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COMPARISON BETWEEN LOCAL VERSUS REGIONAL CLIMATE USING MONITORING DATA OF TIMBER STRUCTURES

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ABSTRACT: Switzerland spans only 350 km from west to east and 200 km north to south. Many microclimates are found, mainly due to the presence of the Alps. Whereas the south is affected by a Mediterranean climate system, the north is cooler and under influence of the weather systems from the Atlantic. The Alps itself are relatively dry and the Central Plateau and Jura are humid. As topography and vegetation affect the climate around a structure, the question is raised whether this could impact design of timber structures. Monitoring campaigns of climate around- and moisture content in- timber bridges were extended and several newly erected timber structures (2017) were instrumented. Data from a total of 12 timber structures could be used to compare measured relative humidity and temperature to the regional climate measured at 133 meteorological stations throughout Switzerland. Measured moisture content was compared to theoretical equilibrium moisture content. The variation found in local climate is reflected in the experimental data.

KEYWORDS: Regional climate versus local climate, building standards, monitoring, moisture content

1 INTRODUCTION

As wood is a hygroscopic material, it undergoes moisture content changes during its lifetime. Moisture content depends greatly on surrounding relative humidity and to a lesser extent on temperature. Hence, the ambient climate the structural member operates in is of special interest to designers and building planners, as it defines the Service Class or Moisture Class must be designed for [1]. Moisture content itself is accounted for with the classification of the Service Classes, moisture content variations however are not. Structural elements located in heated buildings are designed to Service Class 1, meaning that moisture content is below 12 M%. Structural elements in ventilated and unheated buildings are generally designed according to Service Class 2, meaning that moisture contents should remain below 20 M%. Exposure to rain must be avoided. The two mentioned moisture contents correspond to 65 % and 90 % relative humidity, respectively.

Swiss climate, i.e. regional climate, contains several local climates. Engineers need to anticipate to the conditions a structure will operate in. This is difficult to predict when this concerns a special building type or an area in which not much experience has been gained yet. The Alps for instance are known to be dryer than the densely populated Swiss central plateau, but up to which extent this can or needs to be accounted for is not known. Another question often raised is whether a higher humidity needs to be considered when a bridge crosses a river or a paved road due to higher probability of spray, or if a bridge in a forest is subjected to a higher ambient relative humidity as a bridge in an open field. Application of coatings could reduce the development of high moisture contents or moisture content gradients. Traditionally, timber is not coated though and protection is preferred by either building a roof over the structure, providing enough roof overhang, or cladding elements to protect the load bearing timber elements. That eventually provides long service life of timber structures, for example the Kapellbrücke in Luzern which was built in the 14th century and is still used to this date.

This paper evaluates local and regional conditions structures operate in through literature studies, data from experimental campaigns, and simulations with meteorological data. New monitoring efforts (2017) were put on structures where the structural members were protected from direct impact of rain and sun, but were unheated. More specific, this concerned (1) structures located in climates where relative humidities were over 90 %RH (e.g. 20 M% moisture content) for large parts of the year, (2) structures located in the Alps above 1500 meters above sea level (m.a.s.l.), and (3) bridges. The bridges were already instrumented in former monitoring campaigns, but data acquisition was continued where possible and analysed further.

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The study focusses on annual developments of relative humidity and temperature, not on topics of global warming or carbon storage of timber.

2 STATE OF THE ART

2.1 SWISS CLIMATE

Swiss climate is affected by the presence of the Alps, the Atlantic Ocean, and Mediterranean climate. Figure 1 shows the four main regions, three cities: Geneva, Bern, and Zurich, and the distribution of 133 meteorological stations (not all) across the country. Data from these stations is used later in Chapter 4.

Within the Alps, dry climates are found and arctic temperatures can be reached in winter time. The central plateau is at an altitude of roughly 500 m above sea level, is mild and affected more by prevailing currents from the westerly and northerly direction. It is also a region that is known for a cloudy overcast in autumn and winter. Most areas in Switzerland, including the Jura mountain ridge, have plenty of rainfall throughout the year. The alps act as a climate barrier and therefore the south is affected more by the Mediterranean Sea, with milder winters [2].

Maps with design snow and wind loads per area are available in the swiss building standards [3]. Similar is found for wind loads. The Swiss timber construction standard recommends the same subdivision into Service Classes as found in the Eurocode 5 [1][4]. Note is made that equilibrium moisture contents in the pre-Alpine region (north of the Alps) and the Jura are higher. Within the Alps itself, equilibrium moisture contents are to be assumed lower than normal. How much higher and lower this is and if this should affect the design, is not mentioned. It does mention that the designing engineer should consider local effects.

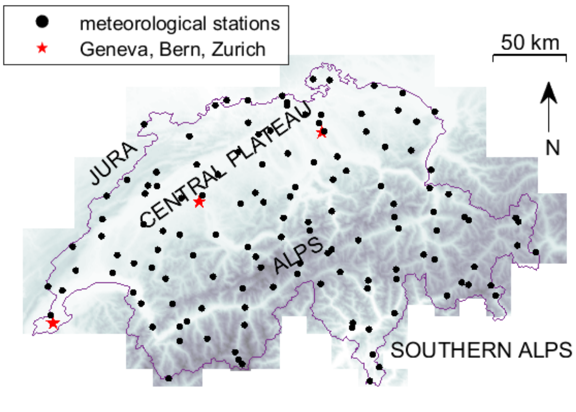

***Figure 1**: Overview of the different meteorological stations and regions in Switzerland*

The Köppen and Geiger maps [5] offer a classification of climates. General application of these maps is for instance in agriculture or medicine. A set of climates is defined based on temperature and rainfall per region. Detailed distributions can be found within this classification, but at least three climates are distinguished in Switzerland: (1) Cfb: warm temperate, fully humid, warm summer, (2) Dfc: snow, fully humid, cool summer, and (3) ET: polar tundra. The latter two are found in the Alpine region. In Austria four climates are found with an additional variation of the second climate class, indicating hot instead of warm summer. Germany is practically covered by only the first climate. The Köppen-Geiger classification indicates that separate climates can be found, but whether it can be used to appropriately predict expected moisture content in timber structures is to be better investigated.

Theoretical equilibrium moisture content was calculated for 262 locations in the US and 122 locations across the globe [6]. The purpose of these calculations was to know what the moisture content of timber could be if it was stored outside. The theoretical equilibrium moisture content was calculated per month using relative humidity and temperature. Autumn is the wettest period and spring is the driest. However, further analyses use monthly data, these are representative for the seasonal trends. The calculated monthly average moisture contents for Geneva, Bern, and Zurich are shown in Table 1. Little difference between these is found. These cities are all located in the central plateau, see also Figure 1.

***Table 1**: Theoretical equilibrium moisture contents (M%) per month in three different cities [6].*

[M%]	March	June	Sept.	Dec.
Geneva	13.0	12.0	13.7	16.3
Bern	13.7	12.5	14.1	18.3
Zurich	13.0	13.1	14.9	18.3

2.2 STUDIES USING CLIMATE ACROSS THE EUROPEAN CONTINTENT

Studies on a continental level were also performed. The effect of climate on theoretical moisture content distributions and moisture induced stresses in glued laminated timber cross sections on the European continent was studied. Here too, relative humidity and temperature obtained from meteorological stations was used. Simulations showed that the moisture content variations and following moisture induced stresses in timber cross sections in northern Europe were larger than those found in southern Europe [7] for instance.

The Durable Timber Bridges project (DuraTB) [8] focused the application and durability of wood in bridges. Measured climate was also used, although not necessarily only with relative humidity and temperature. Along with measurements of resistance of timber to decay, maps were set up to indicate areas in Europe where wood was prone to degradation and where amount of free driving rain was highest. Risk for driving rain in the Alps is comparable to that found in Germany, that of wood degradation though is medium.

2.3 CLIMATES IN DIFFERENT STRUCTURES

A large monitoring campaign to measure indoor climate in halls and moisture content in load bearing beams was performed in southern Bavaria, Germany [9]. A total of 21 buildings were instrumented. The instrumented structures in this campaign were three swimming pools, four ice rinks, three riding halls, three sports halls, two production halls, three riding rinks, three livestock halls, and three storage halls. The monitored swimming pools had a stable climate due to their climatization installations. The sports halls were a little damper than production halls, but moisture contents were still below 12 M%. Riding rinks and livestock halls were a little wetter than the unheated storage halls. The climate in the ice rinks could not be generalised, as two of these were actively climatized and the two others only had a closed building envelope. The climatization is installed to facilitate a large training season.

Ice rinks are a point of concern as high relative humidities can easily develop due to the low air temperatures above the ice. Subsequently, high moisture contents develop and load bearing capacity of the structure is at stake. Amongst the reasons accounted to the collapse of the roof of the Bad Reichenhall Arena, one was the high relative humidity which weakened the adhesive [10].

The timber structure located above the ice surface is colder than the structure around it [11]. It was estimated that surfaces facing the ice were 2°C to 3°C colder than the surrounding air. Based on absolute humidity, an increase of roughly 7% in relative humidity and up to 4 M% in moisture content can be expected. If relative humidities are high, the risk of condensation of water on timber beams in ice rinks is high as well. Problems with condensation occur typically when outside temperature are high compared to what is found inside.

Ice rinks have been temporarily closed for public before, even though maximum allowable snow loads were not achieved yet. The beams in the ice halls roof were said to be soaked with water for instance [12]. This was a well-ventilated building with only part of its perimeter closed. The region in which this ice hall was located is known for its cloudy overcast. In the roof of a second ice hall, moisture contents around fibre saturation point were measured in winter.

2.4 THEORETICAL EQUILIBRIUM MOISTURE CONTENT

The theoretical equilibrium moisture content is calculated using the mathematical equation:

$$U_{EMC} = \frac{1800}{M_p}\left(\frac{K_1\varphi}{1-K_1\varphi} + \frac{K_2K_1\varphi + 2K_3K_2K_1^2\varphi^2}{1+K_2K_1\varphi + K_3K_2K_1^2\varphi^2}\right) \quad (1)$$

In which:

$$\begin{aligned} M_p &= 349 + 1.29t + 1.35\cdot10^{-2}t^2 \\ K_1 &= 0.805 + 7.36\cdot10^{-4}t - 2.73\cdot10^{-6}t^2 \\ K_2 &= 6.27 - 9.38\cdot10^{-3}t - 3.03\cdot10^{-4}t^2 \\ K_3 &= 1.91 + 4.07\cdot10^{-2}t - 2.93\cdot10^{-6}t^2 \end{aligned} \quad (2)$$

The parameters φ and t represent relative humidity and temperature, respectively. The equation was presented in [13] and is based on the Keylwerth & Noack diagram. Figure 2 visualises the mathematical relation for 20 °C. This is only one of the many mathematical formulations

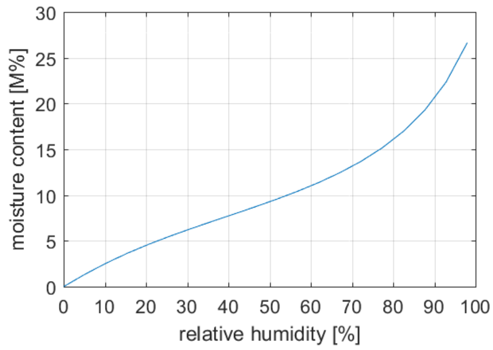

***Figure 2**: Visualisation of the sorption isotherm for 20°C [13]*

through which similar relations between relative humidity and moisture content are obtained.

2.5 MONITORING MOISTURE CONTENT

Extensive comparisons between methods and equipment to measure moisture content can be found [14][15][16]. Only the principles of electrical resistance and measurement of climate in a void in the structure are considered. Electrical resistance measured between two pins, see Figure 3 (left), is one of the most commonly applied methods. The second method is the measurement of the temperature and relative humidity in a hole in the wood, see Figure 3 (right).

If gauges are small enough, measurement of moisture content using electrical resistance methods is non-destructive. The oven dry method [17] is more accurate but also destructive. The electrical resistance method has been widely applied but is not very popular due to uncertainties between 1 M% to 2 M% [16]. General uncertainties are the material density, calibration, temperature, equipment, exact distance between the gauges, type of gauges, chemical composition, etc. New instrumentation methods are still developed [15][18]. Measuring moisture content bellow -5 °C is not recommended, and considered unreliable below -10 °C [19]. Measurement of material temperature along with resistance is done to correct for an increase of the resistance as temperature drops. A rule of thumb suggests a correction of 1 M% should be made per 10 °C [14].

Salt increases the electrical conductivity of wood. Salt storage buildings are often built in wood to the high corrosivity of steel. Increased conductivity can also be imagined in road bridges where salt is used to prevent ice formation on the road deck. Once a leakage occurs in a road deck and salt seeps through with the water, measurements will be equally affected.

An alternative to the electrical resistance method is offered by measuring relative humidity and temperature in a small void in the timber structure [20], see Figure 3 (left). The method has been applied before, but instead of using regular sorption isotherms, specially developed sorption isotherms need to be used to determine the relation between relative humidity, temperature, and moisture of the wood [15]. Moisture content of wood surrounded by a relative humidity and temperature is different from the relative humidity and temperature measured in the wood with the same moisture content.

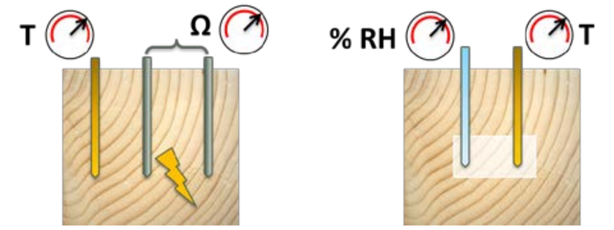

***Figure 3**: Illustration of moisture content measurement using the resistance method (left) and the measurement of climate within a small void (right)*

3 INSTRUMENTED STRUCTURES

3.1 INSTRUMENTATION

Both electrical resistance methods and climate monitoring in a small void were applied. The second method was installed for sake of redundancy and comparison. The gauges were installed within 70 mm of the cross-section's surface, see Figure 4. The pairs were placed 30 mm apart. The climate in the structure was logged as well and compared to the climate obtained for meteorological stations in the vicinity. The instrumentations were done on soft wood structures.

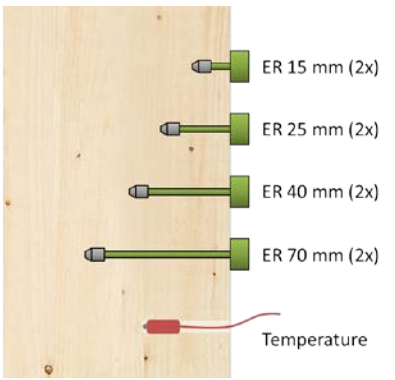

***Figure 4**:Measurement of moisture content through electrical resistance methods*

3.2 MONITORED BRIDGES

Seven bridges were already instrumented in former monitoring campaigns [21]. Five of the six instrumented bridges crossed a river, one crossed a road, see Figure 5. Measurement intervals occurred every 6 to 12 hours. The monitoring of these bridges was performed to:

- Measure how the moisture content developed throughout the cross section over time. How fast would an equilibrium moisture content be achieved and what is the equilibrium moisture content?
- Detect leakage in the asphalt deck.
- Monitor moisture content developments in sections of large beams that could not be inspected visually or with hand-held tools.

Leakage in the road deck was indeed timely detected on one bridge. Repairs were made and now monitoring is performed to observe the drying process again.

***Figure 5**: The monitored Horen bridge close to Aarau that crosses a road, photographed from the north side. The width of the load bearing beams is about 1600 mm.*

3.3 MONITORED BUIDLINGS

The newly instrumented structures were: one riding rink in the pre-alps, three ski-lift/cable car stations in the alps, and two ice rinks. The horse riding rink was instrumented because these are generally known to damper due to the wetting of the sand to minimise the amount of dust while riding. Moreover, this structure was also located in a damp area in the pre-alpine region at about 880 m.a.s.l.
Three ski-lift/cable car stations were instrumented as no measurements had been made until now in these types of structures. One station was built at an altitude of 1460 m.a.s.l., a second at 1860 m.a.s.l., and a third at 2600 m.a.s.l. above sea level, see Figure 6. As more and more structures on high altitudes are built in timber, the obtained data and experience would contribute to the modern building practice.

***Figure 6**: Cable car station located at 1950 m above sea level*

Finally, also two ice rinks were instrumented in the Jura mountain range. These were almost identical from a structural and functional point of view, see Figure 7. These structures were located 60 km apart, but differed about 600 m in altitude. Both structures were open and only half of the perimeter, the windward side, was closed. The ice rink located in the wetter region was at a 430 m.a.s.l. and the one in the dryer region was at 1020 m.a.s.l. above sea level. Differences in the dimensions of the structural elements are related to design snow loads or wind loads. The ice rinks stand a couple of

__Figure 7__: Ice rink located at 430 m.a.s.l. during a training late in the afternoon. Note the opposite long side is open and the short side is closed.

years already. The lower structure was erected in 2011, the higher one was erected in 2004. The instrumentation was less extensive as the other structures mentioned above.

4 CLIMATE AND MOISTURE CONTENT

4.1 THEORETICAL MOISTURE CONTENT PER MONTH

Measured temperature and relative humidity were obtained from the Federal Office for Meteorology and Climatology of Switzerland, MeteoSwiss. Monthly average relative humidity, temperature, and theoretical equilibrium moisture content was calculated. Data from each of the 133 meteorological stations plotted in Figure 1 was used.

Hourly values, measured 2 m above ground, of relative humidity and temperature obtained from MeteoSwiss spanned a total of 10 years, from 1 January 2005 until 31 December 2014. Extreme effects of single years are averaged out and the set was expected to make a good mix between amount of data and number of meteorological stations. Since 2013 the norm periods are recalculated every 10 years instead of every 30 years. Otherwise, practically every year would be warmer than normal due to the high rate at which the atmosphere is currently warming up.

Average theoretical equilibrium moisture contents in June and December were lowest and highest, respectively, as seen already in Table 1. As temperature decreases at a rate of about 6 °C per 1000 m increase of altitude, a correlation is expected between altitude and relative humidity as well. If absolute humidity remains constant over altitude, relative humidity should increase, and so should theoretical equilibrium moisture content. The dependency of relative humidity, temperature, and theoretical equilibrium moisture content on altitude is seen in Figure 8. The values are plotted for two months: June is shown in orange, December in blue. The size of the markers indicates the amount of data available per station, which could be small if the station was installed halfway or even close to the end of the span of the selected period. It is necessary to mention that no special methods were used to calculate of theoretical equilibrium moisture contents or account for moisture transport

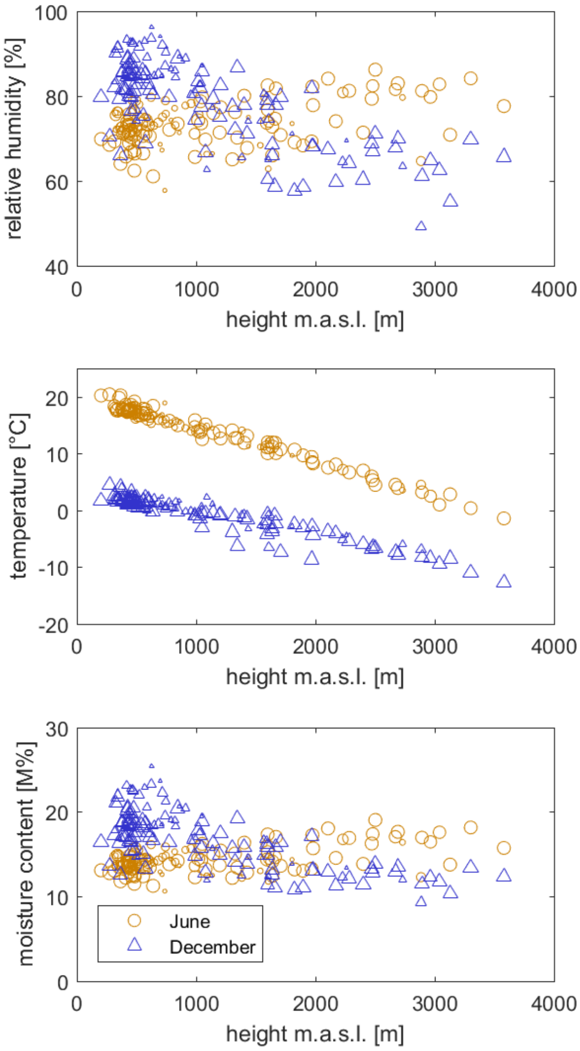

__Figure 8__: Average relative humidity, temperature, and moisture content plotted as a function of altitude above sea level. The size of the marker indicates the amount of data available for each station.

blow 0 °C. As water transfers to ice at a certain point, not directly under 0 °C, transport might significantly be reduced and theoretical moisture content values for December, or generally winter, might not be correct.

The positive relation between relative humidity and altitude is reflected in the data for June shown in Figure 8. The relation is negative though for December, probably due to the cloud overcast over central plateau in autumn/winter above 1000 m.a.s.l. forming a temperature barrier between the climate beneath and above the overcast. The relation between temperature and altitude also shows a larger spread between 1000 m.a.s.l. and 2000 m.a.s.l. than on other temperatures. It is expected that if the stations are arranged according to biogeographical regions, better insight could be obtained. The spread in the relative humidity is also observed in the calculated theoretical equilibrium moisture contents. Per altitude, spread 8 M% to 10 M% can easily be found in December. In June, the spread in relative humidity, temperature and theoretical equilibrium moisture contents are smaller.

4.2 MEASURED RELATIVE HUMIDITY IN THE MONITORED BRIDGES

The bridges that were monitored were all located in the middle land and in the pre-alpine region (northern side). Some of these bridges were monitored over one year only, others were monitored for several years. Temperature and relative humidity sensors were installed along with moisture content monitoring. These were located below the bridge. Relative humidity measured over the years is visualised in Figure 9, where the monthly averages are plotted. The highest bridge was located at 770 m.a.s.l.. The spread in the average relative humidities over the year was also observed in Figure 8. Note that only one of these bridges, the Horen bridge, is located over a road. All the others cross rivers. The climate shows a spread of about 20 %RH throughout the year. It is difficult to distinguish whether this is due to the bridge being located over water or a road, orientation, or it being in an open field or in an area with vegetation.

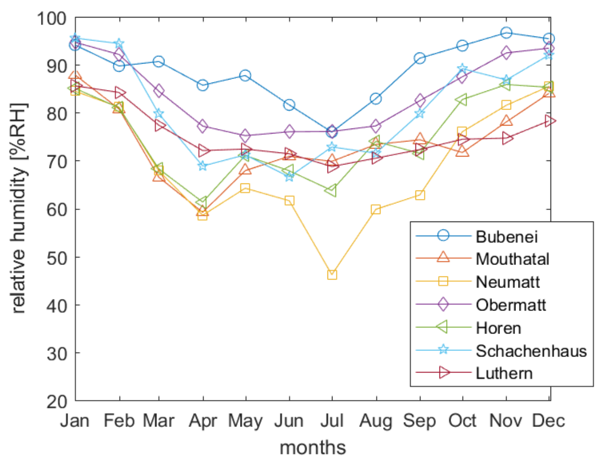

__Figure 9__: Relative humidities measured at the bridges calculated per month. Note that for some bridges, only one year of data was measured.

4.3 MEASURED RELATIVE HUMIDITY IN THE MONITORED BUILDINGS

Since the new monitoring objects were only installed recently, not much data is available yet. However, whatever is available is plotted in Figure 10. The measurements were done every three hours. The figure shows the measurements made in the lower ice rink and the riding hall (top), and the measurements in the cable car stations (bottom).

The relative humidity in the structures in the alps shows a large spread than in the structure at 880 m.a.s.l. This is not only related to building physics. All structures are well ventilated and the climate outside the structures in fact shows higher variations. The building envelope dampens the extremes. Minimum relative humidities are around 30 %RH and humidities of 50 %RH are regularly encountered.

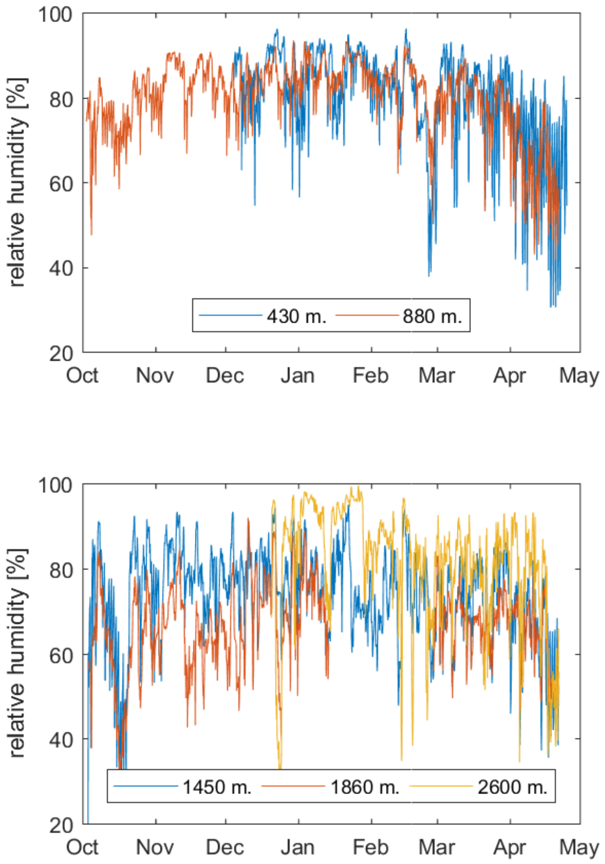

__Figure 10__: Visualisation of relative humidities measured in the structures under (ice rink and riding hall) and above 1000 m.a.s.l. (ski stations)

4.4 COMPARISON OF MEASURED CLIMATES WITH REGIONAL CLIMATE

The relative humidity and temperature measured in and around the monitored structures were approached in a similar way as was done with the meteorological data from the 133 stations in Figure 8. These experimental data are visualised in Figure 11, along with the meteorological data which is plotted with small markers. The experimental data is shown with large, filled markers. The measured moisture contents averaged over a year, because instrumentation (gauge depth) was not uniform over the different structures. Variations in moisture content measured close to the surface can be around 4 M% and only 1 M% to 2 M% in the centre of cross sections. Differences would be barely recognisable. As instrumentations were performed in the autumn of 2017, data for the whole year is not available yet for the new instrumented buildings. The figure will be updated as years progress and data is acquired.

The figure shows that the structure at 2600 m.a.s.l. experienced a high relative humidity in December. As the instrumentation was done late in the month, the point might not be representative. Generally, the measured data shows overlap with the conditions measured throughout the country. Temperatures overlap quite well with the meteorological data. The spread in relative humidity and theoretical moisture content calculated

from the meteorological data is reflected in the experimental data. For the moment, the average moisture content shows a slight negative dependency on altitude. As some of the structures were erected only a year ago, average moisture contents might not have been achieved yet within the timber in all structures.
Since temperatures were below zero for extended periods of time on the structures located on high altitudes, the measurement of climate in a small void was used to estimate the moisture content. As mentioned in Section 2.5, using the electrical resistance method below 0 °C becomes unreliable.

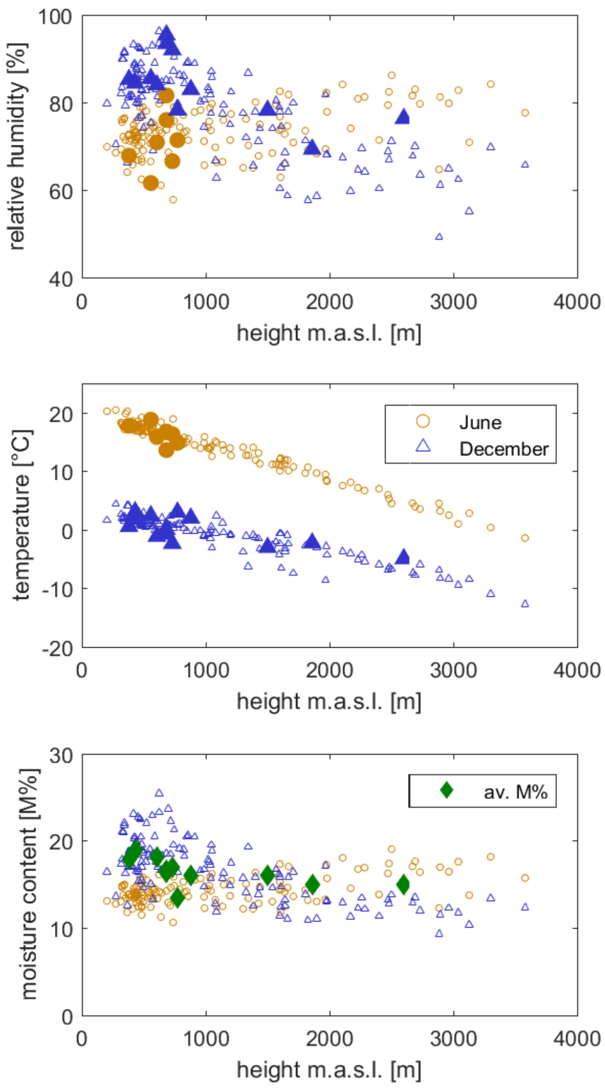

***Figure 11**: Comparison of monthly means of relative humidity, temperature and theoretical equilibrium moisture contents (empty markers) compared with experimental data (full markers). The yearly averages for moisture content are shown because instrumentation is non-uniform and variations are small.*

5 CONCLUSION

The analysis of the climate obtained from the meteorological stations across the country showed that there is a large spread in the relative humidities that can be expected throughout the country. It is therefore recommended to use biogeographical classification perhaps to identify damp or dry areas. This could help to refine the geographical classification found in the SIA 265:2012 [4]. In a humid region for instance, extra attention could be paid to ventilation of the structure. The spread in the observed climate is reflected in the Köppen and Geiger classification.
As to the monitoring of timber bridges, no difference in moisture content could be distinguished yet if the obstacle crossed was either a river or a road. Many factors probably affect the local climate around the bridge, but adequate detail design and proper maintenance and ventilation are perhaps more important.
The levels of average temperature in the colder months prove that the electrical resistance method at these altitudes above 1500 m.a.s.l. to 2000 m.a.s.l. is not suitable. The alternative is offered by measuring climate inside a void, but the method probably needs to be understood in more detail. Whether there is any significant moisture transport below 0 °C, or if the transport is significantly reduced and the moisture content resembles that found above 0 °C, needs to be clarified.
The monitoring of the structures helped to better understand the climate to which the timber structures are subjected, although some work still needs to be done. It has at least been clarified more what can be expected when building on greater height. Relative humidities reduce to normal Service Class 2 conditions, around 1000 m.a.s.l. and higher. Special conditions due to the building type or building location must always be considered though.

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