Sustainability of the Swedish Built Environment Toward Climate Change: Hygrothermal Effects and Design Criteria for Buildings with Respect to Future Climate Scenarios

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ABSTRACT

Most predictable climatic impacts on buildings can be successfully managed by an adequate construction. However, possible deviations in predicted climatic loads and especially the long-term ones may change the building expected response. For example, changes in snow and wind loads and short-time precipitation are of great interest for constructions with large, flat roofs. Climate projections from climate models point to a warmer climate with an intensified hydrological cycle in the future. Warmer summers lead to increased demand for cooling energy, while a warmer, more humid climate will possibly increase risks for moisture and mold-growth problems. This paper gives some outlines from a new research project on the sustainability of Swedish built environment towards climate changes. The project will be conducted at Chalmers University of Technology, Sweden, in cooperation with the climate research unit Rossby Centre at the Swedish Meteorological and Hydrological Institute.

INTRODUCTION

Climatic impact from precipitation, wind, temperature and exposure to the sun causes extensive degradation and damage to the built environment every year. Our understanding of how and why degradation and damage occur and how this can be best reduced is of considerable importance in the design and construction of building structures. And what is about to come? Climate projections from climate models point to a warmer climate with an intensified hydrological cycle in the future. But, such changes are already observed both globally and regionally. In Sweden, for instance, the last 10-15 years have been mild and wet compared to previous periods. The trend in the recent Swedish warming is in line with climate change scenarios. The climate projections include changes in both average conditions and in the frequency and magnitude of extreme events.

Present Swedish building regulations (BBR 2006) and codes are based on past weather data. For building, physical phenomena with short-time response such as heat, snow and wind loads, regional variations of climatic impacts are sufficiently described by a few single parameters or statistically averaged diurnal variations (a reference year). Moisture safety issues involve long-term processes where events from quite a number of years in the past play a crucial role. This is because moisture loads depend on several correlated climatic parameters, as well as the impact they have on the construction. Moisture damage is frequent and costly. Future climate scenarios could magnify the problem.

Statement of the Problem

Most buildings have an expected lifetime of 60 to over 100 years, during which they offer a shelter from weather to human beings, animals, and property. Weather and its variations cause degradation of building materials and structures. The climate parameters such as ambient air temperature and humidity, solar radiation, wind, precipitation, and ground water cause different deterioration processes on buildings. Thus, variations in ambient air temperatures and solar radiation can cause freezing and thawing of the material (especially harmful to porous material and surface finishes), paint staining, movements in joints, deformations of sealants, cracks in concrete, etc. Water vapor in air and water from rain and

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ground that is absorbed in the construction damages walls on the onset of freezing, causing salt decomposition, mold and rot, chemical conversion, biological attack, and corrosion of metal components.

Not only the climate parameters but also their interaction is critical to the impact they have on buildings. A change in one parameter affects the others and, therefore, can exacerbate the whole situation. Furthermore, weather data on a large scale, such as a region, must be studied in context of both external factors (e.g. proximity to urban areas, air quality, distance from the coast, land formation in the immediate vicinity, and influence of adjacent buildings) and internal factors (e.g. properties of building materials, building performance, indoor air quality, and the inhabitants' use of energy). The transformation of regional weather data to the local scale can be done with statistical downscaling that relates the large scale to the local scale using observed properties of the climate on both scales. The transformed data are then called a microclimate load, as Figure 1 shows.

Predictable climatic impacts can be successfully managed by an adequate construction. Some combinations of building materials, designs, and levels of performance show better durability than others. However, possible deviations in predicted loads – and especially the long-term ones – may change the building designed and, consequently, the expected response. For example, changes in snow and wind loads and short-time precipitation are of great interest.

CLIMATE CHANGE SCENARIOS

Climate change scenarios for the future build on emissions scenarios and climate model simulations. The uncertainties of future population growth and economic development make it impossible to rely on any simple forecasts for the future. Instead, there has been a development of different scenarios with specific emissions of greenhouse gases and aerosol precursors. The most recent climate change experiments use the family of emissions scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) as presented in their Special Report on Emissions Scenarios (SRES, Nakienovi et al. 2000).

Global Model Results

Climate model experiments can be done with coupled atmosphere-ocean general circulation models (AOGCMs). These models are applied with different external climate forcing factors as changing greenhouse gas concentrations or changes in solar intensity etc. The response of the climate system to changes in forcing factors depends on the climate sensitivity of the AOGCM. Climate sensitivities differ between AOGCMs as they differ in how details of the climate system are described in them and as they may include different feedback mechanisms related to, for instance, land-surface processes, the carbon cycle, or the atmospheric composition.

Common to climate change scenarios (including future increases in greenhouse gas concentrations) is an increase in the global mean temperature. By the end of the century, the increase may be 1.8-4.0^{o}C, depending on which emissions scenario is chosen (IPCC 2007). In addition to these central numbers acquainted with the emissions scenarios, the model's uncertainty increases the range to 1.1-6.4^{o}C according to the latest IPCC report that takes into account more than 20 AOGCMs.

Regionalization of Global Climate Model Results

The change in global mean temperature is rather well-confined among the models. Associated with it are a number of regional climate change signals not just in temperature, but also in precipitation and wind characteristics. As state-of-the-art AOGCMs have a rather coarse resolution (often 100-300 km), they do not adequately represent details on a regional scale. This concern both land-sea distribution and topographic features on models. A commonly used approach to improve the resolution and thereby provide more useful scenario results to end-users is to use a regional climate model (RCM) for downscaling the results from the AOGCM. In such an experiment, an RCM takes lateral boundary conditions and sea surface temperatures and sea-ice conditions from the AOGCM at a certain frequency (typically once every 6 hours) and calculates its own atmospheric state in the model domain at higher frequency (typically once every 30 minutes).

The boundary conditions provided by the AOGCM are of fundamental importance for the model behavior in the area of interest. The RCM cannot deviate too far from it as the boundaries are updated at a high frequency. The addition of an RCM in the calculations adds an additional level of uncertainty to the

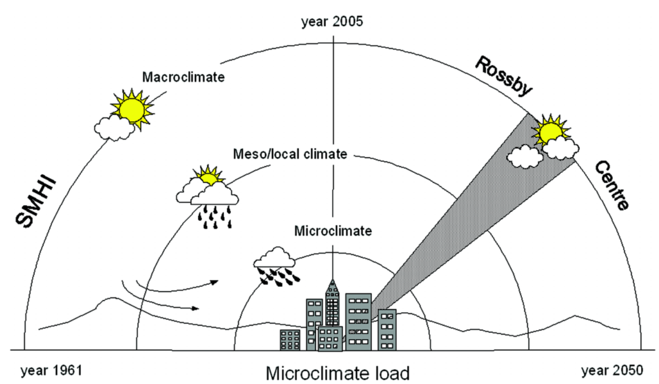

Figure 1 *The transformation of large-scale meteorological conditions to the microclimate load, close to the surface of the building envelope. The microclimate load varies as a result of interaction between climate parameters themselves as well as between the climatic parameters and the surrounding. The time axis illustrates past (measured by the Swedish Meteorological and Hydrological Institute—SMHI) and future (from Rossby Centre, SMHI) climatic data or interest for the analyses.*

climate change projections as there are also uncertainties in model formulation at the regional scale. Déqué et al. (2007) address the question of uncertainties due to emissions scenario, selection of AOGCM, and selection of RCM building on results from the European PRUDENCE project (Christensen et al. 2007). The uncertainty due to the choice of AOGCM generally dominates over the choice of RCM and that the choice of emissions scenario is most important in regions with a large response to climate change, such as the Mediterranean area in summer.

Climate Modeling at the Rossby Centre

At the Rossby Centre, a regional climate model RCA3 is used that includes a description of the atmosphere and its interaction with the land surface. Originally, RCA stems from the numerical weather prediction model HIRLAM (Undén et al., 2002). RCA3 includes a land surface model (Samuelsson et al. 2006) and a lake model, PROBE (Ljungemyr et al. 1996). RCA3 in its present form builds on the previous version RCA2 which is described in Jones et al. (2004). Further documentation of RCA3 can be found in Kjellström et al. (2005).

RCA3 has been used extensively for several climate change experiments. In the present study, results from three specific climate change experiments are used in which the time period 1961-2100 is simulated. Lateral boundary conditions and SSTs are updated every six hours from either of two global coupled atmosphere-ocean general circulation models, which are: the ECHAM4/OPYC3 (Roeckner et al. 1999), and the ECHAM5/OM1 (Roeckner et al. 2006) – both developed at DKRZ, the Deutsches Klimarechenzentrum GmbH, and the Max-Planck Institute for Meteorology in Hamburg.

Changes in future greenhouse gases and sulphate aerosol concentrations are accounted for in terms of equivalent CO_2 concentrations following the SRES A2, A1B, and B2 emission scenarios. The A2 and B2 scenarios were used with ECHAM4 boundary conditions, and the A1B scenarios with ECHAM5 boundaries. For further details of the application of the climate forcing factors conditions in the ECHAM4 experiments, see Kjellström et al. (2005).

In addition to pre-existing scenarios, the Rossby Centre is planning a new set of experiments, now at 25 km horizontal resolution. These new scenarios will be a part of the European ENSEMBLES project (Hewitt 2005), which aims at constructing probabilistic climate change scenarios that can be used for impact modeling.

Results with Possible Implications for Buildings

According to the climate change scenarios this paper has discussed, the future climate in northern Europe can be summarized as warmer and wetter. This is particularly true for wintertime conditions when retreating snow cover amplifies the warming at high latitudes. Also, precipitation is expected to increase in all of northern Europe in these scenarios for the winter. Summer temperatures are also projected to increase, but precipitation will increase only in northernmost Scandinavia while decreases in precipitation are projected for most of Europe. These results are not unique features of our simulations but well in line with what many state-of-the-art climate models say about climate change in the future (IPCC 2007).

EFFECT OF CLIMATE CHANGE ON BUILDINGS

The meteorological parameters that are most important for buildings are temperature, humidity, wind, precipitation, and solar radiation. Both average values and variations with maximum and minimum values are needed, as well as the probability of certain conditions. The local climate at the site of a building is important, as it can be quite different from the climate found in the atmosphere or at meteorological observational sites, even if they are located relatively close to each other. It is not possible to measure the parameters everywhere; instead, observations with corrections for local surroundings are used. Data normally represent a 30 year average so that variations between individual years are eliminated. The last 30 year reference periods are 1931 to 1960, and 1961 to 1990. An example of how temperature can vary over time at an observational site is seen in Figure 2, which illustrates the temperature in Stockholm from 1757-2002. There is a considerable variability from year to year, reflecting the natural variability of the climate. Additionally, there are variations on longer time scales, like decades. These features are partly due to natural variability but may also be caused by other factors. Part of the long-term temperature increase in Stockholm during the 20th century was caused by the growth of the city of Stockholm. But, there is also a notable increase in temperature during the last 15 years, which is coherent with other observations from rural locations in Sweden and, therefore, indicates an overall warming during this period. The temperature increase during the last decades is also seen as a reduction in the number of heating degree-days.

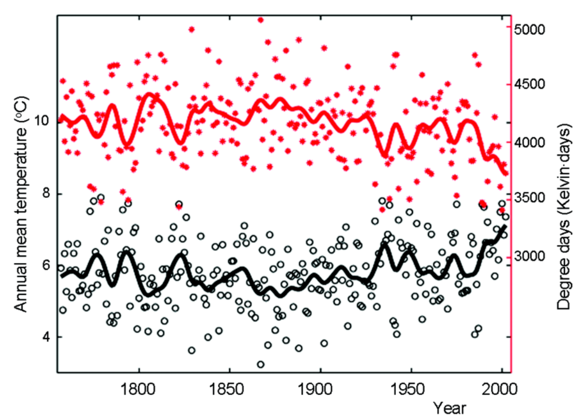

Figure 2 *Variations in annual mean temperature and heating degree-days from 1757 to 2002 for Stockholm, Sweden. Single years and ten-year moving average. Data from Moberg et al. (2002).*

Temperature. Temperature is used for calculations of the energy use in buildings (Taesler 1972; Taesler and Anderson 1995) in the form of a test reference year (TRY) or average monthly mean temperatures. An alternative method is to calculate the heating degree-days. The lowest outdoor temperatures are used for calculation of the effect for the heating system in buildings. The highest temperatures or typical summer days are used in calculation of the cooling load of buildings. An alternative is using some kind of cooling degree-days, but then it does not include solar radiation. Frost degree-days are the sum of temperatures below zero during a year. This is used in dimensioning of insulation against frost damage in buildings. For the lifetime of many materials, the temperature variation is important as it can lead to cracking when the material changes dimension with fluctuating temperature. One unique problem involves the freezing of moist materials, as freezing expands the water and can damage materials like bricks. This will only happen under certain conditions. Considering the number of freezing and thawing cycles is a good way to estimate the risk to buildings.

Humidity. Humidity is important because many materials degrade faster in high humidity. Biological attack on building materials is also increased at higher humidity. Condensation can get inside building constructions in a humid climate, but in most cases, the risk will depend more on the use of the building and the moisture production inside. Regardless, a change in temperature and humidity can increase the risk for moisture damages in a building (Nielsen 2002; Nielsen 2003). These damages are a serious problem in the building sector. An example is discussed in Case 1. Many building materials such as wood, cellular concrete, and concrete have higher moisture content in the construction phase than in later use of the building. Before materials with high moisture content can be used for construction, the moisture has to dry out. This process takes longer during periods of high relative humidity. A climate change with higher humidity will increase the risk for moisture damages.

Wind Speed. Wind speed and direction are important in non-airtight buildings, as it will change the wind pressure on the roof and facades of the building. An increase in mean wind speed will give a higher infiltration rate (not controlled ventilation) and a higher energy use in building. Higher wind speeds will increase the drying out of moist materials, but, on the other hand, they will intensify the driving rain during the rainy periods.

Precipitation. Precipitation is an important factor for the lifetime of building materials. Most building materials have to be protected against precipitation as water will change the properties of the materials. For instance, thermal insulation gets a higher thermal conductivity with higher moisture content. The result is a higher energy use. Leakage in roofs or facades from rain and snow is some of the most difficult damage to repair. The result can be a deteriorated construction and a bad indoor climate. Driving rain occurs when rain combines with wind. The amount of driving rain depends on the location of the building (Högberg 2002) and maximum amounts of driving rain are normally found in coastal areas with high wind speeds and much precipitation. Icicles on roofs are a serious problem in the winter period if the building design is wrong; this is discussed in Case 3. A changing climate with increased occurrences of precipitation will create higher risks for moisture damages in buildings.

Solar Radiation and Cloud Cover. Solar radiation and cloud cover are important for the energy balance of the building. In passive houses, the solar radiation is used as a free energy source to reduce the heating energy demand. Solar radiation can also give problems with overheating in the summer. This can be controlled with solar shading devices. Solar radiation increases the surface temperatures, and thereby can also degrade materials such as roofing felts. Solar radiation has a positive effect in drying out moisture from materials. A change in climate to more solar radiation could reduce the energy use for heating buildings but also give a higher risk for overheating in the buildings.

Climate Scenarios. Climate scenarios consist of all these meteorological parameters and must be used in the final evaluation of climatic effect on buildings. To define the risk in the construction, we also need to know hygro-thermal conditions inside the buildings, i.e. variations in indoor air temperature, humidity, and air movement. The simulations on these combined effects have not started yet.

CASE STUDIES

We have selected three cases to give some ideas of the expected effect from climate change on buildings. These examples are cases where we know the effect of some of the climate parameters, but they are not selected to be the best or worst cases. The first case is a very complex one with ventilated attics where we know that a change in building methods has increased the risk for moisture problems. The second case is an inverted roof, where the climate has an effect on both the heat and moisture design. The last case is icicles – a clear practical problem that will occur if certain climatic conditions are combined with building design. These cases and others will be simulated with the expected climate scenarios in a later phase of the project. In all of these cases, it is possible to change the design so that the effect of climate change and climate variability is reduced.

Case 1: Ventilated Attics

The attic is the part of a building that is most exposed to the environment. Diurnal, daily, and seasonal variations in weather directly impacts roof surfaces: snow cover, wetting by rain, staining due to the sun, exposure or wind washing. Depending on how well the attic is separated from its surroundings (thermally, but also in terms of moisture and air-tightness), these climatic loads may have problematic consequences: melting and freezing of snow, (Nielsen 2005), condensation and freezing of water vapor from air and, as a result, mossy covering or a mold growth, etc. For energy saving purposes, the present Swedish building tradition recommends well-insulated attic floors under pitched roofs (cold attics), (Samuelson 1998). In practice, these attics often face problems of the mold growth due to the water condensation and accumulation from air on the internal side of the roof (Geving 1997). According to the tradition, ventilation is seen as a remedy for this problem.

A research process for the ventilated attic is schematically presented in Figure 3. A detailed study on the hygro-thermal response of the attic, (Sasic 2004; Sasic and Mattson 2005), the past external and internal loads (denoted with white arrows), and the knowledge of their future variations (grey arrows), will give a basis for the present and future hygric response and moisture safety assessment.

For the stated problem, the climatic impact must be presented in form of thermal loads (air temperature, solar and long-wave radiation), hygric loads (air relative humidity and precipitation), and wind loads and their combined effects. The change in either of these parameters will be noticeable by the resulting hygro-thermal state in the attic, as shown in Figure 4. The given example shows relative humidity inside the wooden board (normally used in Sweden as an underlay of a pitched roof) for two consecutive years. The difference in the climate load from the first to the second year (the second year much warmer and slightly more humid than the first one) is clearly seen – higher relative humidities are present in the roof during the winter of the second year. Note that the initial moisture content in both attics (in the beginning of the simulation) is much higher than one year later. This does not necessarily lead to the problem of mold growth on the wooden board in the second year, but it carries a potential risk if the trend continues.

Even though the problem is focused on moisture complications and damage, at the same time it addresses thermal loads and will thereby provide important and detailed information for energy calculations.

Climate Change. A warmer climate will lead to a more intense hydrological cycle with more evaporation due to the higher temperatures and greater resulting water vapor in the atmosphere; ultimately, this also leads to more precipitation. This is likely to cause more humid conditions as illustrated in Figure 5, which shows an increase in the number of humid days (here defined as days with the relative humidity larger than 90% as a diurnal mean) that are warmer than a certain threshold (diurnal average temperature 10°C). These conditions become more frequent the warmer the climate gets as illustrated for the two time periods. These changes can be seen as a possible risk of increasing problems with mold growth.

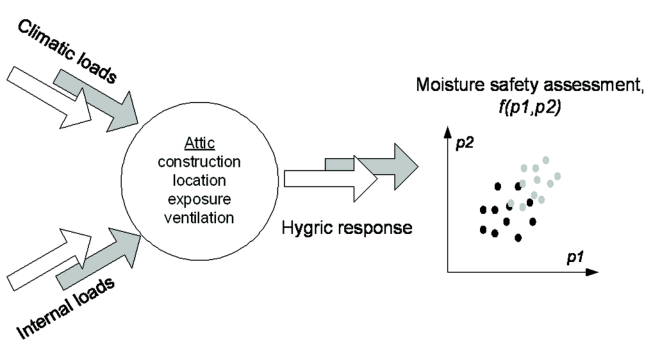

Figure 3 *The process for hygrothermal design of building components—example: the attic. The loads from climate and the building design can result in an assessment of the moisture safety of the design.*

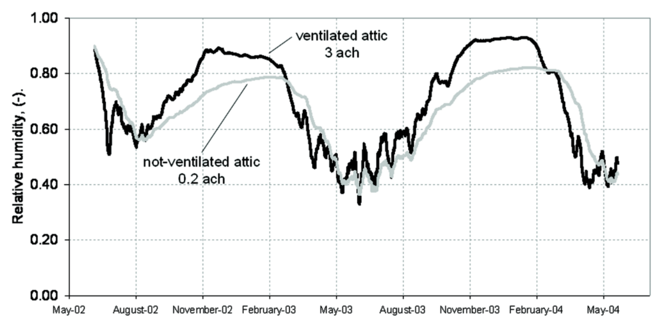

Figure 4 *Relative humidity on internal side of a pitched roof (in the middle of a 19 mm thick wooden board), above well-insulated attic floor, for two consecutive years. Besides obvious differences between the ventilation strategies applied (the yearly mean values are given), there are clear differences in climate load between the years. Numerical study made by Sasic using HAM-Tools (Sasic 2004).*

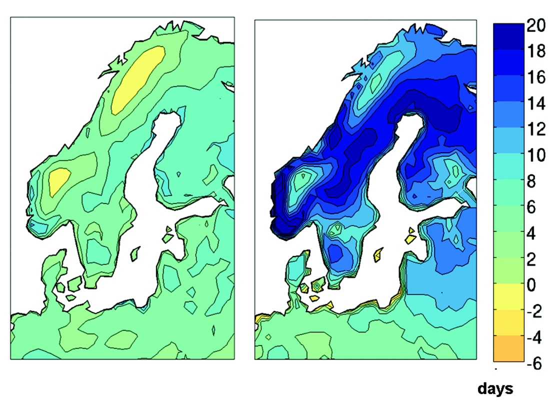

Figure 5 *Change in the number of days with temperature greater than 10°C and relative humidity greater than 90% in September–November. The left panel shows the average change for 2041–2070 (the right panel shows that for 2071–2100) compared to 1961–1990. The results are taken from a simulation with RCA3 using boundary data from ECHAM4/OPYC3 under the SRES A2 scenario.*

Case 2: Inverted Roof

An inverted roof is made with thermal insulation placed above the roofing felt. The result is that precipitation will reach this thermal insulation material that in a normal roof is protected by the roofing felt. Inverted roofs have been used in Scandinavia for many years in the form of turf placed on top of birch-bark on pitched roofs. Today, this system is still in use in some buildings in the original style but with improved membrane and very often with additional insulation underneath.

In flat roof constructions, the inverted roof system has had a limited use in Scandinavia so far, mainly because of the demand for thick insulation. A new house cannot be built with an inverted roof system without additional thermal insulation below the roofing material. Therefore, the existing inverted roof systems can also be of interest for extra insulation.

Thermal Design. It is important to know the moisture uptake in the insulation and the influence of the precipitation. The values for recommended design moisture content are based on the results from the field survey and supplemented from other investigations described in literature (Nielsen and Paulsen 1985; Petersson 1980). The basis for the design of thermal insulation is taken from the Norwegian rules given in Norwegian Standard NS3031.

The thermal conductivity values normally given in the standard are relevant only for dry materials. The value used in the design of inverted roofs must take into account the moisture uptake during the lifetime of the roof. The result from many field tests has shown that for insulation of extruded polystyrene (EXPS) in one layer with gravel on top, the design moisture content is 1% vol. In the case that there are pavers on top of the insulation, the design moisture content is 3% vol.

The added heat loss from moisture uptake in insulation as well as precipitation must be accounted for. The design heat transmittance coefficient (U_d, W/m^{2}K) for the inverted roof is found by adding the normal total U-value (U_t) to the effects of the joints as follows:

$$U_d = U_t + U_{joint} \quad (1)$$

where U_{joint} is dependent on the type of ballast or insulation configuration and has been found from field measurements and theoretical calculations. This effect is most important for the roof with all the thermal insulation above the membrane.

For the normal roof design with a ballast of gravel or pavers this value depends on the amount of insulation under the roofing membrane:

- For 0-40%: U_{joint} = 0.04 W/m^{2}K.
- For 40-60%: U_{joint} = 0.02 W/m^{2}K.
- For 60-100%: U_{joint} = 0.00 W/m^{2}K.

The calculated U_d-value is used both for effect and energy design.

A climate change with higher outdoor temperatures and more precipitation will influence the design rules and the expected energy use in these types of buildings. Recordings of temperature give the possibility to study the influence of joints on the overall thermal conditions. A field test at the Norwegian Building Research Institute (Nielsen and Paulsen 1985) has looked at the relative joint temperature (RJT) defined by the formula (see also Figure 6):

$$RJT = (TJ - TG) / (TC - TG) \quad (2)$$

where

TJ = temperature in joint at lower side of insulation

TG = temperature on top of insulation board

TC = temperature under centre of insulation board

If RJT equals 1, there is equal temperature under the board and in the joint. If RJT < 1 the temperature in the joint is lower than under the center of the board, thus causing a higher heat loss at the joint region. This will happen if it is raining and water runs down in the joint. Consequently, the converse is true in case of RJT > 1. The latter could happen if the outdoor temperature is higher than the indoor temperature. The RJT model can be compared with ordinary roofs.

A computation of RJT for various outdoor temperatures shows a marked difference between periods below and above the freezing point.

Temperatures below freezing RJT variations in an inverted roof are very close to that for an ordinary roof. The conclusion is that there is no difference between the roofs in this case. Snow on the roof will increase the thermal insulation, but that will happen on all roofs. For the part of the year when the outdoor temperature is above 0°C, the rain in the joints has a marked influence. The relative joint temperature is greater than 0.96 for 10 % of the time in the ordinary roof, while for the inverted roof with extruded polystyrene it is 0.88 for 10 % of the time (Nielsen and Paulsen 1985). These deviations between the 2 types of roofs for part of the time correspond to periods with precipitation where the rainwater will flow into the joints with the effect of partial cooling. The effect will depend on variation in climate. With more precipitation, there is an increased probability for water flow in joints and then a higher energy use.

Figure 6 *Drawing of inverted roof of extruded polystyrene EXPS on roofing felt on concrete with temperature-measuring points TJ, TG, and TC—TJ in joints below the insulation, TG on top of the insulation, and TC under the center of the insulation board.*

The main conclusion of these test results is that the most common method of thermal design of an inverted roof is not quite logical, mainly because an inverted roof behaves like an ordinary roof in the coldest period. When designing, the maximum power of the heating system in the building with the inverted roof can be treated like the ordinary roof. The thermal conductivity of the insulation, however, must be corrected for moisture content depending on type and drying out conditions.

Energy U-Value. For an ordinary roof, there should be no difference between the two U-values. This is true for the normal roof; for the rest of the inverted roof, the measured U-value is higher than the calculated. This indicates that the heat loss in an inverted roof is higher than in the ordinary roof. The measured differences can be used to find a U value that must be added in the thermal design of inverted roofs. The U_{joint} was found to be 0.04 W/m^2K for single layer extruded polystyrene. The value will depend on the climate, specifically the precipitation and periods with frost. Calculations based on climatic data show that in northern Sweden with long periods of snow U_{joint} is 0.016 W/m^2K and the areas in western Sweden with the highest precipitation (and also the most rain) U_{joint} is 0.057 W/m^2K.

Effect U-Value. The effect U-value is not the same as the energy U-value, the period with the maximum effect and the coldest period in the year. At that time, we will have frost weather and from the field measurement, the inverted roof will behave as a normal roof having the same U_{joint} equal to 0. When designing the maximum demand for heating in the building, the heat resistance for the inverted roof is the same as for an ordinary roof. But the thermal conductivity of the insulation in the inverted part must be increased by 1% for a single layer of extruded polystyrene with gravel.

Climate Change. The effect of climate change on this construction can come in at least two areas: risk for water leakage and expected energy use. The risk of water leakage will increase as there will be more precipitation, most of which will be in the form of rain in a warmer climate. For energy use, it is much more complicated. A higher outdoor temperature will reduce the energy used for heating but increase the risk that energy is needed instead for cooling. Increases in precipitation in the form of snow will reduce the energy use, and the U_{joint} will go down. From the climate scenarios, we can expect more precipitation but also higher temperatures that taken together will lead to a shorter period with frost (as shown in Figure 7) and therefore a higher U_{joint}. In conclusion, the energy use will be reduced from higher temperatures but increased due to more precipitation in the form of rain. The end result is nearly no change in energy use but an increased risk of water damage.

Case 3: Icicles

A typical winter problem is snow and ice on roofs. This can cause a lot of problems that are related to building physics. An example of these problems is icing and the generation of icicles on roof edges. Icicles hanging from the eaves look nice, but they are a serious problem as they can fall down onto people walking beneath them. In the worst case scenario, falling icicles can kill people. Such incidents have happened in Sweden and Norway. According to Swedish law, it is the owner of the building who is responsible for the prevention of sliding of snow and ice from his or her building.

The problem with icing and icicles on roof is a complex one involving architecture, meteorology, glaciology, and building physics. The architect decides the layout of the building and the form of roof used. The architectural solution can reduce or increase the risk of icicle generation. The meteorology aspect pertains to weather, as this science will indicate the periods that are not favorable to icicle formation and the periods with high risk for sudden fall of icicles. Glaciology holds the information on the physics behind ice and snow. The building physics are as important as heat when air and moisture transfer is involved. More information on this problem is provided in Nielsen (2005).

Roofs can be divided in two types: cold (ventilated) roofs and warm (non-ventilated) roofs. In warm roofs, it is normal to have internal drainage with down pipes in the building. This solution has no or very little risk for icicles. Freezing of the melting water on the roof can still be a problem. Ventilated roofs introduce a ventilated gap or roof space to prevent moisture problems and to keep the surface of the roof cold. In most cases, these roofs are sloped. The drainage is external to gutters along the eaves and to down pipes. The result is a high risk for icicles if, for instance, the melting water freezes in the gutter.

Freezing of dripping water or melted snow forms icicles, as shown in Figure 8. Icicles are found not only occurring on roofs but also in nature on trees, waterfalls, fences, and the

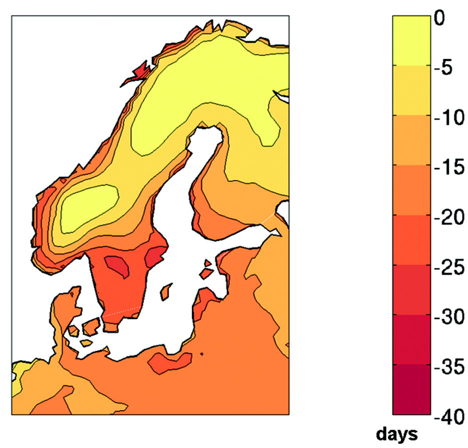

Figure 7 *Decrease in the number of days with frost (defined as days when the minimum temperature is below 0°C) in Scandinavia during winter (December, January, and February). The results are taken from a simulation with RCA3 using boundary data from ECHAM5 under the SRES A1B scenario. Shown is the average change for 2041–2070 compared to 1961–1990.*

Figure 8 Icicles at roof eaves.

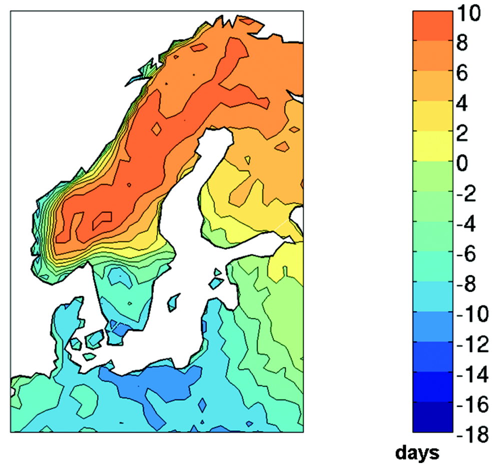

Figure 9 Change in the number of days when the temperature crosses 0°C in Scandinavia during winter (December, January, and February). The results are taken from a simulation with RCA3 using boundary data from ECHAM5 under the SRES A1B scenario. Shown is the average change for 2041–2070 compared to 1961–1990.

like. The form of icicles is either cone-shaped or spiky with the thick end at the top. Their shape varies depending on the local conditions, as snow crystals are also unique. The source of the icicles is liquid water, so temperatures above freezing are needed to generate them. A water source at the root of the icicle will make a liquid film on the surface of the icicles that can cover its entirety. For the icicle to grow, the air temperature must be below 0C. When the icicle grows, the latent heat from freezing must be taken from the ice-water interface. The heat loss rate from the surface to the surrounding area will control the growth rate of the icicle. In cold temperatures, the freezing will occur faster, but the humidity, wind speed, and solar radiation are also important. The heat loss from the surface to the air is caused mainly by thermal convection and evaporation. Radiation to the surrounding area is of minor importance, and heat conduction in the interior of the icicle is negligible. When the water flows down the surface of the icicle, parts of it will freeze. However, if the water supply is large enough, a water drop will form at the end of the icicles. This drop grows until it reaches a certain size, around 5 mm in diameter, and then falls, after which a new drop will be formed. Dripping is no problem, but falling icicles is.

Icicles fall when their weight exceeds their. When does this occur? The problem is complex, but the temperature is expected to be above 0^{o}C. A typical winter day has freezing temperatures during the night and above-freezing temperatures during the day, coupled with possible solar radiation. At night and in the morning, when freezing temperatures occur, the risk of falling icicles is low. When the temperature goes up, this risk will increase from the influence of both the increasing amount of melting water and solar radiation. The evaluation in Nielsen (2005) is that the risk is low in the morning and will increase during the day. In days without incoming direct solar radiation, the highest risk will be in the afternoon. If there is solar radiation, the risk is greater and will depend on the orientation and slope of the roof. Direct solar radiation on the roof surface before noon increases the risk in the late morning.

In many towns, it is normal to have gutters along the street, above pedestrian path. This will always create a risk for people getting injured by falling icicles. One solution is to have some type of garden along the façade of the building with a width of approximately 2 m, if the overhang is around 50 cm. Then, the icicle will fall in the garden. The threat of falling icicles is still a possibility in regards to doors in the façade, but if doors are constructed with an overhang, this protects against icicles. An alternative solution is to place doors at the gable end of the building to eliminate foot traffic along the length of the building. This solution is not easily adopted by existing buildings in many towns where the building is placed along the pedestrian lane.

Climate Change. As the formation of icicles is a complex process, it is not trivial to judge what impact climate change may have on their occurrence. In a warmer climate, the snow season and the amount of snow will decrease in most areas which will favor diminishing the problems. The number of days when the temperature is critical, i.e. going from below to above 0^{o}C, will be lower in the southern part of Scandinavia but higher in the north, as seen in Figure 9. This indicates that the problems with icicles will not disappear and may even be worse in some areas, but the risk can be higher or lower depending on the climate scenarios.

CONCLUSION AND OUTLOOK

We know that the climate will change in the future from the increased emission of CO_2 and other greenhouse gases.

The best way of presenting this is in the form of possible scenarios. This gives the possibility of making predictions on the effect on different problems related to climate for energy use in buildings, risk for moisture damages and reduced life-time of materials. Use of energy to heat buildings is an important part of the total energy use. To reduce the CO_2 emission, the use of energy in general has to be reduced – including the energy used for heating buildings.

For new buildings, the building authorities have made new rules that will increase the amount of thermal insulation in roofs, walls, windows and floors. The result is that new buildings will use less energy. The design must be made so that the risk for moisture damages in not increased. But new buildings are only a few percent of the total building stock.

For existing buildings, energy reduction is much more complicated. Measures like retrofitting with more thermal insulation and new windows have to be considered at the same time as the effect of climate change. Both will influence the energy and moisture balance in the building. As old buildings have been built in a different building tradition and according to different building codes, predictions have to be made for many different types of buildings in order to analyze which buildings will have a higher risk for moisture problems. It is then possible to devise recommendations to increase the thermal insulation in buildings, and if necessary, how to change the ventilation and heating of the buildings.

This project started at Chalmers University of Technology in cooperation with SMHI, aiming at improving the hygrothermal performance of buildings through examination of both new and existing buildings.

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