima 2010, Antalya, Turkey, May 9-12, 2010*.

VI. Nik, V., "Studying the importance of two uncertainty factors of the future climate in energy simulation of the Swedish building stocks", *5th International Building Physics Conference, 28-31 May 2012, Kyoto, Japan*.

Preface

This work was carried out at the Division of Building Technology, Department of Civil and Environmental Engineering, Chalmers University of Technology, in collaboration with the Rossby Centre at the Swedish Meteorological and Hydrological Institute (SMHI).

It was a great privilege to work under the supervision of Associate Professors Angela Sasic Kalagasidis and Erik Kjellästrom. I am most grateful to Angela Sasic Kalagasidis whose experience and knowledge in building physics was invaluable. I have gained a lot under her supervision. The support from Erik Kjellästrom was very helpful in working with the climate data. I have learned a lot from his comments when I was working on papers. The insightful comments of both of my supervisors helped me enormously in conducting the research and developing my skills as a researcher for which I am truly indebted.

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My deepest and sincere thanks are extended to my family, specially my parents who were always supporting me. I like to express my warmest gratitude and wishes to my sister Samira. I was very lucky for having her in Sweden.

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Vahid Nik

Gothenburg, April 2012

Contents

1.

Introduction

Buildings are in contact with the outdoor climate and their performance is influenced by its variations. Climatic impact from precipitation, wind, temperature and its variations causes extensive degradation and damage to the built environment every year. Under the changing climate conditions, acceptable functionality is required during the expected lifetime of buildings, which is usually 60 to over 100 years. The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC 2007) projects an increase in global mean surface temperature of 1.1-6.4^{o}C over the period 1990-2100 together with an increase in climate variability and extreme events (IPCC 2012). The last 20 years in Sweden have been mostly mild and wet compared to the 1961-1990 climate reference period. After a few relatively cold years in the mid-1980s, practically all years have been warmer than the preceding 30 years average. The trend in the recent Swedish warming climate is in line with the climate change scenarios which project warmer climate with intensified hydrological cycles.

With increasing concerns about effects of the climate change on buildings, it is essential to perform impact analysis using the available future climate scenarios. This was the initiation of this project; "Sustainability of the Swedish built environment towards climate change. Hygro-thermal effects and design criteria for buildings with respect to future climate scenario", which started in 2007. Two major factors regarding sustainability of the Swedish buildings are the moisture safety and the energy demand. Moisture damages are frequent and costly which can be magnified in the future climate conditions. The moisture safety of the Swedish buildings was assessed by studying cold attics, which are highly susceptible to moisture condensation and mould growth. Moreover, energy simulations have been performed for the residential building stocks of four cities in Sweden. The impact studies of the climate change were done by looking into heating and cooling demand and also the indoor temperature of the building stocks.

1.1. Course of the project work

The first phase of the project started by receiving the simulated climate data from the Rossby Centre which is the climate modelling research unit at the Swedish Meteorological and Hydrological Institute (SMHI). Research activities at the Rossby Centre focus on regional climate modelling including model development and evaluation as well as modelling applications on process studies, climate system studies, climate change research and impact studies. Most of the climate data for this project were the outputs of the RCA3 regional climate model developed by the Rossby Centre.

Preparing the climate data for the building simulations was a time consuming task. All the climate parameters were synchronized since they did not have the same time scale. Meanwhile, the relative humidity and the solar radiation components were calculated based on the available parameters in the RCA3 climate data. A more detailed description about the climate data and preparations is available in Chapter 2 and the licentiate thesis (Moussavi Nik 2010). Climate data of four cities in Sweden have been used in this work: Gothenburg, Lund, Stockholm and Östersund. These cities are located in south and middle of Sweden which are the most populated parts of the country. Besides, they represent four different climate zones which are more discussed in Chapter 2.

The climate projections include changes in both average conditions and in the frequency and magnitude of extreme events. Knowing more about climate simulations introduced new challenges in performing and analysing the building simulations. The two very demanding challenges in this research were assessing the long term data sets and coping with different climate uncertainties. Consequently, a lot of time was dedicated to explore different statistical methods and writing codes in Matlab to assess the climate data, building simulation results and to consider the uncertainties. Paper I tells about some of the statistical methods which were mostly used to assess data of the hygrothermal simulations. The statistical methods also have been discussed thoroughly in the licentiate thesis (Moussavi Nik 2010). Knowing more about the climate data, their uncertainties and the statistical methods was a gradual learning process. This work load was not predicted in the very early phase of this project and this is the main reason for deviations in the aims of the work which had been noted in the project description. Instead of analysing or developing building codes more time was dedicated to fundamental research, meanwhile applied in building simulations.

The prepared climate data were used in the hygrothermal simulations of buildings, which were numerically modelled and simulated in Matlab using HAM-Tools (Sasic 2004) which is a building simulation library in the Simulink toolbox of Matlab. More description about the building models and simulations can be found in chapters 4 and 5, Paper II and the licentiate thesis. During the first phase of the project, the main concern was assessing the moisture safety and the hygrothermal conditions of the cold attics in Sweden. Simulations were done using the RCA3 climate data for the four cities which are described in chapter 2. Most of the results for this phase of the project were published in the licentiate thesis (Moussavi Nik 2010). Different solutions for having a moisture safe attic were tested and results are available in Paper II. Mould growth was used as a performance criterion while assessing the hygrothermal conditions of the attics because of its dependence on temperature, relative humidity and time. Two mould models were used in the assessments; a model by Hukka and Viitanen (1999) and a model by Isaksson et al. (2010).

Impact analysis of the climate change on the energy demand of buildings was performed by simulating the building stock of the four cities. The heating and cooling demands and the indoor temperature were the three performance criteria when comparing different simulation results.

1.2. Methodology

Since the downscaled climate data from the regional climate models (RCMs) were available for this project, there was no need for *creating* suitable climate data for simulating buildings, though there was the requirement of *synthesizing* the RCM data. The synthesizing procedure is briefly described in Chapter 2. Using the RCM data gave the chance of having access to the climate data of around 13 climate scenarios for the period of 1961-2100. The intention was looking into different scenarios and assessing the performance of buildings in the presence of climate uncertainties. An important advantage of using the RCM data is the ability to assess the changes and their variations during time. This is the main reason of not generating climate data for test reference years and performing the building simulations using the RCM data.

The climate data were applied to the validated models to simulate the hygrothermal conditions inside attics and the energy performance of the building stocks. Since the future conditions cannot be validated, assessments were mostly based on comparative analysis of data sets. For example in many cases the climate data of RCA3-ERA40, which is described in chapter 2, was assumed as a reference for the past climate and other climate scenarios were compared to that one. Comparisons were mainly done using the long periods of 20 or 30 years. Since the natural variability of the climate data are high, it is recommended not to make comparisons using shorter periods. In many cases the period of 1961-1990, which is called CTL, was representing the recent climate conditions and the future conditions was represented by the climate data during 2071-2100, which is called SCN. The CTL data was used as a reference for assessing the changes of the future during the SCN period. In some cases, like the energy calculations, the whole period of 1961-2100 was divided into seven periods of 20 years and the evolution of the climate change was assessed during time. There was also a reference construction for assessing the hygrothermal conditions of attics; one reference attic was compared to three suggested measures for decreasing the mould growth problem in attics. More description is available in Paper II.

In the case of energy simulations, building stocks of four cities were statistically represented by limited number of buildings. These buildings were used in the energy simulations. A method was developed to avoid simulating all the building and save more time. This method is described in detail in Paper III.

1.3. Outline of the thesis

This thesis consists of four papers and an introductory part which gives a short description about the subjects of the study.

Chapter 1 is the introduction which gives a brief description about background, aim and deviations of the work.

Chapter 2 describes the climate data which have been used in this project. Differences between the climate data sets and their uncertainties are mentioned.

Chapter 3 briefly describes the statistical methods which have been used to assess different type of data. Paper I is in connection with this chapter in which two statistical methods, specially defined for analysing long climate data sets, are introduced.

Chapter 4 gives a very brief description about hygrothermal simulation of the cold attic. More information about this subject is presented in Paper II and Paper IV.

Chapter 5 is about energy simulations of the building stock in three cities of Gothenburg, Lund and Östersund. Heating demand of the building stocks is calculated considering the four climate uncertainties. Also, the probable need for having cooling systems in the future is assessed. This chapter is longer than the other chapters since it presents results of the energy simulations for the first time.

Chapter 6 contains some general conclusions about the whole project and more detailed conclusions about energy simulations. The specific conclusions about different subjects of the research can be found at the end of papers and the licentiate thesis.

Paper I is mainly focused on introducing the statistical methods and their abilities in analysing the long term data sets. One non-parametric and one parametric method are introduced. The main application of the parametric method has been in analysing the hygrothermal conditions of the cold attics.

Paper II presents more information about the attic simulations and compares four measures of the attic construction for coping with the mould growth problem in the future. It compares the probability of the mould growth rate for different constructions. The paper also finds the riskiest city, among four, in Sweden concerning the mould growth and checks effects of the uncertainty of the climate data which was induced by emissions scenarios.

Paper III is about impact analysis of the climate change on the energy demand of the building stock in Stockholm. Heating and cooling demands and the indoor temperature of the building stock are analysed while four uncertainty factors of the climate data are considered.

Paper IV makes a sensitivity analysis for the mould growth rate in the cold attic concerning four climate data sets of RCA3 forced by different global climate models.

2.

Climate data

The most populated parts of Sweden, the south and the middle part, are rather flat. In this work these areas were divided into four climate zones; west, south-west, east coastal and middle inland regions (in the south part of Sweden). Each climate zone is represented by the weather data for one city within the zone.

Fig. 1. Geographical location of the four cities which have been considered in this research.

Climate conditions of four cities in Sweden have been considered in this work; 1) Gothenburg on the west coast of south-western Sweden with the oceanic climate influenced by the nearby ocean, 2) Lund in southern Sweden with oceanic climate, 3) Stockholm on south-central east coast of Sweden with humid continental climate and 4) Östersund in the middle of Sweden with temperate continental climate. Geographical locations are marked on Fig. 1.

The climate data which were used in this work is the result of climate models. Climate modelling is pursued by means of models of varying complexity ranging from simple energy-balance models to complex three-dimensional coupled global models. On a global scale the global climate models (GCMs) are used. These consist of individual model components describing the atmosphere and the ocean. They also describe the atmosphere-ocean interactions as well as with the land surface, snow and sea ice and some aspects of the biosphere. GCMs generally have a rather coarse spatial resolution (often 100-300 km). To downscale the GCM results, regional climate models (RCMs) are used which help to achieve a higher spatial resolution over a specific region. Climate models are applied with different external forcing factors as changing greenhouse gas concentrations, changes in solar intensity, etc. Differences in these factors, RCMs or GCMs result in having different climate data which consequently affect the building simulation results. Therefore these differences are introduced as uncertainty factors.

Several sets of climate data were used as input data for the building simulations. The Rossby Centre pursues advanced climate modelling: development, evaluation and application of regional climate modelling in climate and climate change research. Most of the climate data were results of the latest version of the Rossby Centre regional climate model, RCA3 (Samuelsson et al. 2011). This model includes a description of the atmosphere and its interaction with the land surface. It includes a land surface model and a lake model. In their study Samuelsson et al evaluated the performance of RCA3 with "perfect" boundary condition experiments in which the model is run using boundary conditions from the ERA40 reanalysis experiment (Uppala et al. 2005). ERA40 has been recognized as the most comprehensive account of the state and behaviour of the atmosphere during the last four decades. The ERA40 reanalysis constitutes a realistic description of the state of the atmosphere including its evolution in time for the 1961-2002 period. The boundary conditions for the experiments are taken from the European Centre for Medium range Weather Forecasts (ECMWF) ERA40 data set, extended with operational analyses to cover the whole period from 1961 to 2005. Therefore, the ERA40-driven simulation can be compared to observational data in a more meaningful way and it is used for model evaluation purposes and studies of climate variability in the last few decades. RCA3 has converged to both ERA40 and concurrent observations of different kinds (Persson et al. 2007).

RCA3 can operate at different spatial resolutions. Here, data from two spatial resolutions of 50km×50km and 25km×25km are used. RCA3 is set up so that a 50km grid is exactly covered by four grids in the finer-scale 25km integrations. In the present application temporal resolutions of the simulations are 30 min for 50km and 15 min for 25km. This means that the models generate a state of the atmosphere for each of these time steps also in long integrations over a century. As the lateral boundary conditions are identical in the two simulations there is no time lag between the 50 km and 25 km data sets although the local details can differ. But it has been shown that the difference in details do not affect the building simulation results considerably (Moussavi Nik 2010) (Nik, Kalagasidis, and Kjellström 2012).

Building simulations were done for the whole period of 1961-2100, but while working with the climate data, it is recommended to consider relatively long periods and not short ones as the natural variability in the climate system is large. Typically 30-year periods are studied (Kjellström et al. 2007) (Kjellström et al. 2011). In this work assessment of the hygrothermal conditions of attic were done mostly by comparing results during the CTL (1961-1990) and SCN (2071-2100) periods. For energy simulations, 20-year periods were used.

2.1. Synthesizing the climate data

The weather data received from the Rossby Centre, which is called raw data here, needed to be processed before being applied in the building simulations. The raw data were synthesized and processed by coding in Matlab. The synthesized weather data, which were introduced as a matrix to the building simulations, contained the following parameters:

1. Time [sec]
2. Air temperature [^{o}C]
3. Relative humidity [%]
4. Global radiation [W/m^2]
5. Diffusive horizontal radiation [W/m^2]
6. Direct normal radiation or Beam [W/m^2]
7. Long wave sky radiation [W/m^2]
8. Wind direction [degree]
9. Wind speed [m/s]

Relative humidity, diffusive horizontal radiation and direct normal radiation were not in the raw data and were calculated based on the available data. Moreover all the parameters were synchronized with the time step of one hour. In the raw data time step of the parameters was varying from 15 minutes to 6 hours. The synchronizing was done by linear extrapolation or interpolation.

The *relative humidity* was calculated using the *specific humidity* and the *total air pressure* from the raw data. The *diffusive horizontal radiation* and the *direct normal radiation* were calculated by having the *global radiation* based on a method by Taesler and Andersson (Taesler and Andersson 1984). In their method calculations are based on the spectral distribution of solar radiation outside the atmosphere. A more detailed description about preparing the climate data for building simulations is available in the licentiate thesis (Moussavi Nik 2010).

2.2. Uncertainties of the climate data

Future climate is uncertain and different climate change scenarios give different results. These differences are related to a number of uncertainties. One is the external forcing scenarios like emissions scenarios which change the greenhouse gas and aerosol concentrations. Another uncertainty factor concerns the changes in the large-scale circulation determined by GCM. Different RCMs can respond differently to the forcing conditions. All of these factors are introduced as uncertainty factors and five of them were considered in this work. These five uncertainties are caused by GCMs, RCMs, emissions scenarios, initial conditions and spatial resolutions. A handle on these uncertainties can be gained when several models, forcing scenarios and simulations are considered. Whenever the results do not vary much across models and scenarios, it can be taken as an indication of robustness and perhaps of a useful degree of certainty (Persson et al. 2007).

2.2.1. Global Climate Models

A global climate model (GCM) is a mathematical model of the general circulation of a planetary atmosphere or ocean which is based on the Navier-Stokes equations on a rotating sphere with thermodynamic terms for various energy sources like radiation and latent heat. These models are applied with different external forcing factors as changing greenhouse gas concentrations, changes in solar intensity, etc. As the initial conditions in climate simulations with GCMs differ in compared to the real state of the climate system GCMs do not need to follow the actual evolution of the climate system. However, statistics of the simulated states over longer time periods like a 30-year period should be comparable to observational data. This includes both long-term averages but also variability and extreme statistics.

Differences between GCMs depend both on differences in the formulation of GCMs and on differences in initial conditions used in GCMs in the climate change experiments. In this work five different GCMs, which are described briefly in the following, have been considered. RCA3 has been downscaling GCM results to 50km horizontal resolution under the same emissions scenarios (A1B) (Erik Kjellström et al. 2011).

CCSM3: The Community Climate System Model (CCSM3) is a state-of-the-art coupled global circulation model that has been developed under the auspices of the National Centre of Atmospheric Research (NCAR) Boulder, USA. The modules for the atmosphere, land surface, sea ice, and ocean components are linked through a coupler that controls the exchange of energy and water between the components. The current version 3 of CCSM has been released in June 2004 and since then it has been widely used for climate studies (Wyser, Rummukainen, and Strandberg 2006).

CNRM: The CNRM-CM3 global coupled system is the third version of the ocean-atmosphere model initially developed at CERFACS (Toulouse, France), regularly updated at the Centre National Weather Research (CNRM, METEO-FRANCE, Toulouse). CNRM-CM3 includes a parameterization of the homogeneous and heterogeneous chemistry of ozone and a sea ice model from Tokyo University (Salas-Mélia et al. 2006).

HadCM3: Hadley Centre Coupled Model-version 3 is a coupled atmosphere-ocean general circulation model (AOGCM) developed at the Hadley Centre in the United Kingdom. It was one of the major models used in the IPCC Third Assessment Report in 2001. HadCM3 has been run for over a thousand years, showing little drift in its surface climate (Gordon et al. 2000). HadCM3 is composed of two components: the atmospheric model HadAM3 and the ocean model (which includes a sea ice model). Simulations often use a 360-day calendar, where each month is 30 days.

ECHAM5: A coupled atmosphere-ocean GCM developed at the Max-Planck Institute for Meteorology in Hamburg, Germany. The current simulation is one of the contributions to the IPCC AR4 work. In a comparison with observations ECHAM5 has been shown to perform well in terms of surface pressure patterns in west-central Europe indicating that the large-scale circulation over Europe is realistic.

IPSL: The coupled model by the Institut Pierre Simon Laplace des Sciences de l'Environnement Global, IPSL Global Climate Modeling Group, Paris, France. Successive versions of the global coupled model have been developed since 1995 (Marti et al. 2006).

2.2.2. Regional Climate Models

RCMs are used to dynamically downscale the GCM results (Rummukainen 2010). It is a commonly used approach to improve the resolution of the climate simulation results. Compared to the statistical downscaling methods, RCMs have the advantage of generating physically consistent data sets across different variables. The main advantage of the finer resolution that is feasible in RCMs, is a better description of the local topography, land-sea distribution and other land surface properties. These have an influence on surface and near-surface climate conditions (Persson et al. 2007). As it was mentioned most of the climate data used in this work are the results of RCA3, which is the latest version of the Rossby Centre regional atmospheric model (Samuelsson et al. 2011). The RCA3 data has suitable temporal resolution, from 30 minutes to 6 hours, and spatial resolution, down to 6.5 km, for building simulations. RCA3 has been evaluated against present-day climate. Given appropriate boundary conditions these studies have shown that RCA3 is capable of reproducing many aspects of the observed climate, both in terms of means and variability (Persson et al. 2007).

In order to assess the sensitivity of the building simulations to different RCMs climate data of RCA3 downscaling the ECHAM5 model with the spatial resolution of 25km is compared with two other RCMs; KNMI-RACMO2 and DMI-HIRHAM5, both downscaling the same GCM with the same spatial resolution.

2.2.3. Emissions scenarios

Future changes in the atmospheric content of greenhouse gases and aerosols are not known, but the changes are assumed to be within the range of a set of scenarios developed for the IPCC (Intergovernmental Panel on Climate Change). These scenarios build on consistent assumptions of the underlying socioeconomic driving forces of emissions, such as future population growth, economic and technical development. The Special Report on Emissions Scenarios (SRES) (Nakicenovic et al. 2000) introduces four emissions scenario families: A1, A2, B1 and B2. A and B families are distinguished by having more economic and more environmental focuses respectively. Scenario 1 heads to globalization and a homogeneous world. In scenario 2 the pathway changes to a heterogeneous world which is more regionalized. The global mean net warming response is rather uniform across these emissions scenarios during the next few decades but diverges more and more after that (Persson et al. 2007).

In this project three scenarios of the RCA3-ECHAM5 climate model were used which were forced by these emissions scenarios: A2, A1B and B1. Approximate carbon dioxide equivalent concentrations corresponding to the computed radiative forcing due to anthropogenic greenhouse gases and aerosols in 2100 for the SRES B1, A1B and A2 scenarios are about 600, 850 and 1250 ppm respectively (Solomon 2007). The global climate model was run with the observed forcing conditions until the year 2000 (IPCC 2007). So there is no difference in the forcing conditions between different scenarios until 2000. The net effect of the changes in emissions of anthropogenic greenhouse gases and aerosol precursors is approximated by an equivalent increase in the CO_2 concentration. The anthropogenic radiative forcing includes the effect of greenhouse gases plus the indirect and direct effects of aerosols.

2.2.4. Initial conditions

Initial conditions are needed for the full three-dimensional fields in the atmosphere and oceans. Also starting conditions for the soil models and sea-ice models are needed. In addition to this it is needed to prescribe the physiography (orography, type of soils, vegetation cover, etc). Climate simulations with global climate models for the 20^{th} and 21^{st} centuries generally start with preindustrial conditions. This is often taken as the year 1860 which is well before any large changes in atmospheric composition due to human activities. In this way the climate models can simulate the evolution of climate change taking into consideration the effect of changes in forcing factors (like greenhouse gas (GHG) concentrations, aerosol content, etc). The initial conditions back in 1860 are not known since there are no surface based observations of the climate variables like temperature and precipitation, but only at a few points and mostly in Europe and North America. The southern hemisphere is virtually free of observations. In addition, no observation exists of oceanic conditions, sea ice extent, soil moisture, etc.

Climate models are set up and run for pre-industrial conditions as part of their testing. These runs start from some arbitrary initial conditions representative of preindustrial conditions (prescribed GHG concentrations, aerosol content, solar constant, vegetation cover, etc.). These simulations should not show any long-term drift in long simulations (of the order of 1000 years or so) as forcing conditions are kept constant. These simulations are referred to as (preindustrial) control runs. Such a long simulation does not show long-term trends but it shows variability from year to year and from decade to decade (as does the climate system). This variability is referred to as natural variability.

By taking some arbitrary conditions from the 1000 year control run it is possible to get initial conditions representative of preindustrial conditions. This is what was done at the Max-Planck Institute when they set up the ECHAM5_A1B_1/2/3 simulations. So, they simply took a state from the long control run, for example 1st of January in model year 230, as initial conditions for one experiment, 1st of January from model year 560 for the second and 1st of January from model year 980 for the third. The evolution with time in these three simulations differs as the initial conditions are not the same. These differences are present throughout the simulations, i.e. both in the 20th and the 21st century. It can also be noted that these differences that are related to natural variability can be considerable in a regional and local context (Kjellström et al. 2011).

2.2.5. Spatial resolution

In this work, climate data were mostly taken from simulations at 50x50 km horizontal grid spacing. In a previous study data with higher horizontal resolution of 25km×25km were also used. RCA3 was set up so that a 50km grid was exactly covered by four grids in the finer-scale 25km integrations. It was concluded that the increase in resolution from 50 km to 25 km did not have any significant impact on the results. Differences were mainly in the extreme values which had very low probabilities with very small effect on the long term behaviour of buildings.

3.

Statistical Methods

As it was discussed in the introduction using the projected climate data increased the amount of data which were needed to be processed. In this project most of the climate data sets, and consequently the building simulation results, were covering 140 years from 1961 to 2100 with hourly time steps. There were 13 climate data sets for four cities. Moreover different constructions were compared concerning their hygrothermal performance. Meanwhile the presence of the climate uncertainties was impelling the use of suitable statistical methods.

Different statistical methods were used in this work. They can be divided into two groups of nonparametric and parametric methods. The nonparametric methods make no assumptions about the statistical distributions of data. For example when boxplots are used to compare temperature distributions in two cities, it is not important when maximums or minimums happen. In the nonparametric methods which were used here a data set is treated as a bunch of numbers without any track of time. The robust nonparametric methods are useful for quick comparison of data sets. It is possible to increase the accuracy of the comparisons by comparing data sets during narrower time spans. Unlike the nonparametric methods, the parametric methods can track the time. In the case of analysing data using more statistical power the parametric methods can be implemented. Parametric methods make more assumptions than non-parametric methods. They can produce more accurate and precise estimates but the robustness of the method can be questioned.

In this chapter the parametric and nonparametric methods which have been used in the work are briefly mentioned. More detailed descriptions can be found in the licentiate thesis and Paper I which is appended to this thesis.

3.1. Nonparametric methods

One of the widely used nonparametric models in many fields is using *boxplots*. It is based on robust statistics which means it is more resistant (robust) to the presence of outliers comparing to the classical statistics which is based on the normal distribution. The statistics which are described by boxplots are the lower and upper quartiles, median, the lower and upper whishkers and outliers. Boxplots have been used for different purposes like comparing data sets with different spatial resolutions of 25 km and 50 km and also looking into temperature distributions of different climate scenarios.

Histogram is another useful tool to plot the density of data. Histogram displays the tabulated frequency graphically as bars. The accuracy and robustness can be affected by the width of the bars.

In many cases the distribution of data sets were assessed by looking into their *probability density (distribution) function (PDF)* or *cumulative distribution function (CDF)*. These functions describe the relative likelihood of variables to take on a value. They are very helpful to illustrate the distribution of data sets graphically and to compare them. For example in Paper II the performance of four attics are compared by showing histograms of the mould growth PDFs inside them. It is a common approach to illustrate the PDFs by fitting curves. Since many distributions are normal in nature, the normal fit is usually used. Meanwhile the normal distribution tells about two statistics of data; the mean value and the standard deviation. These two help to make the comparisons easier. In chapter 5 it is shown that the normal distribution does not always fit the best with the PDF of data and for example for the heating demand of a building stock, a curve using the *generalized extreme value* function fits better. Nevertheless the normal function has been used for making the comparisons between different scenarios because of its simplicity.

An example of using scatter plots is comparing the risk of mould growth among different scenario as it is shown in Paper IV. Scatter plots show how the population of the calculated mould growth rates are scattered for each climate scenario. This is a qualitative comparison which helps to see the obvious differences quickly.

Another nonparametric method which was mainly used in comparing the two spatial resolutions of the climate data sets is based on the Ferro hypothesis (Ferro, Hannachi, and Stephenson 2005). This method is described in the licentiate thesis and Paper I appended to this thesis. The method provides a good view of the data distribution by using quantiles and increases the accuracy of the assessment in comparison with box plots. It is possible to distinguish if the differences between data sets have been caused by the differences in scale or location.

3.2. Parametric method

Sometimes there is a need to track data and its variations during time in different time scales. Different changes of the climate data may affect the building performance. For example long term changes like annual temperature increment or short term changes like increase in the intraseasonal day-to-day variability. A parametric method which has been used in this work is called *decomposition of variabilities* which was developed by Fischer and Schär (Fischer and Schär 2009). In this method variabilities of a parameter are decomposed into three components: interannual, intraseasonal and seasonal cycle. The method is described in detail in the licentiate thesis and in Paper I.

The parametric method of decomposition of variabilities is a robust method for analysing data. Decomposition of the climate parameters and calculation of their variability components enable to have a multi-time-scale analysis of the data. It provides statistics about data and its variations for a long period with different time resolutions. It considers daily, seasonal, annual and periodical variations of data. Different variabilities of a parameter represent the changes of that parameter in different time scales and periods. In the licentiate thesis the decomposition method was used to see effects of the climate uncertainties on the temperature and the relative humidity inside and outside an attic.

4.

Hygrothermal Simulation of Attics

One of the major parts of this project was assessing the future hygrothermal conditions of attics. There are two reasons that make the outdoor ventilated attic, which is usually referred as cold attic, a very interesting subject of study. The first reason is that cold attics have been declared as one of the riskiest constructions in Swedish buildings with large existing and future mould problems. According to the survey by the Swedish National Board for Housing and Planning mould growth was present in 21 % of attics of 1400 buildings (Boverket 2009). Warmer and more humid climate of Sweden in the future (E. Kjellström et al. 2007) (Nikulin et al. 2011) may increase the number of moisture related problems in attics. The second reason is the climate inside attics; it reflects the outdoor conditions directly and quickly since it is not conditioned and the attic construction is totally exposed to the outdoor environment.

In this chapter a brief description about the attic model is presented. More information about the attic model, simulation and results are available in Paper II and Paper IV, appended to this thesis. Paper II compares four solutions for decreasing the future mould growth in attics while three climate data sets with difference emissions scenarios are considered. Paper IV makes the sensitivity analysis for the predicted risk of mould growth in the attic concerning the uncertainty of having different global climate models for the climate scenarios. An extensive description about the attic simulation results and effects of the climate uncertainties is available in the licentiate thesis (Moussavi Nik 2010). There the climate data and the attic simulation results were analysed using nonparametric and parametric statistical methods during different time periods and seasons. Effects of uncertainties were studied by looking into temperature and relative humidity distribution of the attic and also their variations in different time scales. Moreover there are some other publications about the attic simulations which are not attached to this book (Moussavi Nik and Sasic Kalagasidis 2008; Sasic Kalagasidis et al. 2009; V. Nik and Sasic 2010).

4.1. The attic construction

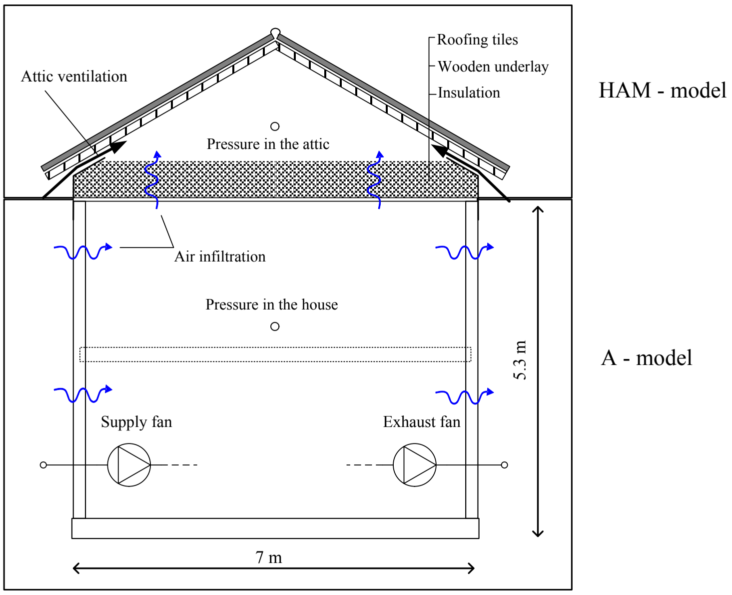

Fig. 2. Sketch of the cold attic and the house.

In order to assess the climate conditions inside attics, a numerical heat, air and moisture (HAM) balance model was developed based on the dimensions of a two storey house with a cold pitched roof as shown in Fig. 2. The roof pitch is 30°, the area of the ceiling is 74.8 m^2 (11m long and 6.8 m wide) and the volume of the attic is 67.6 m^3 (based on 1.8 m height from the insulation to the roof top). The hygrothermal performance of attics was numerically simulated using HAM-Tools (Sasic 2004). Four measures of the cold attic were compared in this work; one reference attic and three alternatives which were modified versions of the reference attic with some changes like insulating the roof of the attic, ventilating from the gables side, or ventilating the attic mechanically. Paper II tells more about the attic model and the future performance of the attics.

4.2. Using mould as the performance criterion

Mould growth occurs if mould spores are exposed to suitable temperature and humidity conditions under sufficiently long time. Dependence of the mould growth on time, temperature and humidity makes it an interesting phenomenon in studying the hygrothermal conditions of buildings. It is a good indicator for measuring the hygrothermal conditions although there are many uncertainty factors affecting the mould growth assessment.

There is no standard model to assess the mould growth but there are some which have shown better agreements with measurements. One widely used model is a mathematical model of the mould growth on wooden materials (Hukka and Viitanen 1999). It calculates the critical relative humidity as a function of temperature and based on that calculates the mould index which is a number between 1 and 6. Another model which calculates the mould dose (Isaksson et al. 2010) also was used and results are presented in Paper IV. The calculated mould doses were compared among different climate scenarios. Both the mould models predict high risks of the mould growth in the future.

4.3. Assessing results using the decomposition method

As it was discussed in the methodology part of the introduction, the analysis is mainly based on comparative assessment of the results. In this part one method of assessing the climate data which was mainly used in the attic simulations is briefly discussed. It is based on using the decomposition method which is described in Paper I. Climate conditions inside and outside the reference attic, which is described in Paper II, are compared during the CTL and SCN periods. The cold attic was simulated using the climate data from four scenarios of the RCA3 climate model forced by different GCMs and also the RCA3-ERA40 reanalysis. Comparing the five scenarios during the CTL period shows their uncertainties in calculating the past conditions and the effects on the attic simulations. RCA3-ERA40 can be used as a reference during the CTL period. The uncertainty analysis is performed also during the SCN period between the four scenarios. Meanwhile comparison of the CTL and SCN periods shows the evolution of the climate change in each scenario.

In the decomposition method each parameter is decomposed into four constructive components. Tables 1 and 2 show the 30-year mean components of temperature, relative humidity and global radiation. Comparisons are made for the spring and autumn seasons. The hygrothermal conditions of attic are more favourable for the mould growth during spring and autumn. According to Table 1 the evolution of climate change is not the same among the scenarios. For example RCA3-HadCM3 has the lowest 30-year mean temperature during CTL period of spring, while during SCN period RCA3-CCSM3 has the lowest 30-year mean temperature. It means in the CCSM3 global climate model the temperature increment is less than RCA3-HadCM3. Hygrothermal conditions inside the attic are nonlinear functions of the outdoor climate. As Table 2 shows differences between scenarios can be amplified inside the attic. For example during the SCN period RCA3-ECHAM5 and RCA3-HadCM3 show the temperature difference of 0.7^{o}C in Table 1, but this difference reaches to 1.8^{o}C inside the attic. This difference is very influenced by the temperature and global radiation differences of the scenarios.

Table 1. The 30-year mean values of temperature, relative humidity and global radiation for the outdoor climate during the CTL and SCN periods. Four scenarios of RCA3 forced by different GCMs, all having the same initial conditions and emissions scenarios, and RCA3-ERA40 are compared.

	CTL period (1961-1990)					**SCN period (2071-2100)**			
	CCSM3	CNRM	ECHAM5	HadCM3	ERA40	CCSM3	CNRM	ECHAM5	HadCM3
30-year mean (Spring)									
$\overline{T}$	4.9	5.7	6.1	4.8	5.4	7	7.5	8.4	7.7
$\overline{RH}$	0.81	0.78	0.82	0.79	0.8	0.83	0.81	0.84	0.83
$\overline{GR}$	155	156	152	167	164	142	145	138	150
30-year mean (Autumn)									
$\overline{T}$	7.2	7.7	8.2	7.1	7.8	9.4	9.9	11.2	11
$\overline{RH}$	0.86	0.86	0.87	0.86	0.86	0.88	0.87	0.88	0.88
$\overline{GR}$	59	62	56	56	60	54	59	52	50

Table 2. The 30-year mean values of temperature and relative humidity inside the attic during the CTL and SCN periods. Four scenarios of RCA3 forced by different GCMs, all having the same initial conditions and emissions scenarios, and RCA3-ERA40 are compared.

	CTL period (1961-1990)					**SCN period (2071-2100)**			
	CCSM3	CNRM	ECHAM5	HadCM3	ERA40	CCSM3	CNRM	ECHAM5	HadCM3
30-year mean (Spring)									
$\overline{T}$	7.2	7.8	8	6.4	7.3	7.5	7.9	8.2	6.4
$\overline{RH}$	0.8	0.76	0.79	0.8	0.8	0.8	0.76	0.8	0.79
30-year mean (Autumn)									
$\overline{T}$	6.7	7.3	7.4	7.2	7.6	7	7.5	7.9	7.6
$\overline{RH}$	0.87	0.86	0.88	0.84	0.88	0.88	0.86	0.88	0.85

The main advantage of using the decomposition method is the ability of studying data and its variations in different time scales. Fig. 3 and Fig. 4 compare the mean cycle of temperature in spring and autumn for RCA3-ECHAM5 and RCA3-HadCM3 during CTL and SCN periods and RCA3-ERA40 during the CTL period. The mean cycle shows how temperature varies during a season in the 30-year period, on the daily scale. For the outdoor conditions in Fig. 3 both the future scenarios are predicting warmer springs and autumns. Inside the attic Fig. 4 differences between the CTL and SCN periods is less than the outside, but differences between scenarios can increase.

Variations of the hygrothermal conditions can affect the building performance. For example in one scenario the hygrothermal conditions may stay in a suitable level for the mould growth for a sufficient time, but in another scenario variations of temperature or relative humidity around that level do not provide the favourable conditions for the mould growth. Hence differences in variations of the climate parameters, which have been induced by differences of the climate scenarios, can affect the future performance of buildings. It is possible to track the variations of climate parameters in different time scales by decomposing their variabilities. Figures 5 to 8 show the four variability components of the temperature and the relative humidity inside and outside the reference attic during spring and autumn.

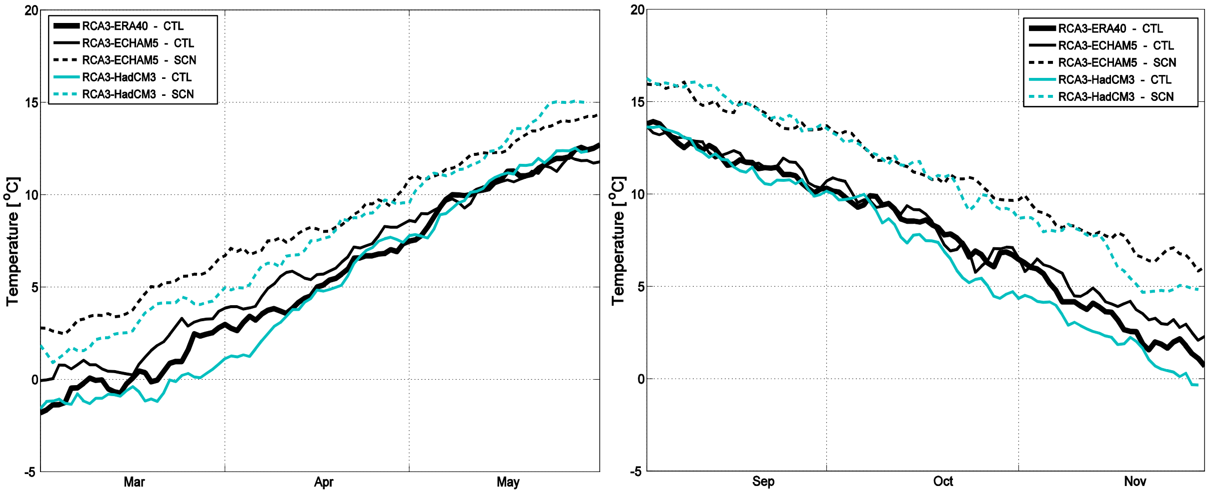

Fig. 3. Mean cycle of the outdoor temperate in Gothenburg during spring (left) and autumn (right) of the CTL and SCN periods. Graphs correspond to the RCA3-ERA40, RCA3-ECHAM5 and RCA3-HadCM3 climate scenarios.

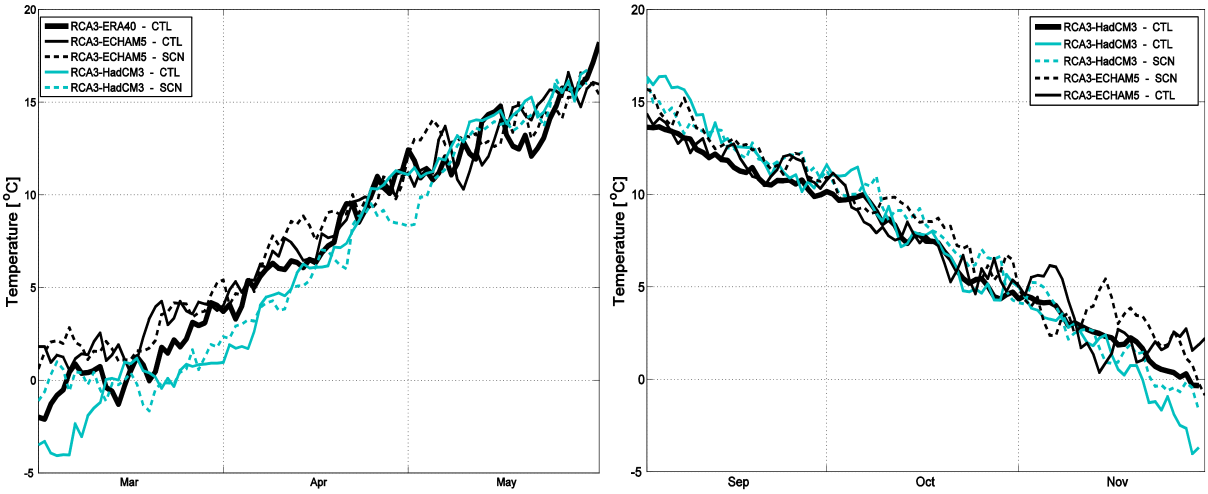

Fig. 4. Mean cycle of the temperate inside the attic in Gothenburg during spring (left) and autumn (right) during the CTL and SCN periods. Graphs correspond to the RCA3-ERA40, RCA3-ECHAM5 and RCA3-HadCM3 climate scenarios.

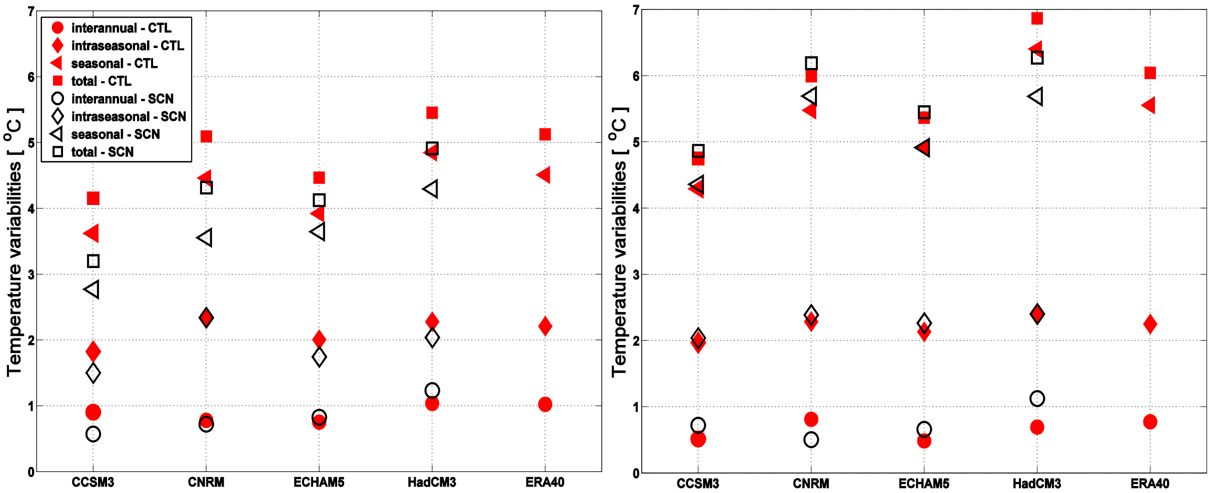

Fig. 5. Variability components of the temperature outside (left) and inside (right) the attic in Gothenburg during springs of the CTL and SCN periods. RCA3-ERA40 and four scenarios of RCA3 forced by different GCMs are compared.

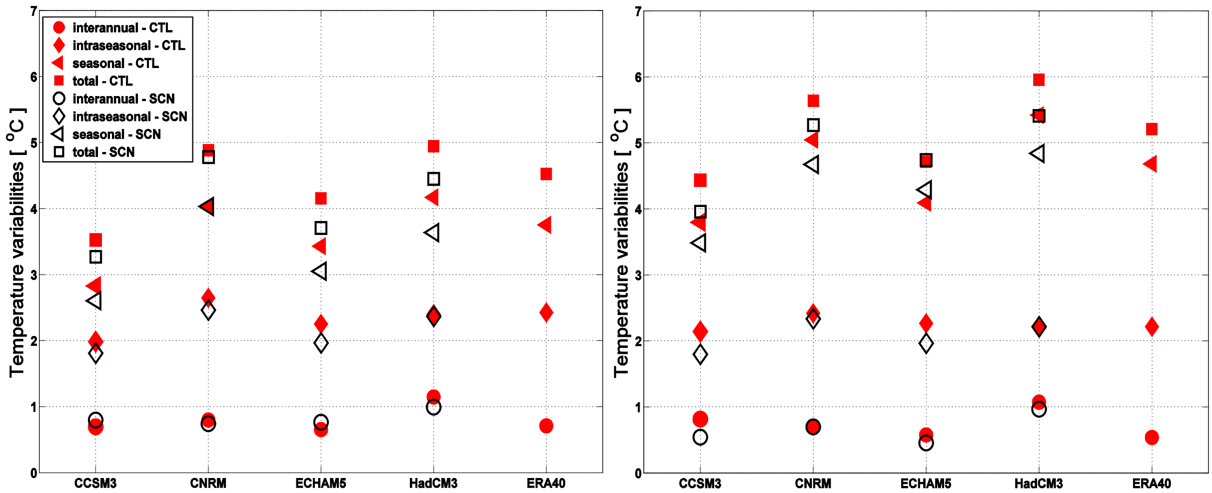

Fig. 6. Variability components of the temperature outside (left) and inside (right) the attic in Gothenburg during autumns of the CTL and SCN periods. RCA3-ERA40 and four scenarios of RCA3 forced by different GCMs are compared.

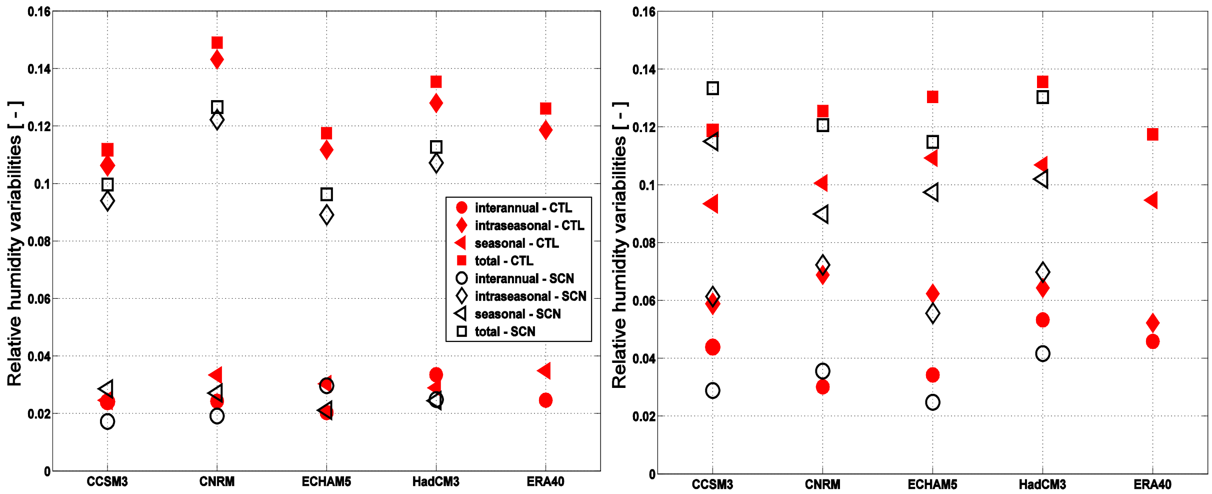

Fig. 7. Variability components of the relative humidity outside (left) and inside (right) the attic in Gothenburg during springs of the CTL and SCN periods. RCA3-ERA40 and four scenarios of RCA3 forced by different GCMs are compared.

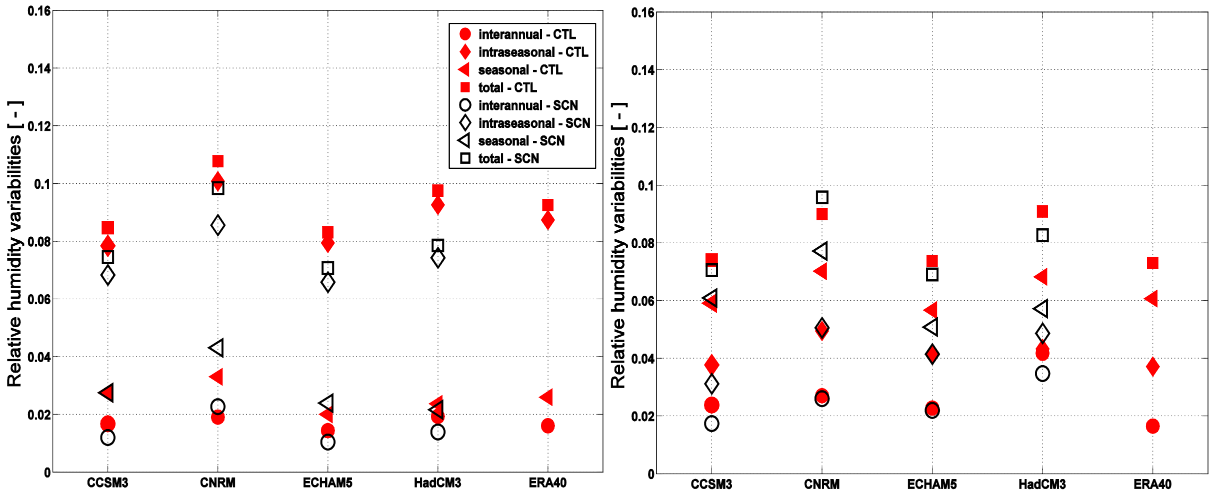

Fig. 8. Variability components of the relative humidity outside (left) and inside (right) the attic in Gothenburg during autumns of the CTL and SCN periods. RCA3-ERA40 and four scenarios of RCA3 forced by different GCMs are compared.

Each variability component has a meaning which is described in Papar I and is repeated here briefly:

The *interannual variability* of a 30-year period gives a general view of deviations of a daily parameter from its 30-year mean value. It is a gauge for showing the difference of the seasonal mean and the 30-year mean values of a parameter in the whole period. The *intraseasonal variability* of a parameter is a measure of the amplitude of daily variations around the seasonal cycle. The *Seasonal variability* is the variability which has been induced by the seasonal cycle. The seasonal variability represents the magnitude of the daily variations of the season during the whole period.

With the help of the decomposition method effects of the climate uncertainties on the attic simulations were assessed in this work. The global warming is obvious in all the scenarios and the SCN period has higher temperatures than the CTL, but the amount and rate of the increment is not the same among the scenarios. Temperature and humidity levels will increase inside the attic which can increase the risk of mould growth. There are not clear correlations between the hygrothermal conditions inside and outside the attic, but some patterns are recognizable as it is discussed in Paper IV. Effects of different variability components on the *total variability* depend on the considered season, parameter, geographical location and place, i.e. inside or outside the attic. Consequently the importance of the uncertainty factors on the attic simulation results also depends on the same factors. For most of the cases the uncertainty of GCMs affects both the climate parameters and their variations. Depending on the case some uncertainty factors of the climate data might be neglected. For example in Paper II the uncertainty of having different emissions scenarios is neglected when assessing the risk of mould growth inside four ventilated attics.

5.

Energy simulations

In most of the countries the residential building sector is one of the main energy consumers. Quantity and quality of the energy usage in the building stock of a region is very dependent on its climate conditions and the building standards. For example cooling buildings in a warm region can be very demanding and the warmer future climate increases the energy demand to higher values. On the other hand heating demand of the buildings located in a cold region may decrease by having a warmer climate in the future. In Sweden the residential sector uses 21% of the overall energy use in the country (Mata 2011). This energy is mainly used for heating. The mild Swedish summers with short periods do not create the need for cooling systems in the Swedish residential buildings. Buildings are commonly and rather effectively cooled down by the means of ventilation with the fresh outdoor air.

An extensive field investigation was conducted by the Swedish National Board of Housing, Building and Planning (Boverket) in year 2009 which is called the BETSI programme (Boverket 2009). 1400 residential buildings were selected in a way to statistically represent the Swedish housing stock. Buildings are distributed in 30 municipalities with different populations and climate conditions. The status of the buildings in terms of energy use, technology status, indoor air quality, damages and maintenance were investigated.

To assess the performance of the Swedish residential buildings concerning their future heating and cooling demands the building stock of four cities in Sweden were studied here. Energy simulation of the building stocks was performed to investigate differences in the heating and cooling demands in respect to the present and the future climate. Simulations were done by a dynamic building energy simulation programme developed in Simulink/Matlab, for the period of 1961-2100 and on hourly basis. The energy model is based on the lumped system analysis approach. Complexity of the model was limited in order to accelerate reading the large input data sets, performing the calculations and generating the output data sets. Therefore, buildings are described by restricted number of parameters expressing the basic features of the energy use in buildings. These include the total heated floor area and the air volume, the total surface of the external walls and windows, the average values for the thermal conductance of walls and windows (U values), the ventilation flow rates, the solar transmittance of windows and the internal heat gains. Accuracy of the Simulink model has been validated (Mata and Sasic Kalagasidis 2009) (Mata 2011) as it is described in Paper III. Managing the energy simulations for different climate and building data sets and also assessing the simulation results were done by coding in Matlab. To upgrade the energy simulation results to the real scale they should be multiplied by the weighting factors which have been provided by Boverket. But in this project results are compared just by assessing the statistical representatives of the building stocks.

Two cooling strategies were tested for the warmer future climate by looking into the indoor temperature distributions: 1) *natural cooling*, i.e. when the indoor temperature is more than 24°C and the outdoor temperature is less than 24°C windows will be opened, 2) mechanical *and natural cooling*, where the natural cooling is used whenever the indoor temperature is above 24°C and the outdoor temperature is below 24°C, but if the indoor and outdoor temperature reaches above 26°C windows will be closed and a mechanical cooling system will work. When the mechanical cooling works its maximum cooling power is limited to a value equal to the maximum heating power of the building. In calculating the mechanical cooling loads only the sensible load is considered.

The impact analysis considered four uncertainties of the climate data caused by GCMs, RCMs, emissions scenarios and initial conditions. Climate scenarios with 5 GCMs, 3 RCMs, 3 emissions scenarios and 3 initial conditions were used in the energy simulations. Simulating the future performance of a building stock for different future climate data sets increases the number of runs. The low thermal inertia of buildings helps to modify the simulations in a way to decrease the number of runs. In the energy simulation of buildings, unlike the moisture simulation, it is possible to interrupt the simulations after each year and restart again by assuming the same initial conditions and still without affecting the outcome considerably. Energy simulations are compared by looking into 20-year periods during 1961-2100. To avoid this large amount of simulations, buildings are simulated just once during the 20-year. Consequently each building experiences just one year of the climate data during each 20-year period. A more detailed description about the simulation method can be found in Paper III.

Results which are presented in this chapter have not been published previously; hence this chapter is longer than the previous chapters. The energy simulation results are presented for three cities in Sweden; Lund, Gothenburg and Östersund. In Paper III the energy simulation of the building stock of Stockholm is discussed.

5.1. Energy simulation of the building stock in Lund

Lund is one the major cities in southern Sweden with oceanic climate. Area of the city is 25.75 km^2 and the population is 82800. In this work the building stock of Lund has the smallest number of buildings comparing to the other cities

5.1.1. Comparing two sampling methods for doing the energy simulations

The building stock in Lund is statistically represented by 52 buildings. Having less number of buildings corresponds to less number of simulations for each 20-year period. For example during 2081-2100 the first 12 years of the climate data are used three times and the last 8 years are used two times. For Stockholm in Paper III with 153 buildings the first 13 years are used 8 times and the last 7 years 7 times. Comparison of the short and long runs in Paper III showed that the results of the short runs are reliable. To check if the less number of buildings causes considerable differences in the simulation results of the building stock, the same comparison is done here.

Results of short runs, with 1 year of climate data per building, are compared with long runs, with 20 years of climate data per building. Fig. 9 compares distributions of the heating demand and the indoor temperature between the two runs. Histograms show the probability distributions while the curves compare their normal distributions. For the heating demand the generalized extreme value (GEV) distributions are also compared. The GEV distribution shows better fit than the normal one. Nevertheless both the normal and GEV fits show very similar distributions of the two runs. Histograms of the heating demands distinguish some differences; for example short run shows higher density for the annual heating demand of 100-120 kWh/m^2 while the long run shows higher density for 20-40 kWh/m^2. Despite of these differences the total energy demand, or the integral of the histograms, are very similar which is already recognized by the normal and GEV fits.

Histograms and normal fits of the indoor temperatures and the cooling demand of the two runs in Fig. 9 and Fig. 10 also confirm the similarity between results of the two runs. Therefore hereafter all the assessments are based on results of the short run simulations.

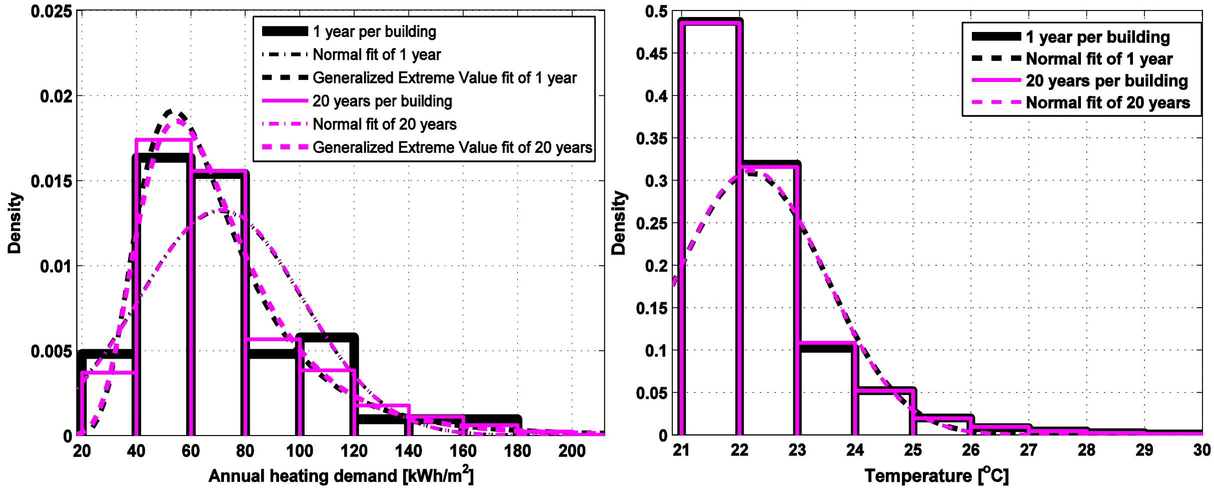

Fig. 9. Comparing two types of simulation by looking into PDFs of the heating demand (left) and the indoor temperature (right). Results are for the energy simulation of 54 building in Lund using 20 years of climate data belonging to the RCA3-ECHAM5-A1B-3 data during 2081-2100. The cooling system is natural cooling.

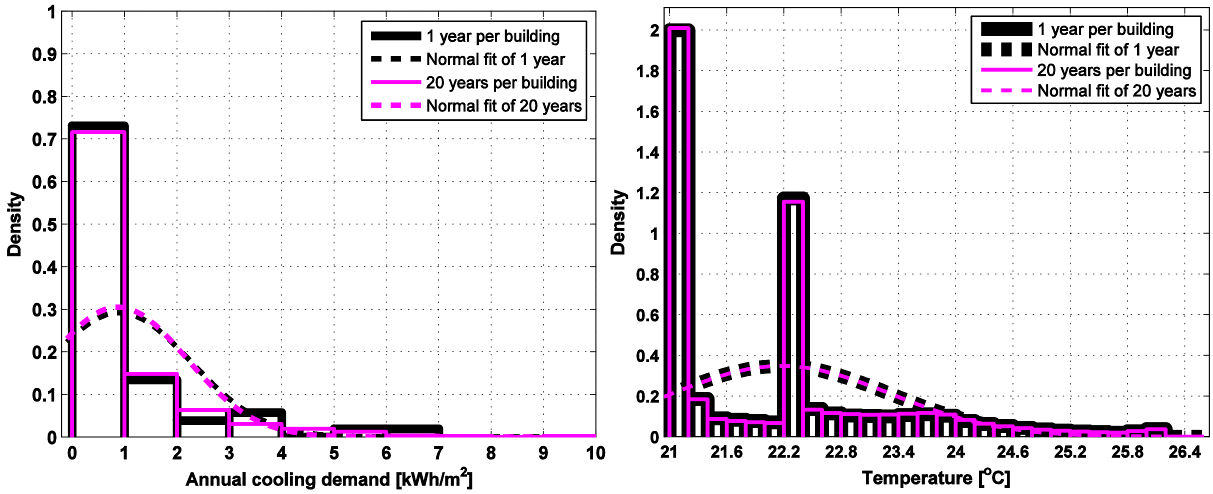

Fig. 10. Comparing two types of simulation by looking into PDFs of the cooling demand (left) and the indoor temperature (right). Results are for the energy simulation of 54 building in Lund using 20 years of climate data belonging to the RCA3-ECHAM5-A1B-3 data during 2081-2100. The cooling system is mechanical and natural cooling.

5.1.2. Climate data

The climate parameters which have been used in the energy simulations are temperature and global radiation. It is interesting to see how the climate uncertainties can change these climate parameters. The 20-year mean values of the global radiation are shown in , considering the four climate uncertainties. The left-up figure compares the values when there are five climate scenarios with different GCMs, all have been downscaled by RCA3 under A1B emissions scenario. The largest difference among these five scenarios is during 1961-1980 where the 20-year mean of the global radiation is around 20 W/m^2 (15% of the maximum value) more than RCA3-ECHAM5. The smallest value of this difference occurs during 2001-2020 which is around 13 W/m^2 or 10% of the maximum 20-year mean global radiation in that period. In other words the maximum difference between the climate scenarios in each period varies from 13 W/m^2 to 20 W/m^2.

Doing the same comparison for the three climate scenarios with different RCMs, downscaling ECHAM5 forced by A1B-3 with the 25km spatial resolution, shows differences in the same order as GCMs. In , right-up, the maximum difference between the climate scenarios is between RCA3 and

DMI-HIRHAM5, which varies from 18 W/m^2 (17% of the maximum value) to 21 W/m^2 (19% of the maximum value). Comparing to the case with different GCMs, regional climate scenarios may cause larger uncertainties concerning the global radiation. Clearly shortwave radiation is a very model dependent variable. The parameterizations of clouds in the models lead to large differences in this respect. Also, the large-scale circulations as described by the GCMs play an important role here. The strong changes in temperature climate in these future scenarios does not however, imply large differences in cloud cover and thereby in shortwave radiation.

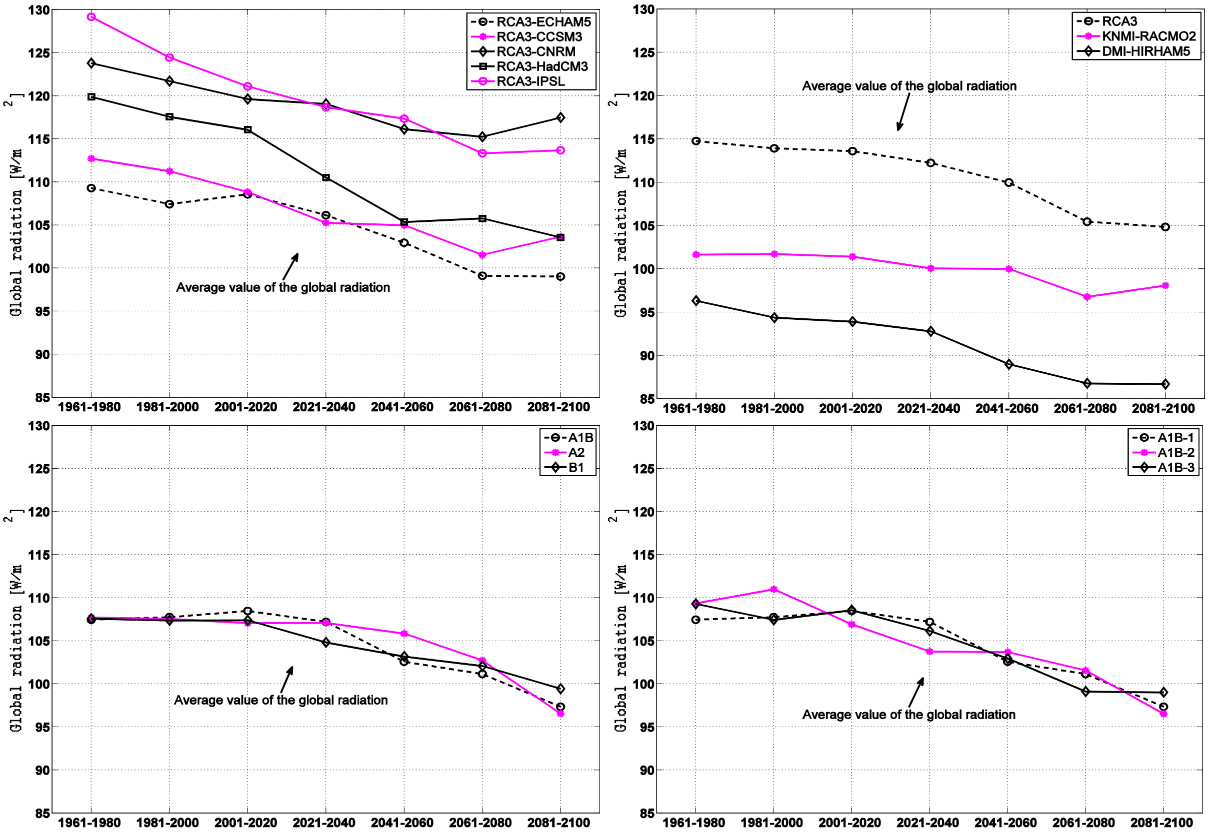

Fig. 11. Average values of the global radiation during the 20-year periods. These climate scenarios are compared; left-up) five GCMs downscaled by RCA3 forced by A1B emissions scenario, right-up) ECHAM5 downscaled by three RCMs, A1B-3, left-bottom) three emissions scenarios of RCA3-ECHAM5 with the first initial condition, and right-bottom) three initial conditions of RCA3-ECHAM5-A1B.

The three emissions scenarios cause smaller variations in the global radiation. In , left-bottom, the 20-year mean value of the global radiation starts from 107 W/m^2 for RCA3-ECHAM5-A1B/A2/B1, all having the same initial conditions. The global radiation decreases to 96 W/m^2 for RCA3-ECHAM5-A2, the scenario with the highest emissions, and 99 W/m^2 for RCA3-ECHAM5-B1, the scenario with the lowest emissions. Difference is around 3% of the highest value, which is negligible comparing to the previous uncertainty factors. Having different initial conditions also does not influence the 20-year mean values of the global radiation considerably. The maximum differences among the three scenarios of , right-bottom, is around 3.6 W/m^2 during 1981-2000.

Effects of the four climate uncertainties on the 20-year distribution of the outdoor temperature are considered in Fig. 12 and Fig. 13. The 20-year mean temperatures are shown in Fig. 12 while Fig. 13 compares the standard deviation of the normal distribution of temperature during 20-year periods. Using this type of graphs helps to see the trends of changes easier than some other methods like using boxplots. Generally temperature increases among all the scenarios while its deviations around the mean value mostly decrease by time. In the case of having different GCMs the maximum difference per period between the scenarios can vary from 1.6°C (15% of the maximum value) during 2061-2080 to 3.1°C (35% of the maximum value) during 1961-1980. The maximum difference per period for the standard deviations in Fig. 13 varies from 2.25°C (32% of the maximum value) during 2061-2080 to 2.8°C (37% of the maximum value) during 2081-2100.

RCA3-IPSL which has the lowest mean values also shows the lowest standard deviations. This scenario underestimates temperature and its variations in Lund. Neglecting RCA3-IPSL, the maximum differences per period among the other four scenarios varies between 0.7°C (7% of the maximum value) and 1.6°C (18% of the maximum value) for the mean temperature and between 2.1°C (30% of the maximum value) and 2.7°C (34% of the maximum value) for the standard deviations. These differences decrease when different RCMs are compared together; for example the largest difference between the mean temperatures is around 0.3°C (4% of the maximum value). It is interesting to see that having different RCMs mainly affects the standard deviations but not the mean values. The maximum difference between standard deviations varies from 0.9°C (14% of the maximum value) during 2081-2100 to 1.6°C (21% of the maximum value) during 1961-1981. For the case with different GCMs both the mean temperatures and their standard deviations were affected considerably by the scenario. But when there are different RCMs, temperatures are distributed around quite similar mean values but with different distributions.

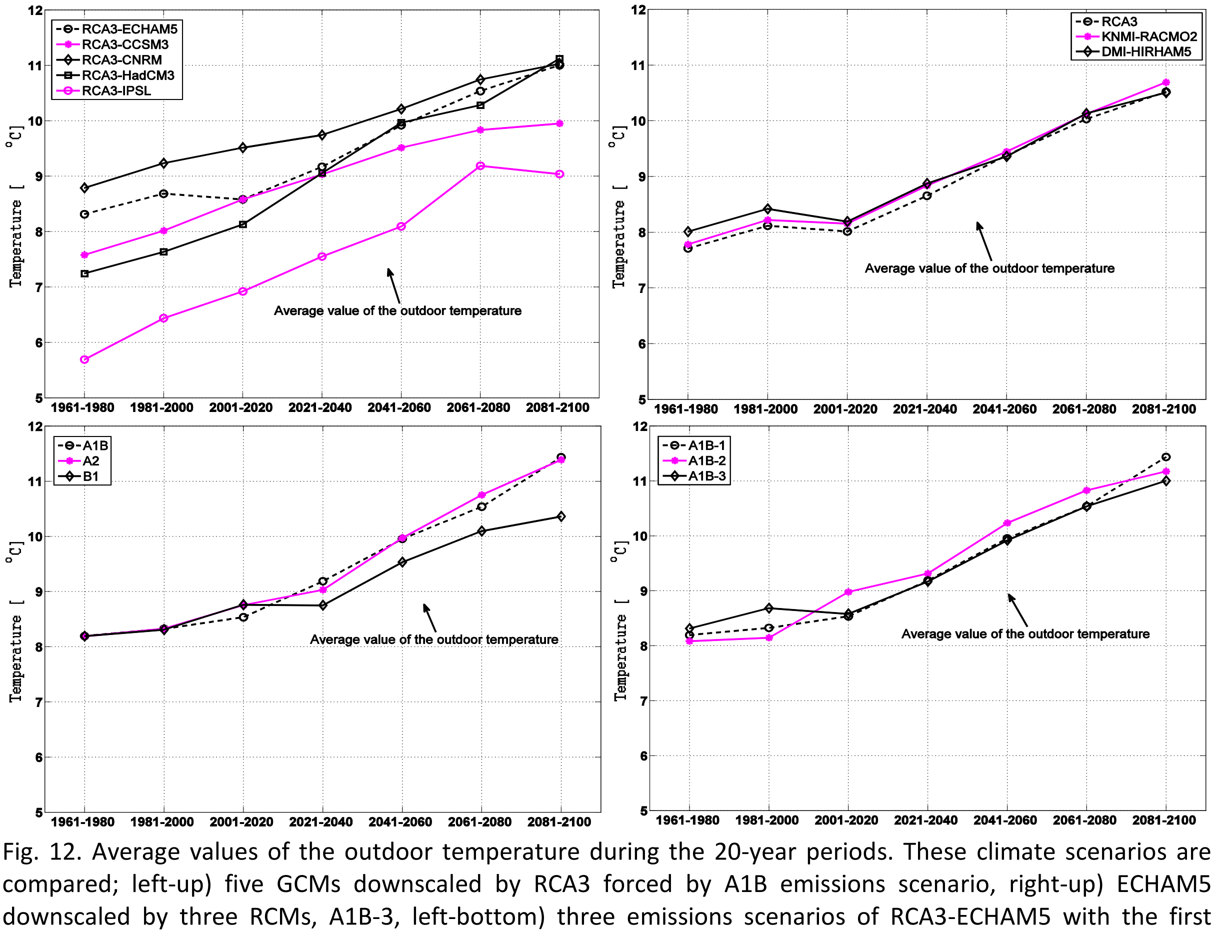

Fig. 12. Average values of the outdoor temperature during the 20-year periods. These climate scenarios are compared; left-up) five GCMs downscaled by RCA3 forced by A1B emissions scenario, right-up) ECHAM5 downscaled by three RCMs, A1B-3, left-bottom) three emissions scenarios of RCA3-ECHAM5 with the first initial condition, and right-bottom) three initial conditions of RCA3-ECHAM5-A1B.

Differences increase by time for both the mean, 1.1°C (9% of the maximum value), and standard deviation, 0.2°C (4% of the maximum value), of the temperature distributions for the three scenarios of RCA3-ECHAM5-A1B/A2/B1. In the presence of different emissions scenarios differences are more pronounced in the mean temperatures, unlike the case with three initial conditions which causes the smallest differences among the mean temperatures but differences between the standard deviations are larger than the case with different emissions scenarios. For example the maximum difference of the mean and the standard deviation of temperatures occur between A1B-3 and A1B-2 during 1981-2000 which are around 0.5°C (6% of the maximum value) and 0.5°C (8% of the maximum value) respectively.

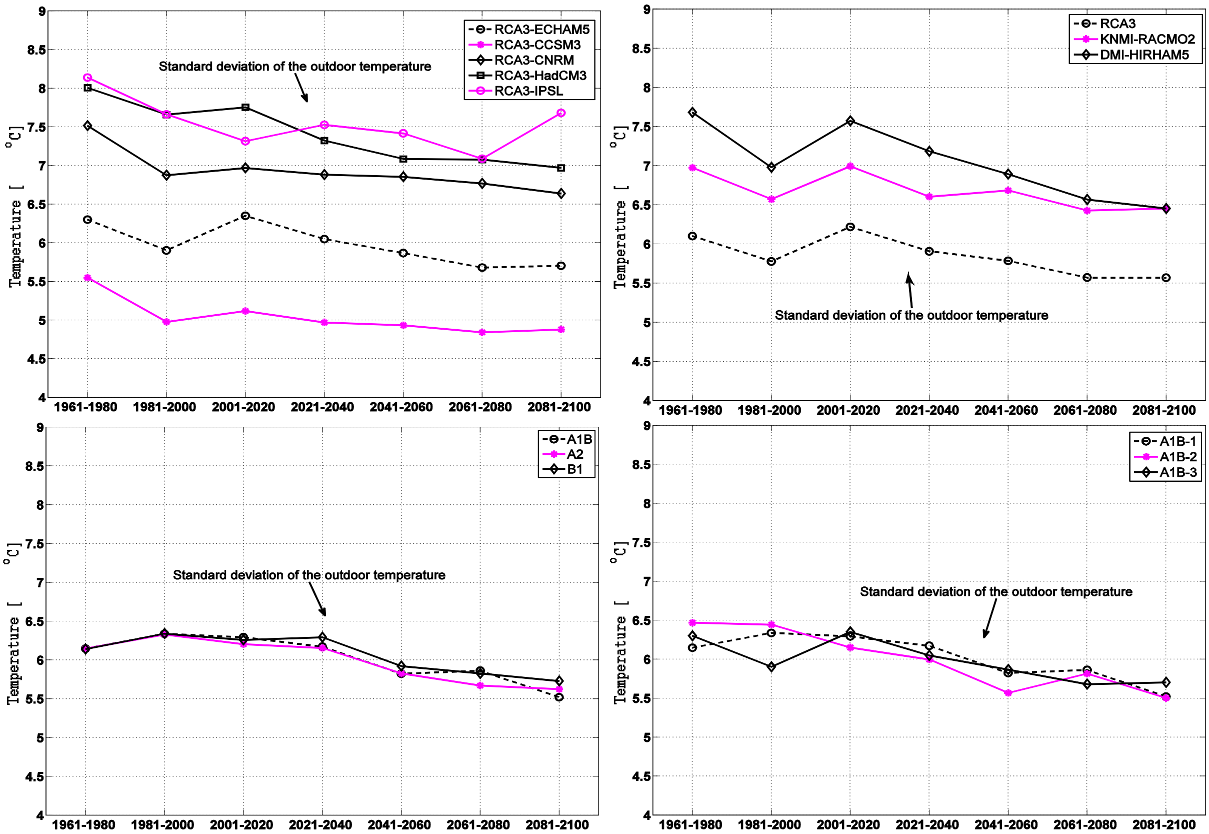

Fig. 13. Standard deviations of the outdoor temperature during the 20-year periods. These climate scenarios are compared; left-up) five GCMs downscaled by RCA3 forced by A1B emissions scenario, right-up) ECHAM5 downscaled by three RCMs, A1B-3, left-bottom) three emissions scenarios of RCA3-ECHAM5 with the first initial condition, and right-bottom) three initial conditions of RCA3-ECHAM5-A1B.

5.1.3. The building stock in Lund

The probability distribution for the U values, the heated floor areas and the window areas of the building stock is shown in Fig. 14. Most of the residential buildings are small family buildings with U values less than 0.6 W/m^2/K.

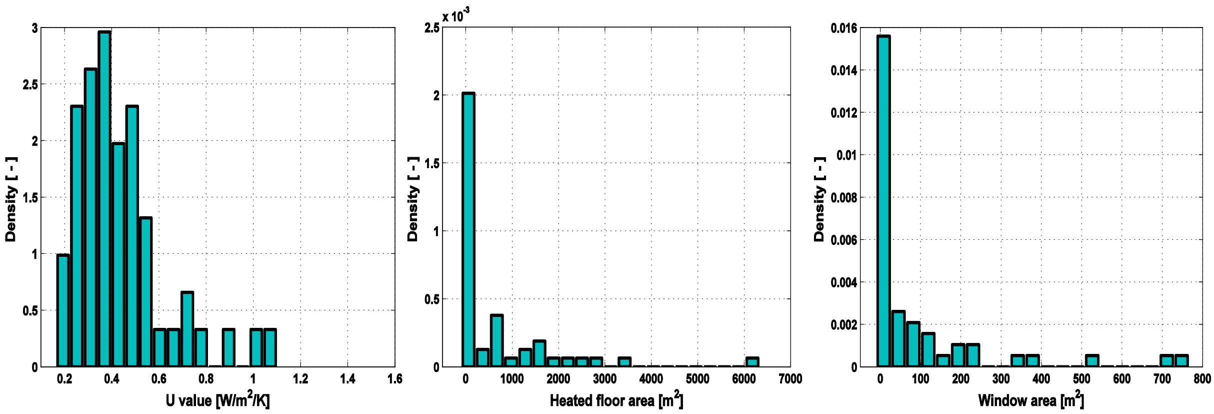

Fig. 14. Distribution of the U values, heated floor areas and window areas of the building stock in Lund. Data are from the BETSI programme (Boverket 2009).

5.1.4. Energy simulation results

Results of the energy simulations of the building stock in Lund are presented in this section. Average values and standard deviations of the heating and cooling demands and the indoor temperature during the periods of 20 years are compared for different climate scenarios. Cooling demand is for the building stock with the second cooling strategy; mechanical and natural cooling. Indoor temperature of the building stock is studied for both the cooling strategies separately.

Heating demand of the building stock will decrease in the future. The downward trend of the graphs in Fig. 15 confirms that all the scenarios predict lower heating demands, with smaller variations around the mean values, as time passes. Rate of changes is not unique among the scenarios and periods. In some cases, like having different RCMs, rates are very similar among the scenarios, but generally there is no correlation between them.

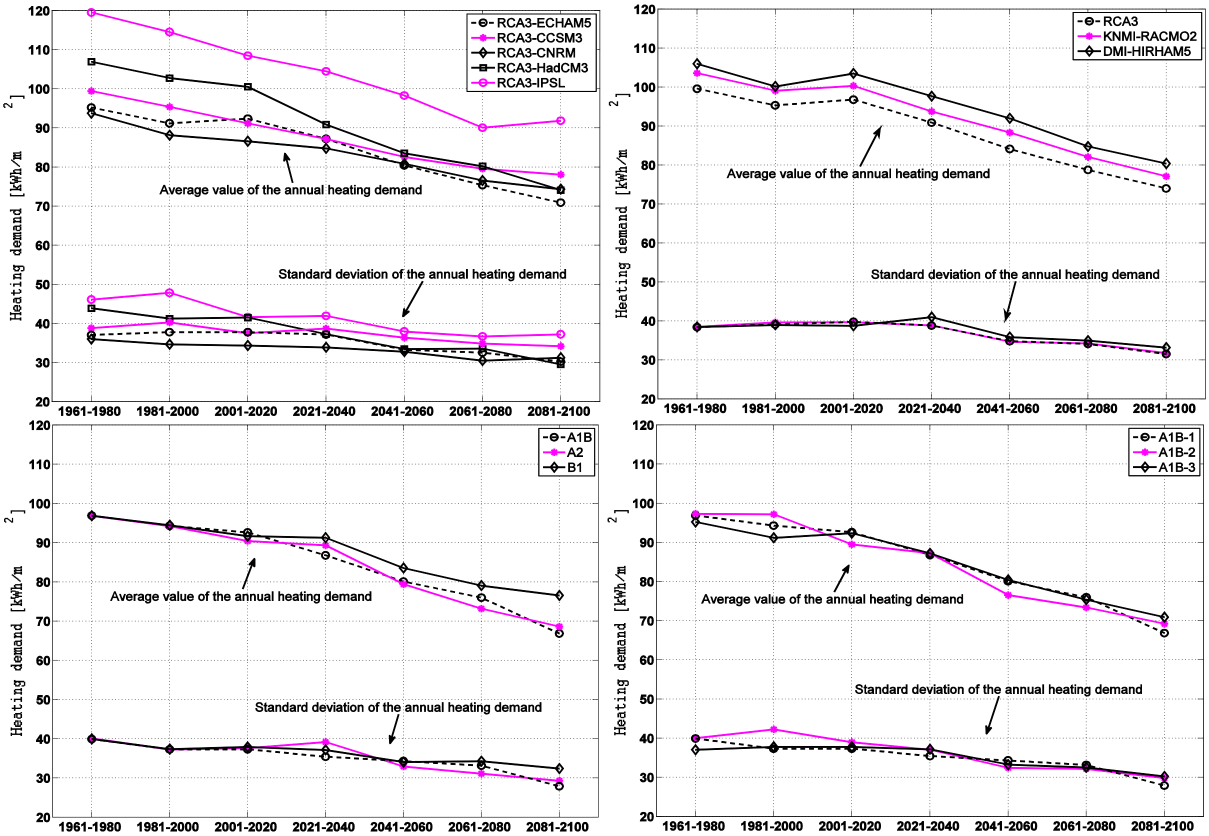

Fig. 15. Average values and standard deviations of the annual heating demand during the 20-year periods. Five scenarios of the RCA3 regional climate model are compared when it has been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

As Fig. 15 shows using climate data sets with different GCMs introduces the largest uncertainty to the energy simulation results comparing to the other three uncertainty factors. Difference in the 20-year mean heating demand can vary between 15 kWh/m^2 (16% of the maximum value) during 2061-2080 to 26 kWh/m^2 (26% of the maximum value) during 1981-2000. The uncertainty in the calculated heating demand while different RCMs and initial conditions are used varies between 6 (7%)-8 (9%) kWh/m^2 and 0.5 (0.5%)-6 (6%) kWh/m^2 respectively. In the case of having three emissions scenarios difference between B1 and A1B increases to 10 (13%) kWh/m^2. The B1 forces the climate model with lower amounts of emissions which results in lower temperature increment and consequently less reduction in the heating demand.

Standard deviations of the heating demand also decrease by time for all the scenarios, but with lower rates than the mean heating demand. In Fig. 13 standard deviations of the outdoor temperature were also decreasing with lower rate than the increment of the mean temperature. Standard deviations of the heating demand correspond to variations of the heating demand during days that are colder or warmer than the mean temperature. The same as the mean heating demand, different GCMs causes the largest uncertainty range for deviations of the heating demand. The maximum difference between standard deviations in each period can vary from 5 kWh/m^2 (14%) during 2041-2060 to 13 (28%) kWh/m^2 during 1981-2000. For different RCMs, emissions scenarios and initial conditions differences can reach to 8 (9%) kWh/m^2, 10 (13%) kWh/m^2 and 5 (12%) kWh/m^2 respectively.

By having warmer climate in the future we can expect higher cooling demands. The trend for changes of the 20-year mean values of the cooling demand and its standard deviations are shown in Fig. 16 and Fig. 17, respectively. For most of the scenarios both the values increase by time although the absolute values are not comparable with the heating demand. For example the maximum 20-year mean value and the corresponding standard deviation are 3.6 kWh/m^2 and 3.4 kWh/m^2, respectively, during 2081-2100 for the RCA3-CNRM-A1B-3 scenario. The minimum for the corresponding values of heating demand are 66.8 kWh/m^2 and 28 kWh/m^2 for the RCA3-ECHAM5-A1B-1 scenario during 2081-2100. This shows that even with the global warming the future need for the mechanical cooling of the building stock in Lund is very low.

Climate uncertainties affect the predicted cooling demand and similarly to the heating demand, the largest deviation is caused by the GCMs in figures Fig. 16 and Fig. 17. In Fig. 16, left-up, the maximum difference between the 20-year mean cooling demand of the scenarios varies from 1.6 kWh/m^2 (92% of the maximum) during 1981-2000 to 3.3 kWh/m^2 (91% of the maximum) during 2081-2100. The corresponding values for the standard deviations in Fig. 17 are 1.5 kWh/m^2 (79%) and 2.6 kWh/m^2 (76%). It means for example during very warm days of 2081-2100, the cooling demand that RCA3-CNRM predicts for the building stock can be 5.9 (3.3+2.6) kWh/m^2 more than the value that RCA3-CCSM3 predicts. This is a relatively big difference between scenarios; around 180% of the 20-year mean value for RCA3-CNRM. Making the same comparison for the heating demand of RCA3-IPSL and RCA3-CNRM during a very cold day of 1981-2000 in Fig. 15, the difference will be around 40 kWh/m^2 or 35% of the 20-year mean value of the heating demand for RCA3-IPSL. Although this difference is relatively lower than the difference for the cooling demands, but it plays a bigger role in designing strategies of the future building stock in Lund.

After GCMs, RCMs introduce the second largest uncertainty in the predicted cooling demands. Maximum differences of the 20-year mean values and the standard deviations respectively vary between 0.9 (80%)-1.7 (91%) kWh/m^2 in Fig. 16 and 0.9 (80%)-1.7 (91%) kWh/m^2 in Fig. 17. For the emissions scenarios difference of the cooling demands between A1B and B1 increase to 0.6 (63%) kWh/m^2 for the 20-year mean and 0.9 (65%) kWh/m^2 for the standard deviations. The uncertainty of having different initial conditions caused differences up to 0.4 kWh/m^2 (44%) for the 20-year mean cooling demand and 0.7 kWh/m^2 (50%) for the standard deviations during 2081-2100. The rare usage of the mechanical cooling during warm days makes a wide distribution of the cooling demand with small mean value. As a consequence differences between scenarios are relatively large and also very visible among the standard deviations.

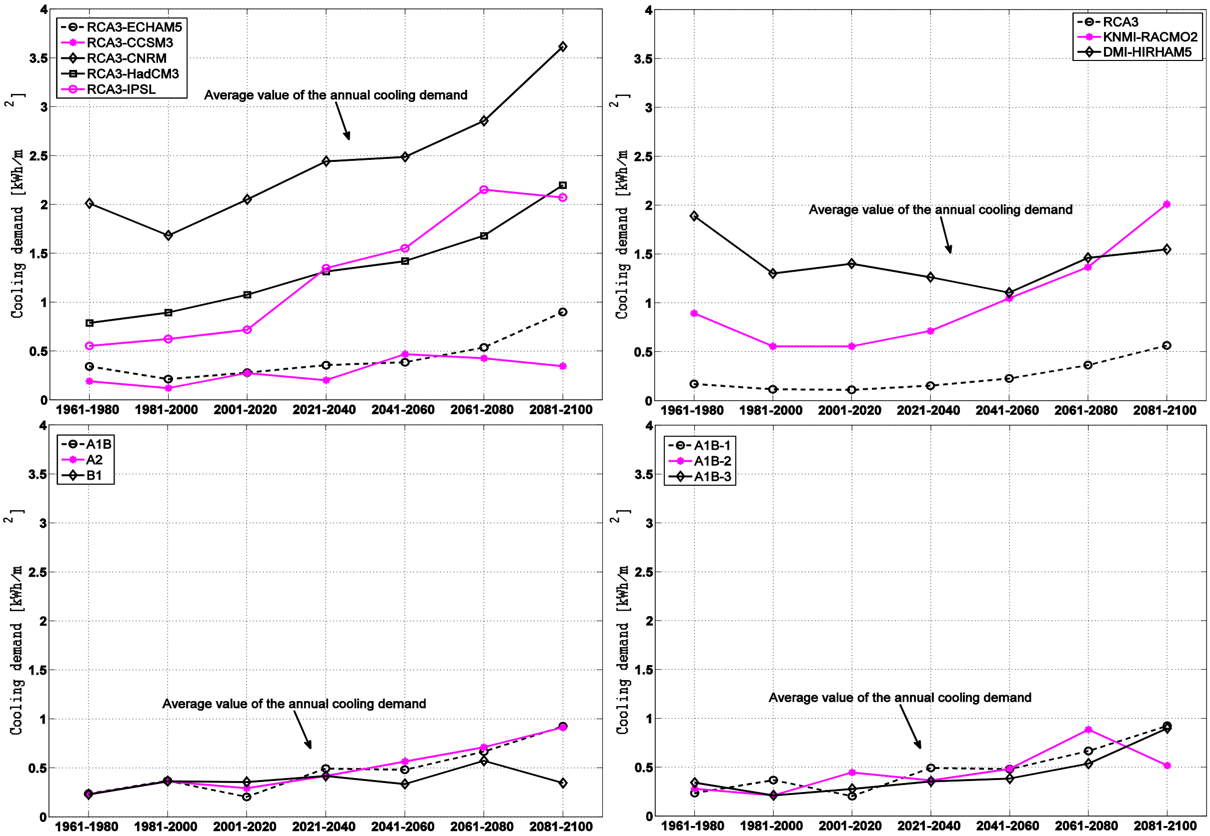

Fig. 16. Average values of the annual cooling demand during the 20-year periods. Five scenarios of the RCA3 regional climate model are compared when it has been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

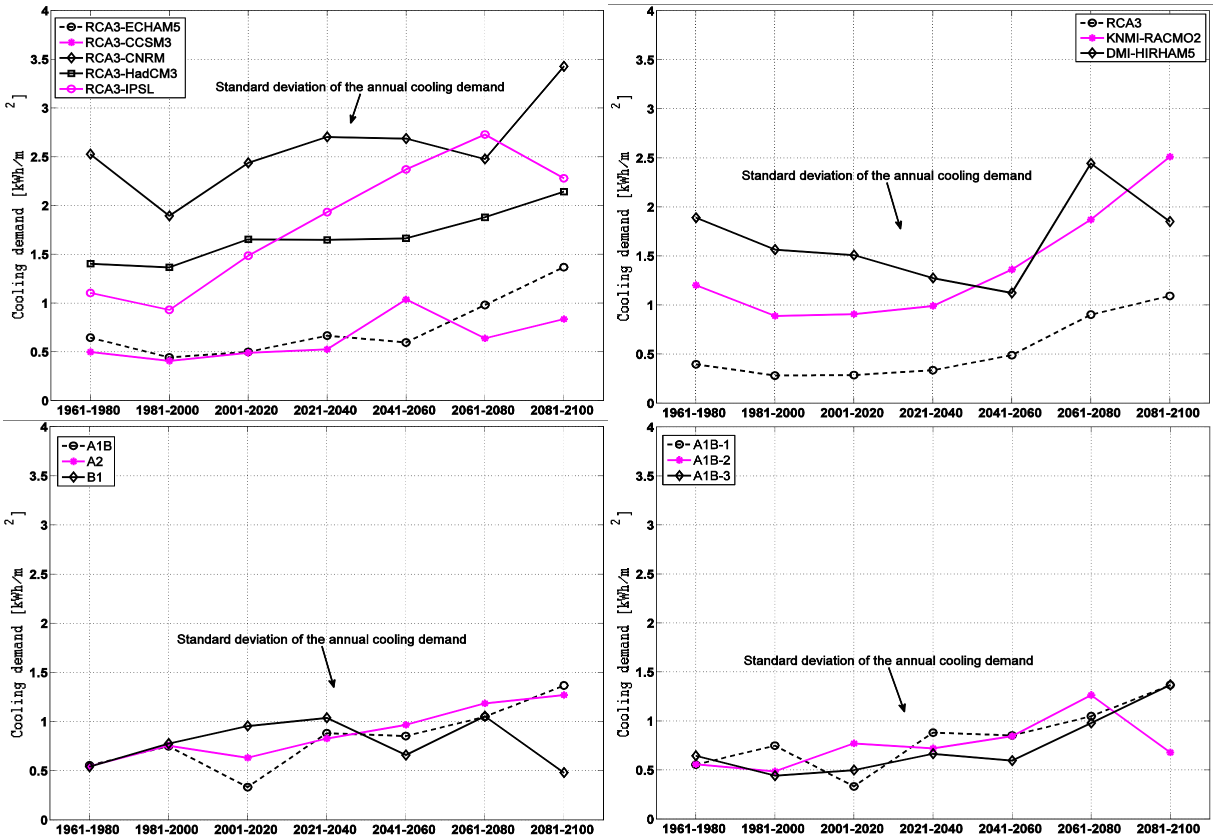

Fig. 17. Standard deviations of the annual cooling demand during the 20-year periods. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

In addition to the heating and cooling demands, uncertainties of the climate data can be indicated in the indoor temperature profile of the building stock. Not surprisingly the biggest uncertainties are caused by GCMs. In Fig. 18 and Fig. 19 the maximum differences between scenarios is between RCA3-CNRM and RCA3-CCSM3, which is between 0.46-0.63°C and 0.37-0.46°C respectively. Differences between the standard deviations of these two scenarios in Fig. 20 and Fig. 21 are between 0.65-0.9°C and 0.4-0.47°C for the natural and natural/mechanical cooling systems respectively. Differences are smaller when the mechanical cooling system is available. Looking to the other three uncertainty factors and comparing the indoor temperature components for the two cooling strategies support the fact that having the mechanical cooling system in the building stock decreases the uncertainty range. For the natural cooling differences of the 20-year mean temperature and its standard deviation are respectively between 0.12-0.26°C and 0.33-0.56°C for RCMs, 0-0.15°C and 0-0.2 for emissions scenarios, and 0.02-0.09°C and 0.03-0.13°C for initial conditions. While when the mechanical system is available these values are 0.08-0.18°C and 0.15-0.27°C for RCMs, 0-0.12°C and 0-0.12°C for emissions scenarios, and 0-0.07°C and 0-0.08°C for initial conditions. The importance of the uncertainty factors on the indoor temperature are in this order; GCMs, RCMs, emissions scenarios and initial conditions.

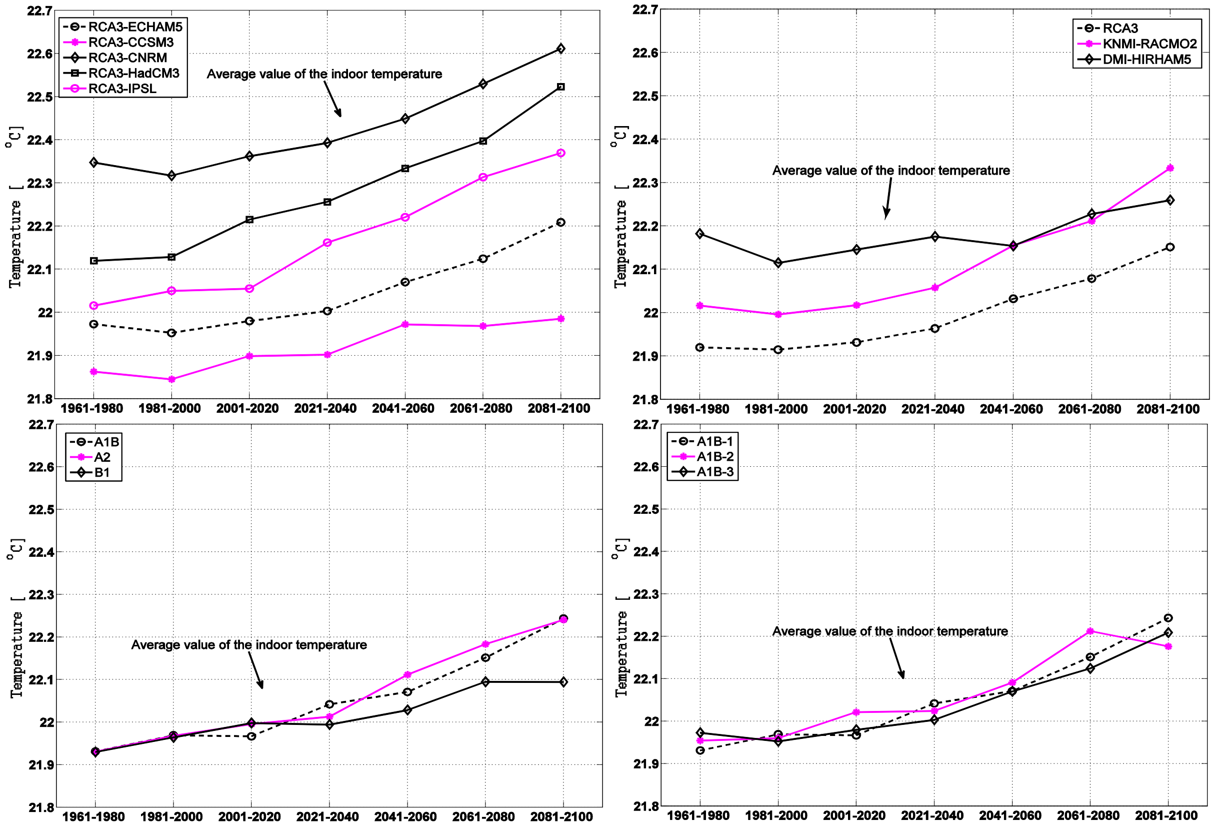

Fig. 18. Mean values of the indoor temperature during the 20-year periods when the cooling strategy is natural cooling. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

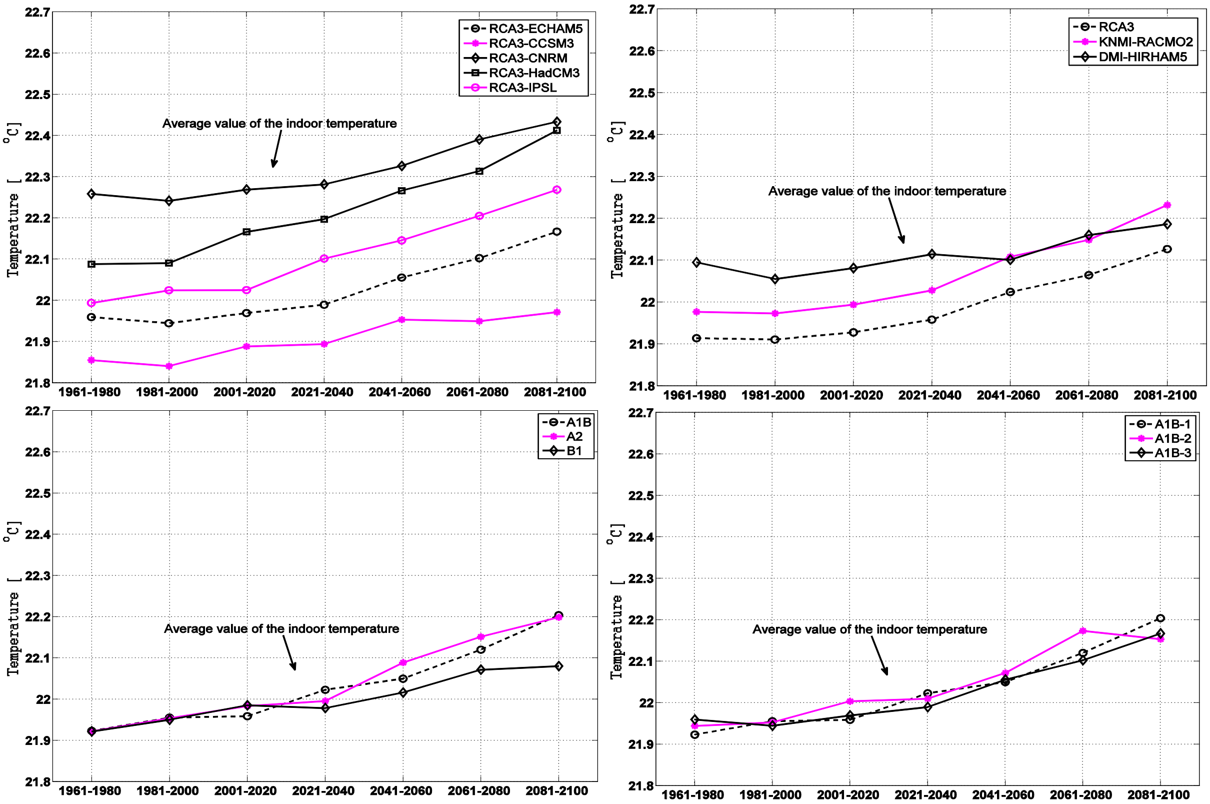

Fig. 19. Mean values of the indoor temperature during the 20-year periods when the cooling strategy is mechanical and natural cooling. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

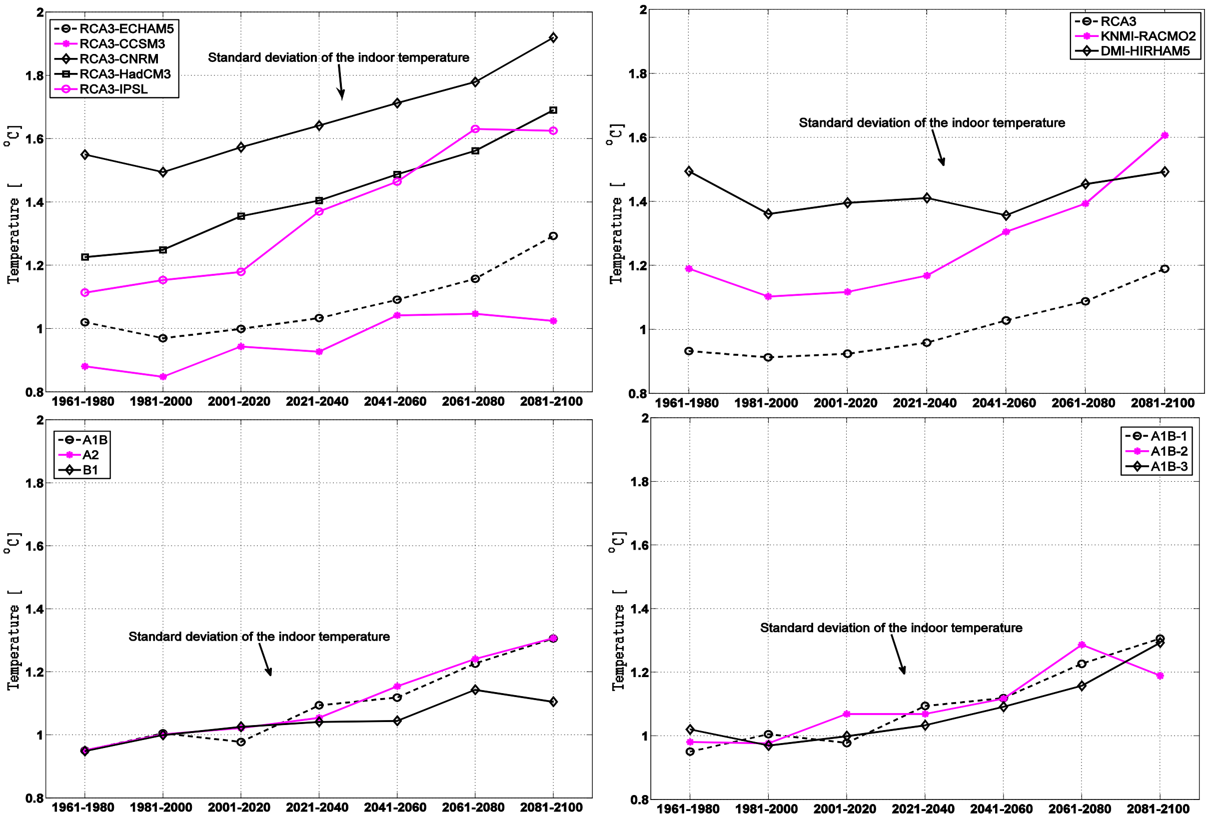

Fig. 20. Standard deviations of the indoor temperature during the 20-year periods when the cooling strategy is natural cooling. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

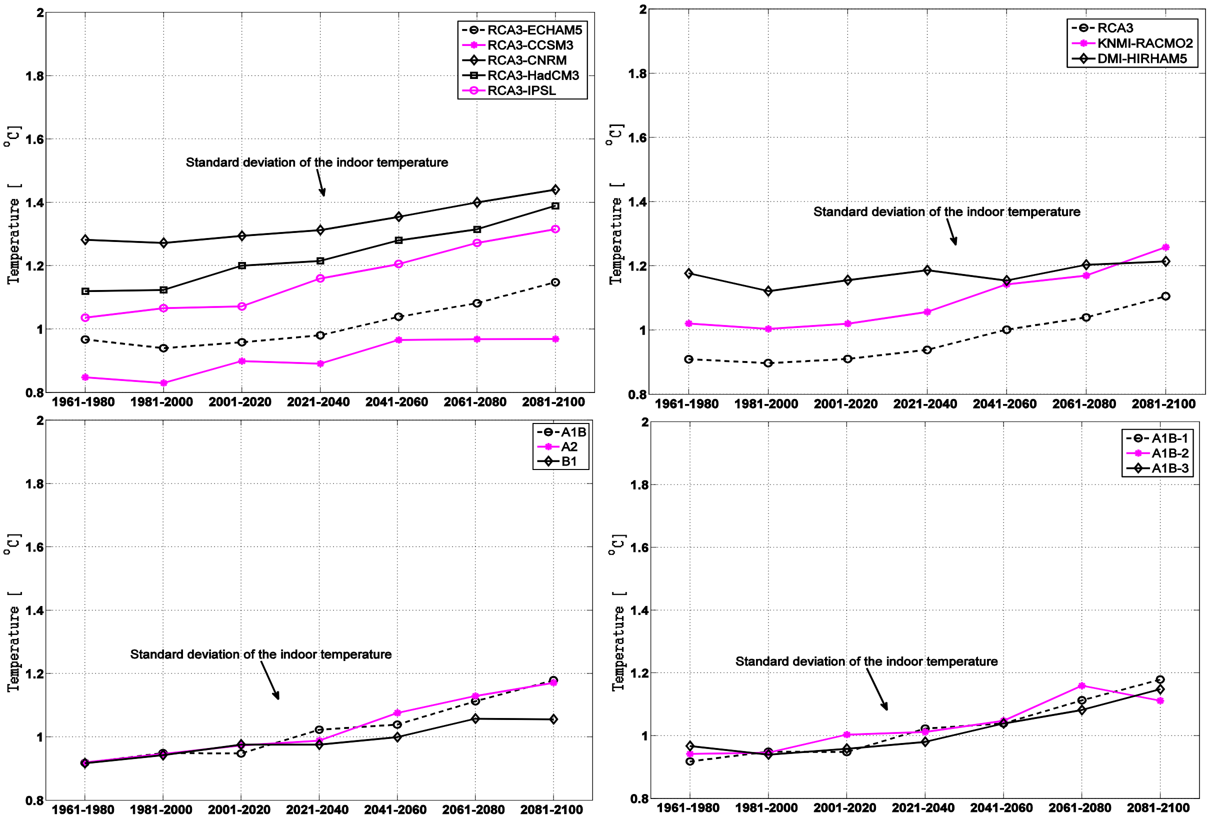

Fig. 21. Standard deviations of the indoor temperature during the 20-year periods when the cooling strategy is mechanical and natural cooling. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

5.2. Energy simulation of the building stock in Gothenburg

Gothenburg is the second large city in Sweden with the population of 52080. The area of the city is around 450 km^2. It is located on the west coast of South-western Sweden with the oceanic climate which is influenced by the nearby ocean. The building stock of Gothenburg has the largest number of buildings in this study, namely 184.

5.2.1. Climate data

The same as Lund, components of the global radiation and the outdoor temperature are compared for different climate scenarios in figures 22 to 24. Global radiation decreases by time for all the scenarios in Fig. 22. The average amount of radiation in Gothenburg is less than Lund, i.e. the maximum is 123 W/m^2 during 1961-1980 for RCA3-IPSL, but the pattern of changes and differences between the climate scenarios are very similar to Lund. For example in the case of having different GCMs, RCA3-IPSL shows the highest amount of radiation and RCA3-ECHAM5 shows the lowest, which was the case also in Lund. Maximum and minimum differences of RCA3-IPSL and RCA3-ECHAM5 occur during the same periods as Lund; the maximum difference is 20 W/m^2 (16.2%) during 1961-1980 and the minimum is 13.3 W/m^2 (11.6%) during 2001-2020. For the three scenarios with different RCMs differences vary between 24.4 W/m^2 (24.4%) during 2081-2100 to 28 W/m^2 (26%). In the case of having three emissions scenarios the uncertainty in the amount of global radiation increases to 3 W/m^2 which is around 3.3% of the global radiation calculated by RCA3-ECHAM5-B1. The uncertainty is less than the uncertainty introduced by the climate models but in the same level as the uncertainty induced by having different initial conditions; difference between the first and the second boundary conditions varies between 1.4 W/m^2 (1.4%) during 2041-2060 and 4 W/m^2 (3.8%) during 1981-2000. It is interesting to see that all these differences in Gothenburg occur during the same periods as Lund.

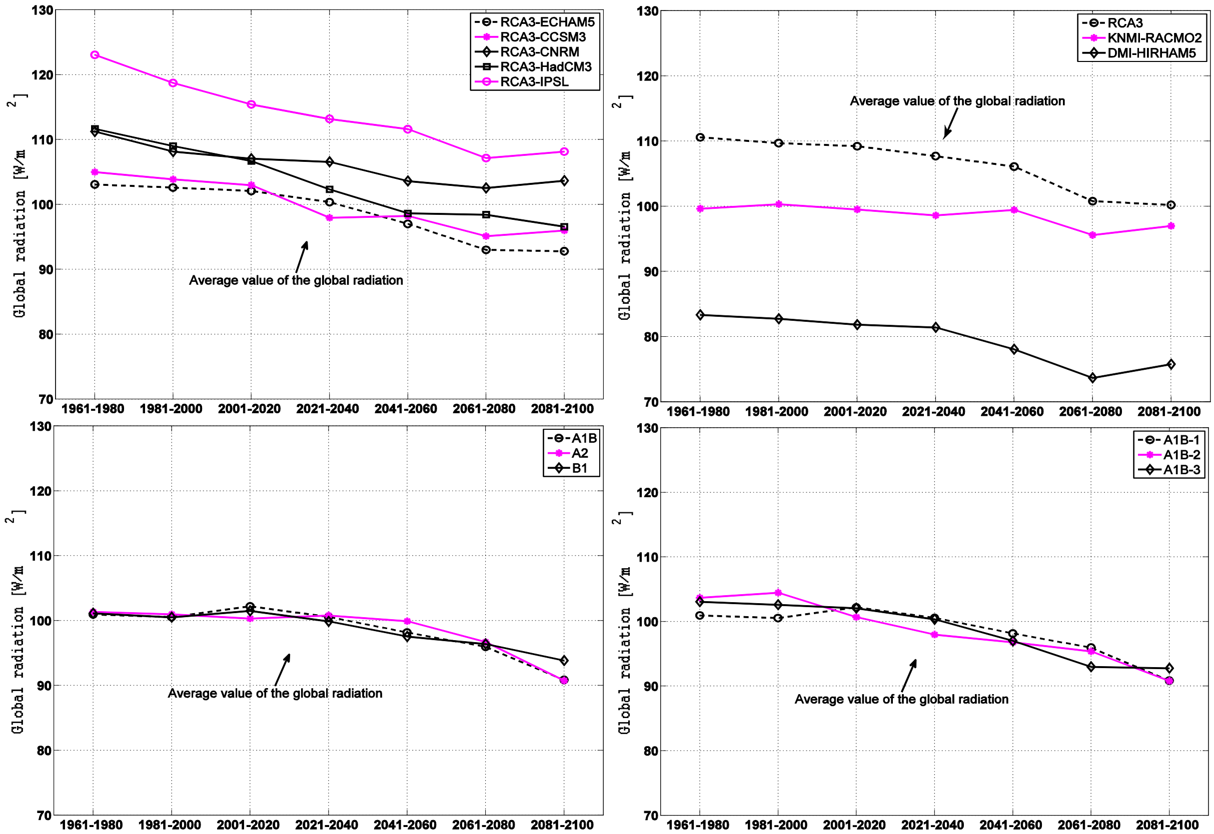

Fig. 22. Average values of the global radiation during the 20-year periods. These climate scenarios are compared; left-up) five GCMs downscaled by RCA3 forced by A1B emissions scenario, right-up) ECHAM5 downscaled by three RCMs, A1B-3, left-bottom) three emissions scenarios of RCA3-ECHAM5 with the first initial condition, and right-bottom) three initial conditions of RCA3-ECHAM5-A1B.

The 20-year mean temperature in Gothenburg in Fig. 23 is lower than Lund in Fig. 12. Patterns for changes and variations of the climate scenarios in Fig. 23 are quite similar to Fig. 12. The only difference is that for Gothenburg the DMI-HIRHAM5 predicts lower temperatures than the other two RCMs. All the scenarios predict a warmer future (see Fig. 23) with smaller variations of temperature around its 20-year mean (see Fig. 24).

The largest uncertainty factor is having different GCMs. The minimum of the maximum difference between scenarios is during 2061-2080 where the 20-year mean temperature for RCA3-ECHAM5 is 1.7°C higher than RCA3-IPSL. This is around 18% of the RCA3-ECHAM5 mean temperature; 9.4°C. The largest value of the maximum difference between scenarios occurs during 1961-1980 which RCA3-ECHAM5 and RCA3-CNRM have the 20-year mean of 7.1°C which is around 3°C (42%) more than RCA3-IPSL. In Gothenburg RCA3-ECHAM5 and RCA3-CNRM show better agreement than Lund concerning the 20-year mean temperatures. Temperature increment by the end of the period of 140 years is around 3.4°C for RCA3-IPSL, while it is around 2.7°C for RCA3-ECHAM5 and 4°C for RCA3-HadCM3. RCA3-CCSM3 with the 20-year mean of 8.5°C during 2081-2100 has the lowest temperature increment by the end of century which is around 2.4°C. It means just by having different global climate models there can be a difference of 1.6°C in the amount of temperature increment by the end of the century.

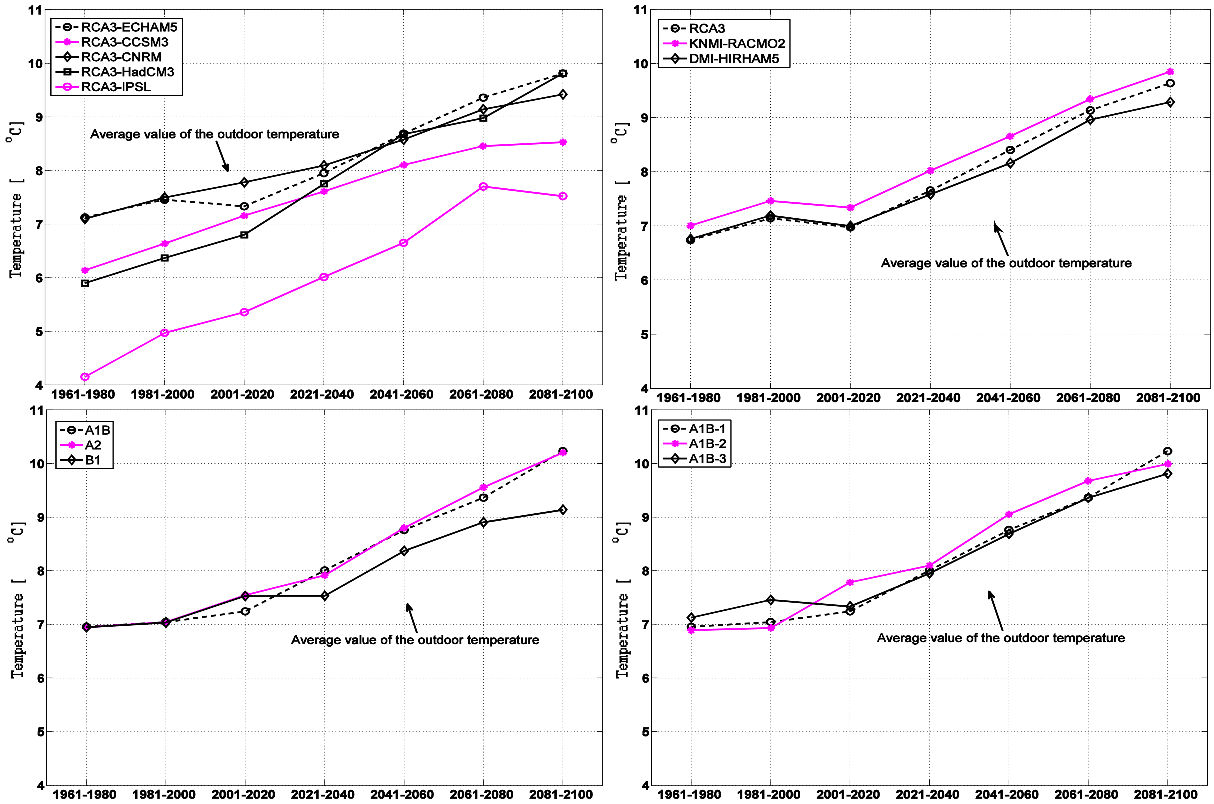

Fig. 23. Average values of the outdoor temperature during the 20-year periods. These climate scenarios are compared; left-up) five GCMs downscaled by RCA3 forced by A1B emissions scenario, right-up) ECHAM5 downscaled by three RCMs, A1B-3, left-bottom) three emissions scenarios of RCA3-ECHAM5 with the first initial condition, and right-bottom) three initial conditions of RCA3-ECHAM5-A1B.

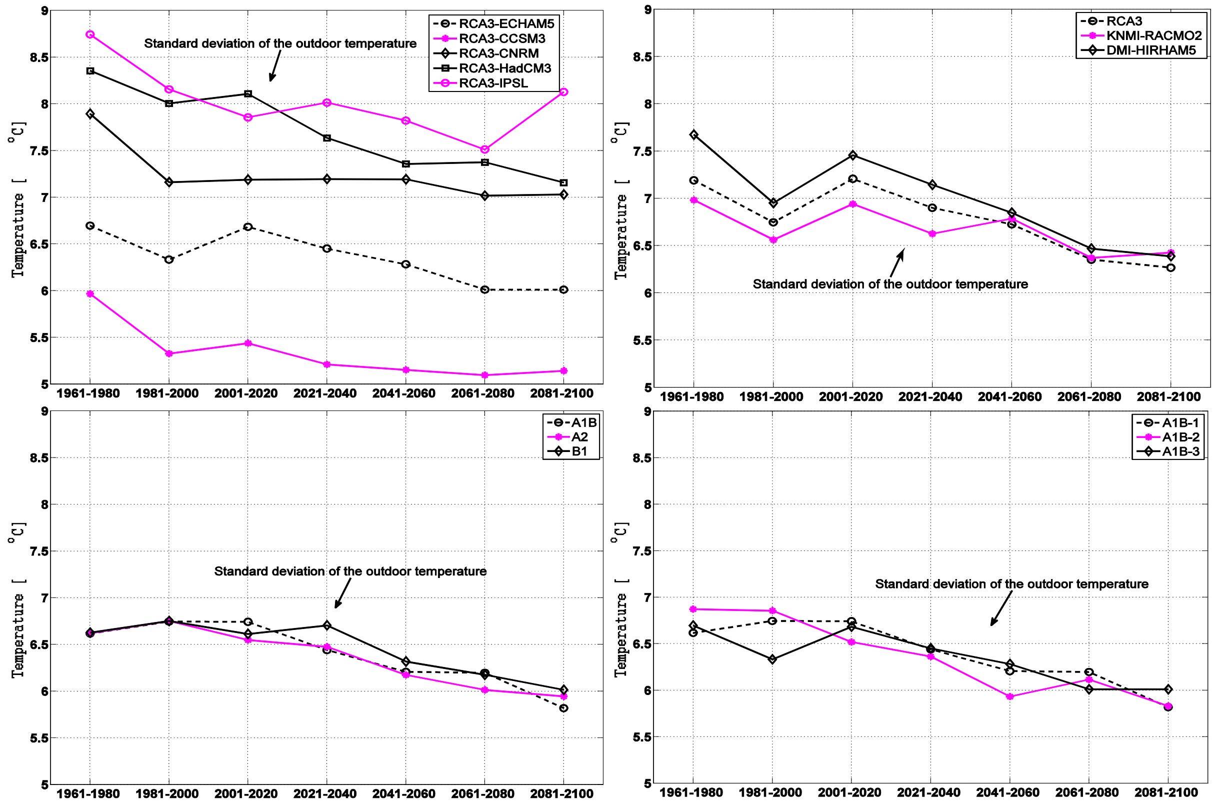

Fig. 24. Standard deviations of the outdoor temperature during the 20-year periods. These climate scenarios are compared; left-up) five GCMs downscaled by RCA3 forced by A1B emissions scenario, right-up) ECHAM5 downscaled by three RCMs, A1B-3, left-bottom) three emissions scenarios of RCA3-ECHAM5 with the first initial condition, and right-bottom) three initial conditions of RCA3-ECHAM5-A1B.

As Fig. 23 shows during the whole period different RCMs and initial conditions induce smaller differences in the 20-year mean temperature than the emissions scenarios. For example in A1B and A2 scenarios the 20-year mean temperature during 2081-2100 is around 1.1°C more than B1 which has the least amount emissions with the 20-year mean temperature of 9.1°C.

The importance of different uncertainties of the climate data sets on the 20-year mean and variations of the outdoor temperature can be summarized by considering the range of maximum difference between scenarios; the 20-year mean temperatures and the standard devotions are varying between 1.7°C (18%)-3°C (42%) and 2.4°C (32%)-3°C (37%) for different GCMs, 0.3°C (4%)-0.6°C (6%) and 0.1°C (2%)-0.7°C (9%) for different RCMs, up to 1.1°C (11%) and 0.2°C (3%) for different emissions scenarios, 0.2°C (3%)-0.5°C (7%) and 0.1°C (1%)-0.5°C (8%) for different initial conditions. According to this comparison the most important uncertainty for the outdoor temperature is having different GCMs. Different emissions scenarios can affect the temperature mean values more than RCMs, however RCMs affect the variations of temperature around the mean value more than emissions scenarios. The same as Lund different initial conditions introduce the smallest uncertainty.

5.2.2. The building stock in Gothenburg

Some characteristics of 184 buildings which represent the building stock in Gothenburg are shown in Fig. 25; most of the buildings are small family houses with U values less than 0.6 W/m^2/K.

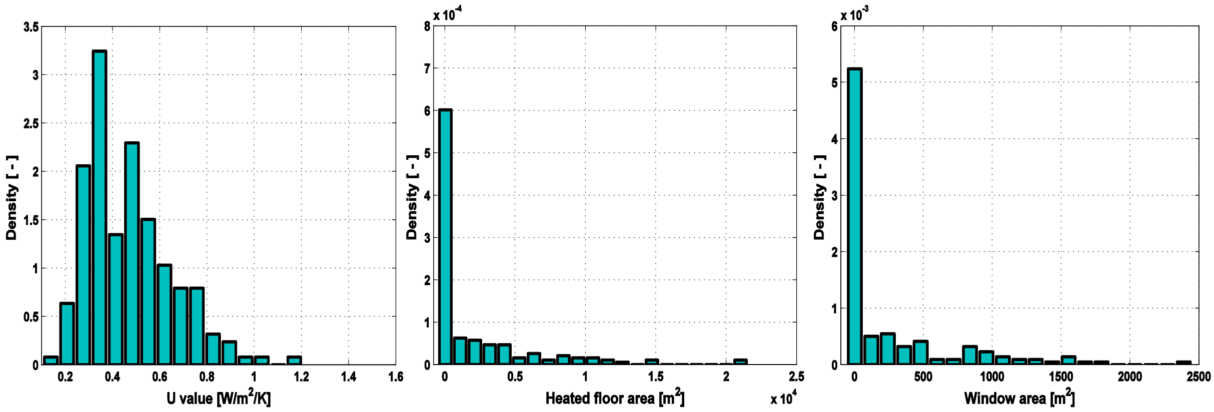

Fig. 25. Distribution of the U values, heated floor areas and window areas of the building stock in Gothenburg. Data are from the BETSI programme (Boverket 2009).

5.2.3. Energy simulation results

Heating demand of the building stock in Gothenburg is considered in Fig. 26 concerning the four uncertainties of the climate data. Comparing to Lund in Fig. 15 the heating demand is higher in Gothenburg and both the 20-year averages and standard deviations show larger values. However the same as Lund the need for heating will be less in the future.

The largest differences between the 20-year mean values of the heating demand are shown in Table 3 during all the 20-year periods. Importance of the four uncertainties of the climate data can be understood by comparing the numbers. The largest difference between the scenarios occurs during 1961-1980 which RCA3-IPSL predicts the heating demand 26.8 kWh/m^2 (21%) more than RCA3-ECHAM5.

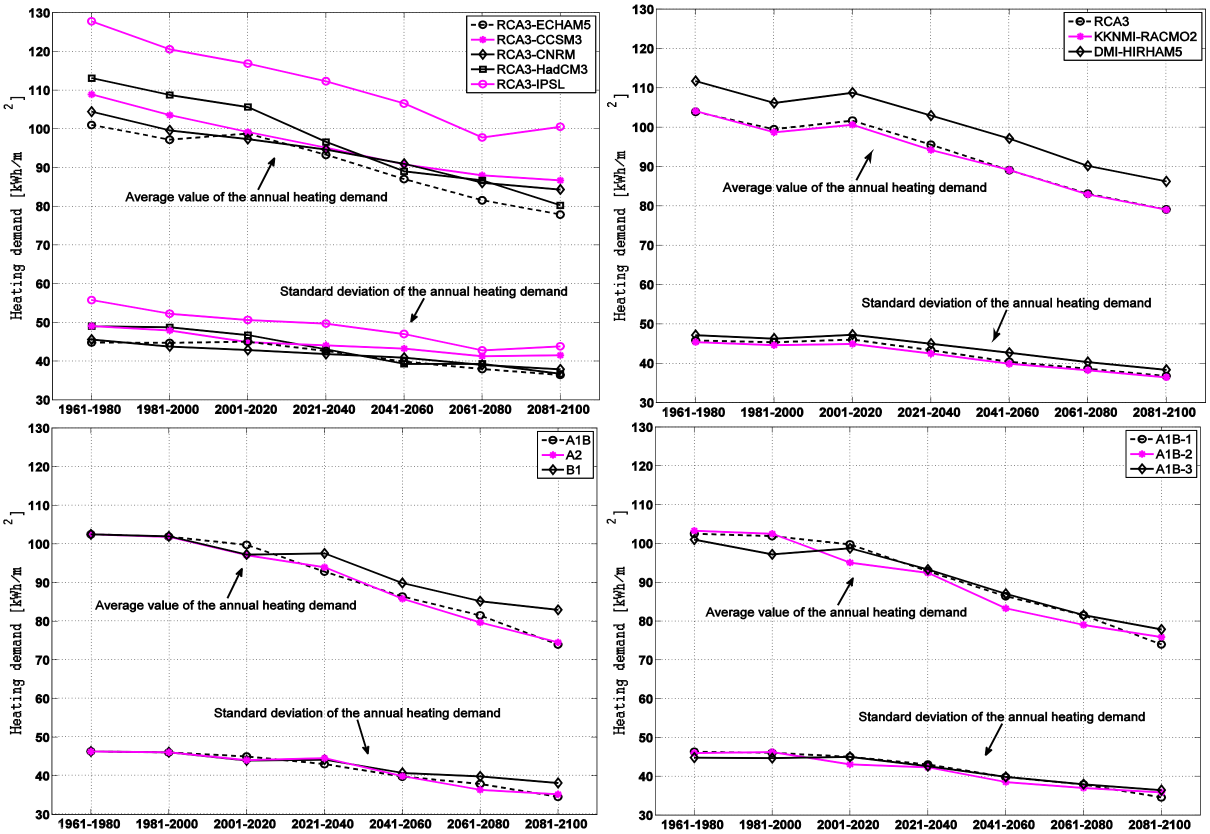

Fig. 26. Average values and standard deviations of the annual heating demand during the 20-year periods in Gothenburg. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

Table 3. The largest difference between the 20-year mean of the heating demand for the building stock in Gothenburg. Importance of the four climate uncertainties are compared (see Fig. 26). Values are showing the differences in kWh/m^2 and percentage with respect to the maximum value in each period.

	1961-1980	1981-2000	2001-2020	2021-2040	2041-2060	2061-2080	2081-2100
GCMs	26.8 (21%)	23.4 (19.4%)	19.5 (16.7%)	19 (17%)	19.5 (18.3%)	16.2 (16.6%)	22.7 (22.6%)
RCMs	7.8 (7%)	7.4 (7%)	8.2 (7.5%)	8.8 (8.5%)	8 (8.3%)	7.3 (8%)	7.2 (8.4%)
Emissions Scenarios	0 (0%)	0.1 (0.1%)	2.7 (2.7%)	4.7 (4.8%)	4 (4.5%)	5.5 (6.5%)	9 (10.8%)
Initial Conditions	2.3 (2.2%)	5.3 (5.3%)	4.7 (4.7%)	0.9 (0.9%)	3.7 (4.3%)	2.5 (3%)	3.9 (5%)

Table 4. The largest difference between the standard deviations of the heating demand for the building stock in Gothenburg. Importance of the four climate uncertainties are compared (see Fig. 26). Values are showing the differences in kWh/m^2 and percentage with respect to the maximum value in each period.

	1961-1980	1981-2000	2001-2020	2021-2040	2041-2060	2061-2080	2081-2100
GCMs	11 (19.7%)	8.5 (16.2%)	7.8 (15.3%)	7.9 (15.8%)	7.7 (16.4%)	4.8 (11.2%)	7.4 (16.9%)
RCMs	1.7 (3.7%)	1.6 (3.6%)	2.3 (5%)	2.5 (5.6%)	2.8 (6.6%)	2.1 (5.1%)	1.9 (5%)
Emissions Scenarios	0 (0%)	0.1 (0.1%)	1 (2.3%)	1.5 (3.5%)	1 (2.4%)	3.5 (8.7%)	3.6 (9.4%)
Initial Conditions	1.5 (3.3%)	1.6 (3.5%)	1.9 (4.3%)	0.7 (1.7%)	1.4 (3.4%)	1 (2.6%)	1.9 (5.1%)

The second largest uncertainty, after different GCMs, occurs at the end of the century in the case of having different emissions scenarios. Differences between the lower and higher emissions scenarios increase by time. The third important uncertainty, which is almost in the same level as the emissions scenarios during 2081-2100, is having different RCMs. The smallest uncertainty in calculating the heating demand was induced by the initial conditions. The same comparison is made in Table 4 for the standard deviations of the heating demand. The uncertainties affect variations of the heating demands less than their mean values.

The mean and the standard deviation values of the cooling demands in Fig. 27 and Fig. 28 tell about the higher cooling demand in the future, however the values are much smaller than the heating demand, the same as Lund. These figures also show that there is not a huge need for installing cooling systems in the considered buildings. Uncertainties of the climate data are visible in the figures and the largest differences during each period are mentioned in and Table 6. GCMs are the largest uncertainty factor and initial conditions are the smallest. RCMs and emissions scenarios are in between. However because of the very low cooling demand they can be neglected.

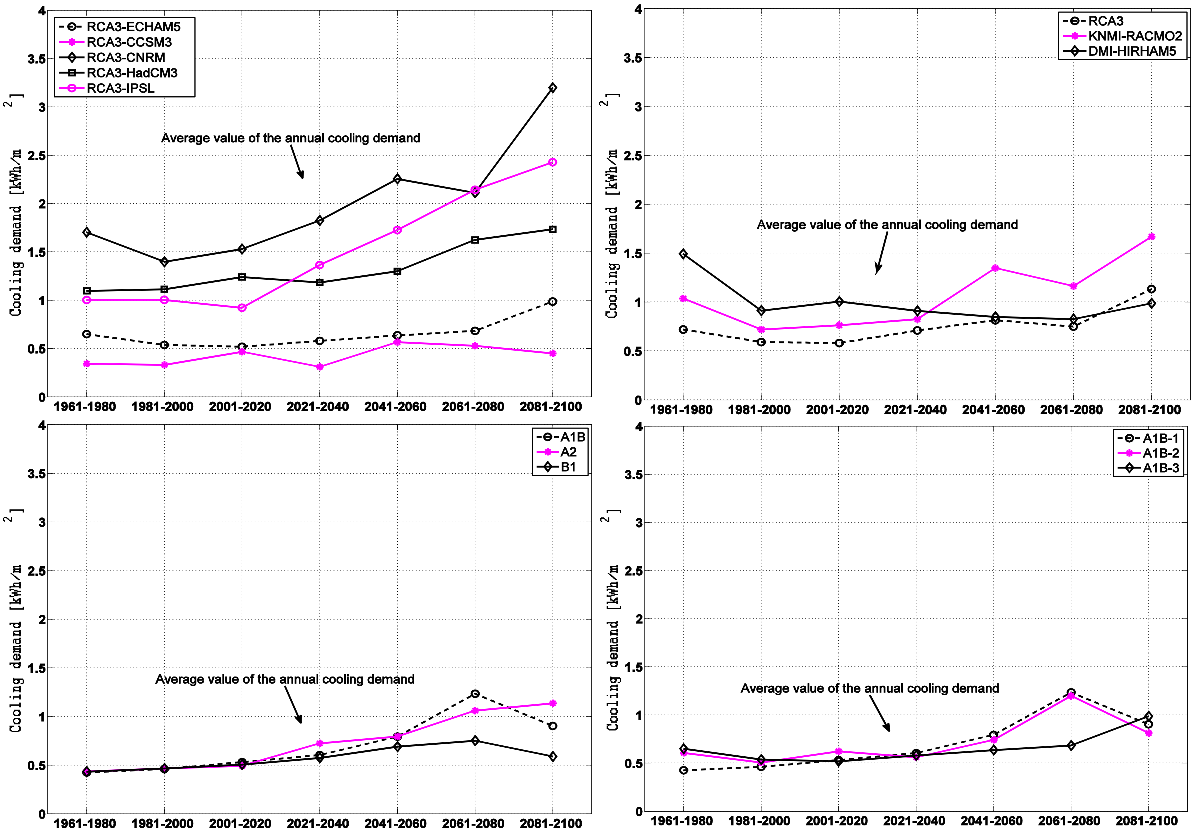

Fig. 27. Average values of the annual cooling demand during the 20-year periods in Gothenburg. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

Table 5. The largest difference between the 20-year mean of the cooling demand for the building stock in Gothenburg. Importance of the four climate uncertainties are compared (see Fig. 27). Values are showing the differences in kWh/m^2 and percentage with respect to the maximum value in each period.

	1961-1980	1981-2000	2001-2020	2021-2040	2041-2060	2061-2080	2081-2100
GCMs	1.4 (80%)	1.1 (76%)	1.1 (69%)	1.5 (83%)	1.7 (75%)	1.6 (75%)	2.7 (86%)
RCMs	0.8 (52%)	0.3 (35%)	0.4 (42%)	0.2 (22%)	0.5 (40%)	0.4 (36%)	0.7 (41%)
Emissions Scenarios	0.01 (2%)	0.005 (1%)	0.04 (7%)	0.15 (20%)	0.1 (13%)	0.5 (39%)	0.5 (48%)
Initial Conditions	0.2 (34%)	0.08 (14%)	0.1 (17%)	0.04 (7%)	0.16 (20%)	0.6 (45%)	0.17 (18%)

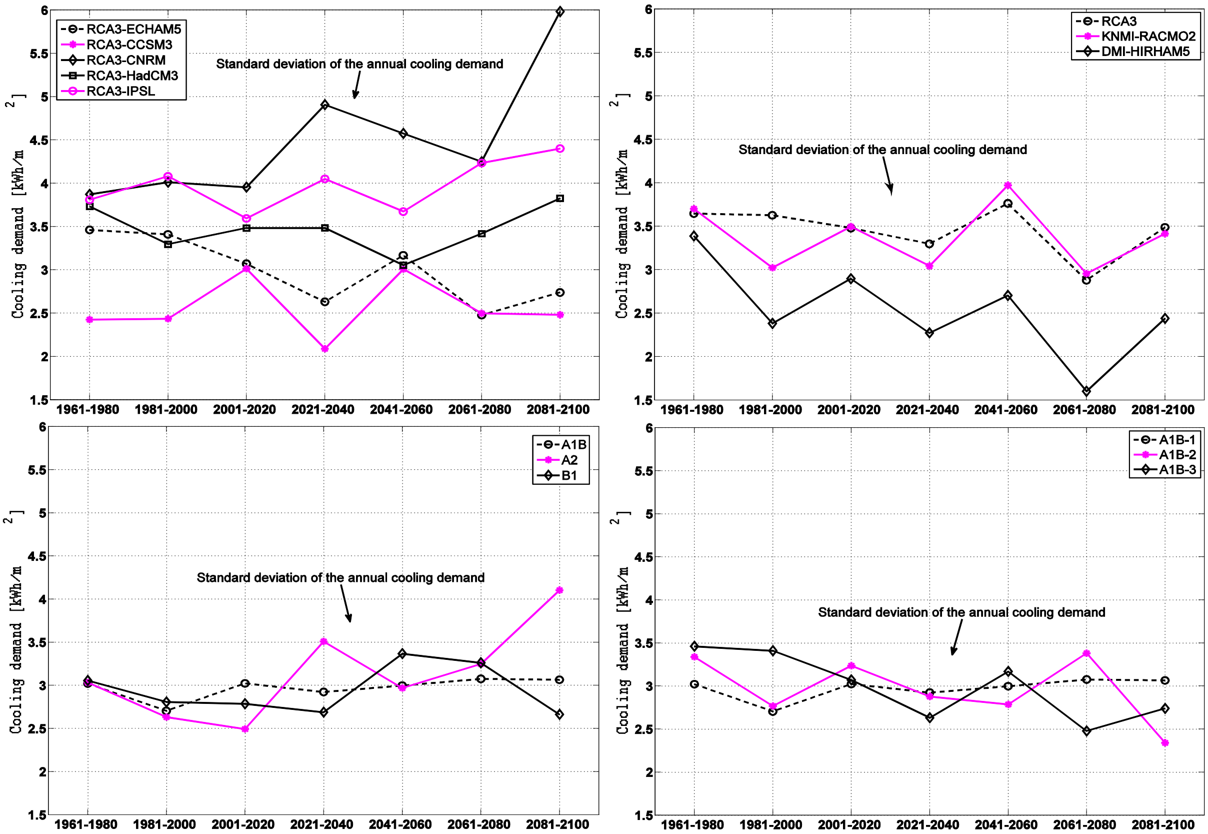

Fig. 28. Standard deviations of the annual cooling demand during the 20-year periods in Gothenburg. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

Table 6. The largest difference between the standard deviations of the cooling demand for the building stock in Gothenburg, Importance of the four climate uncertainties are compared (see Fig. 28). Values are showing the differences in kWh/m^2 and percentage with respect to the maximum value in each period.

	1961-1980	1981-2000	2001-2020	2021-2040	2041-2060	2061-2080	2081-2100
GCMs	1.4 (37%)	1.6 (40%)	0.9 (24%)	2.8 (57%)	1.6 (34%)	1.8 (42%)	3.5 (59%)
RCMs	0.3 (8%)	1.2 (34%)	0.6 (17%)	1 (31%)	1.3 (32%)	1.4 (46%)	1 (30%)
Emissions Scenarios	0.04 (1%)	0.2 (6%)	0.5 (18%)	0.8 (23%)	0.4 (12%)	0.2 (6%)	1.4 (35%)
Initial Conditions	0.4 (13%)	0.7 (21%)	0.2 (7%)	0.3 (10%)	0.4 (12%)	0.9 (27%)	0.7 (24%)

Effects of the climate change on distribution of the indoor temperature are illustrated in figures 29 to 32. The two cooling strategies of the building stock were tested in the presence of the climate uncertainties. Tables 7 to 10 compare the differences in numbers. According to the figures the indoor temperature will increase in the future; the increment for the 20-year mean temperature is less than 0.3^oC even without mechanical cooling. Standard deviations also increase up to 0.5^oC. This means without mechanical cooling the indoor temperature can reach to values 0.8^oC more than the present conditions, which is absolutely acceptable for the building stock in Gothenburg.

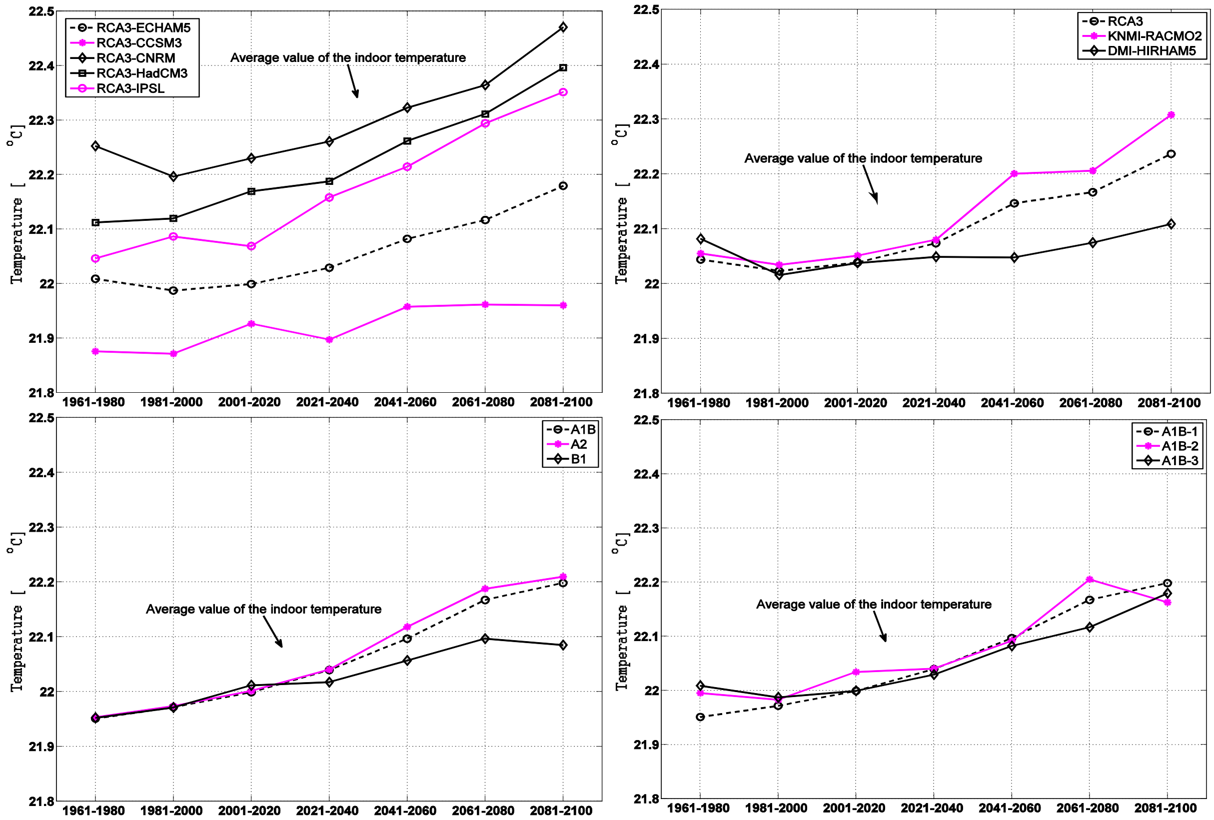

Fig. 29. Mean values of the indoor temperature during the 20-year periods in Gothenburg when the cooling strategy is natural cooling. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

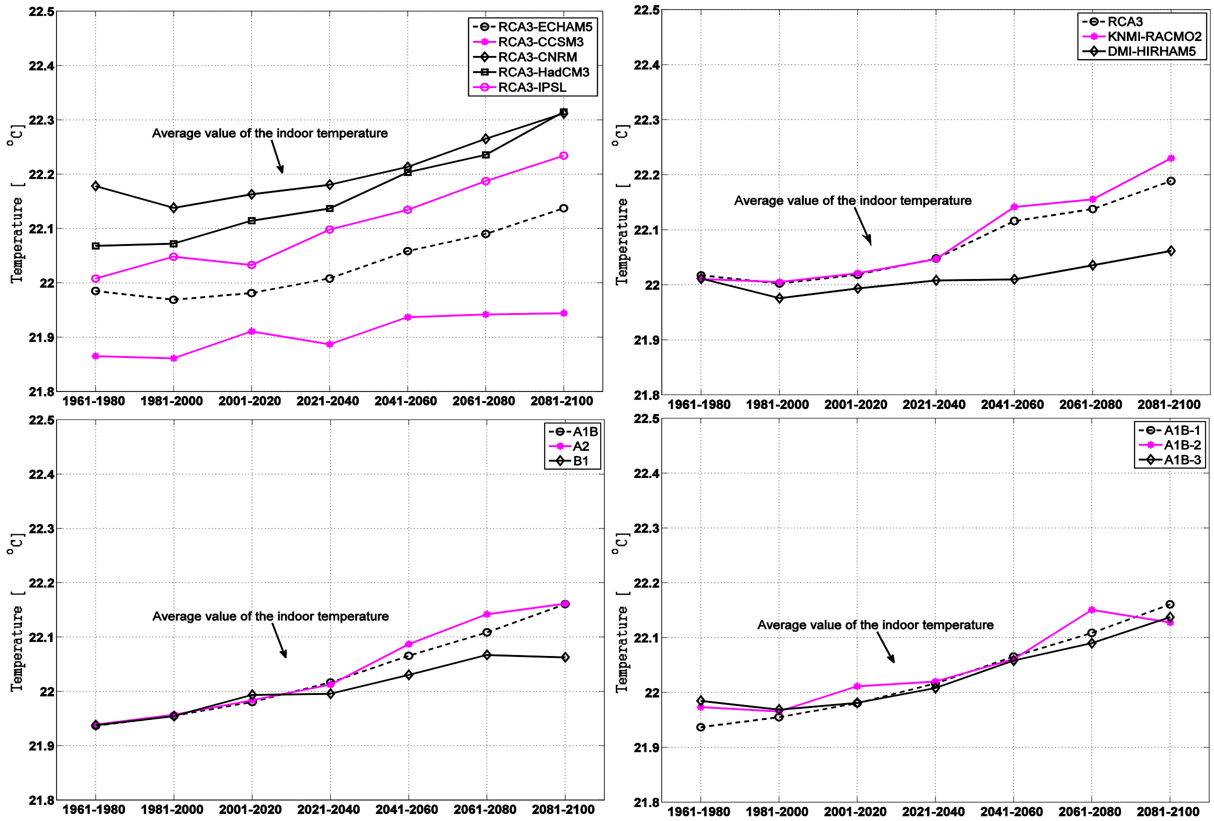

Fig. 30. Mean values of the indoor temperature during the 20-year periods in Gothenburg when the cooling strategy is mechanical and natural cooling. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

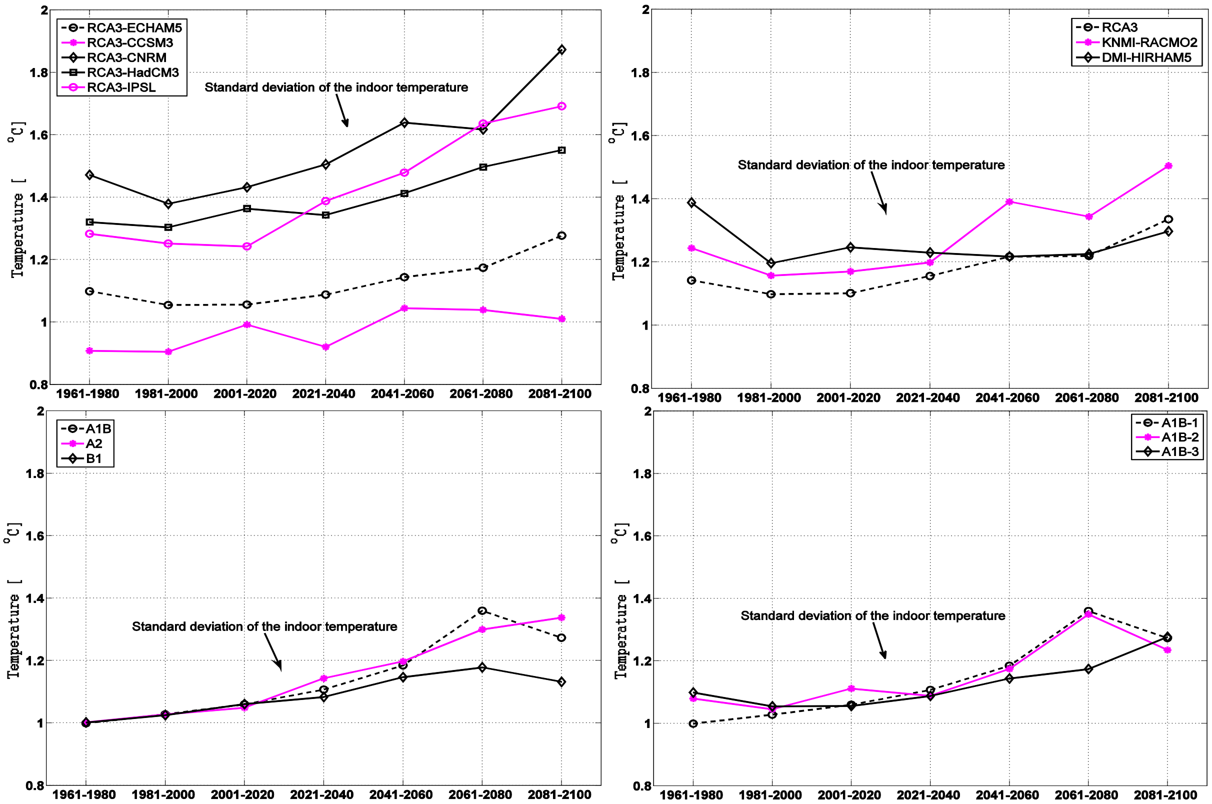

Fig. 31. Standard deviations of the indoor temperature during the 20-year periods in Gothenburg when the cooling strategy is natural cooling. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

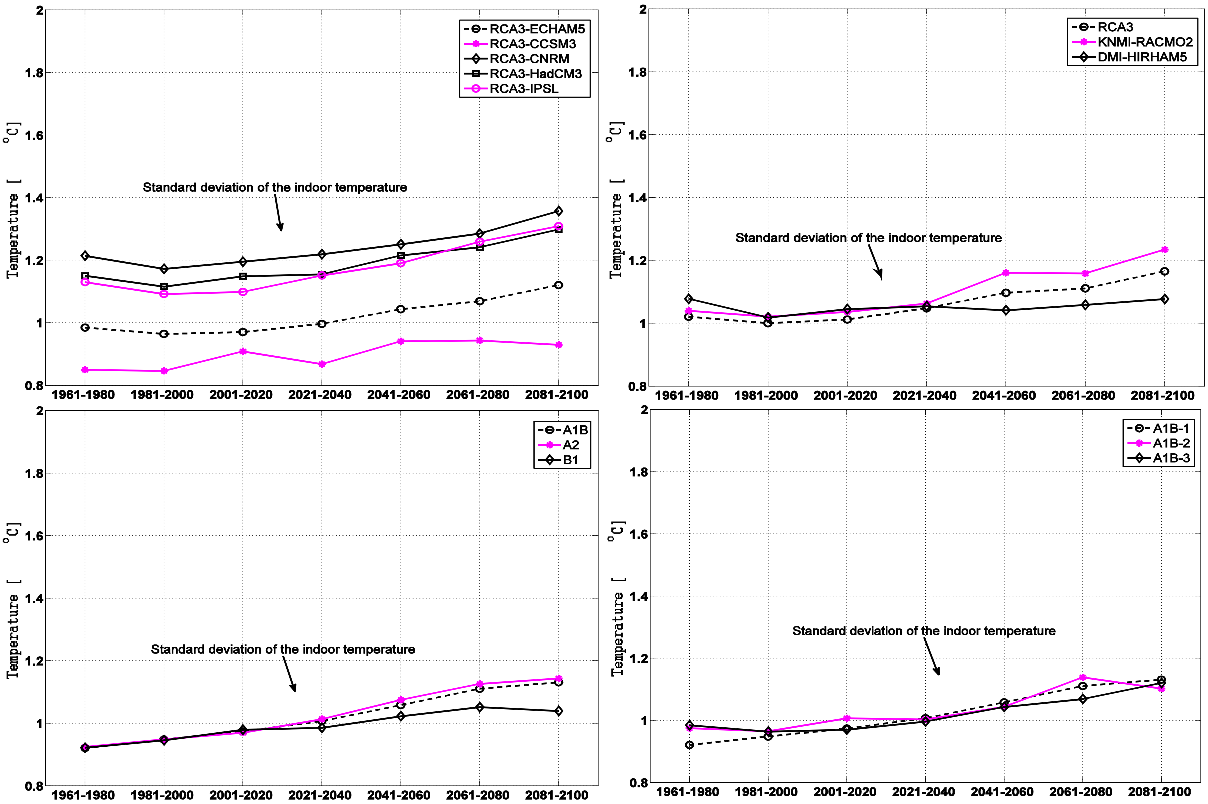

Fig. 32. Standard deviations of the indoor temperature during the 20-year periods in Gothenburg when the cooling strategy is mechanical and natural cooling. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

Table 7. The largest difference between the 20-year mean of the indoor temperature for the building stock in Gothenburg when there is only natural cooling. Importance of the four climate uncertainties are compared (see Fig. 29). Values are showing the differences in ^{o}C and percentage with respect to the maximum value in each period.

	1961-1980	1981-2000	2001-2020	2021-2040	2041-2060	2061-2080	2081-2100
GCMs	0.38 (1.7%)	0.33 (1.5%)	0.3 (1.4%)	0.36 (1.6%)	0.37 (1.6%)	0.4 (1.8%)	0.5 (2.3%)
RCMs	0.04 (0.2%)	0.02 (0.1%)	0.01 (0%)	0.03 (0.1%)	0.2 (0.7%)	0.1 (0.6%)	0.2 (0.9%)
Emissions Scenarios	0 (0%)	0 (0%)	0 (0%)	0.02 (0.1%)	0.06 (0.3%)	0.1 (0.4%)	0.1 (0.6%)
Initial Conditions	0.06 (0.3%)	0.02 (0.1%)	0.03 (0.2%)	0.01 (0.1%)	0.01 (0.1%)	0.1 (0.4%)	0.04 (0.2%)

Table 8. The largest difference between the standard deviations of the indoor temperature for the building stock in Gothenburg when there is only natural cooling. Importance of the four climate uncertainties are compared (see Fig. 31). Values are showing the differences in ^{o}C and percentage with respect to the maximum value in each period.

	1961-1980	1981-2000	2001-2020	2021-2040	2041-2060	2061-2080	2081-2100
GCMs	0.56 (38%)	0.47 (34%)	0.44 (31%)	0.6 (39%)	0.6 (36%)	0.6 (36%)	0.9 (46%)
RCMs	0.25 (18%)	0.1 (8%)	0.14 (12%)	0.07 (6%)	0.17 (12%)	0.12 (9%)	0.2 (14%)
Emissions Scenarios	0 (0%)	0 (0%)	0.01 (1%)	0.06 (5%)	0.05 (4%)	0.2 (13%)	0.2 (15%)
Initial Conditions	0.1 (9%)	0.03 (2.5%)	0.06 (5%)	0.02 (2%)	0.04 (3%)	0.19 (14%)	0.04 (3%)

Table 9. The largest difference between the 20-year mean of the indoor temperature for the building stock in Gothenburg when there is mechanical and natural cooling. Importance of the four climate uncertainties are compared (see Fig. 30). Values are showing the differences in ^{o}C and percentage with respect to the maximum value in each period.

	1961-1980	1981-2000	2001-2020	2021-2040	2041-2060	2061-2080	2081-2100
GCMs	0.3 (1.4%)	0.28 (1.3%)	0.25 (1.1%)	0.3 (1.3%)	0.28 (1.2%)	0.3 (1.5%)	0.37 (1.7%)
RCMs	0 (0%)	0.03 (0.1%)	0.03 (0.1%)	0.04 (0.2%)	0.1 (0.6%)	0.12 (0.5%)	0.17 (0.8%)
Emissions Scenarios	0 (0%)	0 (0%)	0.01 (0.1%)	0.02 (0.1%)	0.06 (0.3%)	0.07 (0.3%)	0.1 (0.4%)
Initial Conditions	0.05 (0.2%)	0.01 (0.1%)	0.03 (0.1%)	0.01 (0.1%)	0 (0%)	0.06 (0.3%)	0.03 (0.1%)

Table 10. The largest difference between the standard deviations of the indoor temperature for the building stock in Gothenburg when there is mechanical and natural cooling. Importance of the four climate uncertainties are compared (see Fig. 32). Values are showing the differences in ^{o}C and percentage with respect to the maximum value in each period.

	1961-1980	1981-2000	2001-2020	2021-2040	2041-2060	2061-2080	2081-2100
GCMs	0.36 (30%)	0.33 (28%)	0.29 (24%)	0.35 (29%)	0.31 (25%)	0.34 (27%)	0.43 (31%)
RCMs	0.06 (5%)	0.02 (2%)	0.03 (3%)	0.01 (1%)	0.12 (10%)	0.1 (9%)	0.16 (13%)
Emissions Scenarios	0 (0%)	0 (0%)	0.01 (1%)	0.03 (3%)	0.05 (5%)	0.07 (7%)	0.1 (9%)
Initial Conditions	0.06 (6%)	0.017 (2%)	0.04 (4%)	0.01 (1%)	0.01 (1%)	0.07 (1%)	0.03 (3%)

Differences between the climate scenarios decrease by having the mechanical cooling. For example during 2081-2100 the largest difference between the 20-year mean values and standard deviations of the scenarios with different GCMs in tables Table 7 and Table 8 are respectively 0.5°C and 0.9°C. Therefor the uncertainty in predicting the indoor can reach to 1.4°C. These differences decrease to 0.37°C and 0.43°C in Table 9 and Table 10 when the mechanical cooling is active.

5.3. Energy simulation of the building stock in Östersund

Östersund is located in the middle of Sweden with temperate continental climate. Area of the city is around 2728 km^2 and the population is 44330. Weather data of Östersund were available from the Rossby Center, SMHI, but there was no statistical data about the building stock of this city. Therefore the energy simulations were performed for the building stock of Sundvall with the climate data of Östersund. The area and population of Sundsvall are quite similar to Östersund; 2746 km^2 with the population of 50712. As Fig. 33 shows Sundsvall is located on the east coast of Sweden and we can expect higher level of the relative humidity for this city comparing to Östersund. It is possible to neglect the differences in the moisture conditions and focus on similarities of the mean temperature during the cold period (see Fig. 34) since the energy performance of buildings is Sweden, with the heating dominated climate, are studied.

Fig. 33. Geographical location of Östersund and Sundsvall.

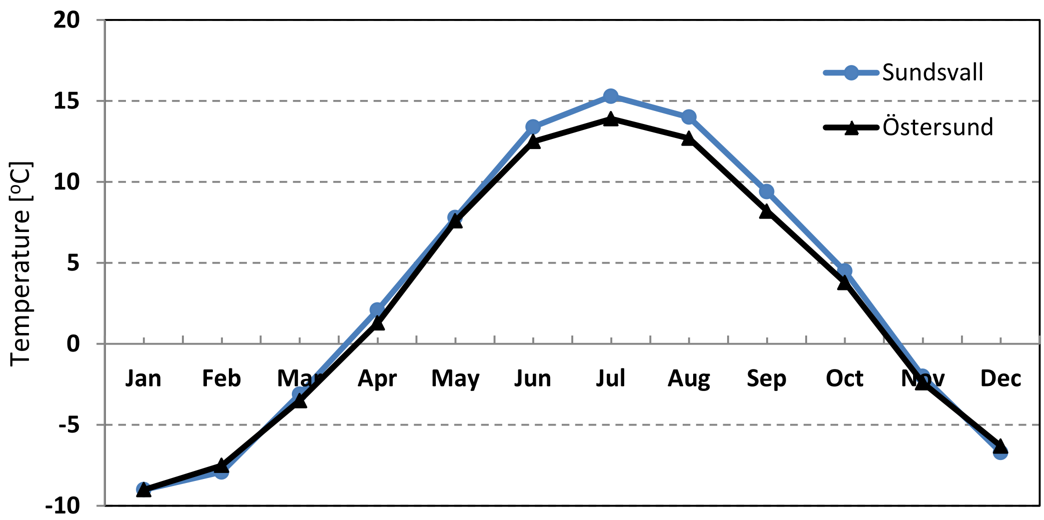

Fig. 34. Monthly mean temperatures for Östersund and Sundsvall. Data are from METEONORM Version 6.1.0.23.

5.3.1. The building stock in Östersund

The building stock of Sundsvall is represented by 63 buildings. Probability distribution of the U values, the heated floor areas and the window areas is shown in Fig. 35.

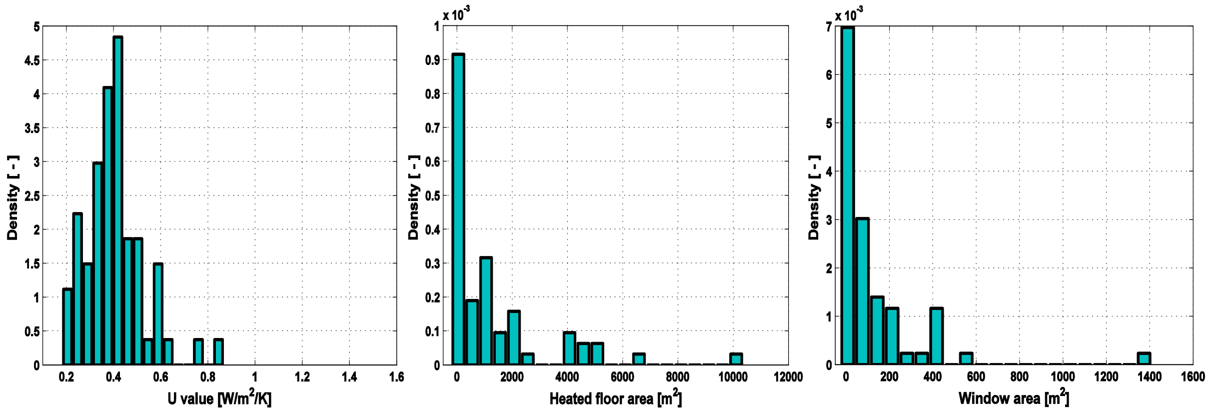

Fig. 35. Distribution of the U values, heated floor areas and window areas of the building stock in Sundsvall. Data are from the BETSI programme (Boverket 2009).

5.3.2. Climate data

Östersund has the coldest climate among the four cities in this thesis. Global radiation in Östersund is less than Lund and Gothenburg and will decrease to lower values in the future as Fig. 36 shows. Similar to the previous cities for the case with different GCMs, RCA3-IPSL shows the highest amount of radiation and RCA3-ECHAM5 shows the lowest. For Östersund also the biggest uncertainty on the calculated global radiation occurs when the climate data is downscaled by different RCMs. Different emissions scenarios affect results mostly during 2081-2100 in Fig. 36, which is still less the effect of different GCMs and RCMs. The three initial conditions play the smallest role as the uncertainty factor on the calculated amount of the global radiations.

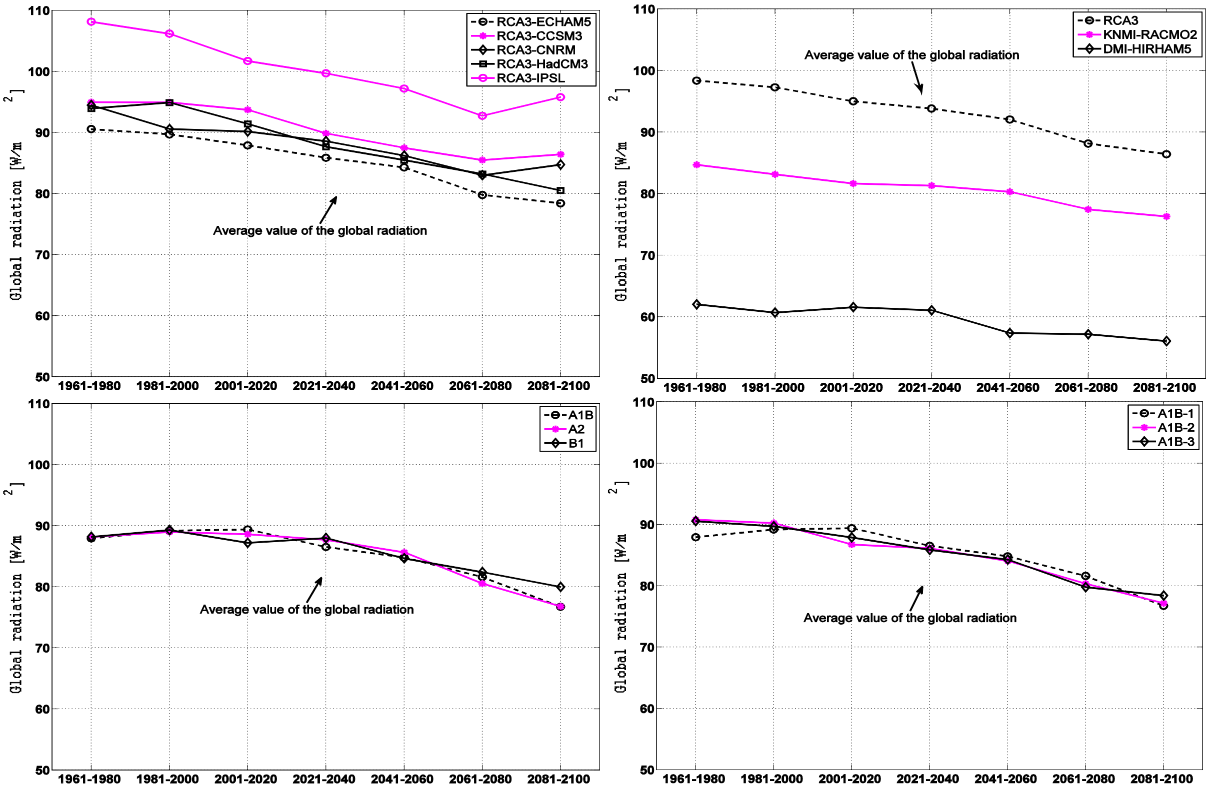

Fig. 36. Average values of the global radiation during the 20-year periods in Östersund. These climate scenarios are compared; left-up) five GCMs downscaled by RCA3 forced by A1B emissions scenario, right-up) ECHAM5 downscaled by three RCMs, A1B-3, left-bottom) three emissions scenarios of RCA3-ECHAM5 with the first initial condition, and right-bottom) three initial conditions of RCA3-ECHAM5-A1B.

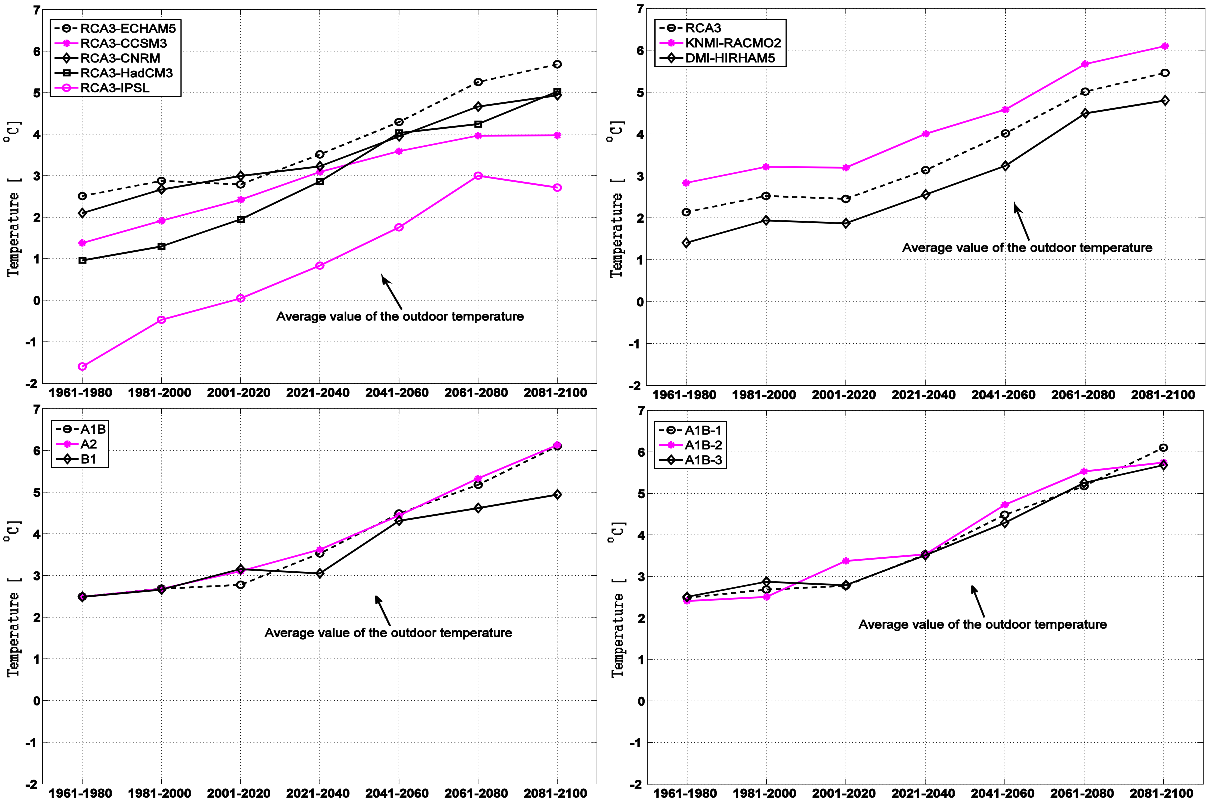

Fig. 37. Average values of the outdoor temperature during the 20-year periods in Östersund. These climate scenarios are compared; left-up) five GCMs downscaled by RCA3 forced by A1B emissions scenario, right-up) ECHAM5 downscaled by three RCMs, A1B-3, left-bottom) three emissions scenarios of RCA3-ECHAM5 with the first initial condition, and right-bottom) three initial conditions of RCA3-ECHAM5-A1B.

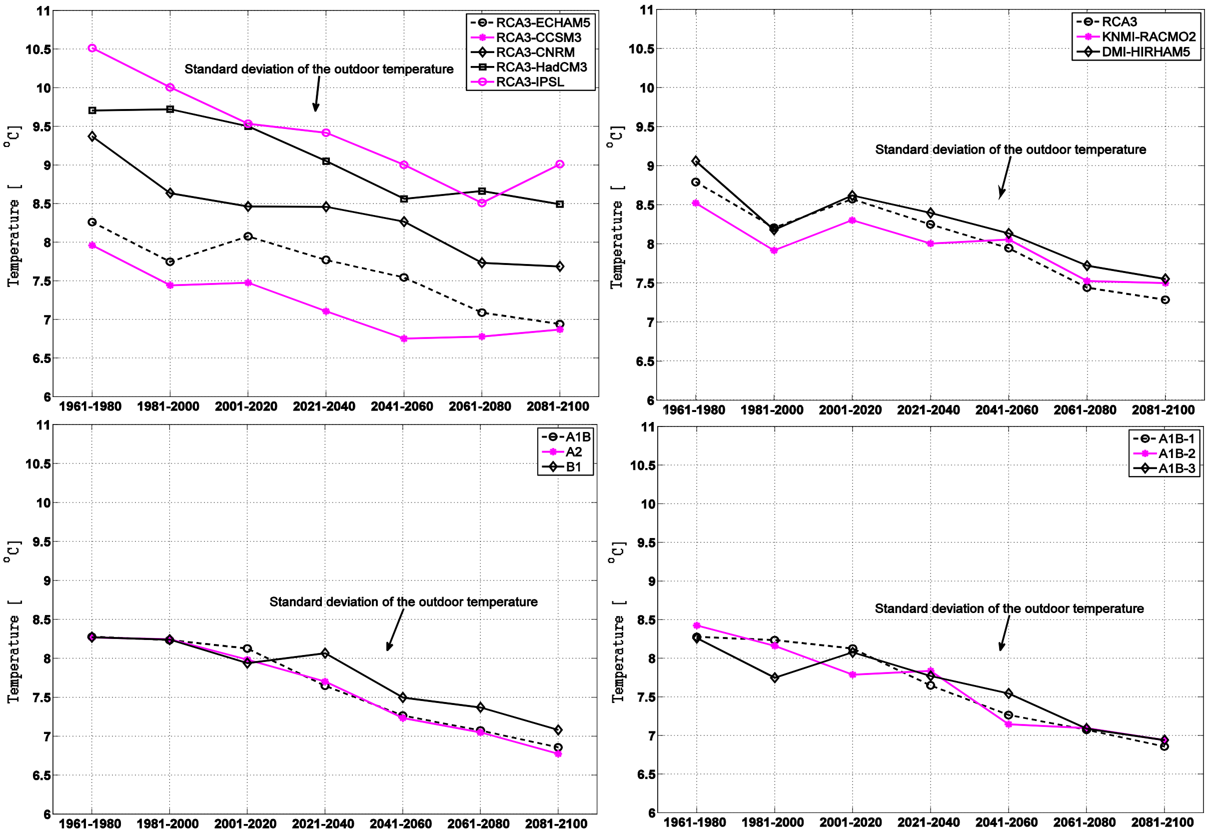

Fig. 38. Standard deviations of the outdoor temperature during the 20-year periods in Östersund. These climate scenarios are compared; left-up) five GCMs downscaled by RCA3 forced by A1B emissions scenario, right-up) ECHAM5 downscaled by three RCMs, A1B-3, left-bottom) three emissions scenarios of RCA3-ECHAM5 with the first initial condition, and right-bottom) three initial conditions of RCA3-ECHAM5-A1B.

The very cold climate of Östersund is very visible in Fig. 37 which shows the 20-year mean temperatures of the outdoor. Again RCA3-IPSL shows the lowest temperatures, but instead of RCA3-CNRM the highest temperatures are predicted by RCA3-ECHAM5. This means we cannot expect the same relation between climate scenarios and it can vary by location. However the importance of the uncertainty factors seems to be on the same level among the three cities; the 20-year mean temperatures are more affected by the selection of the GCM, then RCM and after that the emissions scenario and the initial condition. Variations of temperature around its 20-year mean values increase in Östersund. The standard deviations show larger values than Lund and Gothenburg in Fig. 38. It can cause larger standard deviations for the heating demand of the building stock in Östersund.

5.3.3. Energy simulation results

The 20-year average and standard deviations of the annual heating demand of the building stock in Östersund is shown in Fig. 39. Comparing to the other cities the heating demand is much higher in Östersund. For example the 20-year mean heating demand for RCA3-ECHAM5-A1B-3 during 1961-1980 is around 154 kWh/m^2 in Östersund while it is 104 kWh/m^2 in Gothenburg and 94 kWh/m^2 in Lund. During 2081-2100 this value decreases to 127 kWh/m^2 (18% less than the value in 1961-1980) in Östersund, 84 kWh/m^2 (19% less) in Gothenburg and 74 kWh/m^2 (21% less) in Lund. Standard deviations of the heating demands during the two periods of 1961-1980 and 2081-2100 are respectively 63 kWh/m^2 and 55 kWh/m^2 (13% less) in Östersund, 46 kWh/m^2 and 38 kWh/m^2 (17% less) in Gothenburg and 36 kWh/m^2 and 31 kWh/m^2 (14% less) in Lund.

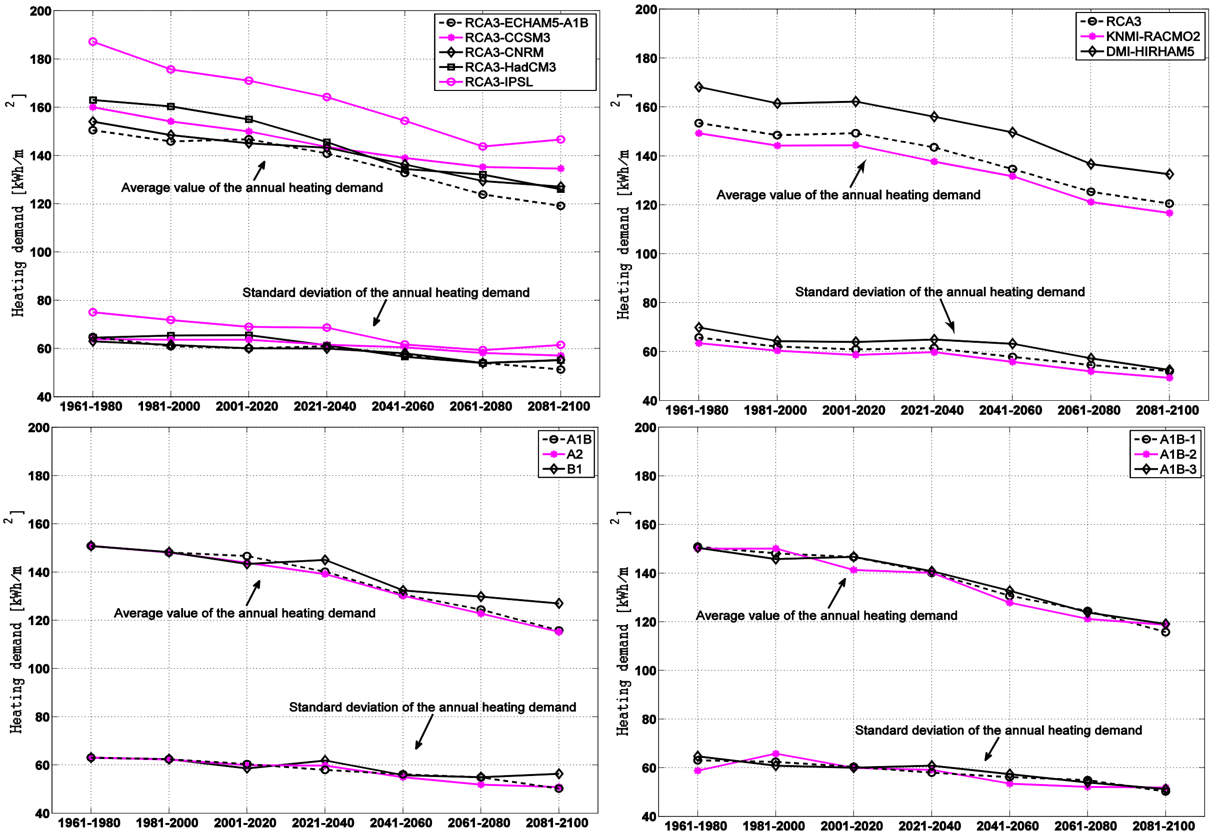

Fig. 39. Average values and standard deviations of the annual heating demand during the 20-year periods in Östersund. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

The 20-year averages and standard deviations of the outdoor temperature, the global radiation and the heating demand for four cities of Gothenburg, Lund, Stockholm and Östersund are compared in Table 11 during two periods of 1961-1980 and 2081-2100. Changes at the end of the century are not the same for all the cities. For example temperature increment is around 25% for Lund but 133% for Östersund. However decrement of the mean heating demand is around 20% for all the cities.

Table 11. Comparison of the 20-year mean and standard deviations of the outdoor temperature, global radiation and heating demand of the building stock during 2061-2080 and 2081-2100 for RCA3-ECHAM5-A1B-3 climate scenario in four cities of Gothenburg, Lund, Stockholm and Östersund.

	1961-1980				2081-2100				Changes respect to 1961-1980 [%]			
	Gothenburg	Lund	Stockholm	Östersund	Gothenburg	Lund	Stockholm	Östersund	Gothenburg	Lund	Stockholm	Östersund
T_{mean}	7.1	8.8	6.4	2.1	9.4	11	9.6	4.9	+32	+25	+50	+133
T_{std}	7.9	7.5	7.6	9.4	7.03	6.6	6.5	7.7	-11	-12	-14	-18
GR_{mean}	111	124	104	94	104	117	91	85	-6	-6	-13	-10
$Heat_{mean}$	104	94	127	154	84	74	96	127	-19	-21	-24	-18
$Heat_{std}$	46	36	78	63	38	31	62	55	-17	-14	-21	-13

The cooling demand is very low in Östersund regardless of the climate scenario. According to Fig. 40 it is totally unnecessary to install mechanical cooling systems in the building stock of Östersund. In figures Fig. 41 and Fig. 42 increment of the indoor temperature is in the acceptable range with the natural cooling system. The maximum indoor temperature is for KNMI-RACMO2 during 2081-2100 where the 20-year mean temperature is 22^{o}C and the standard deviation is 0.85^{o}C. The largest difference between the 20-year mean of the indoor temperatures occur during 2081-2100 where RCA3-ECHAM5 is around 0.13^{o}C warmer than RCA3-IPSL. Standard deviation of RCA3-ECHAM5 is 0.17^{o}C more than RCA3-IPSL. It shows how small are the effects of the climate uncertainties on the indoor temperature in Östersund where there is no need for cooling and the indoor temperature is mostly controlled by the heating system. In other words it is enough to just concern the climate uncertainties while calculating the heating demand of the building stock.

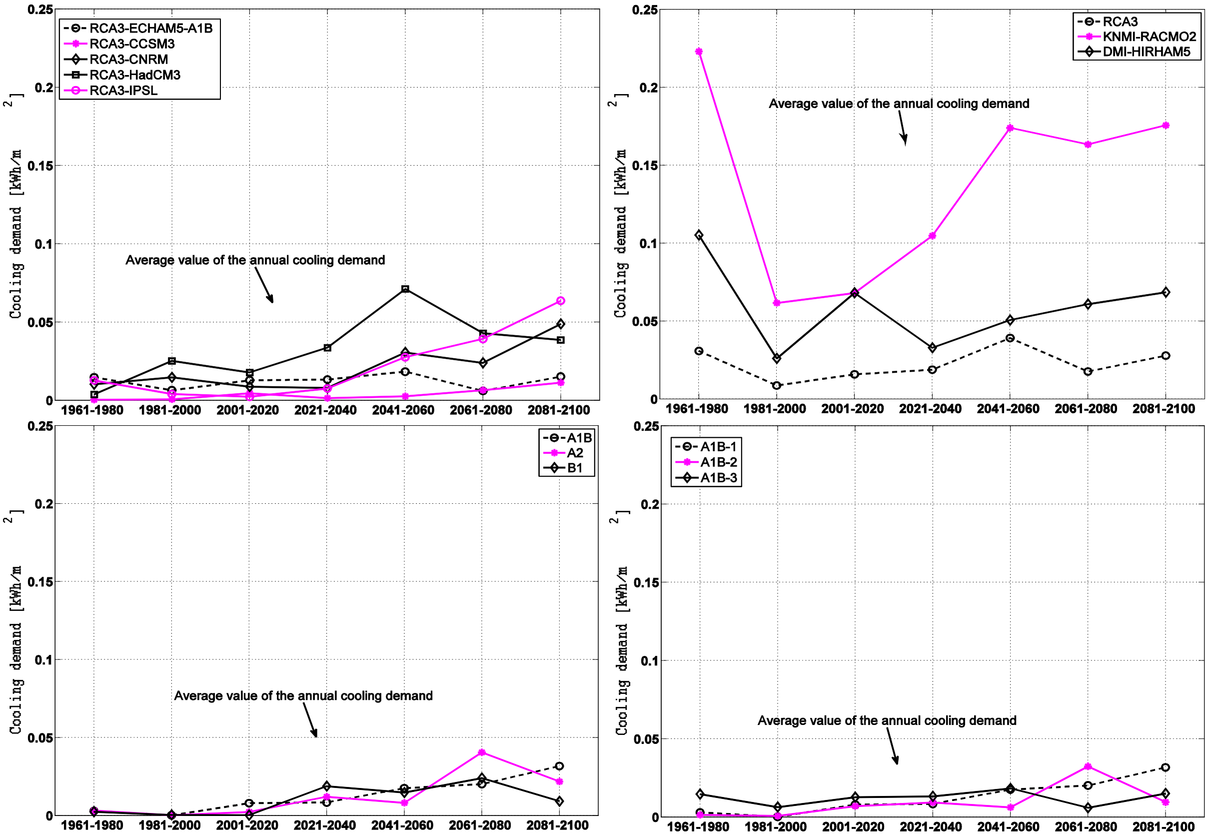

Fig. 40. Average values of the annual cooling demand during the 20-year periods in Östersund. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

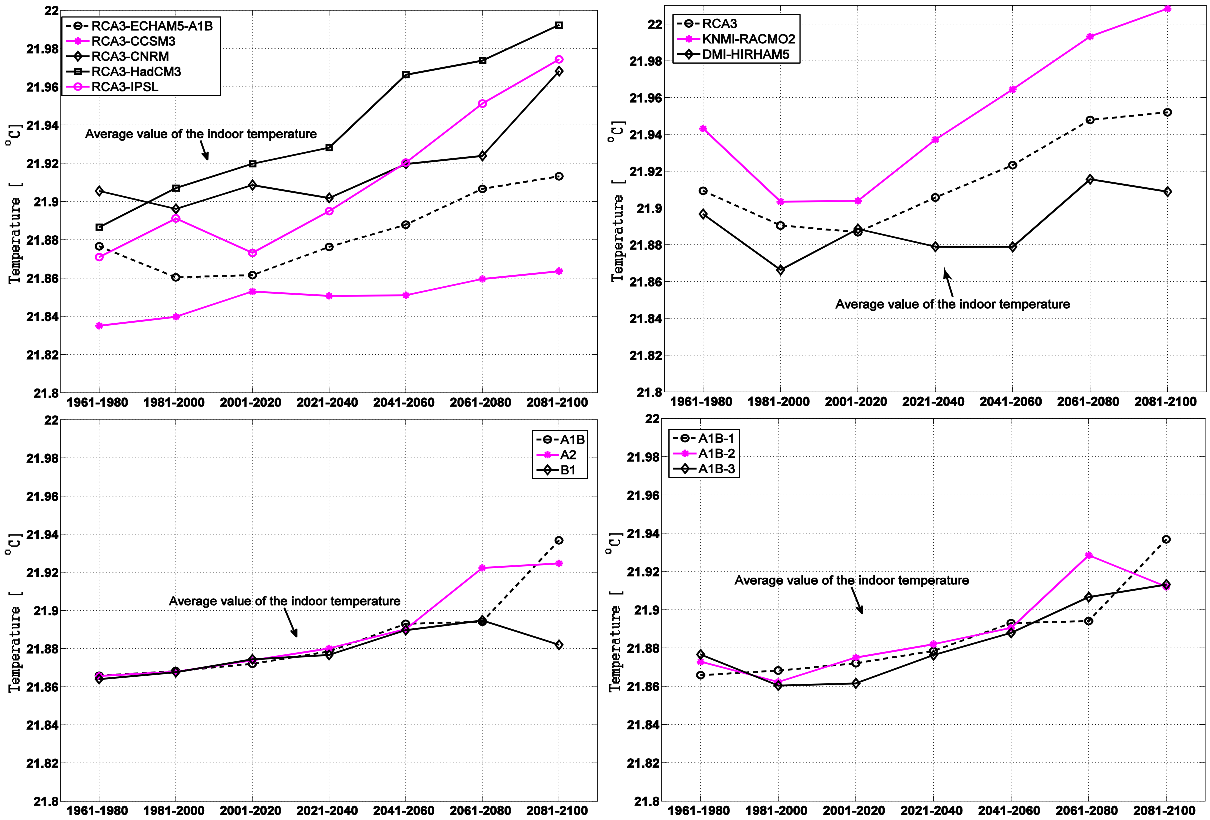

Fig. 41. Mean values of the indoor temperature during the 20-year periods in Östersund when the cooling strategy is natural cooling. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

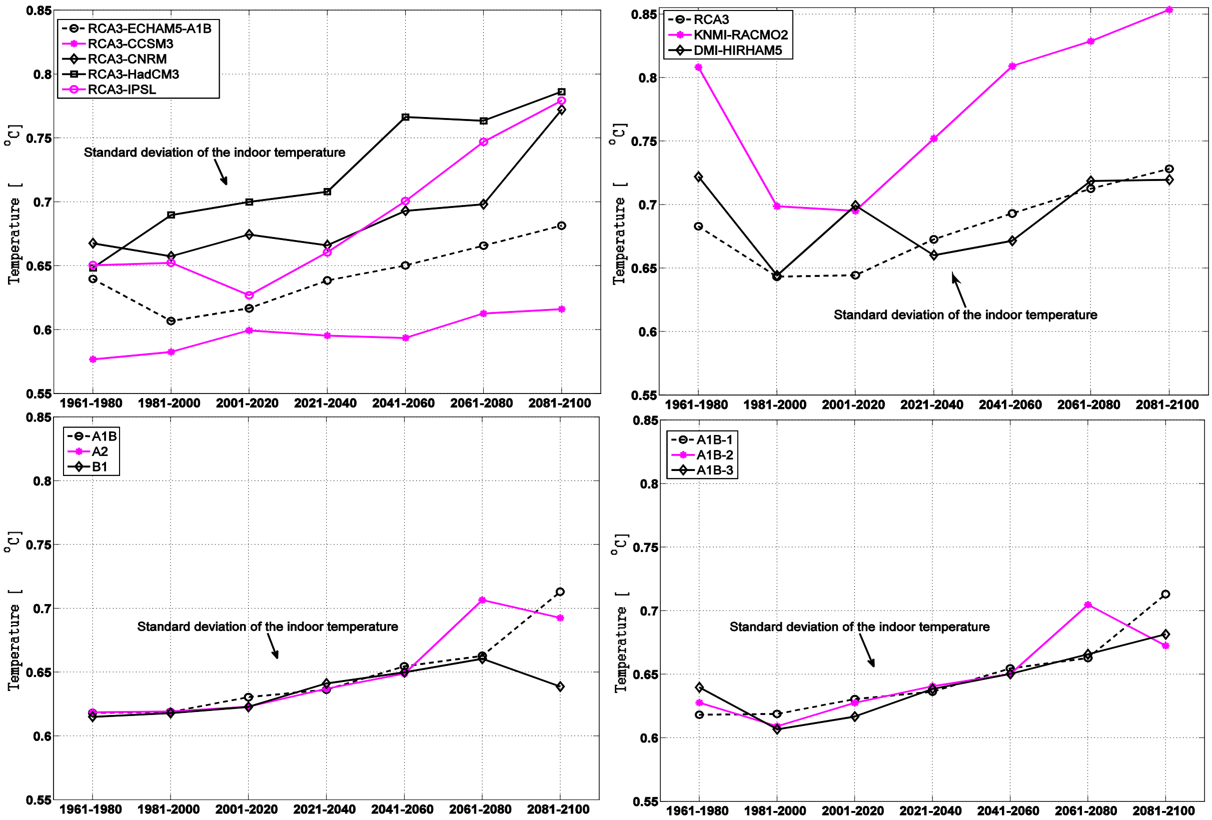

Fig. 42. Standard deviations of the indoor temperature during the 20-year periods in Östersund when the cooling strategy is natural cooling. Results are compared when the climate scenarios have been forced by; left-up) five GCMs, right-up) three RCMs, left-bottom) three emissions scenarios and right-bottom) three initial conditions.

6.

Conclusions

According to the results of this project a reliable impact analysis of the climate change cannot be based on a few number of climate scenarios. Climate projections are influenced by the selection of climate models, initial conditions and boundary conditions which in turn can influence the building simulation results. In this project five uncertainty factors of the climate data were considered which were caused by the selection of GCM, RCM, emissions scenario, initial condition or spatial resolution. The latter was considered just in the hygrothermal simulations of attics, but the rest were considered both in the energy simulations of building stocks and the hygrothermal simulations of attics. In total 13 climate data sets with five GCMs, three RCMs, three emissions scenarios, three initial conditions and two spatial resolutions were used in this project. In addition data from a reanalysis-driven simulation with RCA3-ERA40 was used which constitutes a realistic description of the state of the atmosphere.

Different statistical methods were used in this project to ease the assessment of the long term data sets and the climate uncertainties. The statistical methods can be divided to nonparametric and parametric methods without and with track of the time, respectively. The parametric method of decomposing of variabilities enabled to look into data and its variations in different time scales. This method was mainly used for assessing uncertainties of the climate data in hygrothermal simulations of attics. Moreover data sets were compared by looking into their probability distributions, scatter plots, histograms or boxplots. Results of the energy simulations were mostly assessed by looking into their probability distribution.

The hygrothermal performance of different attic constructions was assessed using different climate scenarios. Since results of the hygrothermal calculations are not fully discussed in this book just a brief conclusion of the previous works is repeated here. Mould growth was used as criterion for comparing the performance of attics. According to the simulation results, temperature and humidity levels will increase in the attics if the climate change happens which can increase the risk of mould growth in attics. There might be some new features of mould growth in the future like having growth during winter with higher rates than today.

There are no clear correlations between variations of the climate data outside and inside the attic which makes the uncertainty analysis difficult. The nonlinearity of the hygrothermal responses makes the assessment complex. But some correlations can be found, for example by using the scatter plots, to decrease the number of calculations. Results showed that the importance of the uncertainty factors on deviating the building simulation results and their variations can vary depending on the season. For example differences between the predicted temperatures of the climate scenarios with different GCMs are larger during summer and winter, when the extremes happen. Depending on the case some uncertainty factors of the climate data might be neglected. The climate conditions inside the attics did not project the difference of emission scenarios as much as the outdoor climate. On the other hand the relative humidity inside the reference attic was reflecting differences between the initial conditions of the climate models.

The risk of mould growth was assessed in four attic constructions. Assessing the future performance of the attic constructions showed that the absolute safe case for preventing the mould growth is using mechanical ventilation in attics. The attic with the insulted roof might be a solution to the mould problem based on the past climate. However it does not show a promising performance if the climate change happens. The insulation in the roof prevents condensation on the inner side of the roof. Nevertheless it cannot be the final solution to the mould problem in the future.

Energy simulations of the residential building stocks in four major cities of Sweden with different climate conditions were performed for the period of 1961-2100. Heating and cooling demand and also the indoor temperature of the building stock were calculated. Four uncertainty factors of the climate data were considered in the energy calculations. Three cooling strategies were assumed for the building stock: natural cooling, natural/mechanical cooling, and only mechanical cooling. The intention was to assess the necessity and effectiveness of each of the cooling strategies. Simulations were done by dividing the whole period of the climate data into 20-year sequences and running each building for just one year in that sequence. Results of the energy simulation were assessed by looking into probability distributions of different parameters. Results showed that the simulation method, short runs, works fine and results are in good agreement with the long runs. This method helps to save some time and also to make an easier comparisons using the 20-year periods.

According to the results the heating demand and its variations will decrease in the future for all the cases. The decrement does not happen with the same rate among the cities and the climate scenarios. However a rough estimate is having around 20% less heating demand from 2061. In the case of having cooling systems, the cooling demand will increase. However comparing the indoor temperature distributions with and without the mechanical cooling system showed that there is no need for mechanical cooling. The natural ventilation helps to keep the indoor temperature in the acceptable range. Although in the case of having mechanical cooling, the change in the cooling demand will be very low.

Uncertainties of the climate data can affect the energy simulation results considerably. For example in the case having different GCMs, there can be differences up to 30 kWh/m^2 (around 30% difference) in the predicted values of the 20-year mean heating demand. The relative differences between the scenarios increase for the cooling demand but since the cooling demand is rather low they can be neglected for all the cases presented in this thesis. Uncertainties of the climate data also affect variations of the parameters in energy calculations. For example the relative difference for the standard deviations of the heating demand in the presence of different GCMs can reach to 30% of the maximum value. Knowing that the standard deviation might be more than 50% of the average heating demand reminds us the importance of considering the uncertainty factors in energy calculations.

Among all the scenarios considered, uncertainties caused by GCMs introduced the largest uncertainties to the energy calculations. The uncertainties of having different RCMs and emissions scenarios affected the energy simulation results almost in the same range. Depending on the case they could introduce deviation around 9-15% in the simulation results. Using climate data with different initial conditions showed the smallest effect on the energy results, around 5% deviations.

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